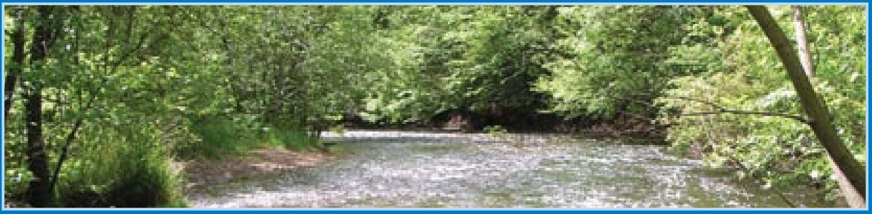
UNIVERSITY OF MINNESOTA

Assessment of Stormwater Best Management Practices

Edited by John S. Gulliver, P.E., Ph.D., and James L. Anderson, Ph.D.



Stormwater Management Practice Assessment Project

April 2008

Assessment of Stormwater Best Management Practices.

Edited by J. S. Gulliver and J.L. Anderson.

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http://wrc.umn.edu/outreach/stormwater/

Stormwater Management Practice
Assessment Project

Table of Contents

Preface

This manual, "Assessment of Stormwater Best Management Practices," is one deliverable of a project that was created with funding provided by the Minnesota Pollution Control Agency, project number 347-6053, with Bruce C. Wilson as Project Manager. Funding for partner projects was provided by the Minnesota Metropolitan Council Environmental Services, project number 347-6054, with Jack Frost as Project Manager, and the Minnesota Local Road Research Board, contract number 81655 Work Order 162, with Jon Haukaas as Technical Liaison. In-kind assistance provided by Dakota County through a study funded by the Water Environment Research Foundation was appreciated.

There are a number of individuals who worked on this project and the partner projects, including:

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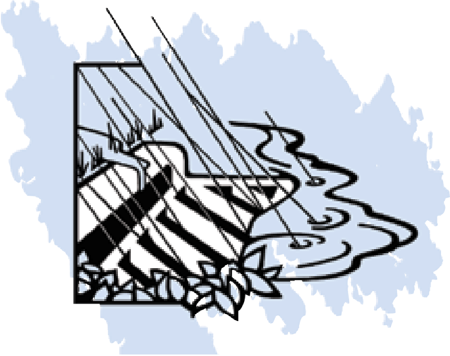

1.

Introduction

A. J. Erickson, J. S. Gulliver (gulli003@umn.edu), R. M. Hozalski, P. T. Weiss, J. L. Anderson, University of Minnesota

The Minnesota Pollution Control Agency (MPCA) is required by the Clean Water Act Section 303 (d), Total Maximum Daily Load (TMDL), to assess water quality and to identify impaired streams and lakes. In the most recent of these assessments (MPCA 2006), there were 2,250 impaired water bodies identified in Minnesota, including 1,013 lakes and approximately 1,162 streams covering 9,099 river miles. Excluding those impaired by mercury, approximately 938 water bodies are listed due to one or more pollutants such as nutrients, turbidity, chloride, temperature, bacteria, and others which are common to stormwater runoff (see figure 1.1). Of the 938 listed water bodies, 118 are impaired lakes located within municipalities. In Wisconsin, 217 of the 643 water bodies are impaired by mercury and 51 are impaired by other pollutants (WDNR 2007) and in Michigan there are 52 approved TMDLs that are not meeting water quality standards (MDEQ 2007). The large number of impaired lakes and rivers indicates that municipalities and communities need to control both the *quantity* and the *quality* of urban stormwater runoff.

Hot Links

Erickson, A.J., J.S. Gulliver, R.M. Hozalski, P. T. Weiss, and J.L. Anderson. 2007. Introduction. In *Assessment of Stormwater Best Management Practices,* ed. J.S. Gulliver and J.L. Anderson. St Paul, MN: University of Minnesota.

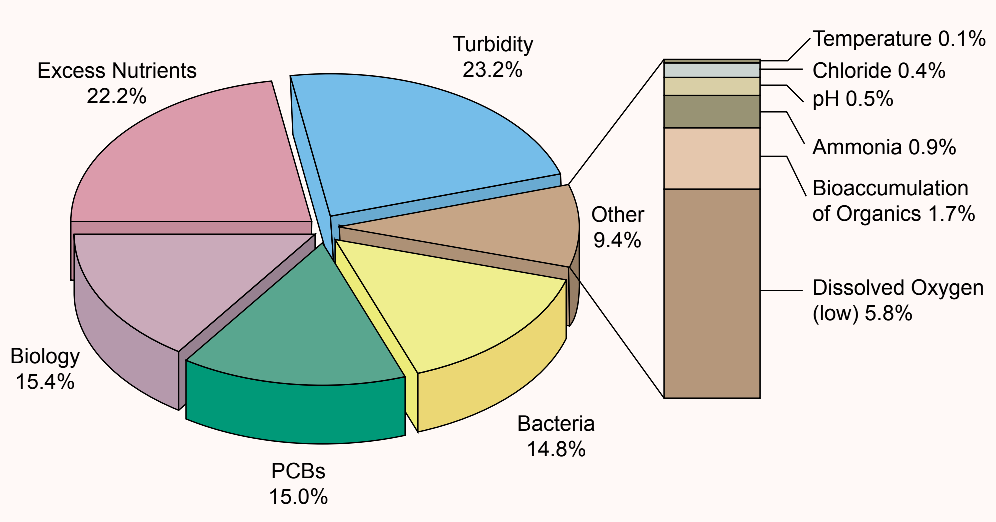

Figure 1.1: Water body impairments in Minnesota (Minnesota Pollution Control Agency 2006)

As a part of the municipal stormwater management efforts regulated by the federal Clean Water Act, city and county resource managers are being asked to define their systems, make improvements, and prevent degradation of downstream water bodies. To do so, urban stormwater Best Management Practices (BMPs) are designed to reduce runoff peaks, volumes, or pollutant loads of phosphorus and solids or turbidity, among others. Over the past five years, designs have increasingly focused on increasing groundwater recharge via infiltration techniques. After design and installation, the next steps in adaptive management include assessing the performance of stormwater BMPs, including optimization of their operation and maintenance. This manual, "Assessment of Stormwater Best Management Practices," is intended to augment information provided in the Minnesota Stormwater Manual (http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html#manual) by providing a range of assessment options and recommendations for use by municipalities and associated support service providers. It is anticipated that standardized performance measures will aid in refining stormwater BMP and pollution prevention practice and maintenance needs.

1.1 Need, purpose, and audience

Existing and developing communities are designing and installing a wide variety of urban stormwater BMPs as well as implementing source reduction BMP measures in order to protect or rehabilitate receiving waters. These efforts will incur significant costs while the environmental and cost effectiveness is still in question. Qualitative and quantitative stormwater BMP effectiveness (see definition in section 1.4 below) is subject to many factors (e.g. seasons, geology, topography, storm events, etc. [Weiss et al. 2005] that have made it difficult to compare many historical stormwater study results. Hence, it is advantageous to develop reasonably consistent methods for accurate assessments that will aid in sharing information and developing technologies. To meet these needs, the University of Minnesota's Water Resources Center has collaborated with the Department of Civil Engineering, St. Anthony Falls Laboratory, and the Department of Bioproducts and Biosystems Engineering to provide diverse expertise and to develop:

- Four levels of assessment ranging from relatively simple visual inspections to state-of-the-art monitoring;
- More accurate methods for flow measurement in stormwater conveyance systems;
- Advanced sampling methodologies that will help minimize typical sources of bias;
- Source reduction measures along with estimation spreadsheets for municipal uses;
- Data analyses and standardized inspection checklists; and
- An assessment manual that includes specific considerations for categories of stormwater BMPs.

The Minnesota Stormwater Manual (Minnesota Stormwater Steering Committee 2005, http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html#manual) provides guidance for the design and installation of stormwater BMPs. After design and installation, the next step in adaptive management for stormwater BMPs is *assessment of stormwater BMPs to determine their effectiveness* at reducing stormwater runoff quantity (e.g. peak flow, volume, or both), improving stormwater quality, or both. This manual, “Assessment of Stormwater Best Management Practices,” has been developed to provide guidance and explanation of assessment methods for stormwater BMPs.

A standardized methodology for the assessment of stormwater BMPs creates guidelines that users can follow to accurately assess performance and report results such that broad comparisons can be made despite differences in geography, stormwater BMP type, season, and watershed. There are many potential end-users of this information, such as:

- A municipal engineer, responsible for stormwater, needs to perform and document city-wide stormwater BMP inspections. Visual assessment (level 1, see section 1.2 below) standard procedures could be used to accomplish a system-wide review using available public works personnel in a cost-effective manner. Seasonal visual inspections can also help refine operation and maintenance schedules and procedures.
- A watershed district is recommending municipal stormwater allocations for a downstream lake Total Maximum Daily Load (TMDL) effort and needs to estimate the effects of reducing municipal general sources (e.g. street sweeping, urban forestry etc.) of phosphorus. Assessment of source reduction methods (Chapter 7) could be used to estimate the phosphorus load reduction of these practices.
- A watershed management organization is working with several cities to evaluate the effectiveness of all rain gardens in specific districts, identifying those requiring maintenance. Visual Inspection (level 1, see section 1.2 below) evaluations will determine those that have failed. Capacity testing (level 2, see section 1.2 below) will provide general information on infiltration rates including data for use in predictive models. Synthetic runoff testing (level 3, see section 1.2 below) assessments will quantify water and pollutant load reductions.
- A consulting engineer has been tasked with developing a municipal stormwater monitoring program (level 4, see section 1.2 below), including a nearby trout stream, that will allow refinement of

operation and maintenance procedures and help prevent excessive temperature export.

- The county environmental services department has been directed to work with cities to organize more efficient monitoring of all the regional highway stormwater ponds and estimate the life stage of the ponds. Some of the monitoring objectives would be better served by accurate level 2 or level 3 testing (see section 1.2 below), and department personnel may wish to use this manual to make this suggestion.

As shown by the list of possible users, the intended audience for this assessment manual is diverse and varied. Assessment of stormwater BMPs can be a complex task and may require technical understanding of processes that occur in stormwater management. To simplify the use of this manual, technical background explaining why a procedure is being recommended have been set off with the label "Advanced Discussion." An example of an Advanced Discussion section is shown below:

ADVANCED DISCUSSION

Advanced Discussion sections provide detailed explanations, tool comparisons, and other technical information pertaining to assessment of stormwater BMPs. Readers are encouraged to read these sections to become familiar with the information that is provided, but can bypass these sections during subsequent uses of the manual.

1.2 Assessment

The assessment of stormwater BMPs has historically been accomplished with monitoring (e.g., Anderson *et al.* 1985; Bell *et al.* Undated; Kovacic *et al.* 2000; Lin and Terry 2003; Silvan *et al.* 2004; Winer 2000). Monitoring is the most comprehensive form of assessment and can estimate the multi-objective performance of a stormwater BMP within a given watershed. Monitoring programs, however, also require costly effort (discussed in Chapter 3) for a relatively long period (often 14 or more continuous months) to sample a needed range of storm sizes (U.S. EPA. 2002b). Unfortunately, the results of monitoring studies are often uncertain because of poor characterization of discharge into and out of the stormwater BMP, pollutant sampling problems (e.g., difficulty obtaining a representative suspended solids sample), or both. There are alternative stormwater BMP assessment techniques currently in use or in development that are more specific to a given situation. This manual has categorized the available assessment techniques into four levels of increasing effort and duration. The four levels are described in detail in Chapter 3, but a brief description of each of the four levels follows:

1. **Visual Inspection:** Rapid assessment procedure that visually evaluates and photographically documents the effectiveness of a stormwater BMP device. The primary purpose of visual inspection is to identify, diagnose, and schedule maintenance for non-functional stormwater BMPs.
2. **Capacity Testing:** An assessment method used to evaluate the primary function of a stormwater BMP. For example, level 2 assessment of infiltration practices measures infiltration capacity and level 2 assessment of a dry pond (sedimentation) measures the

sediment accumulation and sediment storage capacity using spatially distributed, relatively rapid, and simple point measurements.

3. **Synthetic Runoff Testing:** An assessment method that simulates stormwater runoff in a controlled environment to assess stormwater BMP effectiveness. Controlling discharge and pollutant (e.g., sediment) concentrations allows for accurate evaluation of BMP effectiveness for runoff volume reduction or pollutant removal from stormwater.
4. **Monitoring:** An assessment method that relies on natural rainfall or snowmelt runoff. Discharge measurement and sample collection and analysis are required to determine the mass of water and pollutants entering and leaving the system, which, in turn, is used to estimate effectiveness. Monitoring is the most comprehensive method of multi-objective assessment.

1.3 Document organization

This manual, "Assessment of Stormwater Best Management Practices," is organized into 13 chapters. Each chapter is intended to provide guidance and information on stormwater (e.g., stormwater processes), a specific step in assessment (e.g., water budget measurement), or assessment considerations specific to a process (e.g., sedimentation practices). To help the reader find specific information within this guidance manual, table 1.1 lists several common stormwater BMPs and the corresponding chapters in which they are discussed. In addition, each chapter and appendix is described below.

Chapter 1: Introduction. The introduction describes the audience, need, and purpose for a manual on the "Assessment of Stormwater Best Management Practices." The introduction also includes the organization of the document and a list of nomenclature commonly used in stormwater management and assessment.

Chapter 2: Stormwater Treatment Processes. Chapter 2 discusses characteristics and processes relevant to stormwater runoff, including stormwater composition and biological, chemical, hydrologic, and thermal processes. Understanding stormwater characteristics and processes is critical to developing a successful assessment program.

Chapter 3: Developing an Assessment Program. Assessment of stormwater BMPs requires organization and planning. Chapter 3 outlines

Table 1.1: BMPs and assessment tools with corresponding chapters and appendices.

BMP	Chapter(s) and Appendices	
Constructed wetlands	11.	Biologically enhanced practices
	Appx B.	Selection and use of permeameters and infiltrometers
Dry ponds	10.	Sedimentation
	Appx B.	Selection and use of permeameters and infiltrometers
Erosion control	7.	Source reduction
Fertilizer management	7.	Source reduction
Infiltration basin	9.	Infiltration
	Appx B.	Selection and use of permeameters and infiltrometers
Infiltration trench	B.	Selection and use of permeameters and infiltrometers
Porous pavement	9.	Infiltration
	Appx B.	Selection and use of permeameters and infiltrometers
Rain gardens (bioretention practices)	11.	Biologically enhanced practices
	Appx A.	Case studies
	Appx B.	Selection and use of permeameters and infiltrometers
Sand and salt management	7.	Source reduction
Sand filter	4.	Water budget measurement
	8.	Filtration
	Appx A.	Case studies
	Appx B.	Selection and use of permeameters and infiltrometers
Soil filter	4.	Water budget measurement
	Appx B.	Selection and use of permeameters and infiltrometers
Street Sweeping	7.	Source reduction

a practical method for developing and implementing a successful assessment program based on assessment goals and utilizing the four levels of assessment (visual inspection, capacity testing, synthetic runoff testing, and monitoring).

Chapter 4: Water Budget Measurement. Assessment of stormwater BMPs requires an understanding and accurate measurement of the water budget. Chapter 4 describes several methods for measuring water budget inflows and outflows, such as open channel flow, conduit flow, infiltration, evaporation, transpiration, and rainfall, and provides recommendations for simple, accurate water budget measurement.

Chapter 5: Sampling Methods. One possible goal of an assessment program is to determine the pollutant removal efficiency of a stormwater BMP. To determine pollutant removal efficiency, one must measure pollutant amounts (e.g., mass or concentration) in stormwater runoff. Chapter 5 discusses methods for measuring pollutant(s) in stormwater runoff, such as winter sampling, and for measuring pollutants such as temperature and suspended solids.

Chapter 6: Analysis of Soil and Water. Stormwater often contains several pollutants at various concentrations. Determining target pollutants and accurate analytical methods are important to developing a simple and cost-effective assessment program. Chapter 6 describes common stormwater analyses and quality assurance/quality control considerations such as bias, precision, and inspection.

Chapter 7: Source Reduction. Source reduction is a method of stormwater management that reduces or limits sources of pollution before pollutants enter the stormwater collection system. Source reduction techniques include management of lawns and lawn fertilizers, management of soil and erosion control practices, and street sweeping, among others. Chapter 7 discusses source reduction techniques and how they can be assessed for performance.

Chapter 8: Filtration Practices. Filtration is a stormwater process that removes pollutants by physical sieving. Chapter 8 describes filtration practices and assessment considerations specific to soil and sand filters. Chapter 8 also includes standard procedures for conducting level 1 assessment (visual inspection) for filtration practices.

Chapter 9: Infiltration Practices. Infiltration is a stormwater process in which stormwater runoff enters the soil and is transported subsurface to groundwater or surface outflows. Infiltration can be used as a stormwater management practice to reduce runoff volumes and recharge groundwater. Chapter 9 describes infiltration practices and assessment considerations specific to infiltration trenches, infiltration basins, and porous pavements. Chapter 9 also includes standard procedures for conducting level 1 assessment (visual inspection) for infiltration practices.

Chapter 10: Sedimentation Practices. Sedimentation is a stormwater process that removes pollutants by settling. Chapter 10 describes sedimentation practices and assessment considerations specific to dry ponds, wet ponds, wet vaults, and proprietary devices. Chapter 10 also includes standard procedures for conducting level 1 assessment (visual inspection) for sedimentation practices.

Chapter 11: Biologically Enhanced Practices. Biologically enhanced practices are stormwater management practices that utilizevegetation in addition to filtration, infiltration, or sedimentation processes for stormwater storage, conveyance, and treatment. Chapter 11 describes biologically enhanced practices and assessment considerations specific to bioretention practices (a.k.a. rain gardens), wetlands, swales, and filter strips. Chapter 11 also includes standard procedures for conducting level 1 assessment (visual inspection) for biologically enhanced practices.

Chapter 12: Data Analysis. Chapter 12 describes methods for analyzing assessment data such as summation of loads and the efficiency ratio method. Once assessment data is analyzed, conclusions about performance can be made with corresponding uncertainty. Results from visual inspections should be reported to regulatory agencies according to local regulations, but guidance is provided in chapter 12.

Chapter 13: Future of the Manual. Chapter 13 describes the authors' intentions for "Assessment of Stormwater Best Management Practices," including areas of future research, knowledge gaps, and potential collaborative efforts.

Appendix A: Case Studies. Appendix A includes several case studies of assessment for stormwater BMPs including rain gardens, underground proprietary devices, and infiltration basins. Case studies are real-world examples of assessment that discuss procedures, results, and, often, lessons learned.

Appendix B: Procedures for the Visual Inspection of Stormwater Best Management Practices. Appendix B contains all the checklists for visual inspection of stormwater BMPs. The visual inspection checklists can also be found at the end of chapters 8–11.

Appendix C: Selection, Construction, and Use of Permeameters and Infiltrometers and Permeameters. Appendix C includes discussion of selection, construction, and use of various permeameters and infiltrometers, including the Philip-Dunne Permeameter for use in level 2 assessment (capacity testing).

Appendix D: Automatic Sampling of Waters Containing Suspended Solids. Automatic sampling of stormwater that contains suspended solids has documented inaccuracies. Appendix D discusses the inaccuracies and introduces some of the research that is currently investigating methods to more accurately collect samples that contain suspended solids.

Appendix E: Assessing Thermal Impacts of Stormwater BMPs. This appendix provides instruction on how to assess thermal impacts of stormwater BMPs via monitoring influent and effluent flow temperatures.

As mentioned above, the Minnesota Stormwater Manual (Minnesota Stormwater Steering Committee 2005) http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html#manual) provides guidance on design and installation of stormwater BMPs and may be used concurrently with this guidance manual during the design phase to include design elements specific to flow measurement (chapter 4) or sampling (chapter 5) to facilitate testing, monitoring, or both. Alternatively, this manual may be used as a guideline for retrofitting stormwater BMPs to facilitate assessment.

It is important to note that this manual does not contain information on all methods of assessment for all available stormwater BMPs. This manual is, however, intended to be a 'living' document and therefore be updated as technology advances and more techniques and practices become known.

1.4 Nomenclature

Variability in nomenclature concerning stormwater and stormwater treatment can be confusing and misleading. The stormwater-related terms used throughout this manual are defined below. Additionally, there is an index at the end of this manual that lists where each term occurs.

Assessment: Assessment, with regard to stormwater best management practices (BMPs), is the process for determining whether a stormwater BMP is effective at meeting one or all of its design objectives. Assessment may include visual inspection and testing or monitoring.

Best Management Practice: Best management practice is a business term that designates the best of a variety of management practices. A stormwater BMP refers to the best of a variety of practices designed to best meet the objectives of stormwater treatment.

Biologically Enhanced Practices: Biologically enhanced practices are stormwater BMPs that use vegetation to enhance the quantity control or pollutant retention performance of the stormwater BMP in addition to filtration, infiltration, sedimentation, or some combination thereof. Examples include wetlands, rain gardens (bioretention), filter strips, and swales.

Capacity Testing: Capacity testing is the second level of assessment and relies on a set of point measurements to estimate the stormwater BMP's permeability or sediment retention capacity.

Discharge: Discharge is the rate at which fluid (water) is transported in units of volume per time (e.g., ft^3/s, m^3/s, gallons/day, etc.)

Effectiveness: Effectiveness, for stormwater BMPs, is a measure of the ability of a stormwater BMP to meet an objective (e.g., reduce peak runoff volume or rate, reduce total runoff volume, increase groundwater recharge, or retain one or more target pollutants), typically expressed as a percentage. *For example, the effectiveness at reducing runoff volume of a bioretention facility that reduced runoff volume by 54% through infiltration, evapotranspiration, and other processes is 54%.*

Evapotranspiration: Evapotranspiration is the combined effects of evaporation and transpiration. Evaporation is the process by which surface water or soil moisture is converted to water vapor and released to the atmosphere. Transpiration is the process by which vegetation releases water vapor to the atmosphere.

Filtration: Filtration, for stormwater treatment, is the process by which a pollutant is removed from stormwater runoff by passing through filter media (sand, soil, or other). Stormwater filters use a collection system (e.g., perforated pipe) to capture treated stormwater and transport it to a stormwater delivery system or receiving waters.

Flow: Flow is the process by which water is transported from one location to another. For stormwater, there are two principal methods in which flow can be transported: open channel flow and pressurized conduit flow.

Infiltration: Infiltration is the process by which surface water seeps into the soil and percolates to the groundwater system. Depending on the depth of infiltration, groundwater flow patterns, and topography, infiltrated water can re-emerge as surface water at a different location and a later time.

Monitoring: Monitoring is the fourth level of assessment and relies on sampling during natural storm events using permanent (or semi-permanent) data collection equipment (flow meters, samplers, rain gauges). Monitoring is typically a long-term process involving data collection over several storm events and spanning two or more rainy seasons.

Open channel flow: Open channel flow is the process by which water is transported by gravity with with a free surface exposed to atmospheric pressure. The channel which forms the means of conveyance can be natural (e.g., streams, rivers) or constructed (e.g., culverts, canals, swales). Flow in conduits that does not fill the conduit is also open channel flow.

Pressurized conduit flow: Conduit flow is the transport of water in closed conduits (e.g., pipes) that are flowing full. Flow occurs because there is a longitudinal pressure difference along the conduit.

Sedimentation: Sedimentation is the process by which solids settle out of a water column, generally described by Stoke's Law.

Synthetic runoff testing: Synthetic runoff testing is the third level of assessment. It uses synthetic stormwater applied at a controlled rate with or without a well characterized amount of sediment to determine the effectiveness of stormwater BMPs.

Source reduction: Source reduction is the process by which stormwater runoff volume is reduced, stormwater runoff quality is improved, or both, *before* the stormwater enters a treatment device or the storm sewer system. For example, street sweeping is source reduction because it removes sediment and other particulate pollutants before stormwater runoff carries them into the storm sewer system.

Stormwater best management practice (BMP): The U.S. EPA defines a best management practice (BMP) as "Schedules of activities, prohibitions of practices, maintenance procedures, and other management practices to prevent or reduce the discharge of pollutants to waters of the United States. BMPs also include treatment requirements, operating procedures, and practice to control plant site runoff, spillage or leaks, sludge or waste disposal, or drainage from raw material storage." (U.S. EPA. 2004a)

A stormwater BMP is a means for improving stormwater runoff quality, reducing runoff volume, reducing runoff peak flow, or any combination thereof. Examples of stormwater BMPs are source reduction, sand filters, infiltration basins and trenches, rain gardens (bioretention), dry ponds, wet ponds, constructed wetlands, swales, filter strips, wet vaults, and underground proprietary devices.

Stormwater runoff: The water that flows over the ground surface or into conduits as a result of rain storms, snowmelt, or both. Water from rainfall events that infiltrates into soil, evaporates, or transpires directly from the surfaces of vegetation is no longer stormwater runoff.

Treatment process: A treatment process is a mechanism by which the stormwater BMP improves the quality of stormwater runoff. For example, a dry pond holds stormwater and releases it slowly (relative to uncontrolled conditions) to downstream receiving waters. The *primary* treatment process of a dry pond is sedimentation because most of the pollutants in stormwater that are retained by a dry pond are settled out while the stormwater runoff is held in the pond.

Visual inspection: Visual inspection is the first level of assessment and sometimes can be used to determine when a stormwater BMP requires maintenance, replacement, or other levels of assessment.

Water budget: A water budget, for a stormwater BMP, is the accounting of water that enters, exits, and is stored by the stormwater BMP. The water budget assigns flow rates to each of the processes that affect the fate of water,

Table 1.2: Typical concentrations for stormwater runoff and regulatory standards (U.S. EPA. 2002a, Minnesota Pollution Control Agency 2003, U.S. EPA. 2004b, Weiss and Hondzo 2004).

	Total Suspended Solids	**Total Phosphorus**	**Nitrate**	**Nitrite**	**Chloride**	**Copper**	**Zinc**	**Cadmium**	**Lead**
Mean highway runoff concentrations (Twin Cities, MN), (Weiss and Hondzo 2004)	116.3 mg/L	0.43 mg/L	0.77 mg/L (total N)		11.5 mg/L	0.023 mg/L	0.123 mg/L	0.0025 mg/L	0.242 mg/L
Mean highway runoff concentrations (nationwide), (Weiss and Hondzo 2004)	157.3 mg/L	0.48 mg/L	0.79 mg/L (total N)		33 mg/L	0.0527 mg/L	0.923 mg/L	0.0063 mg/L	0.254 mg/L
Drinking water standards (U.S. EPA. 2004b, U.S. EPA. 2002)	500 mg/L (TDS)	NA	10 mg/L	1 mg/L	250 mg/L	1.300 mg/L	5.00 mg/L	0.005 mg/L	ZERO
Water quality standards, Class 2 Aquatic Life and Recreation (Minnesota) (Minnesota P.C.A. 2003)	10 NTU	NA	NA	NA	230 mg/L	CS: 0.009 mg/L^1 MS: 0.0149 mg/L^2 FAV: 0.030 mg/L^3	CS: 0.0907 mg/L^1 MS: 0.100 mg/L^2 FAV: 0.200 mg/L^3	CS: 0.0009 mg/L^1 MS: 0.0272 mg/L^2 FAV: 0.0544 mg/L^3	CS: 2.52 mg/L^1 MS: 64.78 mg/L^2 FAV: 129.55 mg/L^3

NTU: Nephelometric Turbidity Units
Nitrate and Nitrite: measured as Nitrogen
NA: Not Applicable
**standards calculated based on hardness of 83.21 mg/L as $CaCO_3$, which is an average hardness for Twin Cities, MN, creeks and rivers as reported by Weiss and Hondzo (2004).*
[1] *CS: Chronic Standard*
[2] *MS: Maximum Standard*
[3] *FAV: Final Acute Value*

Table 1.3: Mean and Maximum values for constituents in stormwater runoff (Weiss and Hondzo 2004).

	Moxness, 1986		Moxness, 1987		Moxness, 1988		Drapper et al., 2000		Sansalone and Buchberger, 1997		Driscoll et al., 1990 (Mpls/ St.P.)		Driscoll et al., 1990 (nationwide)	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Hardness (as $CaCO_3$)(mg/L)	34	79	128	410	56	86	N/A	N/A	67.600	92	N/A	N/A	N/A	N/A
Copper (mg/L)	0.034	0.330	0.025	0.071	0.008	0.017	0.090	0.340	0.135	0.325	0.025	N/A	0.052	N/A
Zinc (mg/L)	0.147	0.960	0.200	0.560	0.021	0.033	0.523	1.850	4.280	15.244	N/A	N/A	0.368	N/A
Cadmium (mg/L)	0.001	0.007	0.0025	0.017	0.004	0.018	N/A	N/A	0.007	0.011	N/A	N/A	0.017	N/A
Lead (mg/L)	0.225	1.700	0.450	1.300	0.030	0.100	0.224	0.620	0.064	0.097	0.262	N/A	0.525	N/A
Phosphorus (mg/L)	0.333	2.430	0.570	0.988	0.500	1.100	0.700	1.800	N/A	N/A	0.328	N/A	0.435	N/A
Chloride (mg/L)	31	570	63	200	49	304	N/A	N/A	N/A	N/A	11.500	N/A	33	N/A

including input processes (e.g., direct precipitation into the BMP, surface runoff, and conduit or open channel flow) and output processes (e.g., infiltration, evapotranspiration, and conduit or open channel flow). The goal for developing a water budget is to balance the inflows and outflows with minimal error.

Water quality: Water quality refers to the physical, chemical, and biological properties of the water. Stormwater quality is typically determined by analyzing the concentrations of pollutants in the stormwater and then comparing the pollutant concentrations to water quality standards (see tables 1.2 and 1.3 above). One goal of many stormwater BMPs is to improve the quality of stormwater runoff by reducing the concentrations or load of pollutants in stormwater runoff before delivery to receiving waters.

Water quantity: Water quantity of stormwater runoff refers to an amount of water that is treated by a stormwater BMP. Water quantity control of stormwater runoff is the process by which a stormwater BMP stores runoff, reduces the peak flow, converts stormwater runoff to stormwater infiltration, evaporation, transpiration, etc, or any combination thereof.

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2.

Stormwater Treatment Processes

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2.1 Stormwater processes

This chapter examines a conceptual framework of the hydrologic, physical, biological, chemical, and thermal processes that alter the flow and quality of urban stormwater. This conceptual framework, called the process assessment framework (PAF), can be used to guide the design of an assessment program for a given stormwater BMP or for an entire stormwater management program for a watershed. The main goal of the PAF is to focus the stormwater assessment program on key processes and the limitations of these processes to treat stormwater. For example, the PAF for a wetland treatment system starts by examining the processes occurring in a wetland treatment system that are needed to achieve stated goals. The resulting assessment program would focus on these processes.

The PAF can also be used to ask appropriate questions about the function of each stormwater BMP and how it should be assessed, such as:

1. What hydrologic processes occur and how do they affect the flow of water to streams and groundwater?

Hot Links

1. Characteristics of urban stormwater
2. Designing a process assessment framework
3. Physical, biological, and chemical processes

Baker, L.A., J.S. Gulliver, B.N. Wilson, O. Mohseni, A.J. Erickson, and R.M. Hozalski 2007. Stormwater treatment processes. In *Assessment of Stormwater Best Management Practices,* ed. J. S. Gulliver and J.L. Anderson. St Paul, MN: University of Minnesota.

2. What processes are involved in the generation of pollutants and how can these processes be altered to reduce pollution at the source?
3. What are the physical, biological, and chemical processes that retain pollutants in stormwater BMPs?
4. What is the fate of pollutants and how does that fate affect operations and maintenance of the BMP?
5. What processes alter the temperature of stormwater and what can be done to minimize thermal pollution in urban streams?
6. What other factors limit long-term sustainability of key processes involved in stormwater treatment and how do these affect operations and maintenance?

Section 2.2 describes general characteristics of urban stormwater and the types of impairment caused by urban stormwater. Section 2.3 then develops a PAF flowchart to guide development of the assessment process. Section 2.4 examines key processes involved in stormwater BMPs, with a focus on limiting factors.

As a first step in a stormwater assessment program, PAF analysis is used to identify key processes and their limiting factors. Chapter 3, “Developing an Assessment Program”, describes a method to accomplish these goals.

2.2 Characteristics of urban stormwater

A first step in developing a PAF is to understand characteristics of the stormwater being treated. This section examines hydrologic and chemical characteristics of urban stormwater and the potential impacts of urban stormwater on urban streams.

2.2.1 Composition of stormwater

The composition of urban stormwater is highly variable among watersheds and, within a watershed, through time. Because the chemical composition of stormwater varies tremendously within a storm event, concentrations are often presented as event mean concentrations (EMCs), where the EMC is calculated by equation 2.1.

Equation 2.1: Event mean concentration

$$EMC = \frac{\sum_{i=1}^{n} C_i Q_i}{\sum_{i=1}^{n} Q_i}$$

where

Q_i = flow in time interval i, and

C_i = concentration in time interval i

Median concentrations of stormwater constituents are provided in tables 2.1 and 2.2. Two major analyses of urban stormwater throughout the United States (USEPA 1983; Pitt et al., 2004) show that EMCs vary enormously among storms, and thatrelationships between annual median EMCs and land uses are weak. Values in tables 2.1 and 2.2 should therefore be used only as rough approximations. Field measurements are required to establish these concentrations for a given watershed.

Table 2.1: Composition of urban stormwater—concentrations of major constituents (Brezonik and Stadelmann 2002; Steuer et al. 1997; Waschbusch et al. 1999; USEPA 1983).

All values in are mg/L.
TSS = Total suspended solids; VSS = volatile suspended solids; TP = total phosphorus; DP = dissolved phorphorus; COD = chemical oxygen demand; BOD = biological oxygen demand; TKN = total Kjeldahl nitrogen; NO_3^-N = nitrate nitrogen; NH_4 = ammonium.

Metropolitan Area	TSS	VSS	TP	DP	COD	BOD	TKN	NO_3^-N	NH_4
Twin Cities, MN (Minneapolis-St. Paul)	184	66	0.58	0.2	169	N/A	2.62	0.53	N/A
Marquette, WI	159	N/A	0.29	0.04	66	15.4	1.5	0.37	0.2
Madison, WI	262	N/A	0.66	0.27	N/A	N/A	N/A	N/A	N/A
U.S. cities (median for all sites)	100	N/A	0.33	0.12	65	9	1.5	.68	N/A

Twin Cities, mean EMC (Brezonik and Stadelmann 2002)
Marquette, geometric means (Steuer et al. 1997)
Madison, geometric means (Waschbusch et al. 1999)
U.S. cities, medians (USEPA 1983)
N/A: Information not reported in the source.

Table 2.2: Composition of urban stormwater—metals (in mg/L) and coliforms in #/100 mL (Brezonik and Stadelmann 2002; Steuer et al. 1997; Waschbusch et al. 1999; USEPA 1983).

Metropolitan Area	Total lead	Total zinc	Total copper	Total cadmium	Coliforms
Twin Cities, MN	0.060	N/A	N/A	N/A	N/A
Marquette, WI	0.049	0.111	0.022	0.0006	10,200
Madison, WI	0.032	0.203	0.016	0.0004	175,106
U.S. cities (median for all sites)	0.144	0.160	0.034	N/A	21,000

Twin Cities, mean EMC (Brezonik and Stadelmann 2002)
Marquette, geometric means (Steuer et al. 1997)
Madison, geometric means (Waschbusch et al. 1999)
U.S. cities, medians (USEPA 1983)
N/A: Information not reported in the source.

2.2.2 Impacts of urban stormwater

Urban stormwater is responsible for about 15% of impaired river miles in the United States (USEPA 2000). The impacts of stormwater are hydrologic, chemical, biological, and physical. The impacts of greatest concern are sediment and habitat alteration, nutrients, toxic substances, chloride, bacteria, temperature, oxygen-demanding substances, and biological integrity (USEPA 1992).

Flow and channel alteration

Urbanization, as reflected by increased impervious surface, alters watershed hydrology in several ways. The runoff coefficient (inches of runoff/inches of rainfall) increases as the percentage of impervious surface in the watershed increases. Figure 2.1 shows this relationship for sites studied in EPA's National Urban Runoff Study (USEPA, 1983). Increasing imperviousness also leads to greater flashiness in stream hydrographs, with higher flood flows and lower base flows (Paul and Meyer 2001). Some of the effects of altered flow on biota include: higher peak temperatures, altered sediment discharge, unstable channels, fewer pools, and simplified habitat due to channelization. Evaluations of stream habitats indicate that flow and channel alteration are major contributors to the observed decline in biological integrity often associated with increased imperviousness (see reviews by Paul and Meyer 2001, Pitt 2002, Booth et al. 2002, and Scheuler 2000a).

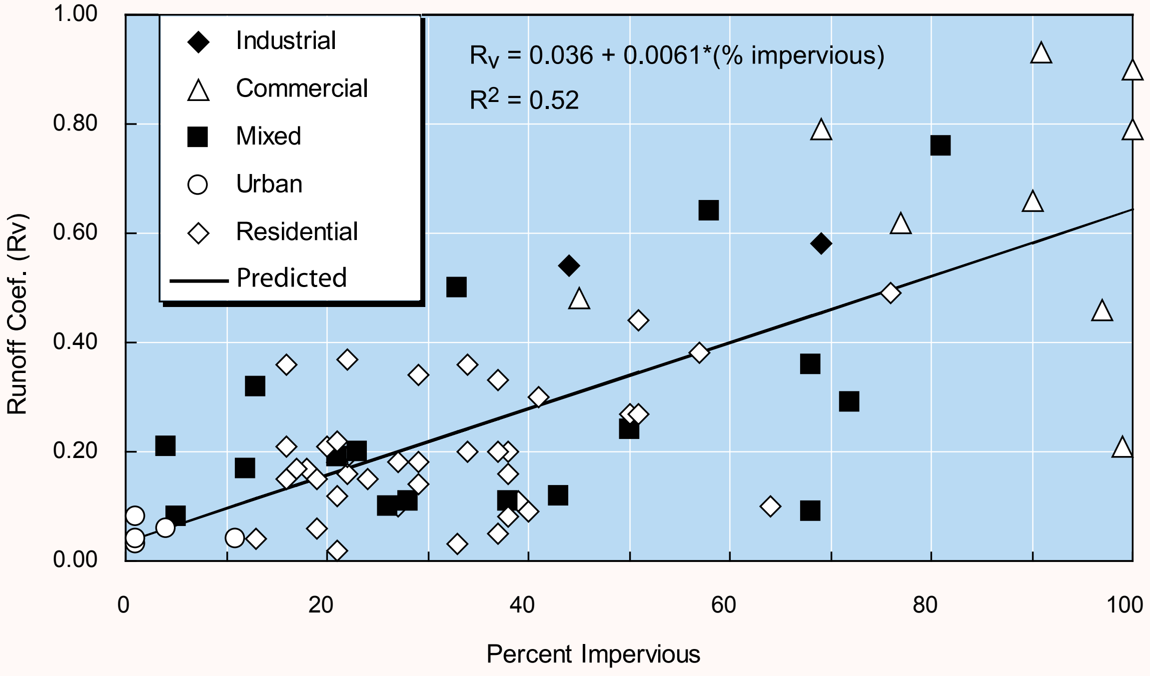

Figure 2.1: Percent impervious surface versus runoff coefficient for watersheds included in the National Urban Runoff Program (NURP) study (EPA 1983).

Nutrients

Nutrients, mainly phosphorus and nitrogen, increase plant growth in streams and lakes. In many parts of the country, stormwater entering lakes causes nutrient enrichment (eutrophication), reduces water clarity, increases the presence of undesirable blue-green algae, and makes treatment for drinking water more difficult and expensive. Because of urban sprawl, residential land is now the dominant land use in 64% of the nation's water supply reservoirs (Robbins et al. 1991). Eutrophication caused by nutrients in stormwater often impairs municipal drinking water supplies. An excellent example is the Vadnais Chain of Lakes that supplies water to the city of St. Paul, Minnesota, which for many years has experienced serious taste and odor problems, in part because much of its watershed is residential land that contributes significant quantities of phosphorus (Walker 2000). Nutrients can also stimulate the growth of undesirable rooted aquatic plants in streams.

Toxic substances

A large number of potentially toxic substances occur in stormwater. Several metals, including copper, zinc, and lead, are ubiquitous in urban stormwater. Lead concentrations in the environment have declined since the 1970s, when lead in gasoline and paint was banned. Note the lower lead levels in the three newer stormwater studies in table 2.2 compared with those in the NURP study from the early 1980s. There is little evidence of short-term toxicity of urban stormwater, but considerable evidence of long-term toxic effects from exposure of organisms to contaminated sediments (Pitt 2002).

Chloride, the result of road salting, is an emerging urban pollutant. Chloride concentrations in streams have been directly correlated with percent impervious surface (Kaushal et al. 2005). Peak chloride concentrations in urban streams during winter can be several thousand mg/L. For comparison, Minnesota has a maximum (acute) standard of 860 mg/L for cold water (Class 2A) streams.

Bacteria

The potential for bacterial contamination is generally indicated by coliform counts. Minnesota's standards are based on fecal coliforms (MPCA 2005). Although most fecal coliforms are not pathogenic, they are indicative of human pathogens. In one study, the number of gastrointestinal diseases per 1000 swimmers was shown to increase linearly with coliform counts (Durfor 1984, cited in Wenck 2003). One outcome of elevated coliform levels is beach closings. In Minneapolis, there were 11 beach closings in 2001 and 10 in 2002. Fecal coliform concentrations are generally highest just after rainstorms. A study of Minnehaha Creek (Wenck 2003) reported that fecal coliforms > 2000 CFU/100 mL were found only within three days of a rainstorm. This indicates that a high percentage of fecal coliforms are a result of stormwater runoff.

Temperature

Urbanization generally requires removing crops, trees, and native plants from parcels of land and replacing them with roads, parking lots, lawns and buildings. These changes in land use affect hydrology, i.e. volume and peak runoff, and heating of runoff in these areas, which results in increases in summertime temperatures of nearby streams. This is especially important for trout streams fed by groundwater. A higher and warmer discharge of water from impervious surfaces will dilute the colder groundwater and threaten the trout habitat. In a study of 39 trout streams in Wisconsin and Minnesota, stream temperatures increased 0.25 °C (0.5 °F) per 1% increase in watershed imperviousness (Wang et al. 2003). For coldwater streams (Class 2A), no temperature increase is allowed. For warmwater streams (Class 2B), the allowable temperature increase of 3 °C (5 °F) would be exceeded with only 11% of the impervious area in a watershed.

Oxygen-demanding substances

Degradable organic matter in streams utilizes oxygen, often rapidly enough to reduce dissolved oxygen concentrations to levels that impair aquatic life. Unlike the situation with point source discharges, which cause the most severe oxygen depletion during low-flow conditions, low oxygen conditions in urban streams often occur just after major storms, which wash oxygen-demanding substances into streams.

2.3 Designing a process assessment framework

2.3.1 Conceptual approach

Step 1. Identify the hydrologic, chemical, biological, and thermal goals of the stormwater assessment program (figure 2.2). This would generally be done in the context of receiving water goals and local runoff regulations.

Step 2. Identify the physical, chemical, and biological processes that are needed to meet these goals. These should include “limiting factors” of key processes.

Step 3. Select the appropriate assessment methods using key assessment issues identified with the PAF. These methods are (1) visual assessment, (2) capacity testing, (3) simulated runoff testing, and

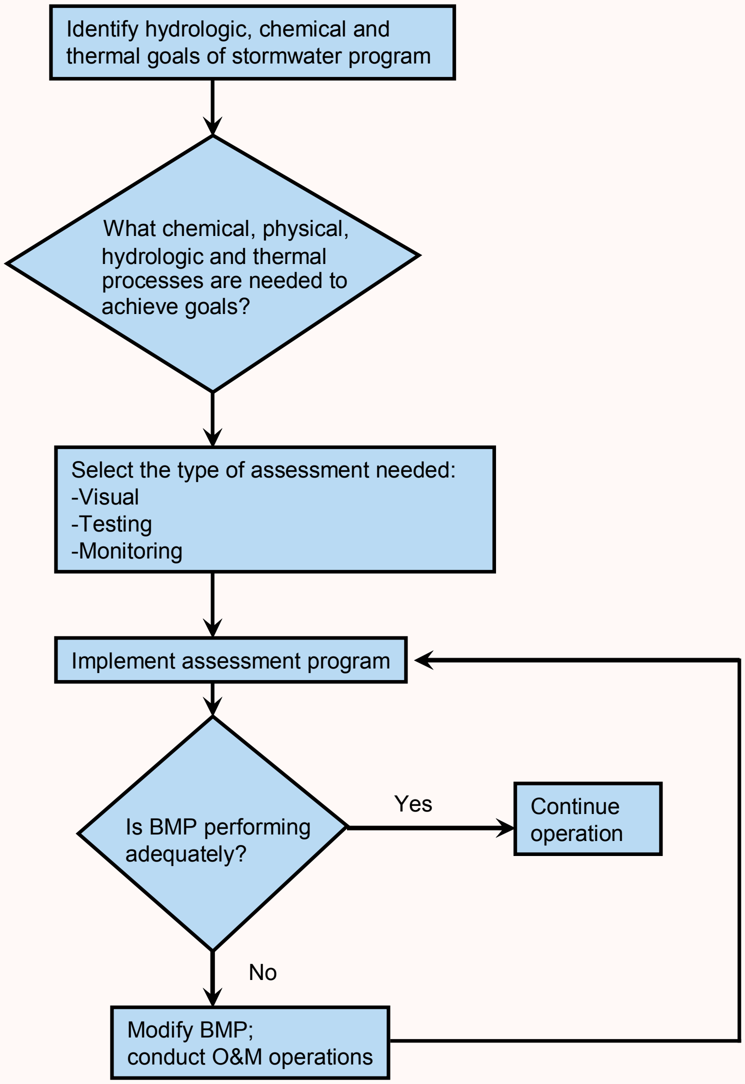

Figure 2.2: Flow chart of Process Assessment Framework

(4) monitoring. These assessment methods are described in Chapter 3.

Step 4. Results from the initial assessment program are used to ask the question: is the BMP performing adequately? If not, the operation or design of the BMP may need to be altered to improve performance.

Step 5. Performance may need to be reassessed following modifications.

2.3.2 Pollutant mass balances

The PAF should address the question: what is the ultimate fate of pollutants removed by a BMP? A pollutant mass balance (figure 2.3) illustrates the fate of pollutants. Pollutants may originate from managed landscapes, construction sites and bare ground, winter road maintenance (sand and salt), wearing of tires and brakes, and other sources. After pollutants enter a structural BMP, some of them are converted to gaseous end products such as CO_2 (from biological degradation) and N_2 (from denitrification). However, most pollutant removal in structural BMPs occurs by accumulation. Accumulation occurs by sedimentation (which removes particles and adsorbed pollutants), deposition of plant debris, filtration, and adsorption. Accumulation of pollutants is eventually unsustainable: at some point, accumulated pollutants must be removed and transported to an ultimate disposal site. Pollutant removal can be a major O&M cost for stormwater BMPs. Pollutants remaining in the water exit the BMP. Pollutant removal efficiencies in stormwater BMPs (typically, 30–80%) are generally far lower than removal efficiencies in modern wastewater treatment plants (typically, 80–99%).

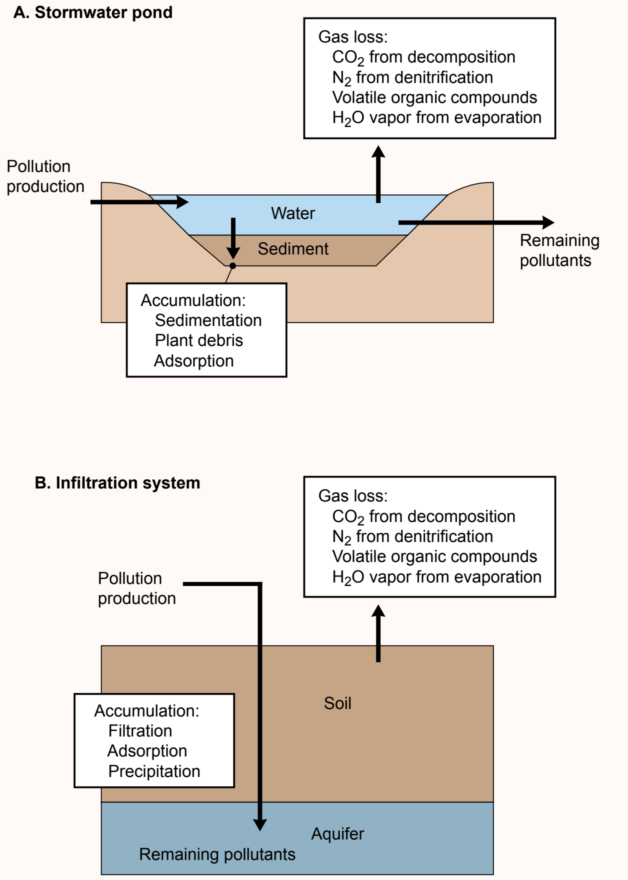

Figure 2.3 Schematic for fate of pollutants in (A) a stormwater pond, and (B) an infiltration system.

2.3.3 Importance of key processes in BMPs

The relative importance of key processes for various stormwater BMPs is shown in tables 2.3, 2.4, and 2.5. These diagrams are intended to be a rough guide to developing Step 1 of the PAF. Section 2.4 (below) outlines key biological, chemical, hydrological, and thermal processes that alter the characteristics of urban stormwater during treatment.

Table 2.3. Qualitative comparison of hydrologic characteristics among stormwater BMPs. ● = important; ◉ = somewhat important; ○ = not very important; i = insufficient information.

	Surface flow reduction	Peak flow reduction	Infiltration	Evapotranspiration
Source reduction				
Landscape management	●	●	●	●
Filtration practices				
Sand filters	○	◉	○	○
Soil filters	○	◉	○	○
Infiltration practices				
Infiltration basins/trenches	●	◉	●	○
Porous pavements				
Sedimentation practices				
Wet ponds	○	●	○	◉
Dry ponds	○	●	◉	○
Proprietary devices	Variable	○	○	○
Biologically enhanced practices				
Rain gardens	●	◉	●	◉
Wetlands	○	●	○	◉
Swales	●	◉	●	◉
Filter Strips	○	○	◉	◉

Table 2.4. Qualitative comparision on chemical and biological processes among stormwater BMPs. ● = important; ◉ = somewhat important; ○ = not very important; i = insufficient information.

	Biol. decay	Denitrification	Plant uptake	Coliform die-off	Precip. and adsorption	Filtration	Erosion control and sedimentation
Source reduction							
Landscape management	○	○	●	i	◉	◉	●
Filtration practices							
Sand filters	◉	i	○	◉	◉	●	○
Soil filters	◉	i	○	◉	◉	●	○
Infiltration practices							
Infiltration Basins/trenches	i	○	◉	i	◉	●	◉
Porous pavements	i	i	i	i	○	◉	○
Sedimentation practices							
Wet ponds	●	◉	◉	◉	◉	○	●
Dry ponds	○	○	◉	○	○	◉	●
Proprietary devices	○	○	○	○	*Variable*	*Variable*	*Variable*
Biologically enhanced practices							
Rain gardens	◉	○	●	○	◉	○	●
Wetlands	●	●	●	◉	◉	◉	●
Swales	○	○	●	○	◉	●	●
Filter Strips	○	○	●	○	◉	●	●

2.4 Physical, biological, and chemical processes in stormwater treatment

2.4.1 Physical processes

Erosion and sediment transport

Process. Soil erosion is a natural process that plays an important role in the dynamics of landscape features at large geologic time scales. Our interest primarily lies in accelerated erosion as a result of human-related activities. Sediment is the largest, by mass, pollutant in our waterways. In addition, soil particles often provide a mode of transport for other contaminants, such as phosphorus and metals. Best management practices for reducing the impact of these contaminants are often the same practices used to control erosion and sediment transport. Movement of soil particles into water bodies is a two-step process. First, the soil particles are detached. These detached particles are then transported from their original location to a water body. Either of these two steps can limit the sediment yield delivered from a hillslope.

Soil detachment occurs by raindrop impact or by forces associated with surface runoff. Detachment potential of rainfall is dependent on the size and number of raindrops, both of which increase with storm intensity. Raindrops typically fall uniformly over a bare hillslope, and therefore the corresponding potential detachment is roughly equal at all points. Erosion for this situation is often referred to as sheet erosion because soil is removed from the area as a mostly uniform sheet. Soil detachment also occurs when the shear forces of surface runoff exceed the gravity and cohesive forces of the particles. Detachment by surface runoff is not uniform over the surface, resulting in channels carved into the landscape. Small channels are called rills, and the corresponding erosion is called rill erosion. Erosion by detachment in rills is usually greater than erosion by raindrop impact. Occasionally, the detachment by surface runoff can result in unsightly gullies and corresponding large sediment losses.

After detachment, soil particles are delivered to water bodies and transported as suspended solids or as “bed load,” which is sediment that moves with the flow but has frequent contact with the bed. Although raindrop splash moves some particles, the vast majority of sediment transport occurs by particles entrained in surface runoff. Sediment transport is primarily dependent on the weight of particles and velocity of runoff. Sediment is often deposited in the landscape at locations where localized conditions reduce the transport capacity of runoff. Deposition then occurs if the sediment load in the flow is greater than the reduced transport capacity. This process is common at the toe of hillslopes where a change in slope corresponds to a reduction in transport capacity. The difference between eroded particle mass and deposition is called sediment yield. The ratio between sediment yield and eroded mass is called the sediment delivery ratio.

Assessment considerations. Five major factors impact erosion in urban areas: (1) erosivity of rainfall, (2) soil erodibility, (3) slope length, (4) slope steepness, and (5) land cover. These factors are multiplicative in the framework of the Universal Soil Loss Equation. Rainfall erosivity is generally not a controllable factor, and site conditions often limit flexibility in reducing erosion losses by manipulating the slope length and steepness. A large soil erodibility is roughly 5 times greater than a small erodibility. Although the range in this factor is significant, the land-cover factor varies by a magnitude of 1000. The best practice for controlling erosion is usually tied to maintaining good land cover. Vegetative cover, mulches, and erosion control blankets are effective in reducing soil erosion. One major assessment issue is evaluation of the installation and maintenance of erosion measures designed to reduce erosion at construction sites. This is discussed in chapter 7 (Source Reduction).

A second major assessment issue is particle size distribution of eroded sediment. Large-sized particles are easier to trap with gravitational settling practices (see equation 2.2). Clay particles are chemically more active and therefore more likely to bond with land-applied chemicals. They also settle so slowly that is difficult to remove them by settling practice. Soil can be eroded as water-stable aggregates composed mostly of clay particles. These aggregates can be large enough to be trapped by settling practices, which would not capture the individual clay particles. Standard particle size analyses use a dispersion agent to break down aggregates to determine the primary particle sizes. Since aggregates are important in the performance of sediment control practices, it is important that a dispersion agent not be used in determining the particle size distribution of sediment.

Equation 2.2: Stokes Law

$$V_s = \frac{g(\rho_s - \rho_w)d^2}{18\mu}$$

where

V_s = terminal settling rate
g = gravitational acceleration
ρ_s = density of settling particle
ρ_ω = density of water
d = diameter of particle
μ = dynamic viscosity

Filtration

Process. Filtration (chapter 8) is the retention of suspended particles while water is passing through granular media. The main mechanism of filtration is straining, in which suspended solids are trapped between media particles. Filtration removes suspended solids and sediment-bound pollutants from solution, but allows them to accumulate in the filter. Filtered material eventually clogs filters, reducing the flow rate through the filter. For this reason, sediment must eventually be removed by backwashing, surface scraping, or media replacement.

Assessment considerations. Filtration efficiency is generally expressed as the ratio of concentration at the top of the filter bed (Co) to the concentration at the bottom (C). Filtration efficiency is highly dependent on particle size. Filtration is generally limited by clogging of the filter, which can be measured by the drop in head loss across the filter, a reduction in filtration rate, or an increase in the time required for filtration.

Sedimentation

Process. Sedimentation of particles is an important pollutant retention process in many stormwater BMPs (Chapter 10). In theory, sedimentation rate under quiescent conditions is predicted by Stoke's Law as given by equation 2.2.

Turbulent eddies in the stormwater BMP counter the settling by mixing the water column so the resulting sediment concentration profile is a balance between settling and mixing. At the bottom of the stormwater BMP, however, the turbulence dissipates, so that the concentration that exists at the bottom settles out according to Stokes Law. It is the mixing that determines, for a given solids supply, what this concentration at the bottom will be.

Assessment considerations. Equation 2.2 illustrates several variables that affect settling. Sedimentation rate increases as the density and size of particles increase. For a given particle type, settling velocity (V_s), also depends on the properties of water. The net effect of rising temperature is faster sedimentation, because the effect of decreasing viscosity is greater than that of decreasing density. From 0 °C to 30 °C (32 °F to 86 °F), settling for fine silt (0.02 mm diameter (7.87 x 10^{-4} inches) approximately doubles (figure 2.4). Salinity also affects V_s, but the effect is minor even at the highest levels expected with road salt (~20,000 mg/L).

The implication of this for the Upper Midwest states is that retention of inorganic suspended solids in stormwater BMPs that rely on sedimentation will be lower in spring and fall than during the summer. During warmer weather, algae growing in wet ponds would have much lower sedimentation rates because they have much lower density than inorganic particles, and some species can regulate their buoyancy.

Solids removal will occur more quickly with a concentration profile that increases with depth. This occurs at the high V_s and the low mixing level, indicated by bottom shear velocity, u_*.

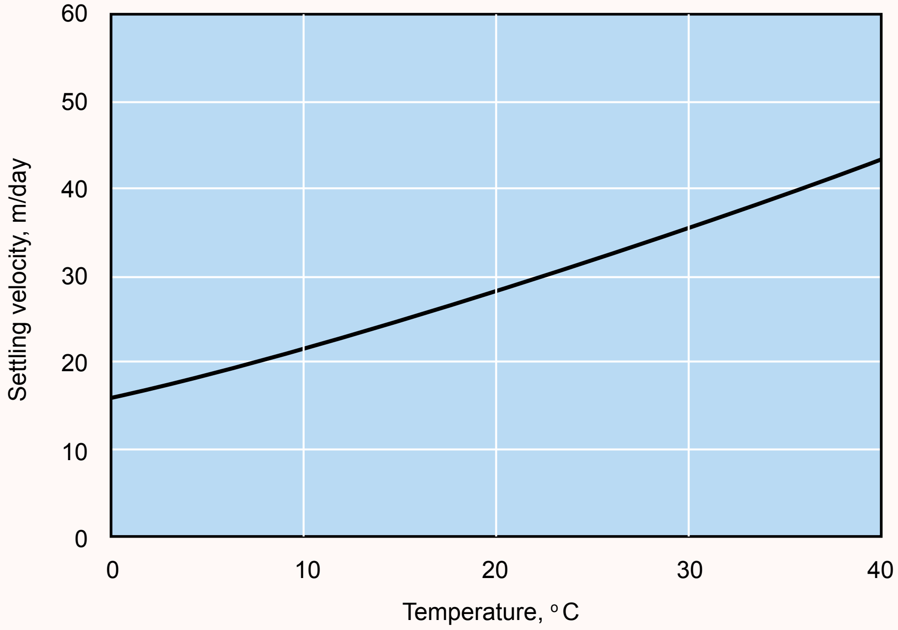

Figure 2.4: Effect of temperature on the terminal settling velocity of fine silt (d = 0.02 mm (7.87 x 10^{-4} inches); density = 2. 5 g/cm^3). [Temperature in °F=((°C)(1.8) + 32); one meter = 3.281 feet.]

Thermal processes

Processes. Thermal pollution of coldwater streams through stormwater runoff happens under two conditions: (1) when the temperature of rainfall is higher than the temperature of the receiving stream and this rainfall becomes runoff, and (2) when land surfaces are preheated prior to a storm such that they heat up the raindrops as they flow over the surface. Water bodies, such as wet ponds, with large thermal mass (thermal inertia) can also be a source of thermal pollution for nearby streams during hot summer days.

Rainfall temperature throughout a storm event is very close to dew point temperature. In the Upper Midwest, dew point temperature exceeds 18 °C (65 °F) for at least several days every year (18 °C is the trout upper lethal temperature over a week). These high dew points are often followed by thunderstorms that produce warm rainfall. With urbanization, the area of impervious surfaces increases, and thus the volume of warm runoff during those thunderstorms also increases.

The temperature of land surfaces is controlled by several processes: solar radiation during the daytime, atmospheric long wave radiation, long wave back radiation from the surface, evaporative heat flux, and sensible heat flux. Land surfaces are heated above ambient air temperature primarily by solar radiation. Herb et al., 07a showed that paved surfaces in Minnesota can be heated up to 65 °C (149 °F) during hot summer days, while the temperature of bare soil surface reaches about 45 °C (113 °F).

Evaporation from water surfaces or evapotranspiration by plants tends to cool surfaces. The surface temperature of lands with vegetation cover is often lower than the ambient air temperature. Solar radiation causes the high temperature of roofs and paved surfaces on mid-summer days, and the shading effects of canopy keep the temperature of vegetated areas relatively low. The surface temperature of residential roofs drops at night because of their small thermal mass; sometimes the nocturnal roof temperature drops below the ambient air temperature due to higher long wave back radiation from the roof.

Finally, land surfaces can be warmed by the overlying atmosphere (if the atmosphere is warmer than the land surface) or cooled by the overlying atmosphere (if the overlying atmosphere is cooler than the land surface). This heat transfer occurs mainly by convection.

Prior to storm events, clouds move in, and in summer as clouds block solar radiation, the roof surface temperature drops to ambient air temperature (Mohseni et al. 2007). Surface temperature of paved surfaces, such as driveways, roads, and parking lots also drops prior to the storms, but their surface temperature may stay above 40 °C (104 °F) due to their high thermal mass. Throughout a storm event, heat transfer between the land and the sheet flow over the land is larger than heat transfer between the air and the flow. When the land surface temperature is higher than the dew point temperature, the temperature of the flow generally increases. In this process, the land surface temperature drops, but at a lower rate, until the two temperatures reach equilibrium. By this process, storm runoff is heated during hot summer days, resulting in thermal pollution to nearby streams.

Wet detention ponds are often built as mitigation measures to lower the peak flow during storms and to remove the pollutants from storm runoff. However, water stored in wet detention ponds is heated during hot summer days, and as stormwater enters the pond, the heated surface water is displaced. The temperature of water stored in wet detention basins is often warmer than that of streams, so as this warm water flows out of the pond it becomes a thermal pollution point source for nearby streams. Sheltered wet detention ponds stratify during the day and become well mixed at night, which results in high surface temperatures during hot summer days. Since the outflow from wet detention ponds is usually from the surface, stratified ponds discharge warmer water during daytime storm events. In wetlands and

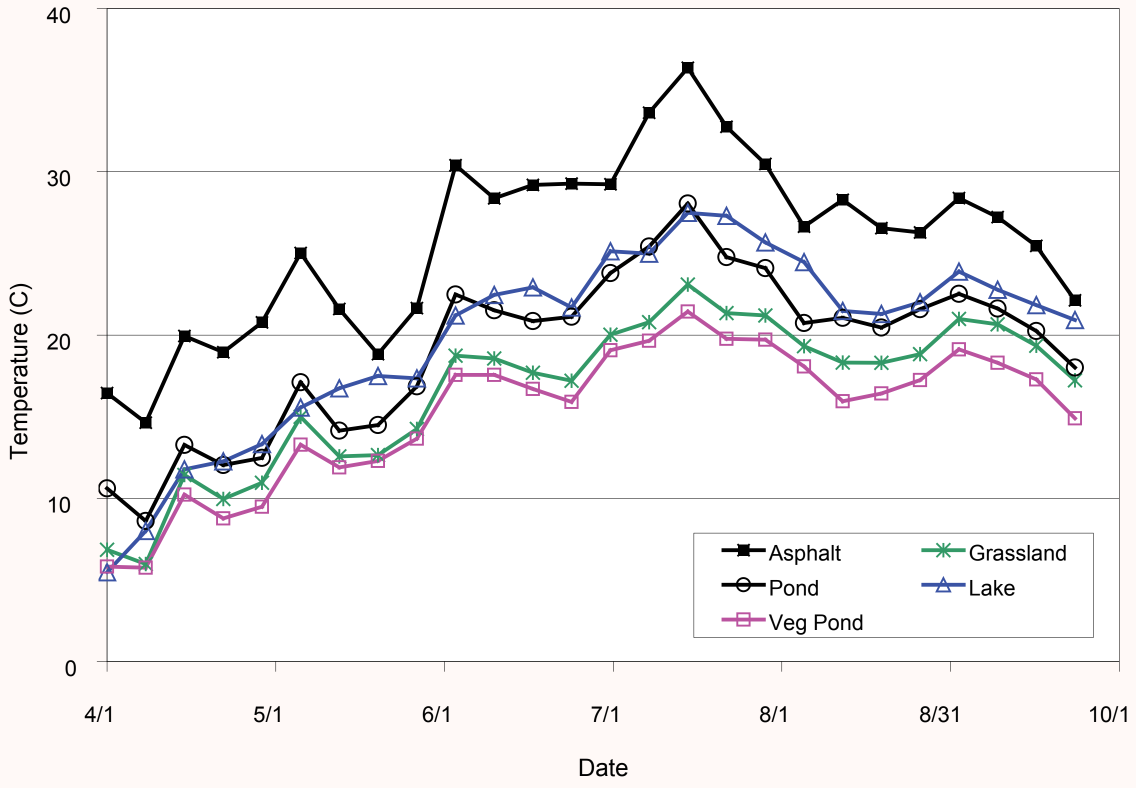

Figure 2.5: Simulated average weekly surface temperature for five land uses calculated with hourly climate data from St. Paul (2004). The vegetated pond represents a pond with fully covered emergent macrophytes (from Herb et al. 2007b). [Temperature in °F=((°C)(1.8) + 32).]

vegetated ponds, shading and evaporation tend to cool water. These BMPs may produce lower outflow temperatures than wet detention ponds.

Dry detention ponds or infiltration ponds built near the receiving stream may mitigate the long-term impacts of urbanization that result from a decrease of infiltration in the upland areas due to impervious surfaces. However, when these ponds are built very close to the receiving streams, they may not address the short-term effects: the heated infiltrated water may not lose much heat if it travels only a short distance below the surface before it reaches the receiving stream.

Figure 2.5 gives the simulated average weekly surface temperature of five types of land uses in St. Paul, Minnesota, from April to November of 2004, where asphalt weekly surface temperatures are about 18 °C (65 °F) warmer than grasslands or vegetated ponds in mid-summer months.

Assessment considerations. Urbanization not only increases the volume and peak storm runoff, but also redistributes surface and subsurface flows, resulting in more overland runoff and less infiltration. Overland runoff from impervious surfaces is also warmer than overland runoff from vegetated surfaces. Coldwater streams are fed primarily by groundwater, which is generally cooler than summer runoff in this region. Any reduction in infiltration in upland areas caused by impervious surfaces will likely reduce base flow to the receiving stream during dry periods, which may result in elevated temperatures during hot summer days because of the smaller thermal inertia of shallow water. Overland runoff that has been warmed by impervious surfaces (see discussion above) may further increase stream temperatures during summer rain events. Quantifying the long-term impact of a single small urban development on the base flow of the receiving stream may be quite difficult. However, the cumulative impact of numerous developments or of an extensive urbanization program on the base flow of the receiving stream can be assessed using mathematical models.

2.4.2 Biological processes

Degradation of organic matter

Process. Several biological processes are involved in pollutant retention. The first is microbial respiration, in which organic matter in water is oxidized to CO_2 as described by equation 2.3, which represents the oxidation of organic matter (represented as CH_2O) to carbon dioxide (CO_2).

Equation 2.3: Oxidation of organic matter

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

Assessment considerations. In practice, readily degradable organic matter is measured as biological oxygen demand (BOD). Oxidation of BOD produces CO_2 and water. The BOD decay constant, “k” (equation 2.4), is dependent upon temperature. Although the magnitude of k is dependent upon bacterial population, the temperature effect on decomposition is generally described as shown in equation 2.5. Thus, one temperature can be adjusted to another, as long as the bacterial population is similar.

Equation 2.4:

$$C = C_o exp^{-kt}$$

where

C_o = BOD concentration at t = 0,
k = BOD decay coefficient, day-1, and
t = time, days

Equation 2.5: Temperature effect on decomposition

$$k_2 = k_1\theta^{(T_2-T_1)}$$

where

T_1, T_2 are temperatures 1 and 2 in °*C*, and k_1 and k_2 are the BOD decay constant, *k*, at temperature 1 and 2, respectively. The constant k_1 is presumed to be determined through field measurements.

A common value for the empirical constant (θ) is 1.05 (Metcalf and Eddy 1991). Calculations using this value in equation 2.5 show that it takes three times longer to achieve a 50% BOD reduction at 5 °C (41 °F) than at 25 °C (77 °F) (figure 2.6). This implies that BOD decay would be least effective during the snowmelt period, when temperatures are just above freezing.

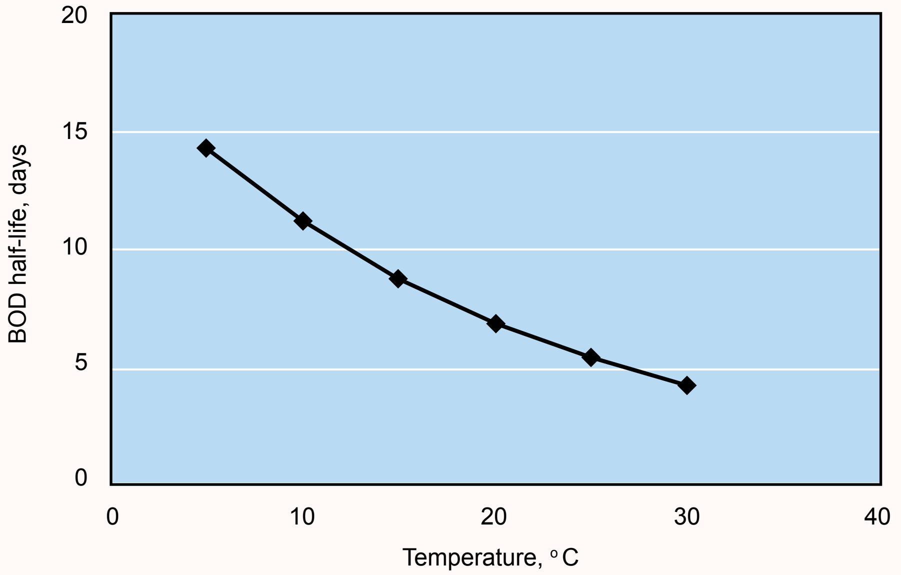

Figure 2.6: Half-life of BOD (time needed to reduce BOD by 50%) as a function of temperature with k_{20} = 0.1 day^{-1}. [Temperature in °F=((°C)(1.8) + 32).]

Denitrification

Process. Denitrification is a bacterial reaction that occurs under anaerobic (no dissolved oxygen) conditions, which are typical in sediments. Denitrification converts nitrate (NO_3) in stormwater to nitrogen gas (N_2), as described in equation 2.6. Organic matter (again represented as CH_2O) “fuels” the denitrification process; denitrification cannot occur without a source of organic matter.

Equation 2.6: Denitrification

$$1.25CH_2O + NO_3 + H+ \rightarrow 0.5N_2 + 1.25CO_2 + 1.75H_2O$$

Assessment considerations. Nitrate (NO$_3$) is generally less than one-third of the total nitrogen in urban stormwater (table 2.1). Denitrification can therefore remove only about one-third of stormwater nitrogen, unless additional nitrate is produced by nitrification (oxidation of ammonia). The end products are harmless gases. Denitrification bacteria require a source of organic matter (represented as CH_2O) and an environment with little or no oxygen, such as can occur in sediments.

These conditions occur in wetlands, where rooted plants supply the carbon, and in pond sediments, where carbon is supplied by dead algae. If the assessment program reveals that nitrate removal efficiencies are lower than desired, assessment of the organic carbon supply may be warranted. As with other biological processes, denitrification is also controlled by temperature. Kadlec and Knight (1996) suggest a θ value of 1.09 be used in equation 2.8 for denitrification in treatment wetlands.

Plant growth and nutrient uptake

Process. Many stormwater BMPs include plants: algae in ponds; emergent aquatic plants in wetlands and ponds; and grasses and other plants in rain gardens, buffer strips, and swales. Plants assimilate (take up) nutrients during growth. Algae growth can be represented (approximately) by equation 2.7. Algae are represented in this equation as a chemical formula: $C_{106}H_{236}O_{110}N_{16}P$.

Equation 2.7: (6,10) Algae growth

$$106CO_2 + 16NO_3- \ + HPO_4- + 122H_20 \rightarrow \quad C_{106}H_{236}O_{110}N_{16}P + 138O_2$$

Equation 2.7 shows that photosynthesis (the forward reaction →) converts carbon dioxide (CO_2), nitrate (NO_3^-), phosphate (HPO_4^-) and water to algae, producing oxygen (O_2). Respiration (or death) is represented by the backward reaction (the reverse reaction ←). Respiration removes oxygen from the water while releasing carbon dioxide, nitrate, and phosphate to the water. For algae, periods of growth and senescence alternate in periods of a few weeks. Rooted aquatic plants obtain most of their nutrients from sediment during growth. When they decompose in late summer or fall, nutrients are released rapidly (days to weeks), which may result in increased nutrient concentrations in the water column (Landers 1982). A portion of nutrients remains in a refractory fraction, which becomes part of the sediment and decomposes slowly or not at all.

Assessment considerations. A large fraction of the nutrients assimilated by plants in stormwater BMPs are released during decomposition. Most of the nutrient uptake by plants is therefore non-permanent. In wetland and pond systems, deposition of partially decayed (refractory) plant material will accumulate. Assessing the rate of accumulation can be important because plant debris will eventually need to be cleaned out. For example, Scheuler (1992) suggests that clean-out of wetlands is required at intervals of 2–10 years.

Coliform production and loss

Processes. Fecal coliforms are excreted from the bodies of warm-blooded animals. For urban stormwater, sources may include humans (via illicit sewage connections to stormwater conveyances), dogs, cats, geese, and other wildlife. Although generation rates (number of coliforms excreted per day) for various organisms (dogs, geese, humans) are well known (Scheuler 2000b), there is little information regarding "delivery ratios" (the fraction of excreted coliforms that enters runoff) for urban stormwater. Coliforms entering the natural environment die off according to equation 2.8. K values in streams are often on the magnitude of 1 d^{-1}.

Equation 2.8: (7,11) Coliform die-off (NAS 2000)

$$N = N_o exp(-kt)$$

where

N_o = the initial coliform count (CFU/100 mL)
k = die-off rate constant
t = time, in days.

Fecal coliforms can also regrow in the environment under warm conditions with a supply of organic matter for food, conditions that might occur in wetlands or stormwater ponds. Regrowth is not readily modeled in natural environments. Coliforms are readily removed by filtration during infiltration through soils, except in the case of very coarse soils.

Assessment considerations. A study by the National Academy of Sciences (NAS 2000) noted that very high removal rates—on the order of 99%—would be needed to reduce coliforms from the levels observed in urban stormwater (15,000–20,000/100 mL) to EPA's 200/100 mL criterion for recreational water. Their review indicated that bacterial removal rates in several types of stormwater BMPs were far lower than 99% (table 2.6).

Table 2.6. Comparison of mean bacterial removal rates achieved by different stormwater BMP groups.The number (n) of systems is indicated in parentheses (NAS 2000).

Bacterial Indicator	Bacterial Removal Rate, %		
	Ponds	Sand Filters	Swales
Fecal Coliform	65% (n =9)	51% (n=9)	–58% (n=5)
Fecal Streptococci	73% (n =4)	58% (n=7)	ND
E. coli	51% (n=2)	ND	ND

Studies of coliform regrowth in stormwater ponds have apparently not been reported in the peer-reviewed literature.

2.4.3 Chemical processes

Precipitation and adsorption

Chemical precipitation and adsorption cause soluble constituents to become incorporated into particles. Both result in soluble constituents becoming part of solid particles. These processes are important for metals, phosphate, and salt, although each of these pollutants requires a slightly different assessment approach. The discussion below applies to the condition of equilibrium. These processes are not always at equilibrium, but describing non-equilibrium processes is beyond the scope of this manual.

Processes: metals. The total metals concentration (C_t) includes the concentration on particles (particulate metals concentration, C_p) and the dissolved concentration (C_d), all in mg/L as shown in equation 2.9.

Equation 2.9: Total metals concentration

$$C_t = C_d + C_p$$

where

C_d = dissolved metal concentration, mg/L
C_p = particulate metal concentration, mg/L
C_t = total metal concentration, mg/L

The relationship between C_p and C_d at equilibrium can be calculated as a function of the suspended solids concentration (M, kg/L) and a partition coefficient, K_d (L/kg) (equation 2.10, from Thomann and Mueller, 1987).

Equation 2.10:

$$C_p = K_d C_d$$

where

C_p = particulate metal concentration, mg/L
K_d = partition coefficient, L/kg
C_d = dissolved metal concentration, mg/L

The fraction of metal in the particulate form can then be calculated with equation 2.11.

Equation 2.11: Fraction of metal in particulate

$$F_p = \frac{K_d}{(1 + K_d M)}$$

where

F_p = fraction of metal in particulate
K_d = partition coefficient, L/kg
M = suspended solids concentration, kg/L

For several metals (copper, zinc, cadmium, chromium, lead, and nickel) K_d values are typically 10^4 to 10^5 (Thomann and Mueller 1987). The relationship between particulate (bound) and soluble metals is shown in figure 2.7. Note that when the suspended solids concentration is low, most metals are in the dissolved fraction. When the suspended solids concentration increases beyond ~ 500 mg/L, nearly all metals are in the particulate fraction.

Assessment considerations: metals. Assessment of metal retention in stormwater BMPs would generally be done empirically, by measuring input and output fluxes of metals. In cases where greater metal retention is needed, it may be practical to examine partitioning between metals and

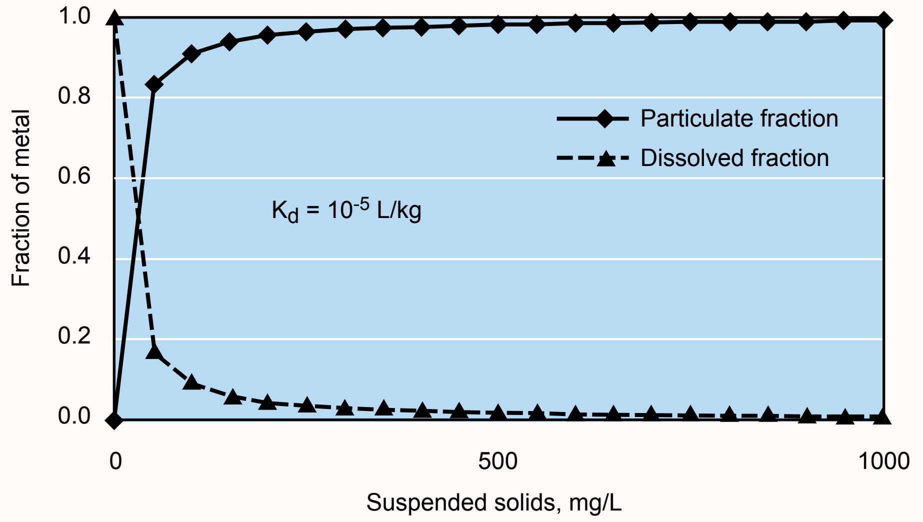

Figure 2.7: Fraction of metals in the dissolved and particulate forms as a function of suspended solids concentrations. [One liter = 0.035 ft^3; one kilogram = 2.205 pounds.]

sediment and sediment retention (below) to determine whether the limiting factor is sedimentation rate or fractionation. For example, metals may be difficult to remove from stormwater with a low suspended solids concentration because the dissolved fraction would be high. Metal retention from stormwater results in metal accumulation in sediment. The metal content of sediments may dictate ultimate disposal of sediments (Polta 2001, 2006). Metals concentrations in sediments of stormwater ponds in the Twin Cities were generally below levels that would require hazardous waste disposal, but copper and iron in pond sediments were often higher than Soil Reference Values for human exposure (Polta 2006). Metal accumulation per kg of soil may be higher in infiltration basins than in sedimentation ponds because soluble metals are adsorbed or precipitated as water infiltrates through soils.

Processes: phosphate. Phosphate undergoes both adsorption and precipitation in soil. Phosphate is sometimes considered immobile in soils, but many studies in the past decade have shown that phosphate adsorption is limited. Adsorption capacity breakpoints are commonly 20–50 mg PO_4-P/kg of “Bray P” soil mass (Pote et al. 1999, McDowell et al. 2001, Fang et al. 2002). Addition of more phosphate beyond this point results in breakthrough, which means that soluble phosphate passes through the soil. Evidence of phosphate breakthrough resulting in groundwater contamination has been observed in septic systems (Robertson et al. 1998), urban soils (Zang et al. 2001), and under wastewater-irrigated fields (Zvomuya et al. 2005). Stream phosphate concentrations have been correlated with average watershed Bray P (Klatt et al. 2003).

Assessment considerations: phosphate. When phosphate retention by soil adsorption is important, the buildup of soil P should be assessed periodically. This can be done with measurements of extractable P using the Bray or Olsen methods.

Processes: sodium. Sodium undergoes ion exchange with other cations (positively charged ions) adsorbed on soil particles, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). When sodium concentrations in stormwater are very high (e.g., road salt contamination), sodium displaces other cations. This causes clay particles to flocculate, which reduces infiltration in soils with moderate to high clay content. The amount of sodium adsorbed relative to other cations is called the sodium exchange percentage. This is the percentage of all adsorption sites that are occupied by sodium. Reduced infiltration occurs when the sodium exchange percentage is >15%.

Assessment considerations: sodium. The extent of sodium adsorption by soils is measured by the sodium exchange fraction. This is the fraction of total ion exchange sites that are occupied by sodium. Values > 15% are considered undesirable for vegetation. Because most waters in Minnesota have low salinity, sodification (buildup of soil sodium) would most likely only occur in sites receiving drainage of road salt. This may include some rain gardens (those receiving runoff from streets) and infiltration basins.

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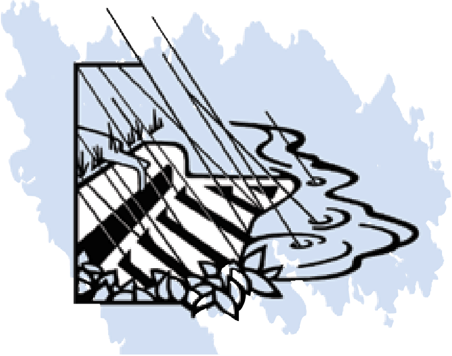

3.

Developing an Assessment Program

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Hot Links

3.1 Programs and goals for assessment

An assessment program is a plan of action for evaluating the functionality and performance of stormwater BMPs. Before developing an assessment program, it is important to have well-defined goals for assessment so that the effort required to develop and implement the program is focused to achieve the desired results. Rather than proposing a series of rigid procedures, we have developed several assessment options that can be used in various combinations depending on information needs, budgetary constraints, time frames, and legal requirements. Collectively, these factors are combined to identify specific assessment goals, including uncertainty estimates and information expectations, that guide short- and long-term assessment efforts. While it is anticipated that most techniques will require technicians with various levels of professional expertise, such as public works or

Erickson, A.J., P.T. Weiss, J.S. Gulliver, R.M. Hozalski, and B.C. Asleson. 2007. Developing an assessment program. In *Assessment of Stormwater Best Management Practices,* ed. J. S. Gulliver and J.L. Anderson. St Paul, MN: University of Minnesota.

monitoring personnel, volunteers may be trained to do some of the visual assessments.

Examples of assessment goals:

- System-wide visual examination of stormwater BMPs – are they working?
- Pass/fail examination of rain garden function;
- Wet pond sediment, bacteria, and phosphorus loading reductions (annual);
- Seasonal (winter included) performance and function of infiltration basins;
- Identification of operation and maintenance needs;
- Sediment particle size removal rates by underground proprietary devices as affected by maintenance;
- Rain garden effects in reducing runoff volumes, phosphorus, and sediment loading rates or the optimization of rain garden life expectancy via targeted operation and maintenance procedures; and
- Estimation of phosphorus and sediment load reductions from municipal pollution prevention (source reduction) efforts.

The details of individual assessment programs will vary depending on the goals of assessment, the stormwater BMP(s) to be assessed, and other variables, but the process of developing an assessment program is universal. Typical assessment goals can be refined by engaging in the following five-step process:

Step 1. Why assess? What is required by permit, voluntary watershed management goals, TMDL allocation, or protection effort?

Step 2. Assessment reconnaissance:

a. Identify stormwater BMP locations, types, drainage areas, design criteria, and life cycle stage (i.e., age);

b. Identify downstream receiving waters and sensitivity;

c. Identify how the stormwater BMPs have been operated and maintained;

d. Identify seasonal treatment needs (e.g., winter for chlorides, summer for bacteria); and

e. Schedule, budget, and personnel realities.

Step 3. Determine the level of assessment needed to address key needs. (See section 3.2, Levels of Assessment, below).

Step 4. Revise steps 1, 2, and 3, if necessary, based on the levels of assessment, the budget of the assessment program, and the assessment considerations in the stormwater BMP chapters (7-11).

Step 5. Fill in the details of the assessment program with dates for visual inspection (level 1 assessment), testing (level 2 and 3 assessment), or monitoring equipment installation (level 4 assessment).

After the assessment program has been developed, the program must be implemented. Implementation of an assessment program may begin with assigning tasks or hiring personnel; purchasing, constructing, or acquiring equipment; installing or transporting equipment; acquiring permits or permission; developing and following safety guidelines; developing or revising operation and maintenance programs; or coordinating with municipal, county, or state entities.

3.2 Levels of assessment

The answers to the questions listed above will be specific to each assessment program. Determining how assessment will occur requires an understanding of the four levels of assessment:

1. **Visual Inspection:** A rapid assessment procedure for qualitatively evaluating the functionality of a stormwater BMP. Visual inspections use a set of criteria that, under certain circumstances (detailed below), determine if the stormwater BMP is malfunctioning.
2. **Capacity Testing:** An assessment method used to determine the permeability (hydraulic conductivity and total infiltration flow rate in volume per time) or the sediment removal capacity (remaining sediment storage volume) of the stormwater BMP from a number of spatially distributed, relatively rapid, and simple point measurements.
3. **Synthetic Runoff Testing:** An assessment method that doses the stormwater BMP with a prescribed amount of synthetic stormwater. Synthetic runoff testing can be used to assess the performance of a stormwater BMP with regards to runoff volume reduction (e.g., through infiltration) and pollutant removal efficiency. Measurements such as drain time and mass of pollutant retained by the stormwater BMP can be made.
4. **Monitoring:** The most comprehensive assessment method, monitoring relies on natural rainfall and runoff. Flow measurement, sample collection, and sample analysis are required to determine the mass of water and pollutants entering and exiting the system. More variables can be assessed with monitoring than with synthetic runoff testing. Because of the uncertainties and variability of the inflow, the results of monitoring will typically have a larger associated uncertainty in assessed performance. Monitoring, however, will assess the stormwater BMP performance within a watershed without requiring modeling.

Developers of an assessment program should consider each of the four levels of assessment in sequence based on effort and uncertainty considerations, and consider the next level only when warranted by the assessment program. By this process, an assessment program may include any combination (e.g., levels 1 and 3) of, including all, the four levels or assessment. The rest of this chapter will give a general description of the four levels of assessment and when to use them. The four levels of assessment, however, will vary in application based on the stormwater BMP and the assessment goals, so detailed descriptions of how each level of assessment can be applied to a

Table 3.1: Comparison of the four levels of assessment

Level	Title	Objectives	Relative Effort	Typical Elapsed Time	Advantages	Disadvantages
1	Visual Inspection	Determine if stormwater BMP is malfunctioning	1	1 day	Quick, inexpensive	Limited knowledge gained
2	Capacity Testing	Determine infiltration or sedimentation capacity and rates	10	1 week	Less expensive, no equipment left in field	Limited to infiltration and sedimentation capacity/rates, uncertainties can be substantial
3	Synthetic Runoff Testing	Determine infiltration rates, capacity, and pollutant removal performance	10–100	1 week–1 month	Controlled experiments, more accurate with fewer tests required for statistical significance as compared to monitoring, no equipment left in field	Cannot be used without sufficient water supply, limited scope
4	Monitoring	Determine infiltration rates, capacity, and pollutant removal performance	400	14 months	Most comprehensive, assesses stormwater BMP within watershed without modeling	Uncertainty in results due to lack of control, equipment left in field

specific stormwater BMP or group of stormwater BMPs can be found in Chapters 8–11. Table 3.1 summarizes the four levels of assessment and the relative effort, typical elapsed time, advantages, and disadvantages of each level.

3.2.1 Visual inspection

The first level of assessment is visual inspection. Visual inspection involves inspecting a stormwater BMP for evidence of malfunction and can be accomplished with a brief site visit. Visual inspection, in some situations, can be used to determine quickly and cost-effectively if a stormwater BMP is not operating properly. If a stormwater BMP is determined to be non-functional based on visual inspection, no further assessment is warranted until the stormwater BMP is repaired or replaced.

The qualitative information gathered is often a valid indicator as to whether the stormwater BMP is malfunctioning, but visual inspection alone cannot provide quantitative information about stormwater BMP performance such as peak flow reduction, runoff volume reduction (e.g., infiltration), or pollutant removal efficiency. Photographs of two rain gardens are shown in figure 3.1; the rain garden on the left contains standing water even though there has been no recent rainfall. The rain garden on the right has no standing water and contains healthy, non-wetland plants. It is visually obvious that the rain garden on the left in figure 3.1 is malfunctioning and that maintenance or some other corrective action is required before any further assessment is warranted. Visual inspection cannot, however, provide quantitative evidence that the rain garden on the right in figure 3.1 is operating as designed or expected.

Considering the minimal effort and low cost required for visual inspection, it is recommended that visual inspection be used as the initial assessment tool for all stormwater BMPs. Quantitative information on performance will require additional assessment at levels 2, 3, or 4.

Figure 3.1: Examples of visual inspection for a rain garden that is not functional (left) and a rain garden that is functional (right).

To ensure that stormwater BMPs continue to function properly over time, visual inspections should be scheduled at least once per year in the beginning of the rainy season after the snow has melted (if applicable). Photographs should be taken as part of any visual inspection to visually document conditions of the stormwater BMP for future reference. As with any field work, safety is an important concern and should be addressed when conducting visual inspection.

The procedure for visual inspection varies for each stormwater BMP and assessment goal, and some stormwater BMPs may require visual inspections more frequently than once per year. Therefore, the reader should refer to the stormwater BMP chapter specific to the stormwater BMP that will be assessed. For example, if an assessment program is being developed to assess a dry pond, the reader should follow the discussion, recommendations, and standard procedures in Chapter 10 (Sedimentation), because dry ponds are discussed in that chapter. Checklists for visual inspection of the more common stormwater BMPs are given in this document (see Chapters 8–11 and Appendix B).

3.2.2 Capacity testing

After visual inspection has been performed and there are no obvious malfunctions, capacity testing should be considered if infiltration or sedimentation capacity is an important function of the stormwater BMP. Capacity testing is an assessment method used to determine either the permeability or the sediment accumulation capacity (sediment storage volume) of the stormwater BMP from a number of spatially distributed, relatively rapid point measurements. The point measurements are distributed spatially to estimate the overall permeability or sediment retention capacity of the stormwater BMP. Capacity testing protocols for other functions, such as chemical retention of stormwater BMPs, have yet to be developed.

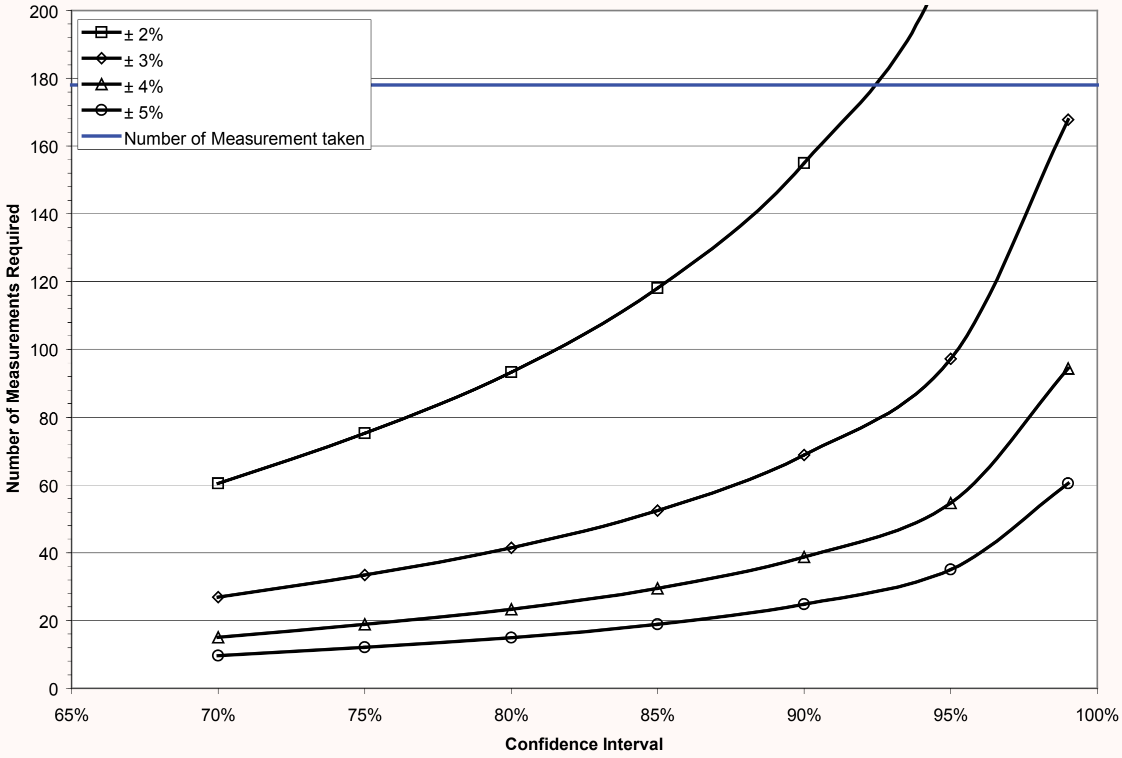


Figure 3.2: Number of measurement locations for capacity testing of permeability

The accuracy of capacity testing is dependent on the number of point measurements taken and the spatial mean and variance of the parameter that is being estimated (i.e., permeability or sediment depth). Research at St. Anthony Falls Lab on permeability in rain gardens has resulted in a relationship between confidence interval and the number of measurements required, as shown in figure 3.2. This relationship can be used to determine the number of permeability measurements that should be taken during capacity testing to estimate the overall permeability. The reader should choose the desired confidence (e.g., 95% confidence), choose the size of the confidence interval (e.g., ± 4%), and then use figure 3.2 to determine the number of measurements required for that level of accuracy (round up to be conservative). An example of this process is given in example 3.1.

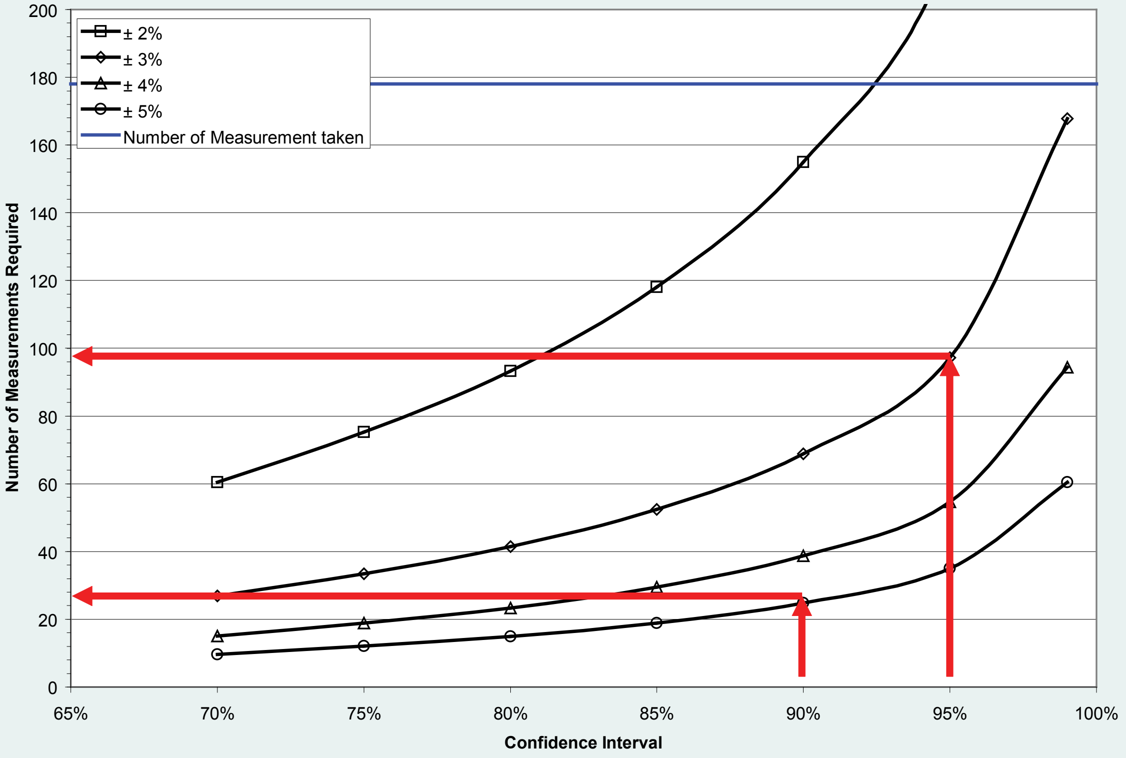
Example 3.1: Number of measurement locations for capacity testing of permeability

Julie, a water resources engineer, is developing an assessment program for an infiltration basin. To determine the number of point measurements required for the assessment, she must first decide what level of accuracy she wants for her assessment.

She wants a high level of accuracy, and therefore chooses a 95% confidence interval with a range of ± 3%. She then uses figure 3.2 to find that she would need nearly 100 measurements to achieve this level of accuracy. Considering her budget constraints and labor available, Julie decides that a 90% confidence interval with a range of ± 5% should suffice for her assessment. Using these values in figure 3.2, she finds that only 25 measurements are required for this level of accuracy. See graph below.

continued

Example 3.1 continued



As with visual inspection (level 1), the procedure for capacity testing (level 2) varies for each stormwater BMP and assessment goal. Therefore, the reader should refer to the processed based stormwater BMP chapter (e.g., filtration practices) specific to the stormwater BMP that will be assessed. As with any field work, safety is an important concern and should be addressed when conducting capacity testing.

Permeability tests

Permeability testing is a method of capacity testing that produces an estimate of the overall permeability of a stormwater BMP using a network of point measurements. Permeability is measured at a number of locations in the stormwater BMP and recorded with the corresponding spatial location. The permeability is then spatially averaged to estimate the overall permeability for the stormwater BMP. The overall permeability can be used to predict the rate at which water will infiltrate into the soil or filtrate through the filter media, which can determine if an infiltration or filtration practice needs maintenance or repair. Permeability tests can be applied to any stormwater BMP that uses sand or soil as a filtration or infiltration medium.

Table 3.2 Usability comparison.

CRITERIA	Double Ring Infiltrometer	Philip-Dunne Permeameter	Minidisk Infiltrometer	Guelph Permeameter	Tension Infiltrometer
Transportability of equipment	2	1	1	2	3
Volume of water needed	3	1	1	2	3
Experiment duration	3	2	1	3	2
Simplicity of operation	2	1	2	3	3
Cost	2	1	1	3	3
Personnel requirements	1	1	1	2	2
Accuracy	?	?	?	?	?

Criteria evaluation: 1 = most desired, 2 = second-most desired, 3 = least desired

Devices that can be used to determine soil permeability include: air-entry permeameter, Guelph permeameter, tension infiltrometer, double- and single-ring infiltrometers, disk infiltrometer, and a Modified Philip-Dunne permeameter. Several of these devices have been evaluated based on specific criteria as shown in table 3.2. As shown in table 3.2, the accuracy of permeameters and infiltrometers is still in question. Research at St. Anthony Falls Laboratory is calibrating several of these devices and, based on the evaluation, the Modified Philip-Dunne permeameter (figure 3.3) is recommended for estimating saturated hydraulic conductivity in the field. For more information, see Appendix C: Selection, Construction, and Use of Field Permeameters and Infiltrometers.

Permeability tests can be performed on the following stormwater BMPs: dry ponds, bioretention practices (rain gardens), sand or soil filters, infiltration trenches, infiltration basins, swales, and filter strips. Permeability in stormwater BMPs may vary based on climatic season, soil conditions, etc., and therefore permeability tests should be performed at several different times throughout the year to get an overall estimation of permeability. An example schedule for permeability tests could include testing in the spring after ground thaw, in mid-summer, and in late fall before ground freeze. Several bioretention practices in the Twin Cities area in Minnesota are being evaluated to quantify the variability in permeability values observed in the field. The goal is to develop a simple correlation that relates variability in permeability values to the number of samples required to predict the infiltration rate at a desired level of accuracy (i.e., typically 95% confidence interval).

Figure 3.3: Permeability testing with a Modified Philip-Dunne Permeameter in St. Paul, MN.

Low infiltration rates as identified by permeability tests may be attributed to clogging of the surface layer with captured sediments or a relatively impermeable subsurface layer. A soil core can be examined for the presence of relatively impermeable layers to determine the cause of low permeability.

An advantage of permeability tests as compared to synthetic runoff testing (level 3) is that it can be performed for all sizes of stormwater BMPs. Synthetic runoff testing is dependent upon an adequate supply of synthetic runoff, which limits it to smaller stormwater BMPs. The advantage of capacity tests compared to monitoring (level 4) is that less time and expense is required to perform the assessment. Another advantage is the ability to evaluate maintenance procedures; because the cause of reduced infiltration capacity can be easily identified using capacity testing. Locations that have poor permeability will be apparent with sufficient permeability testing. Permeability testing conducted annually can also be used to estimate the change in permeability with respect to time (e.g., Δ inches/year).

Sediment accumulation tests

Sediment accumulation tests estimate the sediment accumulated in a stormwater BMP. Sediment surface elevation measurements are taken throughout the stormwater BMP using surveying equipment or GPS units and the data are entered into AutoCAD, Microstation, or similar three-dimensional drafting software. For manholes or proprietary devices, weighing or estimating the removed sediment may be sufficient. The data can then be compared to similar data of initial surface elevation measurements to determine the amount of sediment that has accumulated. The amount of accumulated sediment is then compared to the design sediment storage volume to determine the available capacity. Sediment accumulation tests therefore require as-built plans or topographical data obtained as recently after construction as possible to determine the initial surface elevation. The rate of sediment accumulation can also be calculated for a given time period using equation 3.1.

Equation 3.1: Rate of sediment accumulation

$$\text{Rate of sediment retention} = \rho_s \frac{(V_2 - V_1)}{(t_2 - t_1)}$$

where

ρ_s = density of sediment
V_2 = volume of sediment measured at time t_2
V_1 = volume of sediment measured at time t_1
t_2 = time of measurement of V_2
t_1 = time of measurement of V_1

Sediment accumulation tests can be applied to any stormwater BMP that collects sediment and allows sediment surface elevations to be measured. Sediment accumulation tests can be performed on the following stormwater BMPs: dry ponds, wet ponds, wet vaults, wetlands, wet vaults, and underground proprietary devices.

The major advantage of sediment accumulation testing (level 2) as compared to synthetic runoff testing (level 3) is that it can be performed for all sizes of stormwater BMPs. Synthetic runoff testing is dependent upon an adequate supply of synthetic runoff, which restricts its applicability to smaller stormwater BMPs. Compared to monitoring (level 4), sediment accumulation tests take less time and expense to perform. Another advantage is the ability to use sediment accumulation as a diagnostic test for maintenance procedures because the source of the accumulation can be more easily identified.

Capacity testing conducted annually can be used to estimate the sediment accumulation rate with respect to time (e.g., lbs/year). Capacity testing cannot be used, however, to assess pollutant removal efficiency because it does not measure the concentrations of pollutants and flow rates of stormwater entering and exiting a stormwater BMP. Therefore, if the assessment goals include pollutant removal efficiency, synthetic runoff testing or monitoring must be considered.

3.2.3 Synthetic runoff testing

After levels 1 (visual inspection) and 2 (capacity testing) have been considered and either dismissed or performed, synthetic runoff testing should be considered if warranted by the goals of the assessment program. Synthetic runoff testing can be used to evaluate infiltration rate or the removal of pollutants by a stormwater BMP. Synthetic runoff testing uses a clean water source (e.g., a fire hydrant or water truck) that may contain targeted pollutants at predetermined concentrations or loads to dose the stormwater BMP with a well-controlled, synthetic storm event while measurements of the stormwater BMP performance are made. Adding targeted pollutants to synthetic stormwater may require authorization from local governments (municipal, watershed districts, or state). It is recommended that the reader investigate authorization requirements before performing synthetic runoff tests with pollutants. If the required discharge of water is outside the reasonable discharge of the water source, then level 3 testing is not likely to be feasible.

Filtration, infiltration, and biologically enhanced practices

Synthetic runoff testing can be used to assess total drain time of stormwater BMPs by filling the entire basin with water and measuring the water level change in the basin over time. The drain time is then measured directly. Additionally, synthetic runoff tests may be used to assess pollutant removal performance if all flows can be measured and are accessible for sample collection. Pollutant removal efficiency can be evaluated by spiking the influent water with a well-characterized pollutant (e.g., suspended solids, phosphorus, etc.) to the desired concentration and measuring the amount of pollutant retained by the stormwater BMP, the concentration exiting the stormwater BMP, or both. The goal of synthetic runoff testing for permeability is not to mimic natural storm events, but to estimate the rate of infiltration.

The following conditions must be met for synthetic runoff testing to be feasible: (1) there must be a water supply that can provide the required discharge and total volume of runoff; (2) outflow paths other than infiltration are either measurable or can be temporarily plugged; and (3) the water surface elevation in the stormwater BMP can be measured continuously during the test. When a stormwater BMP can be filled rapidly with synthetic stormwater, there is no need to measure the rate at which water is added because the infiltration rate is small in comparison and the measurement of change in water level with time occurs after the stormwater BMP is full. When the rate at which water is infiltrating is not negligible compared to the rate at which the stormwater BMP is filled, both the rate at which water is added to the stormwater BMP and the rate at which water is infiltrating into the stormwater BMP must be measured or estimated. Synthetic runoff testing to assess drain time can be performed on the following stormwater BMPs: bioretention practices (rain gardens), dry ponds, infiltration basins, sand and soil filters, underground sand filters, and underground wet vaults. The larger of these stormwater BMPs, however, will likely not meet criterion number 1. Permeability in stormwater BMPs may vary based on climatic season, soil conditions, etc., and therefore synthetic runoff testing for permeability should be performed at several different times throughout the year to get an overall estimation of permeability. An example schedule includes testing in the spring after ground thaw, mid-summer, and late fall before ground freeze.

The primary differences between capacity testing (level 2) and synthetic runoff testing (level 3) for measuring permeability relate to the size, vegetation, and subsurface characteristics of the stormwater BMP. Synthetic runoff testing is limited to stormwater BMPs that are small enough to be filled with water, as outlined above. Synthetic runoff testing, however, accounts for the increased infiltration that occurs near and around the stems of vegetation that cannot be measured using capacity testing. There are, however, significant changes that often occur in soil and vegetation as climatic seasons change. Synthetic runoff testing that is limited to a single week or month in a given year may therefore be misleading and should be avoided for stormwater BMPs that change seasonally. Additionally, synthetic runoff testing will show when filtration is limited by the subsurface collection system and not by the surface or near-surface layers.

As with visual inspection (level 1) and capacity testing (level 2), the procedure for synthetic runoff testing varies for each stormwater BMP and assessment goal. Therefore, the reader should refer to the stormwater BMP chapter specific to the stormwater BMP that will be assessed. For example, if an assessment program is being developed to assess an infiltration trench, the reader should follow the discussion and standard procedures in Chapter 9, Infiltration Practices, because infiltration trenches are discussed in that chapter. As with any field work, safety is an important concern and should be addressed when conducting synthetic runoff testing.

Sediment retention testing

Synthetic runoff testing can also be used to measure the sediment retention by stormwater BMPs. Research at the University of Minnesota has shown this technique to be repeatable and accurate on underground sediment retention structures, but it has not been used on most other structural BMPs. Manholes, grit chambers, and many proprietary devices can be classified as underground sediment retention structures. These structures are often suitable for synthetic runoff testing because of their relatively small design discharge. At a specific water discharge, a given quantity and size of sediment can be fed into the sediment retention structure. The mass of sediment retained is then extracted from the structure and weighed. The difference between the sediment fed and the sediment retained is presumed to have passed through the facility, and sediment retention efficiency can be computed for each sediment size and water discharge. Synthetic runoff testing with sediment is an effective means of determining how well a device will remove various sizes of sediment and to verify that a device is functioning as designed. These synthetic runoff tests can be conducted at relatively high levels of accuracy.

Sediment retention testing could be applied to other structural stormwater BMPs. Some stormwater BMPs (e.g., dry ponds) are constructed from soil, and in such cases, separating sediment added to synthetic runoff from the soil that makes up the bottom of the stormwater BMP can be difficult. An alternative solution for such stormwater BMPs may be to use automatic samplers to capture synthetic stormwater samples at the outflow for comparison to sediment that was added to the influent synthetic runoff. Another alternative solution may be to paint sediments introduced into the BMP so that they can be easily separated from sediments already in the stormwater BMP or that are part of the original BMP construction. With these alternatives available, it is anticipated that sediment retention testing can be applied to most stormwater BMPs, including sand and soil filters, underground filters, hybrid filters, dry ponds, wet ponds, underground proprietary devices, wet vaults, rain gardens with a measurable outflow, constructed wetlands, filter strips, and swales.

3.2.4 Monitoring

If capacity testing and synthetic runoff testing are not feasible assessment approaches for a specific location or do not achieve the goals of the assessment program, monitoring should be considered. Monitoring is the most comprehensive assessment technique and can be used to assess water volume reduction, peak flow reduction, and pollutant removal efficiency for most stormwater BMPs by measuring discharge and pollutant concentration during natural runoff events.

To assess runoff volume reduction, peak flow reduction, or both by monitoring a stormwater BMP, the inflow(s) and outflow(s) must be measured or estimated according to the techniques described in chapter 4 (Water Budget Measurement). The summation of the inflows can then be compared to the summation of the outflows to determine the runoff volume reduction, peak flow reduction, or both. Detailed procedures and information about monitoring stormwater BMPs are available in the report “Urban Stormwater BMP Performance Monitoring” (U.S. EPA 2002). A summary of monitoring procedures is presented in the chapters corresponding to each stormwater BMP category (chapters 8–11).

Pollutant removal efficiency can also be determined by monitoring. In addition to measuring or estimating the inflow and outflow discharges, the inflow and outflow must also be sampled according to the techniques described in chapter 5 (Sampling Methods). Pollutant removal efficiency can then be calculated as the difference between the influent and effluent pollutant loads or concentrations, as described in chapter 12 (Data Analysis). See the corresponding stormwater BMP process chapter (chapters 8–11) for monitoring procedures to assess pollutant removal efficiency.

Natural runoff events have variable discharge and duration that require continuous flow measurement (or estimation). Pollutant removal assessment also requires sampling of all flows entering and exiting a stormwater BMP. Monitoring takes more time to complete (typically 14 or more continuous months), more equipment, more labor, and therefore higher expenditures than the first three levels of assessment. Monitoring, however, is the only method that accurately measures the response of a stormwater BMP to the actual runoff that is produced by a watershed. Levels 1, 2, and 3 measure the ability of a stormwater BMP to perform specific processes (e.g., infiltration, sediment retention). These data can be used in models to estimate how a stormwater BMP would perform in a given watershed.

Monitoring has more potential for uncollected or erroneous data as compared to synthetic runoff tests for the following reasons:

1. Weather is unpredictable and can produce various runoff volumes of various durations with varying pollutant concentrations at various times. In order for a storm event to be monitored correctly and accurately, all the monitoring equipment must be operating correctly and the parameters (water depth, etc.) must be within the limit ranges of the equipment.
2. Equipment malfunction due to routine wear or vandalism is more likely. Without consistent inspection and maintenance, storm events can be measured or sampled incorrectly or not at all.

As with the first three levels of assessment, procedures for monitoring will vary for each stormwater BMP and assessment goal. Therefore, the reader should refer to the process chapters (8–11) for information specific to the stormwater BMP that will be assessed. For example, if an assessment program is being developed to assess a soil filter with under-drains, the reader should follow the discussion and standard procedures in chapter 8 (Filtration Practices). As with any field work, safety is an important concern and should be addressed when conducting monitoring.

3.3 Recommendations

As mentioned above, all stormwater BMP assessment programs should include regularly scheduled visual inspections (level 1). Capacity testing (level 2) and synthetic runoff testing (level 3) are techniques to evaluate specific functions of a stormwater BMP with relative accuracy. They can be used to determine how performance of a stormwater BMP is changing with respect to time, changes in the watershed, or both. If the goals of the assessment program cannot be met by capacity testing or synthetic runoff testing, or these techniques are not feasible, then monitoring (level 4) should be considered as part of the assessment program. Monitoring is the most comprehensive assessment technique and will assess stormwater BMP performance within the watershed without modeling. One must, however, be ready to accept more uncertainty in the results because performance is more difficult to assess: due to the variability of natural rainfall events, discharge and pollutant concentration vary widely during monitoring. Table 3.1 summarizes the four levels of assessment and the advantages and disadvantages of each level.

Detailed discussion about the four levels of assessment as they apply to specific BMPs is included in chapters 8–11. Standard procedures that are specific to each stormwater BMP or stormwater BMP category have also been developed for all four levels of assessment. The standard assessment procedures have been formatted such that the procedure sheets can be printed separately from the chapter.

3.4 References

U.S. EPA. 2002. Urban Stormwater Stormwater BMP Performance Monitoring. 821-B-02-001, U.S. Environmental Protection Agency. Washington, D.C. http://www.epa.gov/waterscience/guide/stormwater/

Acknowledgements

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4.

Water Budget Measurement

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Hot Links

1. Water Budgets
2. Open Channel Flow
3. Conduit Flow
4. Infiltration
5. Evaporation and Evapotranspiration
6. Rainfall

It is important to note that this manual does not contain all possible methods of water budget measurement. The intent of this chapter is to discuss the most common methods and provide guidance for method selection. Those interested in other methods of discharge measurement or other water budget parameter estimation should consult discharge measurement (e.g., Bos, 1998, Herschy 1995), fluid mechanics (e.g., Franzini and Finnemore 1997), hydrology (e.g., Bedient and Huber 1992), or other similar texts.

4.1 Water budgets

As defined in chapter 1, a water budget for a stormwater BMP is the accounting of water that enters, exits, and is stored by the stormwater BMP. The water budget assigns discharge values to each of the processes that affect the fate of water, including input processes (e.g., direct precipitation into the BMP, surface runoff, and conduit or open channel flow) and output processes (e.g., infiltration, evapotranspira-

Erickson, A., J. Gulliver, R. Hozalski, O. Mohseni, J. Nieber, B.N. Wilson, and P.T. Weiss. 2007. Water budget measurement. In *Assessment of Stormwater Best Management Practices,* ed. J. S. Gulliver and J.L. Anderson. St. Paul, MN: University of Minnesota.

tion, and conduit or open channel flow). The goal for developing a water budget is to balance the inflows and outflows with minimal error.

Water budgets require measurement of all water transport into and out of the stormwater BMP, including open channel flow, conduit flow, over-land flow, direct precipitation, evaporation, transpiration, infiltration, ground water seepage, and any other influent sources and effluent transport processes. Figure 4.1 is an illustration of water budget processes on a typical stormwater BMP. However, measuring all sources of water transport may not be practical or possible. Some stormwater BMPs (e.g., infiltration basins) do not have a central effluent location that can be measured easily, and some transport processes (e.g., overland flow) are not easily measured or sampled (sampling is discussed in chapter 5). This chapter will discuss water budgets (4.1), the measurement of open channel flow (4.2), conduit flow (4.3), infiltration (4.4), evaporation and evapotranspiration (4.5), and rainfall (4.6). More information can be found in section 3.2.4 of “Urban Stormwater BMP Performance Monitoring” (U.S. EPA. 2002), which can be found at http://www.epa.gov/waterscience/guide/stormwater/files/montch3.pdf.

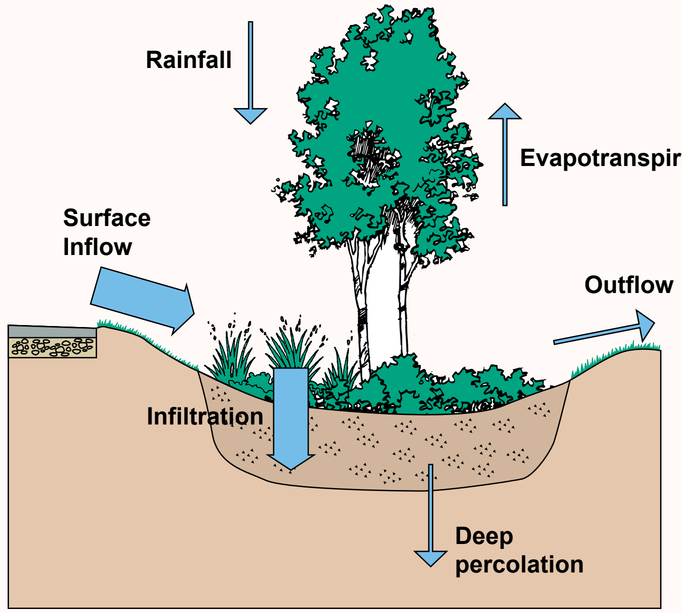

Figure 4.1: Water budget processes for a typical stormwater BMP.

Assessment of stormwater BMPs is significantly simpler and more accurate if the stormwater BMP is constructed or retrofitted to minimize modes of water transport into and out of the stormwater BMP. For example, a detention pond with two or more inlet structures would require multiple discharge-measurement and sampling stations, but if all inlets were combined into a central influent, only one discharge-measurement and sampling station would be required. Assessment costs could therefore be significantly reduced and the process simplified.

4.2 Open channel flow

As defined in chapter 1, open channel flow is the process by which water is transported by gravity with a free surface exposed to the atmosphere. Any of the principal methods of discharge measurement outlined below can be used to measure open channel flow. Some methods are more accurate than others while some methods measure a large range of discharge. Flow conditions common to stormwater often vary and thus the optimal method for measuring stormwater discharge must be able to measure small values of discharge accurately while also having the capacity to measure large values of discharge. For reference, the depth-discharge (also called the stage-discharge) relationship for six discharge measurement techniques is shown in figure 4.2.

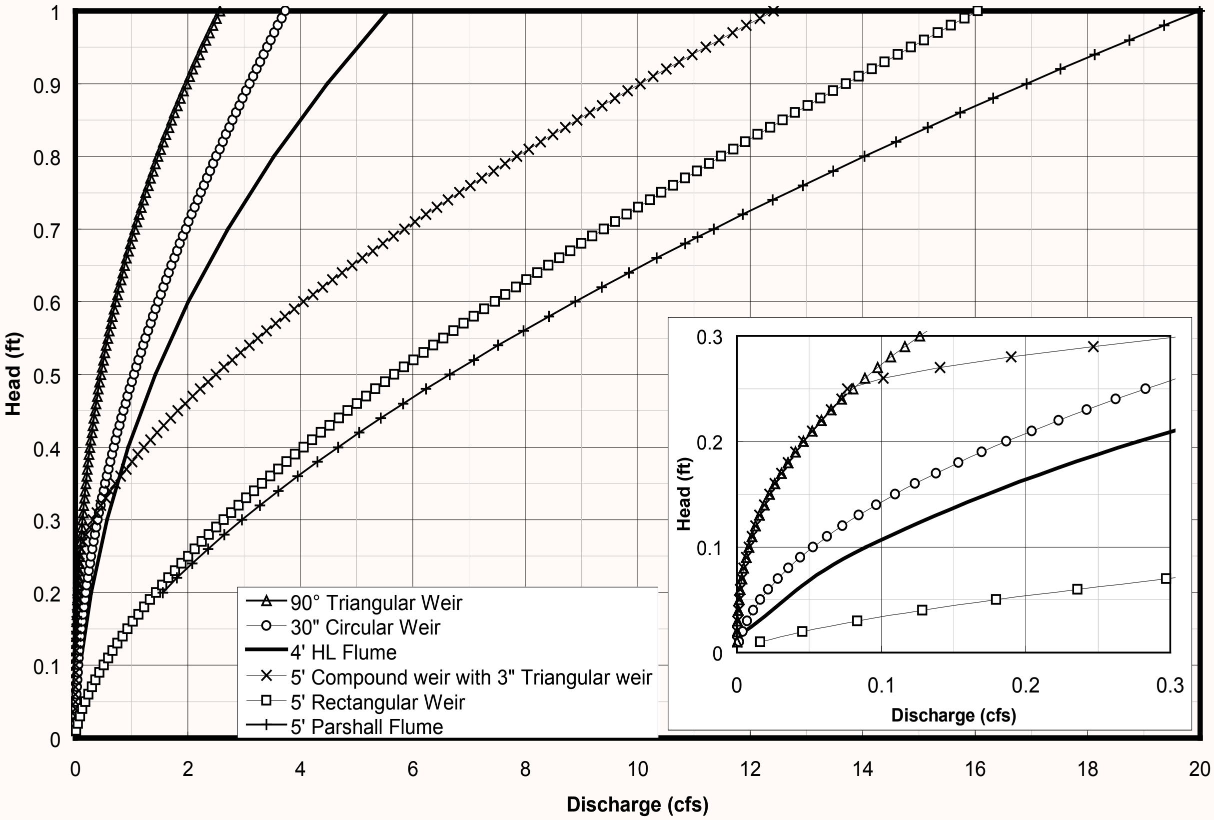

Figure 4.2: Stage-discharge relationships for common discharge measurement devices. [One foot = 0.305 m; 1cfs = 0.028 m^3/s.]

ADVANCED DISCUSSION

It is important to understand the concepts of steady and unsteady flow because the methods for estimating discharge in open channels for steady and unsteady flow are different. For flow to be considered steady, all flow properties (velocity, depth, etc.) must remain constant with respect to time. For example, large open channel flow (e.g., large rivers) can be approximated as steady flow for time periods in which the flow changes are not significant. The principal methods of discharge measurement described below assume steady flow conditions, but in most natural systems, steady flow is only present for short time periods.

To analyze unsteady flow using steady flow concepts, flow data must be collected near-continuously over small time steps. If the time step is small, the flow can be considered steady for that time step and the total volume of flow can be estimated by multiplying the discharge (volume per time) by the time step duration (time) for each data point and summing the products for an entire event (or day, month, year, etc.).

The principal methods to estimate discharge for steady flow are as follows:

- Continuity (Flow rate (Q) = Velocity (V) multiplied by Area (A)): The average flow velocity can be multiplied by the cross-sectional flow area to estimate the discharge.

- Weirs (V-notch, rectangular, circular, compound): As fluid passes over a weir, it transitions to critical flow, where discharge is solely dependent on the cross section. Discharge can be estimated accurately under critical flow conditions using the depth of water behind the weir and equations corresponding to the type of weir used.
- Flumes (Parshall, Palmer-Bowlus, figure 4.3): Discharge measurement flumes produce a constriction in the flow and thus cause the flow to transition to critical flow (Froude number = 1). Similar to weirs, a measurement of the depth of critical flow and relevant flume dimensions can be used to estimate the discharge through the flume.

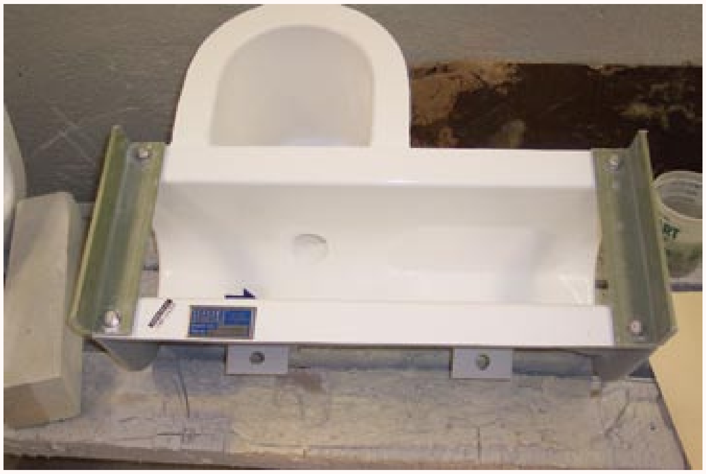

Figure 4.3: Palmer-Bowlus Flume (http://www.tracomfrp.com /palmer_bowlus.htm; Tracom, Inc.)

- Manning's Equation: Robert Manning developed Manning's equation (equation 4.1) in the 19th century to estimate discharge for uniform open channel flow using cross-sectional area, hydraulic radius, energy grade-line slope, and an empirically defined roughness coefficient (n) (Sturm 2001). The potential measurement uncertainty, however, is large, and it is recommended that Manning's equation be used only as a last resort to estimate discharge in stormwater applications.

Equation 4.1: Manning's equation

$$Q = \frac{K_n}{n} R^{\frac{2}{3}} S_f^{\frac{1}{2}} A$$

where

Q = discharge

K_n = unit conversion factor, K_n = 1.0 for SI units, K_n = 1.49 for English units

n = Manning's roughness coefficient

R = hydraulic radius, $R = A/P_w$

A = cross-sectional area

P_w =wetted perimeter

S_f = friction (i.e., energy grade line) slope

ADVANCED DISCUSSION

Two components of Manning's formula make it potentially inaccurate when estimating stormwater discharge. First, the slope of the channel bed (or pipe) is often assumed to approximate the energy grade line; second, the empirically defined roughness coefficient is often estimated from a table of values. For long channels of constant slope, one can often assume that the channel slope approximates the energy grade line, but short channels, transitions, and changes in the flow, which are common in stormwater systems, invalidate this assumption. Additionally, measurement uncertainty is high for short channels of shallow slopes because of human and instrument error. The empirically defined roughness coefficient often must be calibrated for a specific system and is variable if the pipe or channel surface changes (e.g., deposition or erosion of sediments, flow obstructions, etc.). Therefore, the potential measurement uncertainty is large, and it is recommended that Manning's equation be used only as a last resort to estimate discharge in stormwater applications.

- Discharge measurement probes (area-velocity probe, sometimes called area-velocity meter or area-velocity sensor; current meters): Area-velocity (AV) meters use sonic waves to measure the discharge velocity throughout the flow cross-section. The velocity values are multiplied by the corresponding cross-sectional area and summed to estimate the total discharge. To ensure accuracy, area-velocity meters require a minimum water depth over the probe as specified by the manufacturer. Most meters do not correctly integrate negative (i.e., flowing upstream) velocities that may occur as a result of turbulence in a backwater profile. Therefore, these meters can produce limited or erroneous data during low-discharge conditions and in situations with downstream obstructions in the flow (such as a weir or debris) that may cause negative velocities. Current meters measure velocity at a point in the flow that represents a portion (i.e., area) of the flow cross section. Discharge is then computed from continuity (Q = V x A) and related to a stage discharge relationship (i.e., rating curve). For more information on current meters, refer to Chapter 10 of "Water Measurement Manual" (U.S. Bureau of Reclamation 2001).

- Backwater Profiles: Often called water surface profiles, backwater profiles for gradually varied flow use discharge, channel geometry, conservation of energy, and estimates of friction losses (usually based on Manning's Equation) to calculate the water surface elevation in the channel as a function of distance from a channel location of known depth. When used to estimate discharge, the water depth is measured at some distance from a control (such as weir or free outfall) and other variables are either calculated or measured. Backwater profile calculations are performed with a guessed value of discharge that is adjusted until the measured depth at the known distance from the control matches the calculated depth. For a more complete explanation with examples of backwater profile calculations, see an open channel flow text or manual, such as "Open Channel Hydraulics" (Sturm 2001).

Selection of a discharge measurement method is dependent on many factors, including accuracy, cost, range of discharge, and site conditions. For further discussion of individual factors, see Chapter 4 in the "Water Measurement Manual" (U.S. Bureau of Reclamation 2001).

All the discharge measurement principles listed above require a measurement of water depth and a known channel (or pipe, etc.) geometry to calculate discharge. In the case of a weir, the water depth is measured behind the weir and weir equations (discussed in detail below) convert depth to an estimated discharge over the weir. In the case of discharge measurement probes, a water depth is needed to determine the wetted perimeter. The principal methods of depth measurement use pressure under hydrostatic conditions and density. Bubbler probes and pressure transducers, when located under the water surface, measure the pressure of water (i.e., hydrostatic pressure), which corresponds to a specific depth of water. Ultrasonic and Doppler probes, typically positioned above the water surface, locate the water surface using the change in density from air to water because the water surface reflects the acoustic signal back to the probe.

The accuracy of any depth measurement should be verified prior to installation of equipment and re-verified each time the site is visited to ensure that the equipment is calibrated correctly and in good working condition. A graduated ruler (i.e., staff gauge) affixed to a non-moving structure (such as the weir or a post) can be used to verify the depth visually. If the depth measured by the staff gauge does not correspond with that of the depth measurement device (e.g., bubbler), verify that the staff gauge has not been disturbed and that the depth measurement device is working properly. Most manufacturers provide documentation that describes measurement range and accuracy for their respective depth-measurement devices (such as bubblers and probes). For example, Isco (Teledyne Isco Inc. 2006) reports the measurement accuracy for the Isco 4200 discharge meters as shown in table 4.1. The rest of this chapter discusses different flow regimes (open channel, conduit, etc.) that may be encountered and their respective discharge measurement methods.

Table 4.1: Depth measurement device accuracy (Teledyne Isco Inc. 2006)

Depth Measurement Device	Range (ft)	Accuracy (ft)	Range (m)	Accuracy (m)
Ultrasonic Sensor	<1.0[a]	0.02	<0.31	0.006
	1.0 to 10[a]	0.03	0.31 to 3.05	0.009
Pressure Transducer	0.1 to 5.0	0.01	0.03 to 1.52	0.003
	0.1 to 7.0	0.03	0.03 to 2.13	0.009
	0.1 to 10.0	0.1	0.03 to 3.05	0.03
Bubbler	0.1 to 5.0	0.005	0.03 to 1.52	0.002
	0.1 to 7.0	0.01	0.03 to 2.13	0.003
	0.1 to 10.0	0.035	0.03 to 3.05	0.011
Area-velocity probe	0.05 to 5.0	0.01	0.015 to 1.52	0.003
	0.05 to 7.0	0.03	0.015 to 2.13	0.009
	0.05 to 10.0	0.1	0.015 to 3.05	0.03

[a] **Range for** ultrasonic sensor is the actual change in vertical distance between the sensor and the liquid surface. All other ranges are ranges in liquid depth.

ADVANCED DISCUSSION

V-notch weirs measure low discharge accurately (± 1 to 2%, A.S.T.M. D5640-95 2003) because small changes in discharge result in large changes in depth. Therefore, measurement uncertainty associated with the depth measurement has little effect on the estimated discharge. For example, a measurement uncertainty of ± 0.02 ft (0.006 m) in a 90˚ triangular weir with a discharge of 0.1, 1.0, and 10 cfs results in a discharge accuracy of ± 18%, ± 7%, and ± 3%, respectively, as shown in table 4.2. The discharge equation for triangular weirs is given in equation 4.2. Examples 4.1 and 4.2 are provided to show how equation 4.2 is applied in two different situations. The discharge coefficient (C_d) as shown in equation 4.2 varies from 0.58 to 0.62, is dependent on θ and h, and may be determined graphically or experimentally. However, a value of 0.60 may be assumed with a measurement uncertainty of ± 3%.

Table 4.2: Effect of depth measurement uncertainty of ±0.02 feet (0.006 m) on accuracy of discharge estimation methods expressed as a percent of discharge.

Discharge (cfs) =	0.1 cfs	1 cfs	10 cfs
90° V-notch weir	18%	7%	3%
5’ rectangular weir	100%	20%	4%
5’ compound weir with 6’’, 90° triangular weir	18%	20%	5%
30’’ circular weir	61%	18%	6%

Equation 4.2: Flow over a V-notch weir

$$Q = \frac{8}{15} C_d \left[\tan\left(\frac{\theta}{2}\right) \right] \left(\sqrt{2g}\right) h^{\frac{5}{2}}$$

where

Q = discharge

C_d = discharge coefficient

θ = angle of the V-notch

g = gravitational acceleration

h = head above the vertex of the weir

(Franzini and Finnemore 1997)

90˚ V-notch weirs, however, are limited because large discharge requires more depth as compared to other weirs and flumes for the same discharge. For example, a 90˚ V-notch weir requires 0.9 ft of depth to measure 2 cfs whereas a 30-inch circular weir requires less than 0.3 feet of depth, a Parshall flume requires less than 0.25 feet of depth, and a 5-foot rectangular weir requires less than 0.05 feet of depth, as shown in figure 4.2. The rectangular weir requires less depth for the same discharge than all the other measurement devices shown in figure 4.2. The rectangular weir, however, does not accurately measure low discharge because small changes in depth result in large changes in discharge; therefore, measurement errors associated with the depth measurement have a significant effect on the discharge estimation as shown in table 4.2. As mentioned above, the optimal method for measuring stormwater discharge must be able to measure low discharge accurately while also having the capacity to measure large discharge.

A compound weir and circular weir (Addison 1941) both measure low discharge while also having the capacity to measure large discharge. As shown in table 4.2 and figure 4.2, the compound weir composed of a 3-inch 90˚ V-notch section and a 5-foot rectangular section (see figure 4.5) measures low discharge as accurately as a 90˚ V-notch weir but also measures high discharge without large head requirements (e.g., 14 cfs with less than 1.0 ft of head over the weir). Two applications of a V-notch compound weir are illustrated in figure 4.4, and a schematic is shown in figure 4.5. Using the water surface elevation and the weir dimensions, equation 4.3 can be used to estimate the discharge for a 90˚ V-notch compound weir, as performed in example 4.3. A circular weir also measures both small and large discharge but is less accurate at large discharge than the other methods listed in table 4.2.

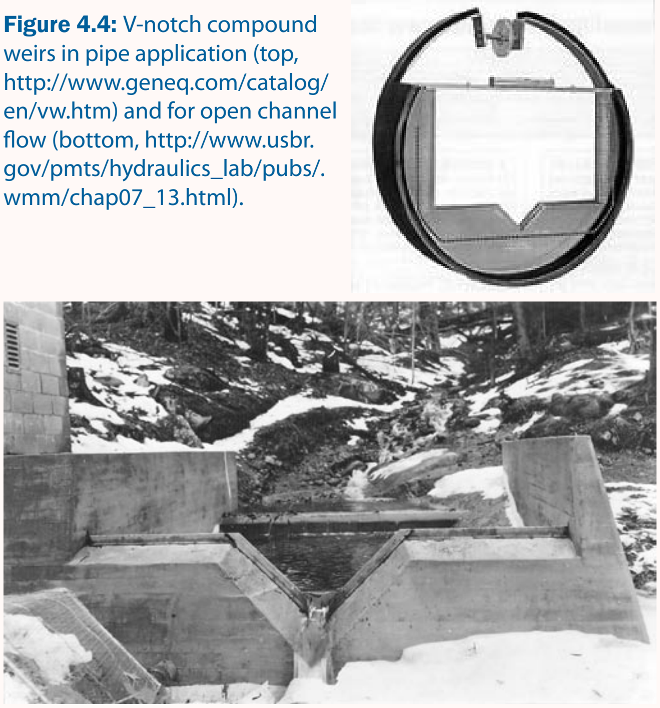

Figure 4.4: V-notch compound weirs in pipe application (top, http://www.geneq.com/catalog/en/vw.htm) and for open channel flow (bottom, http://www.usbr.gov/pmts/hydraulics_lab/pubs/.wmm/chap07_13.html).

Example 4.1: Flow rate calculations

Kevin, a recent civil engineering graduate, is verifying the discharge values estimated by a computer program. He inputs a specific set of conditions into the program: 18-inch (0.46m) conduit, 120° V-notch weir, water depth of 4 inches (0.10m) that does not exceed the top of the V-notch. He then uses **equation 4.2** to verify the discharge estimated by the program:

$$Q = \frac{8}{15} C_d \left[\tan\left(\frac{\theta}{2}\right) \right] \left(\sqrt{2g}\right) h^{5/2}$$

$$Q = \frac{8}{15}(0.60)\left[\tan\left(\frac{120°}{2}\right) \right] \left(\sqrt{2 \times 32.2}\right) (0.33\ ft)^{5/2}$$

$$Q = 0.32[1.73](8.02)(0.064) = 0.278 cfs\ (0.008\ m^3/s)$$

Example 4.2: Flow depth in a V-notch weir

Kevin notices that the program can also calculate a water depth based on a specified discharge. He inputs a discharge of 1.5 cfs, specifies a 90° V-notch weir in the computer program, and uses **equation 4.2** to verify the results:

$$Q = \frac{8}{15} C_d \left[\tan\left(\frac{\theta}{2}\right) \right] \left(\sqrt{2g}\right) h^{5/2}$$

$$1.5 = \frac{8}{15}(0.60)\left[\tan\left(\frac{90°}{2}\right) \right] \left(\sqrt{2 \times 32.2}\right) (h)^{5/2}$$

$$1.5 = 0.32[1.0](8.02)(h)^{5/2} = 2.57(h)^{5/2}$$

$$\frac{1.5}{2.57} = (h)^{5/2} \Rightarrow (0.58)^{2/5} = h = 0.81\ ft\ (0.247\ m)$$

Unit Conversions:
1 foot = 0.3048 meters
1 inch = 0.0254 meters
1cfs = 0.028 m^3/s

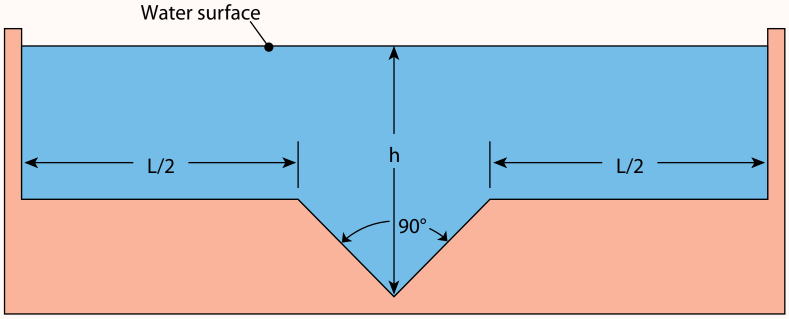

Figure 4.5: Schematic of V-notch compound weir

Equation 4.3: Compound weir with 3-inch (0.0762 m) V-notch section

$$Q = \frac{8}{15} C_{d1}\left(\sqrt{2g}\right) H_1^{5/2} - \frac{8}{15} C_{d2}\left(\sqrt{2g}\right)(\mathrm{H}_1 - \mathrm{H}_2)^{5/2} + \frac{2}{3} C_{d3} L \left(\sqrt{2g}\right)(H_1 - H_2)^{3/2}$$

where

Q = discharge (cfs)
C_{d1} = Coefficient of discharge for the V-notch = 0.57
g = gravitational constant (32.2 ft/s²)
H_1 = Total head above the vertex of the V-notch (ft)
C_{d2} = Coefficient of discharge for the overlapping portion of the V-notch and the Rectangular weirs = 0.55
H_2 = Depth of the V-notch portion (ft) = 0.25 ft
C_{d3} = Coefficient of discharge for the Rectangular weir = 0.64
L = combined length of the horizontal sections (ft)
(Hussain et al. 2006)

Example 4.3: Compound weir flow calculation

Kevin, the new civil engineer, is verifying the discharge values estimated by a computer program. He chooses a V-notch compound weir with 2-foot (0.61 m) horizontal sections on each side and a 3-inch (7.62 cm), 90° V-notch and specifies a water depth of 15 inches (0.381m) above the vertex of the V-notch. He then verifies the results using **equation 4.3** is:

$$Q = \frac{8}{15} C_{d1}\left(\sqrt{2g}\right) H_1^{5/2} - \frac{8}{15} C_{d2}\left(\sqrt{2g}\right)(H_1 - H_2)^{5/2} + \frac{2}{3} C_{d3} L \left(\sqrt{2g}\right)(H_1 - H_2)^{3/2}$$

$$Q = \frac{8}{15} C_{d1} (8.02) 1.25\ \mathrm{ft}^{5/2}$$
$$- \frac{8}{15} C_{d2} (8.02)(1.25\ \mathrm{ft} - 0.25\ \mathrm{ft})^{5/2}$$
$$+ \frac{2}{3} C_{d3} (2\ \mathrm{ft} + 2\ \mathrm{ft})(8.02)(1.25\ \mathrm{ft} - 0.25\ \mathrm{ft})^{3/2}$$

$$Q = \frac{8}{15}(0.57)(8.02) 1.25\ \mathrm{ft}^{5/2} - \frac{8}{15}(0.55)(8.02)(1\ \mathrm{ft})^{5/2} + \frac{2}{3}(0.64)(4\ \mathrm{ft})(8.02)(1\ \mathrm{ft})^{3/2}$$

$$Q = 4.26 - 2.353 + 13.69 = 20.3\mathrm{cfs}\ (0.575 \mathrm{m}^{3}/\mathrm{s})$$

When using a weir to estimate discharge, it is very important to ensure that all flow at the particular location enters by traveling over the weir and not around the weir or under the weir. It must also be noted that:

- The weir (or some other barrier) should be extended into the ground (sometimes three or more feet) to minimize groundwater seepage under the weir.
- To ensure critical flow over the crest of the weir, it is important to maintain a "free outfall" over the weir. As long as the flow conditions downstream of the weir do not affect the flow over the weir, a free outfall is maintained.
- Weirs will back up the flow in the channel or conduit, which may alter the locations of flow entrance or exit for the stormwater BMP.
- The weir itself requires inspection and any necessary maintenance at least once a month to ensure that water does not leak or scour under the weir, that it is free of debris that may collect on the upstream side and disturb the water surface, and that it is in proper, working condition.

A Parshall flume (Parshall 1936) may also be used to estimate discharge in open channels. Parshall flumes are rectangular sections that constrict the flow to create critical flow through a specific section of the flume. The discharge may be estimated by measuring the water surface elevation just upstream of the critical section and converting it to discharge using a calibration curve, which is most often provided by the manufacturer. Parshall flumes are readily available in widths from 2 inches to 120 inches (5.08–304.8 cm).

H, HS, and HL flumes (Gwinn and Parsons 1976) combine the sediment movement capabilities of a flume with the accuracy of a weir. The cross-section of H flumes, which is initially rectangular, converges at the downstream end with the top side walls sloped downward as is shown in figure 4.6. There are three types of H flumes categorized by size: the smallest size is the HS flume, the intermediate is the H flume, and the largest is the HL flume. Many manufacturers sell pre-constructed H flumes with rating curves that provide the relationship between water level and discharge with ranges from 0.085 cfs for HS flumes to 117 cfs for HL flumes (0.002 m^3/s–3.313 m^3/s, respectively).

Figure 4.6: H-flume (http://www.tracomfrp.com/h_flume.htm, Tracom, Inc.)

Compared to weirs, flumes are different in the following ways:

1. When installed upstream of a stormwater BMP, flumes do not create a pool upstream of the flume,
2. Flumes are less prone to collecting debris,
3. Flumes obstruct the movement of sediments less than weirs,
4. Flumes require more space and effort to install,
5. There is, in general, a smaller measurement range of discharge when using a flume as compared to a weir in the equivalent space.

4.2.1 Recommendations

Open channel flow in stormwater applications is most often unsteady and the discharge magnitude is often varied. Compound weirs, as shown in figure 4.2 above, provide a combination of accurate low discharge estimation and capacity to measure high discharge; therefore, it is recommended that compound weirs be used whenever possible. In channels with a high sediment load, weirs may create excessive deposition that will eventually affect the accuracy of the weir. In such cases, a properly sized H-flume (open channel flow) or Parshall flume may be used to measure open-channel discharge.

4.3 Flow in conduits

Conduits can transport two types of flow: pressurized conduit flow and open channel conduit flow. Pressurized conduit flow is defined as the transport of water in closed conduits (e.g., pipes) that are flowing full. Flow occurs because there is a longitudinal pressure difference along the conduit. Open channel conduit flow is transport of water by gravity with a free surface open to atmospheric pressure in which the channel is simply the size, shape, and slope of the conduit.

4.3.1 Conduits flowing full

Stormwater conduits are designed for a specific capacity (i.e., maximum discharge) that depends on the upstream conditions and downstream controls. Conduits flowing full operate at, or near, that capacity. Measuring discharge in a full-flowing conduit with a weir or flume is not recommended because weirs and flumes reduce the capacity of the conduit and the relation between discharge and the water surface elevation is not well established without a critical depth. Area-velocity probes, however, can measure discharge without causing significant obstruction in conditions that provide adequate depth over the probe. The following are advantages and disadvantages to using probes to measure full-flowing conduit discharge in lieu of weirs or flumes:

Advantages:

- Probes create less flow obstruction than weirs/flumes
- Probes can accurately measure depth or discharge in full-flowing conditions
- Probes are usually easier to install

Disadvantages:

- Probes cannot accurately measure low discharge associated with small storm events or the entire rising and falling limbs of hydrographs
- Probes sometimes require calibration, which may be difficult for certain site conditions
- Probes require additional cost and maintenance

A discharge measurement probe is usually attached to a flexible metal ring, which, when compressed, can be slid into the conduit

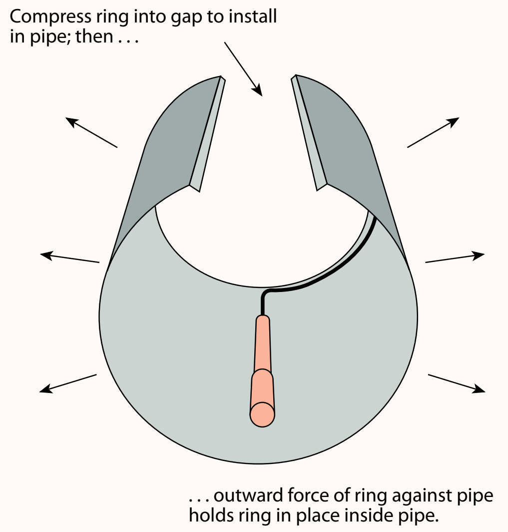

Figure 4.7: In-pipe installation of depth or direct flow measurement probe (diagram adapted from Isco user manual)

to the desired location (figure 4.7). When the compression is released, the ring expands against the inside of the conduit where friction holds the ring and probe in place. The probe is connected to a data logger that records such information as depth and velocity, which is then converted to a cross-sectional area of discharge, and then to a measurement of discharge. Additional equipment, such as tipping bucket rain gages, can be connected to the data logger, as well.

Area-velocity probes must be located at the bottom of the conduit and oriented so they face the oncoming discharge directly. They also require a minimum water depth (usually 1 to 2 inches, ~2.5 to 5 cm) in order to obtain accurate measurements. Stormwater pipe systems often have supercritical flow which, produces large discharge values with minimal water depth. Significant errors can occur when using probes to measure these discharge conditions when the depth does not exceed the minimum suggested by the manufacturer.

Two common brands of area-velocity probes used at the time of publication are Isco (figure 4.8) and Campbell Scientific. Campbell Scientific produces a velocity sensor that must be combined with a depth measurement and area conversion computation to estimate discharge. Campbell Scientific equipment is capable of connecting with equipment from other manufacturers but requires computer code to be written for it to communicate with the equipment. Isco equipment does not require code but it cannot be used in combination with equipment from other manufacturers. Most discharge measurement probes require connection to a data logger to record measurements with respect to time.

Figure 4.8: Isco area-velocity probe (http://www.envitech.co.uk/Prod_FlowMeter4250.html).

Area-velocity probes should be used only when an insignificant portion of the runoff event will occur at depths below those required for accurate measurements. Otherwise, a large portion of the total runoff volume may not be measured accurately.

4.3.2 Partially full conduits

Conduits flowing partially full are a variation of open channel flow in which the channel is simply the size, shape, and slope of the conduit. Therefore, a V-notch compound weir (figure 4.4), a circular weir (Addison 1941, figure 4.9), or a V-notch weir (figure 4.10) may be used to measure the discharge. To ensure accurate discharge measurements in a conduit with a weir, the weirs and probes must receive regular inspection and maintenance to remain free of sediment and debris that may accumulate behind the weir.

All weirs should be constructed so that the bottom of the weir fits the contour of the conduit and can be sealed with a waterproof sealer such as polyurethane. If a circular weir is to be used in a non-circular conduit, it is important that the crest of the weir remains circular (unless a calibration curve is determined for a specialized weir). For a circular weir, depth can be converted to an estimated discharge using equation 4.4. Example 4.4 demonstrates the use of equation 4.4 for discharge estimation using a circular weir.

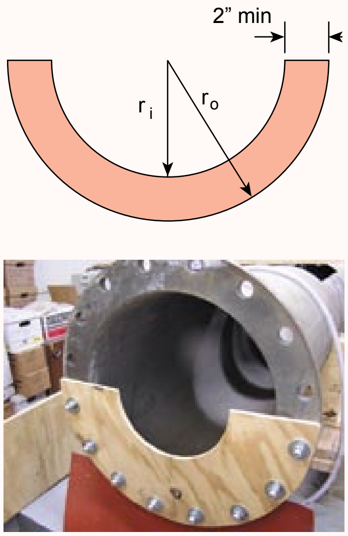

Figure 4.9: Circular weir schematic (top) and test setup photo (bottom, St. Anthony Falls Lab).

A V-notch weir may be used as an alternative to a circular weir for partially full conduit flow, as shown schematically in figure 4.10. For normal flow conditions, discharge can be estimated by equation 4.2, which applies to any V-notch weir section. Note that overflow condi-

Equation 4.4: Circular weir

$$Q = 0.0039C_d\left[10.12\left(\frac{h}{d}\right)^{1.975} - 2.66\left(\frac{h}{d}\right)^{3.78}\right](10d)^{5/2}$$

where

Q = discharge

d = diameter of circular orifice

h = height over the weir

C_d = coefficient of discharge as given by:

$$C_d = 0.555 + \frac{1}{110\left(\frac{h}{d}\right)} + 0.041\left(\frac{h}{d}\right)$$

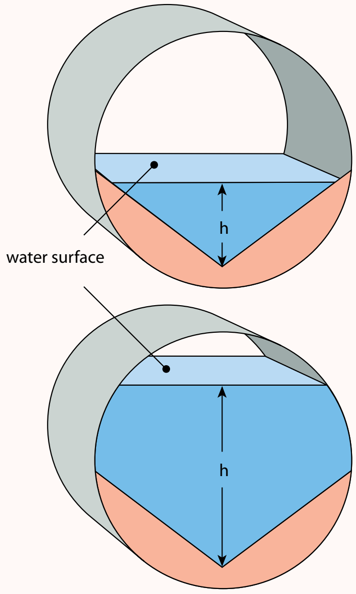

Figure 4.10: Schematic of V-notch weir inside a circular conduit in normal flow conditions (top) and overflow conditions (bottom).

tions shown in figure 4.10 are not estimated accurately by either V-notch (equation 4.2) or compound (equation 4.3) weir equations.

When measuring open channel discharge in a conduit, a Palmer-Bowlus (figure 4.3) flume may be used as an alternative to a weir. A Palmer-Bowlus flume is a Parshall flume modified to fit inside a circular conduit. Commonly available sizes range from 4 inches to 72 inches (10.16–182.88 cm) in increments similar to those of commercially available pipes. Palmer-Bowlus flumes tend to collect less debris compared to weirs because they produce less obstruction to the flow through the conduit. Manufacturer specifications should provide calibration or rating curves along with installation instructions for depth-measurement equipment.

Example 4.4: Discharge over a circular weir

Kevin, the new engineer, is verifying the discharge values estimated by a computer program and his final test of the computer program's accuracy is for a circular weir. He chooses a 15-inch (0.38m) inside diameter circular weir placed in an 18-inch (0.46m) pipe and a 2-inch (0.05m) water depth over the weir. He then verifies the results of the computer program by calculating the discharge using **equation 4.4**:

$$C_d = 0.555 + \frac{1}{110\left(\frac{0.05m}{0.38dm}\right)} + 0.041\left(\frac{0.05m}{0.38dm}\right) = 0.555 + \frac{1}{14.67} + 0.0055 = 0.629$$

$$Q = 0.0039(0.629)\left[10.12(0.133)^{1.975} - 2.66(0.133)^{3.78}\right](3.81)^{5/2}$$

$$Q = 2.45\left[0.189 - 0.0013\right](28.33) = 13.03L/s\ (0.460\ cfs)$$

4.3.3 Recommendations

For conduits with low-discharge (i.e., not sufficient to provide adequate depth over a probe), it is recommended that a weir be used for discharge measurement. Circular weirs provide a good combination of low-discharge accuracy and high-discharge capacity and are recommended for open channel conduit flow. The combination of a circular weir and a pressure sensor has proven to be effective for conduit flow over a wide range of discharges. The pressure measurement can be used to indicate depth over the weir. Pressure sensors in combination with circular weirs have not been tested in high-discharge conditions (nearly full-flowing conduit). In these conditions, it is likely that 'weir flow' is difficult to achieve with a circular weir, and therefore the weir equations reported above would not apply.

If a pressure sensor is to be used in conjunction with a weir, it is important to remember that a minimum depth above the probe is typically required to obtain accurate measurements. It is recommended that the weir height be set to achieve this minimum depth. The weir itself creates an obstruction to the flow that allows for accurate discharge measurement but also creates turbulent eddies upstream of the weir. Turbulent eddies interfere with an AV probe's velocity estimates, which will subsequently generate inaccurate discharge estimations. It is therefore recommended to use either a depth-measurement device or the depth-measurement capabilities of the AV probe with the appropriate weir equations to estimate discharge.

4.4 Infiltration

Various stormwater BMPs use infiltration as a primary or supportive process for stormwater treatment. When developing a water budget for a specific practice, it is important to consider infiltration and determine whether infiltration will represent a significant fraction of the total water outflow. For example, a dry pond may use sedimentation as the primary treatment process, but if the structure does not have an impermeable liner, it could also infiltrate a significant portion of the stormwater entering the pond. Neglecting infiltration may result in discrepancies between water inflow and water outflow in water budget analysis.

Infiltrometers and permeameters measure the infiltration rate at a specific location within a stormwater BMP. Infiltration rates can vary within one meter if soil and surface variations are significant. Therefore, several measurements throughout an area are required to determine a representative infiltration rate if capacity testing is used to estimate the overall infiltration rate. Synthetic runoff testing and monitoring may also be used to estimate infiltration. Refer to section 4.4.3 for information on infiltration measurement devices and chapters 8–11 for specific considerations for measuring infiltration in stormwater BMPs.

4.4.1 Definition of terms

The infiltration characteristics of soils are determined by the physical properties of the soil material. The properties are very dependent on soil texture and on the condition (i.e., compaction, structure, etc.) of the soil. In this section we give a very brief definition of the various terms that relate to the water storage capacity and water transmission properties of soil material. For more detailed information, refer to books on soil classification and soil physics/hydrology (Gardiner 2004, Brady 2004).

Hydraulic conductivity, K. The rate at which water will move in the soil under a unit gradient in the total potential.

Porosity, Φ. The volume of void space per unit volume of soil.

Soil water characteristic, $\theta(\psi)$. Relates the water content to the soil water pressure and quantifies the water holding capacity of the soil. A sample relation is shown in figure 4.11 for three textures of soil.

Soil water pressure, ψ. The energy with which water is held by the soil due to capillary action of the soil and water.

Soil water tension, h. The absolute value of the soil water pressure, ψ.

Water content, θ. The volume of water held per unit volume of soil.

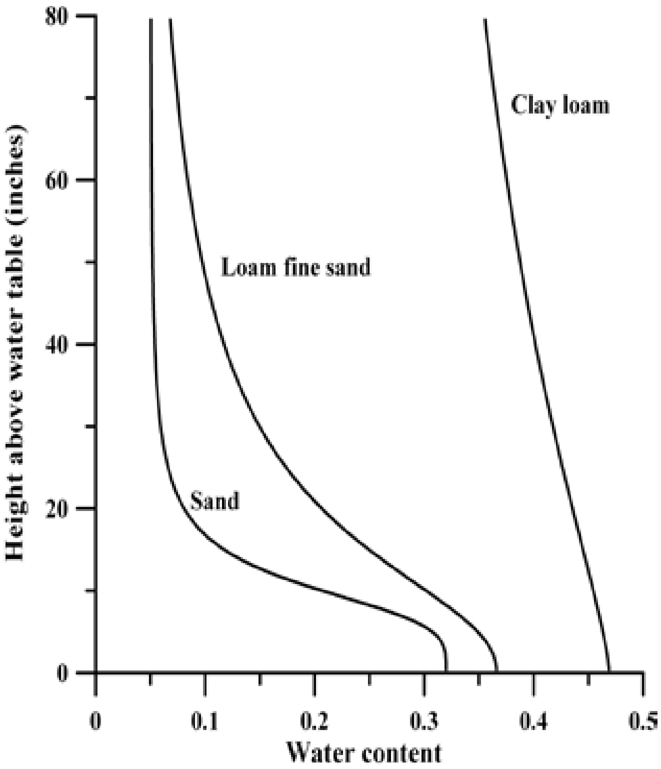

Figure 4.11: Soil water characteristic for three soil textures. [One inch = 2.54 cm.]

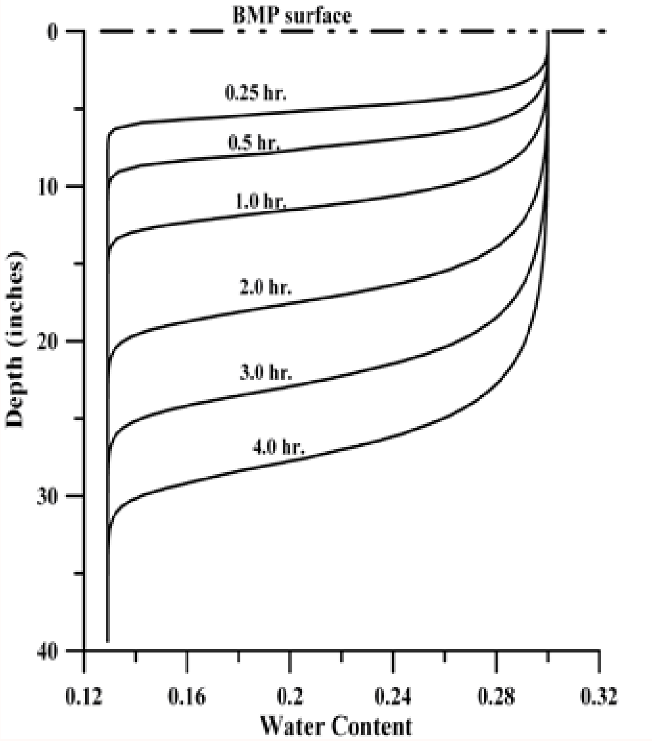

Figure 4.12: Water content distribution in the soil profile during an infiltration event. Note that the wetting fronts are given at various times from the initiation of infiltration.

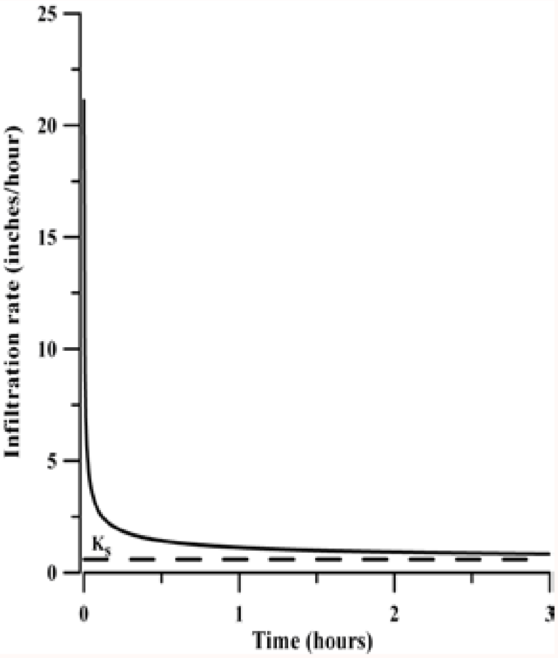

Figure 4.13: Illustration of infiltration rate versus time. [One inch/hr = 7.06 x 10^{-4} cm/s.]

Equation 4.6: Exponential decay curve

$$f = \frac{S}{2\sqrt{t}} + b$$

where
f = infiltration rate
S = sorptivity (ability of the soil to absorb water)
t = time
b is related to the saturated hydraulic conductivity

4.4.2 A brief overview of infiltration theory

Water applied to the soil surface will infiltrate into the soil due to the force of gravity and the suction (capillary action) of the soil. An illustration of water movement in a soil profile is presented in figure 4.12, which shows the distribution of water content with depth at various times from the start of infiltration. This illustration applies for the case where the soil profile is uniform with depth (i.e., no layering) and where the initial water content is uniform. The rate of infiltration into the soil for this case is shown in figure 4.13. It is observed that the infiltration rate decreases exponentially with time.

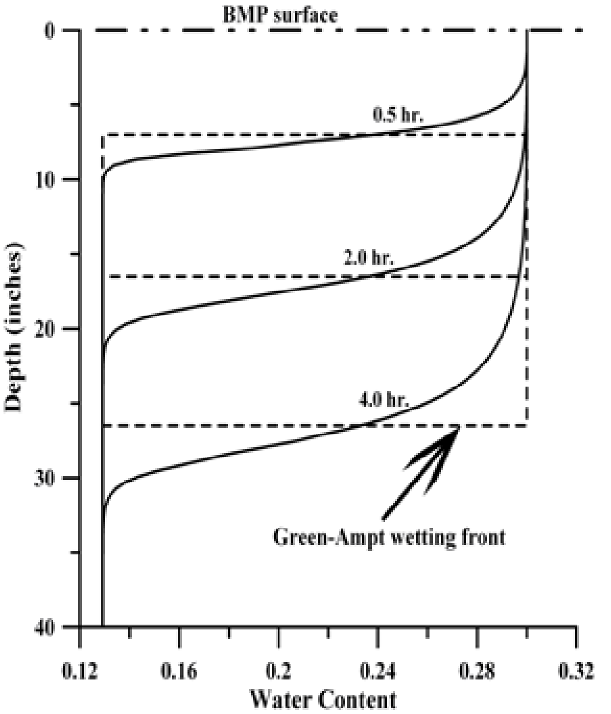

Figure 4.14: Wetting front distribution at various times during infiltration according to the Green-Ampt model. [One inch = 2.54 cm.]

According to the theory of infiltration described by Philip (1969), the exponential decay curve shown in figure 4.13 can be described by equation 4.6.

The value of b generally has the range between $0.35K_s$ and K_s, where K_s is the saturated hydraulic conductivity. The difference is due to degree of entrapped air when the water infiltrates into the soil: the greater the amount of entrapped air, the smaller the value of b.

The sorptivity of the soil can be computed from the relation in equation 4.7.

The cumulative infiltration, F can be derived from equation 4.7 by integrating the infiltration rate over time to give equation 4.8.

Equation 4.7: Sorptivity of the soil

$$S = \sqrt{2K_s h_{wf} \Delta\theta}$$

where
S = sorptivity
h_{wf} = the wetting front suction
$\Delta\theta = (\theta_s - \theta_i)$ is the difference between the saturated water content and the antecedent water content of the soil
K_s = saturated hydraulic conductivity

Equation 4.8: Cumulative infiltration

$$F = S\sqrt{t} + bt$$

where
F = cumulative infiltration
S = sorptivity
t = time
b is related to the saturated hydraulic conductivity

Equation 4.9: Green-Ampt equation (Green and Ampt 1911)

$$f = K_s\left[1 + \frac{(H + h_{wf})(\theta_s - \theta_i)}{F}\right]$$

where
H= depth of water standing on the soil surface
θ_s = saturated water content of the soil
θ_i = antecedent (or initial) moisture content
h_{wf} = wetting front suction
F = cumulative infiltration

An alternative equation for modeling infiltration into the soil is given by the Green-Ampt equation (Green and Ampt, 1911), equation 4.9.

The derivation of the Green-Ampt equation requires that the diffuse (or curved) wetting fronts shown in figure 4.12 be replaced by sharp wetting fronts as illustrated in figure 4.14. Despite its relative simplicity, the Green-Ampt model has been shown to provide a very good approximation compared to more exact (and more complex) equations (Smith et al. 2002). The advantage of equation 4.9 compared to equation 4.8 is that equation 4.9 takes into account the depth of ponding.

Equation 4.10: Cumulative infiltration

$$t = \frac{F - \left[(\theta_s - \theta_i)(H + h_{wf})\right] \ln\left[1 + \frac{F}{\left[(\theta_s - \theta_i)(H + h_{wf})\right]}\right]}{-K_s}$$

where

F = cumulative infiltration
h_{wf} = wetting front suction
$\Delta\theta = (\theta_s - \theta_i)$ is the difference between the saturated water content and the antecedent water content of the soil
K_s = saturated hydraulic conductivity
H= depth of water standing on the soil surface
t = time

An expression for the cumulative infiltration is probably more useful to the person performing design or assessment. This expression is given by equation 4.10.

Equation 4.11: Cumulative infiltration in terms of infiltration time (Salvucci and Entekhabi 1994)

$$F = K_s \left\{ \left(1 - \frac{\sqrt{2}}{3}\right) t + \left(\frac{\sqrt{2}}{3}\right) \left(\chi t + t^2\right)^{1/2} + \left(\frac{\sqrt{2} - 1}{3}\right) \chi \left[\ln(t + \chi) - \ln(\chi)\right] \right\}$$
$$+ K_s \left\{ \left(\frac{\sqrt{2}}{3}\right) \chi \left[\ln\left(t + \frac{\chi}{2} + \left(\chi t + t^2\right)^{1/2}\right) - \ln\left(\frac{\chi}{2}\right)\right] \right\}$$

where

$$\chi = \frac{(H + h_{wf})(\theta_s - \theta_i)}{K_s}$$

F = cumulative infiltration
h_{wf} = wetting front suction
$\Delta\theta = (\theta_s - \theta_i)$ is the difference between the saturated water content and the antecedent water content of the soil
K_s = saturated hydraulic conductivity
H= depth of water standing on the soil surface
t = time

Here the time of infiltration is expressed explicitly as a function of the cumulative infiltration. It is not possible to express the cumulative infiltration explicitly in terms of time, but once one knows the depth that needs to be infiltrated (F) based on the runoff contributing area, the depth of runoff, and the area of the infiltration practice, the time needed to infiltrate that depth of water can be computed immediately from equation 4.10. This equation can be entered into a programmable calculator or spreadsheet, which will enable the cumulative infiltration depth, F, that corresponds to a specific infiltration time to be more quickly calculated.

An alternative to equation 4.10 that expresses the cumulative infiltration explicitly in terms of infiltration time is given by Salvucci and Entekhabi (1994) in equation 4.11.

Equation 4.11 is an approximation to equation 4.10. The equation for the infiltration capacity given by Salvucci and Entekhabi (1994), has an error of approximation of about 2% from the equation. Thus, equation 4.11 can be used without introducing a significant source of error.

4.4.3 Infiltration measurement devices

Various devices are available for simple estimations of infiltration for a specific location within a stormwater BMP such as the single ring infiltrometer, double ring infiltrometer, Philip-Dunne permeameter, Guelph permeameter, and tension infiltrometer. Most infiltration measurement devices also require soil moisture to be measured, procedures for which can be found in Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1, "Physical and Mineralogical Methods" (Klute 1986). Infiltration can also be estimated by numerical methods such as the Horton and Green-Ampt models.

Figure 4.15: Photograph of a single-ring infiltrometer (http://en.wikipedia.org/wiki/Infiltrometer).

Advanced Discussion

Single Ring Infiltrometer

Single-ring infiltrometers (figure 4.15), as described by (Bedient and Huber 1992), are one tool used to measure infiltration. A 30-centimeter (11.81 inches) in diameter, 20-centimeter (7.87 inches) high ring is driven approximately 5 cm (1.97 inches) into the ground and filled with water (Klute 1986). By measuring the depth of water in the ring as a function of time, the rate at which water moves into the ground is determined when the infiltration rate becomes constant. The soil surrounding the ring may also be flooded to encourage vertical flow of water into the soil. Alternatively, a 'double ring' infiltrometer, which also encourages vertical flow of water, may be used.

Figure 4.16: Photograph of a double-ring infiltrometer (St. Paul, MN).

Double Ring Infiltrometer

A double-ring infiltrometer (figure 4.16) is made of two concentric tubes, typically of thin metal or hard plastic, that are both continuously filled with water such that a constant water level is maintained as water infiltrates into the soil. The rate at which water is added to the center tube is measured and used to determine the infiltration rate. This rate is computed from the field data using equation 4.12.

A typical plot of the infiltration rate versus time for a double-ring infiltrometer would take the form of the graph shown in figure 4.13. If the infiltration experiment is carried out long, enough the infiltration

Equation 4.12: Infiltration rate

$$i = \frac{4V}{3.14 D_r^2 \Delta t}$$

where

i = infiltration rate
V = volume of water added in time, Δt
D_r = diameter of the inner ring
t = time

Example 4.5: Application of a double-ring infiltrometer

A dry swale located along a highway in south St. Paul needs to be evaluated for the capacity to control stormwater runoff from the highway. Jacob Marley, a student intern with the City of St. Paul, is given the task of performing capacity testing of the dry swale infiltration characteristics. One of the methods he is to use is the double ring infiltrometer method. Jacob sets up the double ring infiltrometer at the site using an inner ring with a diameter of 8 inches (20.32 cm), and outer ring diameter of 24 inches (60.96 cm). Water is ponded in the inner and outer rings to a depth of 4 inches (10.16 cm), and this depth is maintained in the range of 3 to 4 inches (7.62–10.16 cm) throughout the experiment. The volume of water added each time to bring the water level in the inner ring to 4 inches is recorded along with the time interval between filling times.

continued

Example 4.5: continued

The data collected from the infiltrometer are analyzed with **equation 4.12** to yield the plot shown in **figure 4.17**. Where the infiltration curve is nearly constant, the infiltration rate should be equal to the saturated hydraulic conductivity. According to figure 4.17 and table 4.3, this rate is 5.0 in/hr (0.004 cm/s).

rate will eventually become constant with time. That constant rate of infiltration is assumed to be equivalent to the saturated hydraulic conductivity. Generally about 20–30 minutes are required to reasonably approach this steady-state rate, but the duration of this experiment is dependent on the type and initial dryness of the soil. When performing this measurement, all double-ring infiltrometers should conform to A.S.T.M. standards (A.S.T.M. D3385-03 2005).

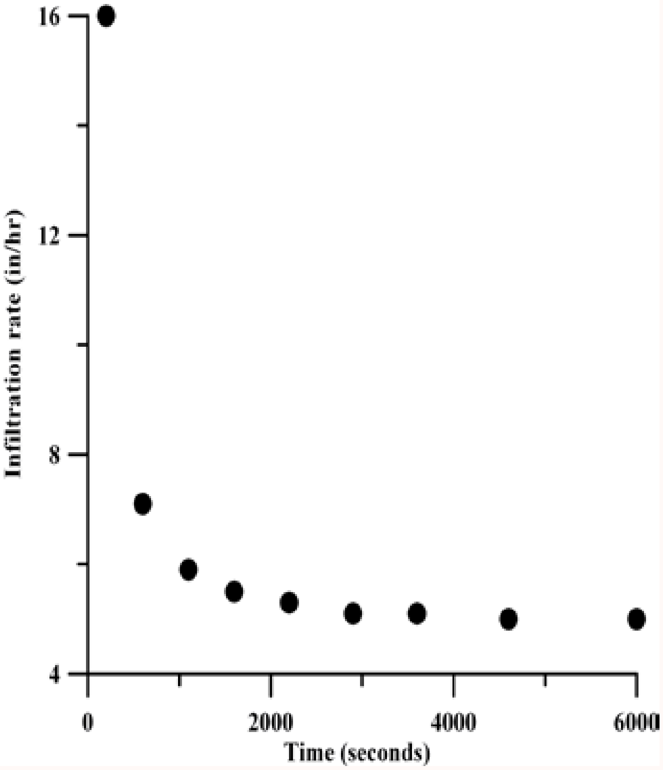

Figure 4.17: Infiltration rates obtained from a double-ring infiltrometer experiment. [One in/hr = 7.06 x 10^{-4} cm/s.]

Guelph Permeameter and tension infiltrometer

The Guelph permeameter (GP, figure 4.18) is another tool for measuring soil-water properties (Bagarello et al. 2004). The GP estimates field-saturated hydraulic conductivity, matrix flux potential, and soil sorptivity based on constant-head calculations (SoilMoisture Equipment Corp. 1986).

Table 4.3: Data from double-ring infiltrometer experiment with analysis for infiltration rate using equation 4.12.

Time from beginning (sec)	Time interval (sec)	Volume added (in3)	Infiltration rate (in/hr)
200	200	45	16.0
600	400	40	7.1
1100	500	41	5.9
1600	500	38	5.5
2200	600	44	5.3
2900	700	50	5.1
3600	700	49	5.1
4600	1000	70	5.0
6000	1400	97	5.0

The Guelph permeameter (GP) is a constant-head well permeameter consisting of a mariotte reservoir that maintains a constant water level inside an augered hole that is typically 4 inches (10.16 centimeters) deep, cored into the unsaturated soil. This permeameter requires steady discharge from two different water levels (heads) in the augered hole. Steady-state discharges are measured at two different water pressure heads. Generally, the water pressure heads are a 2-inch (5.08 centimeter) head to give a discharge of Q_1, and a 4-inch (10.16 centimeter) head for a discharge of Q_2, as recommended by the manufacturer. The measured discharges are used with the change in volumetric water content ($\Delta\theta$) to determine field-saturated hydraulic conductivity (K_s), matric flux potential (ϕ_m), and sorptivity (S). Equations for these parameters are given in equation 4.13.

The parameters G_1, G_2, J_1, J_2, are dimensionless shape factors to account for the three-dimensional nature of the infiltrating flow and are determined based on the diameter of the auger hole and the values of the applied pressure heads. Expressions for these parameters are given in equation 4.14.

A limitation of the GP is that it is applied to a borehole and not to the soil surface. Therefore, the effect of the top layer of the stormwater BMP surface is not reflected in the results. An alternative test to the conventional GP is a GP with a tension infiltrometer (TI) where the TI is auxiliary equipment available for the GP. For unsaturated soil conditions, a tension infiltrometer can be added to the Guelph permeameter setup (figure 4.18).

The tension infiltrometer consists of a porous disc (available in 4 inch or 8 inch (10.16–20.32 centimeter) diameter) connected to a Mariotte reservoir. An illustration of the tension infiltrometer is presented in figure 4.19. The procedures for using the method are described by Reynolds and Elrick (1991). In applying the method, the porous disc is placed in contact with the soil surface. This usually requires that vegetation and debris be removed from the surface and that the surface

Figure 4.18: Guelph permeameter (SoilMoisture Equipment Corp. 1986). Photo on right courtesy of SoilMoisture Equipment Corp.

Equation 4.13: Guelph permeameter equations

$$K_s = G_2 Q_2 - G_1 Q_1$$

$$\phi_m = J_1 Q_1 - J_2 Q_2$$

$$S = \left(2\phi_m \Delta\,\theta\right)^{1/2}$$

where

K_s = saturated hydraulic conductivity (in/hr)
ϕ_m = matric flux potential
S = sorptivity
θ = water content

G_1, G_2, J_1, J_2, are dimensionless shape factors to account for the three-dimensional nature of the infiltrating flow, and these are expressed by

$$G_2 = \frac{H_1 C_2}{\pi\left[2H_1H_2\left(H_2 - H_1\right) + a^2\left(H_1C_2 - H_2C_1\right)\right]}$$

$$G_1 = G_2 \frac{H_2 C_1}{H_1 C_2}$$

$$J_1 = \frac{\left(2H_2^2 + a^2 C_2\right)C_1}{2\pi\left[2H_1H_2\left(H_2 - H_1\right) + a^2\left(H_1C_2 - H_2C_1\right)\right]}$$

$$J_2 = J_1 \frac{\left(2H_1^2 + a^2 C_1\right)C_2}{\left(2H_2^2 + a^2 C_2\right)C_1}$$

where

H_1 and H_2 are the water pressures corresponding to the flow rates Q_1 and Q_2, C_1 and C_2 are parameters associated with the two water pressures and are derived from curves given by Elrick and Reynolds (1985) be flat. In many cases, it is also desirable to place a thin layer of fine sand onto the soil surface to provide good contact between the disc and the soil.

Once the disc is in place on the soil surface, the steady-state discharge for infiltration into the soil are measured for two applied water pressures, H_1 and H_2, where $H_1 < H_2$. The TI can facilitate the measurement of unsaturated hydraulic conductivity for various applied tensions, but typically for stormwater BMPs, only the saturated hydraulic conductivity value is desired. To estimate this value, the pressures need to be slightly negative (i.e., tension). Based on our experience characterizing stormwater BMPs, we suggest successive pressures of –5 cm (1.97 inch) (H_1) and –1 cm (.394 inch) (H_2). At each of these pressures the corresponding steady-state discharge (Q_1 and Q_2) is measured. The steady-state discharge and change in volumetric moisture content ($\Delta\theta$) are used in equations derived by Reynolds and Elrick (1991) to find the desired soil properties. The equations are given as equation 4.14.

Example 4.6: Application of a Guelph Permeameter

The second method that Jacob Marley applied to the dry swale is the Guelph Permeameter. Jacob measured the water content of the soil in the swale prior to the experiment and found that water content to be 0.20. He also measured the saturated water content of the soil to be 0.375. To set up the experiment Jacob augered a 2-inch (5.08 cm) diameter borehole to a depth of 4 inches (10.16 cm), and during the experiment he applied two different water pressures, 2 inches and 4 inches. For each pressure setting the flow was monitored until steady-state conditions prevailed. For this case the steady-state flows were measured to be 7.16 L/hr (437 in^3/hr) at the 2 inches setting, and 9.65 L/hr (589 in^3/hr) for the 4 inch setting.

The parameters C_1 and C_2 are derived from Elrick and Reynolds (1985) to be 0.96 and 1.47 respectively, giving then

$$G_1 = 0.0393\ in^{-2}$$

$$G_2 = 0.0301\ in^{-2}$$

$$J_1 = 0.1644\ in^{-1}$$

$$J_2 = 0.0674\ in^{-1}$$

We then have

$$K_s = (0.0393)(589) - (0.0301)(437) = 0.55\ inch/hr\ \ (3.88 \times 10^{-4}\ cm/s)$$

$$\phi_m = (0.1644)(437) - (0.0674)(589) = 32.2\ inch^2/hr\ \ (0.058\ cm^2/s)$$

$$S = \left(2(32.2)(0.175)\right)^{1/2} = 3.33\ inch/hr^{1/2}\ \ (8.458\ cm/hr^{1/2})$$

Figure 4.19: Illustration of the Guelph tension infiltrometer

Equation 4.14: Guelph permeameter equations

$$K_s = \frac{(G_d \alpha Q_1)}{\left[R(1 + G_d \alpha \pi R) \left(\frac{Q_1}{Q_2} \right)^P \right]}$$

$$P = \frac{H_1}{(H_1 - H_2)}$$

$$\alpha = \frac{\ln\left(\frac{Q_1}{Q_2} \right)}{(H_1 - H_2)}$$

$$\phi_m = \frac{K_s}{\alpha}$$

$$S = (2K_s \phi_m \Delta \theta)^{1/2}$$

where

K_s = saturated hydraulic conductivity ϕ_m = matric flux potential

S = sorptivity

θ = water content

G_d is a shape factor that accounts for the three-dimensional character of the unsaturated flow. This parameter is generally set to 0.25.

The wetting front suction can be computed with equation 4.15.

Equation 4.15: Wetting front suction

$$h_{wf} = \frac{S^2}{2K_s(\theta_s - \theta_i)}$$

where

h_{wf} = wetting front suction

$\Delta\theta = (\theta_s - \theta_i)$ is the difference between the saturated water content and the antecedent water content of the soil

K_s = saturated hydraulic conductivity

Example 4.7: Application of the Guelph tension infiltrometer

Because he wanted to make sure he had a measurement of the infiltration characteristics of the surface soil for the dry swale, Jacob Marley decided to apply the Guelph tension infiltrometer to the site. He was making the measurement on the same day as he made the measurement with the Guelph permeameter, so the initial water content was the same as in that experiment. Jacob had a 4-inch (10.16 cm) diameter tension disk available with his equipment. He performed two infiltration experiments in which he maintained the applied water pressure at the soil surface until steady-state flow conditions prevailed for each experiment. The two applied pressures were H_1= –2 inch and H_1 = –0.4 inch. For these pressure settings, Jacob measured the flows to be 3.94 L/hr (240 in^3/hr) at the H_1 = –2 inch setting, and 4.5 L/hr (275 in^3/hr) at the H_1 = –0.4 inch setting.

Using these figures in the **equations in 4.14**, Jacob found the following infiltration properties:

$$P = \frac{-2}{(-2 - (-0.4))} = 1.25$$

$$\alpha = \frac{\ln\left(\frac{240}{275} \right)}{(-2 - (-0.4))} = 0.084 \text{ inch } (0.213 \text{ cm})$$

$$K_s = \frac{(0.25)(0.084)(240\ )}{\left[2(1 + (0.25)(0.084)(3.1416)(2)) \left(\frac{240}{275} \right)^{1.25} \right]} = 2.83 \text{ inch/hr } (0.002 \text{ cm/s})$$

$$\phi_m = \frac{K_s}{\alpha} = \frac{2.83}{0.084} = 33.8 \text{ inch}^2/\text{hr } (0.061 \text{ cm}^2/\text{s})$$

$$S = (2(2.83)(33.8)(0.175))^{1/2} = 5.75 \text{ inch/hr}^{1/2} \ (14.61 \text{ cm/hr}^{1/2})$$

He then calculated the wetting front suction using **equation 4.15**:

$$h_{wf} = \frac{(5.75)^2}{2(2.83)(0.175)} = 33.37 \text{ inch } (84.76 \text{ cm})$$

Philip-Dunne Permeameter

The Philip Dunne permeameter (Munoz-Carpena *et al.* 2002) estimates saturated hydraulic conductivity using falling-head kinetics and is made of a plastic or metal tube that is inserted between 5 and 15 centimeters (1.97–5.91 inches) into the ground. Munoz-Carpena, *et al.* (2002) utilized an electrical sensor to detect and record the moment when the tube became empty, but a Philip-Dunne permeameter does not require this feature.

In the standard Philip-Dunne permeameter procedure, a tube is inserted into the bottom of an auger hole of the same radius. The initial moisture content of the soil is measured, the tube is filled with water, and the observer measures the time required for the water level in the tube to reach the halfway mark on the tube as well as the time required for the tube to empty completely. After the experiment, the final water content is measured. Generally, the porosity of the soil can be used as the final water content because the soil should be saturated in the vicinity of the auger hole. The radius of the tube, the two measured times, and the measured initial moisture content along with the final water content are used to estimate the hydraulic properties of the soil. The equations for performing this are given in equation 4.16.

Equation 4.16: Hydraulic properties of the soil using a Philip-Dunne permeameter

$$\tau_{\max} = 0.73\left(t_{\max}/t_{med}\right) - 1.1258 \qquad t_{\max}/t_{med} < 5.4$$

$$K_s = \frac{\pi^2 R_{tube}\tau_{\max}}{16 t_{\max}}$$

$$h_{wf} = 39.4\exp\left[-13.503 + 19.678\left(t_{\max}/t_{med}\right)^{-1/2}\right]$$

$$S = \left(2K_s h_{wf}\Delta\theta\right)^{1/2}$$

where

h_{wf} = wetting front suction in inches
t_{med} = time at which the water level in the tube reaches half the initial depth
t_{max} = is the time at which the tube is completely empty of water
K_s = saturated hydraulic conductivity
R_{tube} = radius of the tube
S = sorptivity

Example 4.8: Application of the Philip-Dunne permeameter

After spending most of the day making measurements with the double ring infiltrometer, the Guelph permeameter, and the Guelph tension infiltrometer, Jacob Marley decided to make a measurement using one more method, the Philip-Dunne borehole permeameter. The soil conditions were the same as described for the other infiltrometer methds. Jacob augered a 4-inch (10.16 cm) diameter borehole to a depth of 0.8 inches (2.03 cm). He then filled the tube to a depth of 17 inches (43.18 cm) and observed the drop of the water level in the tube. He particularly took note of the time it took for the tube to empty halfway and the time to become completely empty. He found that it took 441 seconds for the water level to drop to 8.5 inches (21.59 cm), and 1,222 seconds for the tube to become empty. He then used equation 4.16 to calculate the infiltration properties as shown below,

$$\tau_{max} = 0.73\,(1222/441) - 1.1258 = 0.909$$

$$K_s = \frac{(3.1416)^2\,(2)(0.909)}{16(1222)} = 0.000917\ in/sec = 3.3\ in/hr$$

$$h_{wf} = 39.4\exp\left[-13.503 + 19.678\,(1222/441)^{-1/2}\right] = 7.3\ in$$

$$S = \left(2(3.3)(7.3)(0.175)\right)^{1/2} = 2.9\ in/hr^{1/2}\ \ (7.37\ cm/hr^{1/2})$$

4.4.4 Recommendations

Infiltration rates can vary by orders of magnitude, depending on soil texture, plant root structure, etc. Infiltration measurements are recommended to determine the saturated hydraulic conductivity for use in infiltration models.

The most accurate method for estimating infiltration rates in stormwater BMPs is synthetic runoff testing (described in Chapters 3 and 9). Synthetic runoff testing directly measures the rate at which water infiltrates into the stormwater BMP surface under controlled conditions. It also requires sufficient water quantity and discharge to measure the rate of infiltration. Another accurate method for measuring infiltration rates in stormwater BMPs is permeability tests because infiltration is measured directly at several locations throughout the practice to estimate the overall infiltration rate. Monitoring can also be an accurate method for estimating infiltration when the measurement error associated with other water budget components is negligible.

4.5 Evaporation and evapotranspiration

Evaporation (transformation of liquid water to water vapor) and transpiration (water vapor emission from plant surfaces) are outflow processes of water budgets. Evapotranspiration (ET) is the combined process of open water surface evaporation, soil moisture evaporation, and plant transpiration. Stormwater management applications may include free water surfaces (pond, wetland, etc.), vegetation, or both, and therefore may require an estimation of evaporation, transpiration, or both to estimate water level changes between storms. For example, a wetland system includes vegetation, open water surfaces, and exposed moist soils. The combined effects of water surface evaporation and plant transpiration for this system are often large components of annual water budgets.

Equation 4.17: Water balance used on a watershed scale to estimate annual average evapotranspiration

$$\mathrm{P} - \mathrm{ET} - \mathrm{RO} - \mathrm{DS} = \Delta \mathrm{S}$$

where

P = precipitation depth
ET = evapotranspiration depth
RO = runoff depth measured at stream or river gauging station
DS = deep seepage depth (flow path that is not measured by flow at the gauging station
ΔS = change in stored water depth

Evapotranspiration is a complex process. It is a function of meteorological conditions, such as air temperature, wind speed, relative humidity, and solar radiation, and of evaporating/transpiring surface conditions, such as albedo, water temperature, roughness, and water availability. The effective surface conditions of plants are especially complex. Stomata openings in plant leaves are essential for the movement of water vapor and other gases. The number of these openings varies with plant type. The size of these openings varies with changes to the turgor pressure in plant cells resulting from water stress and other factors. Often the complexity of plant canopies is simplified by considering only potential evapotranspiration. Potential ET occurs when the water availability in the soil does not influence ET. Therefore, the complexity associated with water stress is not needed to determine ET. Water stress can be minimized by irrigation systems. Reference plant ET is used to further simplify the determination of ET. (Reference plant ET is the potential ET for a standard reference plant.) The two most widely used reference plants are alfalfa and grass. Reference plant ET allows the impact of meteorological variables to be assessed using relatively constant plant conditions. Complexities related to time-varying vegetal cover and water stress do not need to be considered. The conversion of reference plant ET to potential ET for different plant types is done using plant or crop factors.

Equation 4.18: Estimating evapotranspiration for a watershed in Minnesota

$$\mathrm{ET} = \mathrm{P} - \mathrm{RO}$$

where

P = precipitation depth
ET = evapotranspiration depth
RO = runoff depth measured at stream or river gauging station

Example 4.9: Estimating evapotranspiration for a watershed in Minnesota

Gina, a municipal engineer, is trying to complete a water budget for a watershed near Morris, MN. She uses maps published by the Department of Natural Resources to estimate average annual precipitation and runoff depth. From these maps, she finds that precipitation (P) is approximately equal to 23.8 inches (60.45 cm) and runoff depth (RO) is approximately 2.5 inches (6.35 cm) for Morris, MN. Thus, the average annual evapotranspiration (ET) from equation 4.18 is then 21.3 inches (54.10 cm), assuming deep seepage and change in storage are negligible on an annual basis. Therefore, approximately 89% of the average annual precipitation is returned to the atmosphere by ET for sites located near Morris, MN. Clearly, ET is an important component of an annual water budget.

The average annual ET for a watershed is often estimated using a water balance, which can be described by equation 4.17.

The change in storage increases and decreases during the year; for many years, however, the net change is generally small. Therefore, for average annual ET, $\Delta S \approx 0$, and typically $DS \approx 0$, and equation 4.17 can be simplified to equation 4.18, which indicates that the average annual ET is equal to the difference between the average annual precipitation and average annual runoff depth. The Minnesota Department of Natural Resources publishes maps that allow the average annual precipitation depth and average annual runoff depth to be estimated for any location in Minnesota. Example 4.9 is an illustration of the use of equation 4.18.

ADVANCED DISCUSSION

Eddy correlation techniques have been developed to measure ET directly (Kizer and Elliot 1991). In contrast to annual ET values, these measurements can be used to estimate ET during small time intervals (hourly or less). High speed sensors are placed over the plant canopy or water body. These sensors typically measure simultaneously vertical velocities and absolute humidity values. The product of these two measurements corresponds to the rate of water vapor movement as the result of (mostly) ET processes. Important considerations in using this approach are the frequency response of the sensor, instrument height, and separation distance between sensors. The sensors must be placed carefully to capture the overall movement of water vapor that are transported by turbulent eddies of different sizes. Although eddy-correlation techniques are theoretically appealing, care is needed in setting up eddy-correlation instruments and analyzing their data. They are only recommended for use by professionals with experience in measuring turbulent flows.

Direct measurement of ET by eddy correlation methods is difficult, and therefore estimates are usually obtained indirectly from measured meteorological or other variables. Energy balances provide a useful theoretical framework for converting the indirect measurements into ET estimates. Key energy terms are net radiation, sensible heat loss, and latent heat of ET. The daily energy balance for plant canopies and water bodies can be written as equation 4.19, in which all energy terms have units of energy per unit area per day.

Equation 4.19: Daily energy balance for plant canopies and water bodies

$$R_n = (L)\,ET + H_s$$

where

ET = evapotranspiration depth per day

L = Latent heat of vaporization (approximately equal to 540 cal/cm^3 (1371.6 cal/inch^3))

H_s = sensible heat loss

Net radiation includes incoming and outgoing short-wave and long-wave radiation. Although sensors are available to measure net radiation directly, observed short-wave radiation is more readily available. Jensen et al. (1990) provides a good discussion of approaches that can be used to compute net radiation from short-wave and other meteorological information. (L)ET is the energy used to evaporate the water corresponding to ET. The sensible heat loss is the energy loss by the temperature differences between the evaporating surface and the atmosphere. For plant canopies, an additional energy term for the movement of heat into the soil is sometimes included in equation 4.19. Typically heat moves from the canopy into the soil during the daylight hours and from the soil to the canopy at night. Net sensible heat loss to the soil for a day-night cycle is often negligible.

The Bowen ratio (β) is defined as the ratio of sensible to latent heat terms (i.e., $\beta = H_s/(L)\,ET$). Instrumentation systems have been designed to measure the Bowen ratio (Heilman et al. 1996). From measured Bowen ratio and net radiation, ET is defined directly as given in equation 4.20.

Instruments to measure Bowen ratios require technical skills to be used effectively. This method is only recommended for professionals with considerable experience in designing and collecting experimental data.

The Penman and Penman-Monteith methods are widely used to estimate ET from meteorological variables. Both methods are based on the energy balance given by equation 4.20. The evaluation of the parameters for these methods is done using potential ET or, more commonly, using reference plant ET. For reference plants, ET can be estimated from measured (or estimated) net radiation, maximum and minimum air temperatures, maximum and minimum relative humidity, and wind speed. The reader is referred to Jensen et al. (1990) for more information. Adjustments in the reference plant ET to actual ET are necessary. Penman method can also be used to compute evaporation from water bodies.

Pan evaporation techniques are widely used throughout the United States to measure evaporation from water surfaces and ET from plant canopies (Farnsworth and Thompson 1982, Jensen et al. 1990). With these techniques, pans are filled with water and are placed on or near the water body or within the standard plant canopy conditions. Evaporation rates from the pan are measured and used to estimate evaporation or reference plant ET. Pan evaporation rates are typically higher than actual lake evaporation and reference plant ET rates. Therefore, an adjustment factor, called a pan coefficient, is used and typically ranges between 0.64 and 0.81. For Minnesota, total pan evaporation rates from 1974 to 2004 (April–October) averaged 36.98 inches (93.9 cm) with a standard deviation of 4.71 inches (11.96 cm) as reported in St. Paul, Minnesota, by University of Minnesota researchers (University of Minnesota 2005) at http://climate.umn.edu/doc/agwx.htm. Example 4.10 demonstrates how this information can be used to estimate evaporation with equation 4.21.

Evapotranspiration rates depend on vegetation, soil, and climate variables (such as root depth, vegetative surface area, soil moisture, relative humidity, precipitation, season, etc.). Many studies have developed adjustments for the evaporation methods mentioned above (water budget, mass transfer, energy budget, pan evaporation) to estimate ET (Bedient and Huber 1992), including studies which correlate pan evaporation measurements to ET for specific types of vegetation. For example, ET for grass and clover can be estimated with a pan coefficient of 0.80 applied to pan evaporation measurements (Brutsaert 1982). Parameters for the Penman, Penman-Monteith, and pan evaporation methods are more readily available for reference plants. Reference plant ET needs to be converted to potential ET for other plants using crop coefficients. These crop coefficients are typically divided into four periods of the life cycle of plants: (1) initial growth period of constant crop coefficient, (2) a period of rapid growth where the crop coefficient increases linearly, (3) midseason period of constant and maximum crop coefficient, and (4) a period for late season where the crop coefficients decrease linearly. The Food and Agriculture Organization of the United Nations have parameters

Equation 4.20: Daily energy balance for plant canopies and water bodies

$$\mathrm{ET} = \frac{1}{\mathrm{L}}\left(\frac{\mathrm{R_n}}{1+\beta}\right)$$

where

ET = evapotranspiration depth per day

R_n = net radiation

L = latent heat of vaporization (approximately equal to 540 cal/cm^3 (1371.6 cal/inch^3))

β = Bowen ratio = $H_s/(L)\ ET)$

Equation 4.21: Evaporation Estimation

$$E = A \times C_{pan} \times E_{pan}$$

where

E = annual evaporation

A = area of water surface

C_{pan} = pan coefficient

E_{pan} = pan evaporation rate

Example 4.10: Estimating evaporation

The estimated evaporation for a 1000-square-foot (92.9 sq. m) open water surface (e.g., wet pond), assuming a pan coefficient of 0.75, can be calculated using equation 4.4 as follows:

$$E = A \times C_{pan} \times E_{pan}$$

$$E = (1000\ ft^2)(0.75)\left(\frac{36.98\ inches}{12\ inches/ft}\right)$$

$$E = 2311\ ft^3$$

for these four periods for roughly 100 different types of plants (Allen et al. 1998).

Actual ET can be substantially different than potential ET because of limited depth of available water in the soil. Conversion to actual ET requires a measurement or prediction of the soil moisture. The fraction of available water (FAW) is defined as the ratio of the difference between site moisture content and wilting point to the difference of field capacity and wilting point. When this fraction is greater than 0.6, then the impact of available water is minor and actual ET is well approximated by potential ET. When the fraction is less than 0.6, as a rough approximation, the actual ET can be reduced linearly with FAW to a value near zero at FAW = 0 (Larson 1985).

Evapotranspiration can affect the concentration of most pollutants of concern in stormwater management. Phosphorus, chloride, and solids, for example, will not evaporate, and therefore will become more concentrated as water evaporates from an open surface or from the soil. It is important to recognize this fact and consider ET as a water-budget outflow, where necessary, to avoid miscalculations in the pollutant load budget.

4.5.1 Recommendations for ET

Wetlands, wet ponds, and other stormwater BMPs that are designed to maintain a permanent pool may evaporate or transpire a significant water budget component. Therefore, ET should be estimated for stormwater BMPs with standing water or moisture-rich soil. ET processes play a minor role in the performance of stormwater best management practices that are designed to treat water within a short period of time (less than 4 days). Therefore, the estimation of ET is unnecessary for these practices.

Evapotranspiration can be estimated using indirect (e.g., simplified water budget) or direct methods (e.g., Eddy correlation or daily energy balance, equation 4.19). It is recommended that indirect methods of estimation be used in most cases, but that direct methods be used when more accurate measurements of evaporation or ET are desired.

4.6 Rainfall measurement

Rainfall measurement is an important aspect of any stormwater BMP assessment program. Rainfall data is collected in many locations (e.g., airports), but rainfall amounts and intensities can vary significantly in a short distance. Therefore, to ensure an accurate and complete water budget, onsite rainfall measurement is recommended. Discussion of the importance of rainfall measurement can be found in section 3.2.1.4 of “Urban Stormwater BMP Performance Monitoring” (U.S. EPA 2002) at http://www.epa.gov/waterscience/guide/stormwater/files/montch3.pdf.

Rainfall data provide an accurate account of the amount of rain that falls directly on the stormwater BMP and its drainage area. Rain falling on a stormwater BMP is not measured by the influent discharge measurement device (e.g., weir, probe, etc.) but may constitute a significant portion of water entering the stormwater BMP, depending on watershed and stormwater BMP characteristics.

Several tools are available for rainfall measurement, ranging from the simple depth measurement rain gauge to the more advanced tipping bucket rain gauges that record depth and intensity with a data logger. Depth rain gauges require prompt recording of the rainfall depth to avoid any loss due to evaporation or spillage, and tipping bucket rain gauges may require calibration. All rainfall measurement equipment should be installed according to the manufacturer's instructions and maintained regularly to ensure accurate measurements.

Compared to depth rain gauges, tipping bucket rain gauges (figure 4.20) are a more accurate measurement of incremental rainfall because measurements are recorded near continuously with a data logger. Accumulating rain gauges, however, may be more accurate for measuring total rainfall, but prompt inspection and recording of depth measurements can make depth rain gauges an accurate method of both total and rainfall measurement.

Figure 4.20: Tipping bucket rain gauge (http://www.novalynx.com/260-2500.html).

Some discussion on rainfall estimation models can be found in section 3.2.1.8 of "Urban Stormwater BMP Performance Monitoring" (U.S. EPA. 2002) at http://www.epa.gov/waterscience/guide/stormwater/files/montch3.pdf.

4.6.1 Recommendations for rainfall measurements

It is recommended that rainfall be measured at each assessment location to ensure accuracy. For small drainage areas, a single rain gauge is sufficient, but larger watersheds will require multiple gauges. Manufacturers or hydrologic texts (Bedient and Huber 1992) and manuals can provide additional guidance on spacing and placement of rainfall gauges.

Accurate rainfall measurement can be achieved in a number of ways. Depth rain gauges can measure rainfall for little cost or additional instrumentation but require prompt inspection and measurement recording to be accurate. To ensure timely measurements of rainfall depth and intensity, it is recommended to use a tipping bucket rain gauge with a data logger.

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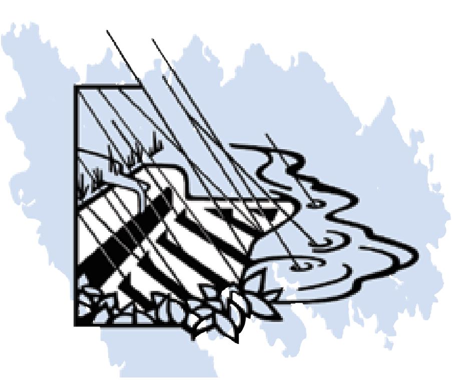

5.

Sampling Methods

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How well a stormwater BMP removes a pollutant or pollutants can be assessed by comparing the amount of pollutant that enters the stormwater BMP to either the amount of pollutant that exits the stormwater BMP or to the amount that is retained. Pollutants are measured in mass or concentration, and these measurements can be taken using one of four methods. First, pollutants can be measured *in situ*, or in place, using pollutant sensors or probes placed directly in the stormwater runoff to collect near-continuous measurements with respect to time. Second, stormwater samples can be collected and analyzed on site with sensors, probes, or by other analytical methods (on-site sampling). Third, a sample can be collected manually in the field and transported back to a laboratory for analysis (manual or "grab" sampling). Fourth, stormwater runoff can be collected with an automatic sampler, retrieved at a later time, and analyzed in a laboratory (automatic sampling). For more information on sampling methods, consult Standard Methods (A.P.H.A. 1998), "Urban Stormwater BMP Performance Monitoring" (U.S. EPA. 2002), or "Wastewater sampling for process and quality control (Manual of practice)" (WEF. 1996).

Hot links

Weiss, P.T, A. J. Erickson, J.S. Gulliver, R.M. Hozalski, O. Mohseni., and W.R. Herb. 2007. Sampling methods. In *Assessment of Stormwater Best Management Practices,* ed. J. S. Gulliver and J.L. Anderson. St Paul, MN: University of Minnesota.

Table 5.1: Comparison of *in situ*, field, and automatic sampling methods

Characteristic	Sampling approach			
	in situ	on-site	grab	automatic
Sample of stormwater collected	no	yes	yes	yes
Personnel required to collect sample	no	yes	yes	no
Sample transported	no	no	yes	yes
Relatively high setup costs	yes	no	no	yes
Possibility of equipment damage or theft	yes	no	no	yes
Parameters or pollutants that can be measured:				
Suspended solids	no	no	yes	yes
Pathogens (i.e., coliforms)	no	no	yes	no
Nutrients:				
phosphate	yes	yes	yes	yes
nitrate	yes	yes	yes	yes
ammonia	yes	yes	yes	yes
Specific organic chemicals[1]	no	no	yes	yes
Oxygen demand	no	no	yes	no
Heavy metals	no	no	yes	yes
Water quality indicators:				
dissolved oxygen	yes	yes	no	no
temperature	yes	yes	no	no
pH	yes	yes	no	no
conductivity	yes	yes	yes	yes
turbidity (a surrogate for suspended solids)	yes	yes	yes	yes
organic carbon	no	no	yes	yes

[1] *Examples include: petroleum hydrocarbons (e.g., benzene), pesticides, chlorinated solvents*

Some advantages and disadvantages of each method are given in table 5.1.

In situ sampling is advantageous in that data can be collected frequently, in small time steps, with the results available remotely (e.g., cellular phone connection) once the sampling equipment is installed. Another advantage of *in situ* sampling is that it can be used to measure some of the water quality parameters that are likely to change during sample storage or transport, such as pH or dissolved oxygen. Although personnel are not required to collect samples or perform the chemical analyses, someone must periodically (e.g., weekly to monthly) visit the site to maintain and re-calibrate the equipment. Unfortunately, a different probe or sensor is required for each pollutant being measured, and not all pollutants can be measured with sensors or probes. There are available, however, *in situ* bundles that include several common probes and sensors used in water quality assessment.

On-site sampling can can also be used to measure water quality parameters that are likely to change during transport. Setup costs for onsite sampling are minimal because it does not require that any equipment remain in the field. Nevertheless, on-site sampling requires someone to collect samples and perform the analysis onsite. Manual sampling requires that someone collect samples and then transport them back to the laboratory. Automatic sampling requires someone to set up the system, but beyond that, time spent in the field is minimal because the automatically-collected samples from a storm even can be retrieved and the automatic sampler reset within a few minutes.

5.1 Sampling considerations

Choosing from *in situ*, on-site, manual, and automatic sampling will depend on budget constraints, personnel availability, and the goals of the assessment program. As discussed in Chapter 3, there are 4 levels of assessment, listed in order of increasing complexity: (1) visual inspection, (2) capacity testing, (3) synthetic runoff testing, and (4) monitoring. Visual inspection (level 1) is the only level of assessment that does not require sampling. Capacity testing for permeability determination often requires soil moisture measurements at each location. The procedures and related sampling required to measure soil moisture is discussed in Chapters 3 and 6. As discussed in Chapter 3, some stormwater BMPs for which synthetic runoff testing is applicable may require sampling of the influent or effluent synthetic runoff, or both. In these cases, the sampling methods for synthetic runoff testing are the same as the sampling methods for monitoring. The rest of this chapter discusses the sampling methods required for synthetic runoff testing and for monitoring.

There are four key questions about sampling that should be asked when developing an assessment program:

1. How many storm events should be sampled to make statistically accurate estimates of performance?
2. How many samples should be collected per storm event?
3. When multiple samples are collected per storm event, should they be collected based on discharge amount, elapsed time, or as individual manual samples?
4. When multiple samples are collected per storm event, should they be collected in individual bottles (discrete samples) or combined into a single bottle (composite samples)?

The rest of this chapter provides discussion and recommendations for each of the above criteria that should be thoroughly considered before sampling is included in any assessment program.

5.1.1 Number of storm events

The most important sampling consideration in an assessment program is the number of storm events to be sampled. The number of storm events sampled and the variance in the results from those storm events will determine the assessment uncertainty. Assessment uncertainty must be minimized so that comparisons to other stormwater BMPs, comparisons to past assessment, predictions of future performance for TMDL calculations, and maintenance scheduling are accurate and reliable. For example, suppose the event mean concen-

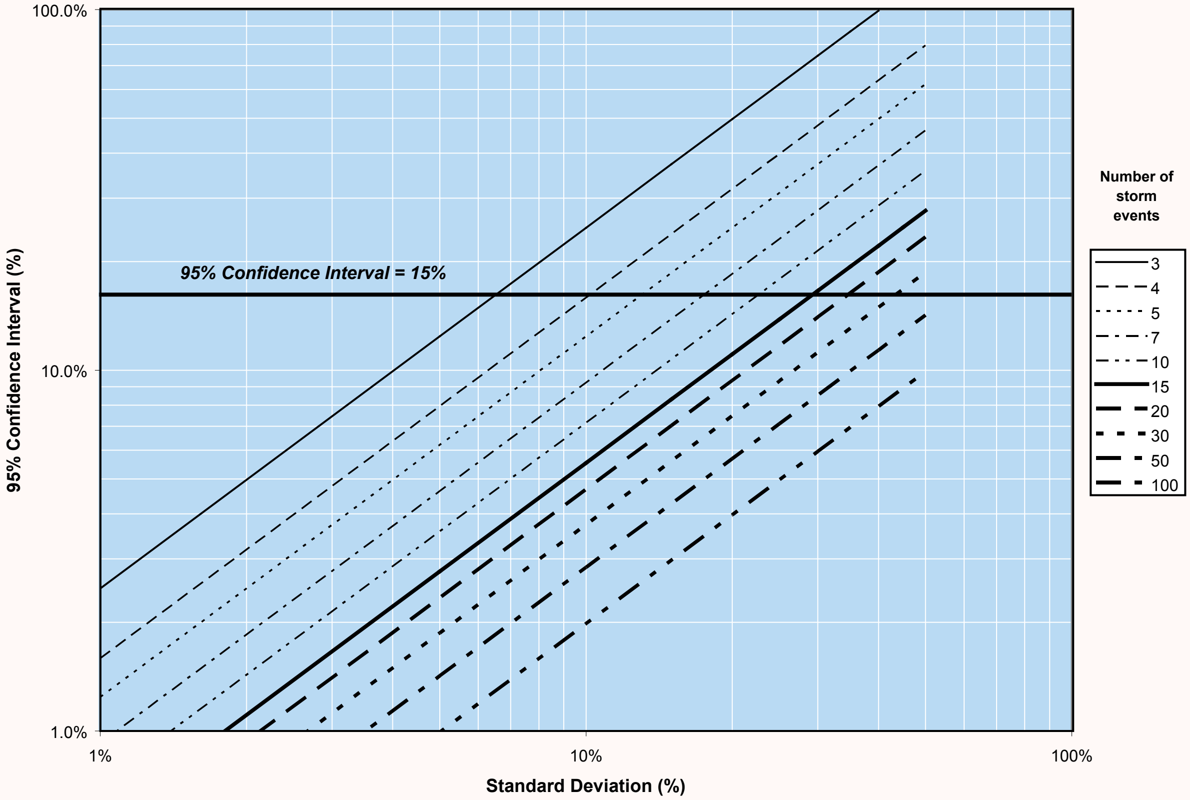


Figure 5.1: Relationship between number of storm events and standard deviation for a 95% confidence interval.

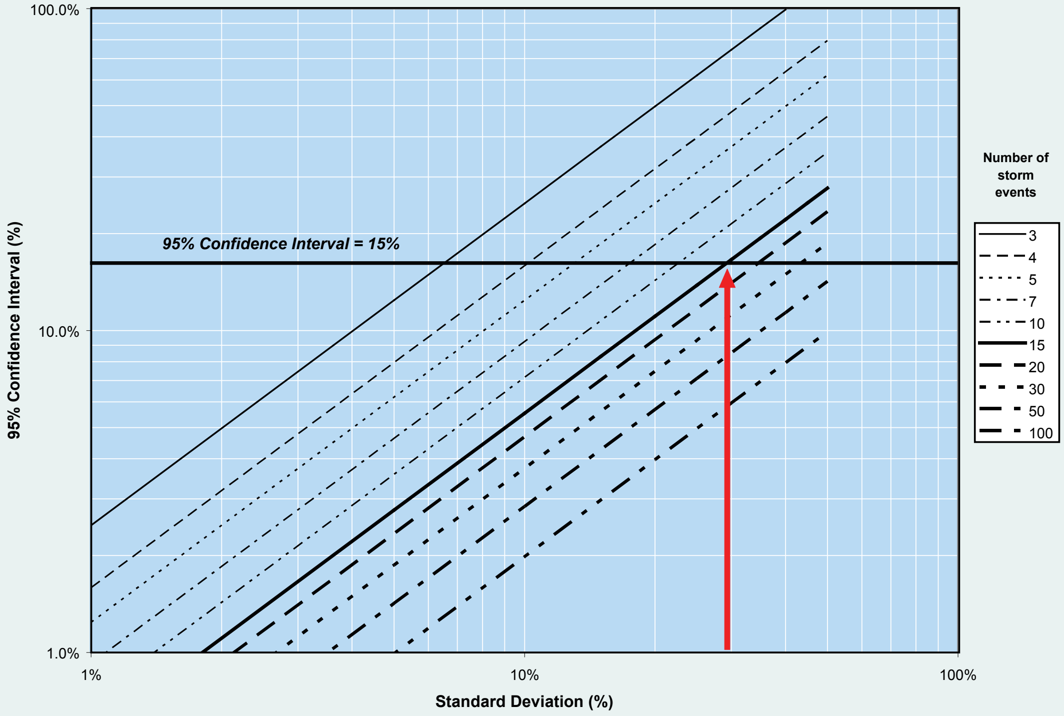
tration for a specific pollutant during a storm was reduced from an influent value of 100 mg/L to an effluent value of 40 mg/L in a stormwater BMP. Nevertheless, it cannot be assumed that the stormwater BMP reduces the event mean concentration by 60% for all storm events. Several storm events, representing a range of conditions (i.e., flow rate and pollutant concentration), need to be sampled and analyzed before predictions of BMP performance can be made. The rest of this section describes a process that can be used to decide upon an appropriate range of assessment uncertainty, and subsequently, to determine the number of storm events that should be sampled.

ADVANCED DISCUSSION

To simplify the statistical analysis, several assumptions can be made. One assumption is that the percent removal data are normally distributed about a mean value and that one storm event does not influence another. Another assumption is that storm event bias, if any, in percent removal varies and therefore is not considered. Finally, the number of storms required will likely be fewer than 30 and therefore the Student (Gosset) t-distribution is used. The Student (Gosset) t-distribution is a probability distribution used to estimate the mean of a normally distributed population from a sample of the population and is more accurate for small ($n < 30$) sample sizes than the similar z-distribution. For more information on distributions, consult a statistics text (e.g., MacBerthouex and Brown 1996, Moore and McCabe 2003).

Example 5.1: Determining the number of storm events required

Laura, an engineer in training (EIT) at a local consulting firm, is developing an assessment program that includes monitoring (level 4). She is tasked with determining how many storms will be required to attain 95% confidence that the mean total suspended solids (TSS) removal is within ± 15%. From previous monitoring data, Laura finds that the stormwater BMP is expected to remove 72% (standard deviation = 27%) of TSS from any given storm. She then uses this information and figure 5.1 to determine that roughly 15 storm events are required:



NOTE: This example illustrates a process but may not represent typical results.

The 95% confidence interval is recommended to represent uncertainty in mean pollutant removal efficiency because it indicates that there is a 95% probability that the mean value is within the confidence interval. For example, if the mean pollutant removal for a stormwater BMP is 72% ± 17% (where 17% is the 95% confidence interval), then the mean pollutant removal would lie between 55% and 89% for 95% (i.e., 19 out of 20) of storm events. The range of the confidence interval (in this case, 17%) is dependent on the variance of the removal data (represented by the standard deviation) and the number of storm events sampled. The relationship between standard deviation and number of storm events for a 95% confidence interval is shown in figure 5.1.

The process for determining the number of storm events can be performed in 3 steps as illustrated in example 5.1. This process should be performed during development of an assessment program to estimate the cost and effort associated with sampling multiple storm events based on the estimated uncertainty. As assessment results are gathered, this process should be performed again using actual assessment data to determine the actual uncertainty.

Step 1) Compute the standard deviation of the percent removal values for storm events that have been sampled. If there are no storm event data, select a standard deviation; typical standard deviations for percent removal of stormwater BMPs range from 20% to 40% (Weiss et al. 2005).

Step 2) Select the desired range of the 95% confidence interval (10 to 15% is recommended).

Step 3) Using the standard deviation (step 1) and the confidence interval (step 2), estimate the number of storm events required to achieve the desired range for the 95% confidence interval from figure 5.1.

5.1.2 Samples per storm event

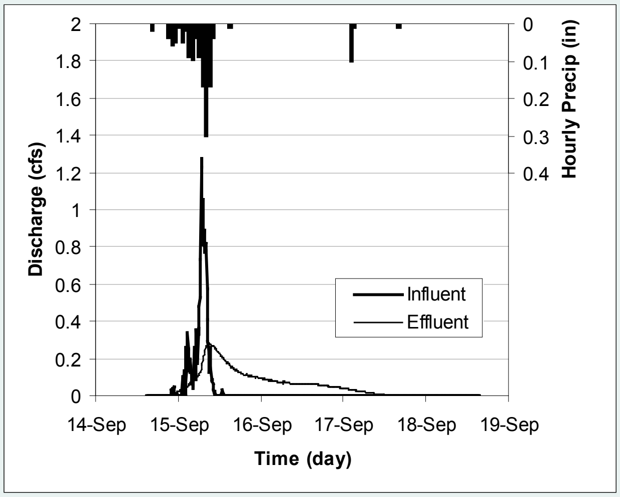
The U.S. EPA (U.S. EPA 2002) recommends that multiple samples be taken throughout a storm event to incorporate changes in concentration and discharge and therefore to represent the storm event accurately. Choosing an appropriate number of samples per storm event will depend upon the basis on which the samples will be taken: discharge, time, or manual samples.

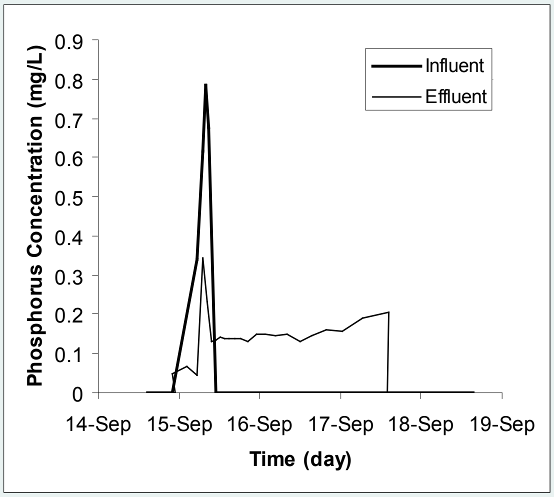
Sampling approaches

There are three approaches to sample collection: (1) flow-weighted, (2) time-weighted, and (3) manual. There are also two methods of sample storage: discrete and composite. Samples are typically described by the method of collection and storage (e.g., flow-weighted discrete samples). In all cases, influent and effluent discharge must

Example 5.2: Error associated with number of samples

Laura, the EIT at a local consulting firm, has been contracted to assess the effectiveness of a dry pond that treats runoff from a Public Works facility. Some preliminary monitoring determined the inflow and outflow hydrographs and pollutographs for total phosphorus (TP), as shown below: [One cfs = 0.028 m^3/s.]





Laura uses the hydrograph and pollutograph data to determine the error associated with the number of samples taken, assuming the sampled concentrations are correct. First she considers the effluent data, in which 23 individual samples were taken, and calculates the pollutant load, as shown in the table below:

Example 5.2 (cont.)

Based on the calculations, the storm produced 18866 cubic feet of effluent discharge with 81.4 grams (0.179 lbs) of phosphorus load. The cost, however, to analyze 23 samples for each storm event could be expensive. Laura estimates what the total load would be if there had been only 6 equally distributed samples taken during this same storm event (black data from table to the right). [One cubic foot = 28.317 liters.]

Sample taken at (mm/dd hh:mm)	Discharge Volume (c.f.)	Incremental Vol (liters)	Conc. (mg/L)	Sum of Mass Load (g)
9/14 10:00 PM	0	0	0.047	0.0
9/15 2:22 AM	675	19110	0.067	1.3
9/15 5:23 AM	1566	25233	0.045	2.4
9/15 7:16 AM	**2573**	**28506**	**0.342**	**12.2**
9/15 8:30 AM	3710	32197	0.232	19.6
9/15 9:39 AM	4832	31774	0.132	23.9
9/15 10:49 AM	5934	31226	0.136	28.1
9/15 12:04 PM	**6976**	**29481**	**0.141**	**32.3**
9/15 1:25 PM	7965	28006	0.137	36.1
9/15 2:54 PM	8862	25407	0.137	39.6
9/15 4:33 PM	9749	25128	0.138	43.1
9/15 6:28 PM	**10631**	**24973**	**0.138**	**46.5**
9/15 8:36 PM	11505	24754	0.131	49.7
9/15 11:03 PM	12416	25799	0.149	53.6
9/16 1:43 AM	13293	24813	0.149	57.3
9/16 4:46 AM	**14167**	**24757**	**0.146**	**60.9**
9/16 8:02 AM	15018	24102	0.151	64.5
9/16 11:49 AM	15877	24329	0.132	67.7
9/16 3:26 PM	16682	22792	0.144	71.0
9/16 7:40 PM	**17527**	**23931**	**0.162**	**74.9**
9/17 12:22 AM	18267	20948	0.156	78.2
9/17 6:23 AM	18785	14670	0.190	81.0
9/17 2:21 PM	**18866**	**2287**	**0.204**	**81.4**

Sample taken at (hh:mm:ss)	Incremental Vol (liters)	Conc. (mg/L)	Sum of Mass Load (g)
9/15 7:16 AM	72849	0.34	24.9
9/15 12:04 PM	124677	0.14	42.5
9/15 6:28 PM	103515	0.14	56.8
9/16 4:46 AM	100123	0.15	71.4
9/16 7:40 PM	95154	0.16	86.9
9/17 2:21 PM	37905	0.20	**94.6**

Laura determines that if only 6 samples had been taken during the storm event, the pollutant load calculated using the same method above would be 94.6 grams (0.209 lbs), which is 16.2% more than the estimate resulting from 23 samples. If, however, the automatic sampler was programmed to collect 4 sub-samples in each sample bottle, the same 23 bottles above would be collected in 6 composite samples and would result in a total phosphorus effluent load calculation of 78.7 g (3.3% error).

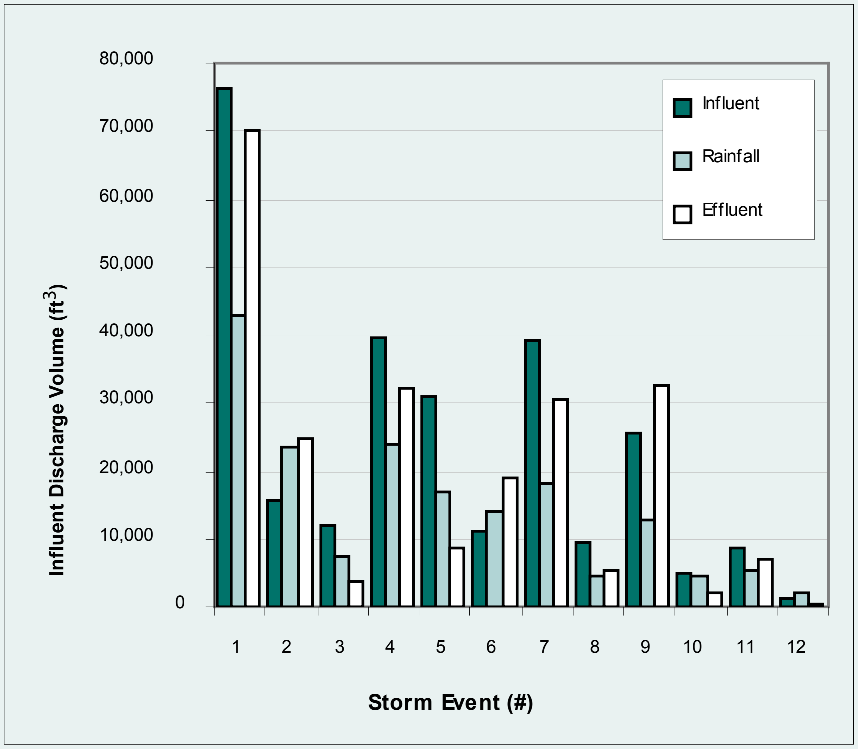
NOTE: This example illustrates a process but may not represent typical results.

be measured and recorded so that pollutant removal efficiency can be determined.

Flow-weighted sampling. Flow-weighted sampling involves collection of samples after a constant incremental volume of discharge (e.g., every 1000, 2000, or 5000 gallons) passes the sampler. Each flow-weighted sample is assumed to represent the average pollutant concentration for the entire incremental volume of water to which it

Example 5.3: Determining the incremental volume for automatic sampling

Laura, the consulting EIT from example 5.1, realizes that storm event volumes will vary and therefore not every storm will produce exactly 24 samples. She therefore does an analysis of the variation of storm events to determine what incremental volume the samplers should be set at to capture the most storm events. Based on the watershed area, runoff coefficient, and the previous season's rainfall, the estimated inflow volumes for 12 storms are:



Based on the influent volumes, Laura calculates the relationship between incremental volume and number of samples for each storm event. She determines the number of samples by taking the runoff volume and dividing it by the incremental volume. She would like to capture as many storm events as possible, including the large storms, so the automatic samplers will be programmed to collect four small samples into each of the 24 sample bottles, allowing for 96 total samples.

NOTE: This example illustrates a process but may not represent typical results.

Volume (ft^3)	**Incremental Volume (ft^3)**				
Influent	**400**	**800**	**1200**	**1600**	**2000**
76,182	> 96	95	63	47	38
15,586	38	19	12	9	7
12,138	30	15	10	7	6
39,752	> 96	49	33	24	19
31,075	77	38	25	19	15
11,312	28	14	9	7	5
39,181	> 96	48	32	24	19
9,280	23	11	7	5	4
25,574	63	31	21	15	12
4,980	12	6	4	3	2
8,630	21	10	7	5	4
1,247	3	1	1	None	None
Effluent	**500**	**750**	**1000**	**1250**	**1500**
70,062	> 96	93	70	56	46
24,744	49	32	24	19	16
3,837	7	5	3	3	2
32,281	64	43	32	25	21
8,796	17	11	8	7	5
18,967	37	25	18	15	12
30,420	60	40	30	24	20
5,184	10	6	5	4	3
32,470	64	43	32	25	21
2,158	4	2	2	1	1
6,926	13	9	6	5	4
220	None	None	None	None	None

Laura determines that an inflow incremental volume between 800 and 1200 cubic feet (22.65–33.98 m^3) would have allowed enough storage space to collect all samples from the largest storm and at least one sample from the smallest storm from the previous year. Similarly, an effluent incremental volume between 750 and 1000 cubic feet (21.24–28.32 m^3) allow ample storage for the largest storm and several samples from the smallest storms, excluding the smallest storm from the previous year.

Laura realizes that this procedure should be revised and adjusted before each rainy season and sometimes during rainy seasons to ensure that the most storm events are sampled. To increase the accuracy of this procedure, rainfall data from more than one preceding year could be used to determine the appropriate incremental volume.

corresponds. If the pollutant concentration changes quickly, drastically, or both, the measured pollutant concentration may not represent the average pollutant concentration accurately for the incremental volume. Small incremental volumes, however, may require the collection of more samples than the automatic sampler can hold (typically 4 to 24 bottles, or 4 to 96 samples), which could result in sampling only part of a storm event. The advantage of flow-weighted samples is that summation of loads and EMC calculations are simplified because the discharge volume is constant for each representative sample. The relationship between sampling accuracy and the number of samples taken is shown in example 5.2.

The number of samples collected depends on the influent discharge of each storm event and the incremental volume. Selecting the optimum volume increment depends on the size of the watershed, land cover, soil type, slopes, and expected rainfall intensity and discharge volume of the storm events. Due to the unpredictability of rainfall, the selection of a flow increment will always involve some uncertainty. An approach for selecting the incremental sampling volume is provided in example 5.3.

Time-weighted sampling. Time-weighted samples are collected at a user-specified, constant time interval (e.g., 30 minutes). Because the discharge of natural storm events is not constant, time-weighted samples do not represent constant volumes of flow with respect to time. Total discharge volume for each time interval must be calculated; then, summation of loads or event mean concentration can be calculated.

The calculations for time-weighted samples can be more complicated than those for flow-weighted samples because each sample must be weighted by the corresponding discharge. In these cases, discharge volume for each time interval must be calculated by integrating the discharge versus time curve.

Selection of the optimal time increment will depend on the duration of a ‘typical’ storm event and the maximum number of samples the automatic sampler can collect. Due to the unpredictability of rainfall events, however, the selection of a time increment will always involve some uncertainty.

Manual samples. Automatic sampling is the preferred method of water sampling, but if equipment or funds are not available for automatic sampling, manual samples may be collected. A manual sample is a discrete sample collected by hand, typically by dipping the sample bottle into flowing runoff (also called grab samples). Portable pumps and tubing may be used to collect samples from locations that are difficult to access, such as the bottom of an underground proprietary device or the center of a wet pond.

The main advantage of manual sampling is that set-up costs are low because automatic samplers do not have to be installed or programmed. Nevertheless, flow measurement equipment must be installed because pollutant removal efficiency and effluent pollutant loads cannot be determined without discharge measurements. The main disadvantages of manual sampling include: (1) inconvenience and cost of sending a crew to the site to collect samples during a storm event and (2) inconsistency resulting from human error.

Discrete versus composite samples

Once it is determined how samples will be collected (flow-weighted, time-weighted, or manual), the next step is to determine whether to collect discrete (i.e., separate) samples or a composite sample. Discrete samples are collected in individual containers and the contents of each container are analyzed separately. Composite samples are collected in a single container and analyzed as a single sample representative of the entire storm event. Both methods can be performed with automatic samplers but most equipment is designed specifically for one method or the other. Thus, in order to ensure compatibility between an assessment program and sampling equipment, it is recommended that the goals and details of the assessment program be developed before purchasing sampling equipment (see Chapter 3 for assessment program development).

Flow-weighted samples can be collected as discrete or composite samples because the volume increment is the same for each sample. Each sample added to a composite sample represents the same volume increment of stormwater and is therefore equally representative. Time-weighted samples, however, can only be collected as discrete samples because each sample represents a different volume of stormwater. It may be important to consider the parameters used by stormwater models (e.g., XP SWMM, WinSLAMM, etc.) when developing a sampling program because some models input sampling parameters (such as discrete samples) directly. Unless the goal is to measure pollutant removal performance as it changes throughout the storm, flow-weighted, composite sampling is recommended because of the cost savings of analyzing only one sample per storm event.

Discrete samples. Discrete samples, in which each sample is stored in a separate container, are collected by automatic samplers equipped with multiple sample containers. Most often, discrete sampling is only necessary when temporal variation in pollutant concentration throughout a storm event (e.g., minimum, maximum, etc.) is desired. The main disadvantage of discrete sampling is that multiple samples must be analyzed for pollutant concentration for each storm event, which can increase the costs of an assessment program.

Composite samples. Composite sampling combines all collected samples into one large storage container and should only be used in conjunction with flow-weighted sampling. Time-weighted composite samples cannot be used to determine pollutant loads or EMC because time-weighted samples do not represent equivalent volumes of discharge. Thus, if time-weighted sampling is used, composite samples should not be collected.

5.1.3 Winter sampling

Stormwater BMPs may function differently during the winter than during the summer. For example, a layer of ice in a wet pond can reduce the effective volume of the pond and cause short-circuiting, which will reduce hydraulic residence times and lower sediment removal rates. Some of the highest concentrations of pollutants in stormwater are found in late winter/early spring runoff (i.e., snowmelt). Unfortunately, it is not common to monitor winter runoff and snowmelt events, most likely due to the inherent difficulties imposed by the weather.

One winter challenge that must be overcome is the formation of ice in and around sampling lines and bubbler lines that are used for water depth measurement at weirs (See Chapter 4, section 2 for open channel flow measurement recommendations). Ice formation in sampling lines can prevent samples from being collected. Ice formation over bubbler tubes will result in erroneously high pressure readings and inaccurate flow measurements. In addition, if an automatic sampler is installed to collect samples when the water depth exceeds a certain value, then a false pressure reading could trigger a sampling sequence when insufficient water is flowing. Because of this possibility, a pressure transducer is recommended to measure water depth. Caution must be exercised, however, because the flexible diaphragm inside a pressure transducer can be damaged by ice formation.

It is possible to maintain a charge on the batteries used to power the sampling and flow monitoring equipment during winter months (Hussain et al. 2007). Solar panels can be used to maintain a full charge on batteries, provided there is adequate sunlight and the panels are free of obstructions. Solar panels should be faced toward the south and angled steeply (near vertical) to capture the most sunlight and to remain free of snow accumulation. Because of the potential problems of winter sampling, manual sampling is advised in conjunction with automatic sampling during winter months to ensure that appropriate samples are collected.

CAUTION:

In one winter monitoring attempt in Minnesota, the bubble tube developed ice over the discharge end, which prevented air from being pushed out of the tube. Although the resistance to air flow and high pressure that developed was due to the ice, the monitoring equipment registered an inaccurately high value of water depth and tried to take water samples when no water was present.

5.1.4 Automatic sampling of water containing suspended solids

The accuracy of automatic sampling of water that contains suspended solids has been documented (Reed 1981), and research is being conducted at the University of Minnesota's St. Anthony Falls Laboratory to investigate the limits of sampling suspended solids and particulates and to improve sampling methods for automatic samplers. For more information, refer to Appendix D.

5.1.5 *In situ,* on-site, and manual sampling

Some pollutants can be measured *in situ* using pollutant sensors or probes that are placed in the stormwater runoff to collect near-continuous measurements with respect to time (*in situ* sampling). Stormwater samples can also be collected and analyzed on-site with sensors, probes, or other analytical methods (on-site sampling). Finally, a sample can be collected in the field and transported back to a laboratory for analysis (manual sampling).

In situ and manual sampling for assessment of stormwater BMPs is cost-effective for some parameters that may be of interest. For example, capacity testing (level 2) of a stormwater BMP for permeability requires measurement of soil moisture content. Soil moisture can be measured either by using a field soil moisture probe (*in situ* sampling) or by collecting a soil sample and analyzing it in the laboratory (manual sampling). Another example includes simulated runoff testing of a wet pond for hydraulic performance using a conservative tracer. Rather than using manual or automatic sampling, a conductivity probe could be used *in situ* to estimate salinity when sodium chloride (NaCl) is used as the conservative tracer. In this case, *in situ* sampling is simpler and cheaper than manual or automatic sampling, and therefore recommended.

In situ and manual sampling for stormwater assessment are often limited by the availability of inexpensive probes for many pollutants of concern. In addition, *in situ* probes may become fouled when they are not maintained as recommended by the manufacturer's instructions, and this can produce erroneous measurements. It is also important to recognize changes that occur over time in the stormwater BMP system that may affect *in situ* measurements such as sediment collection in an inlet pipe or structure. Some *in situ* probes, such as pressure transducers, may require recalibration as conditions change. The following sections describe *in situ* and manual sampling techniques as they apply to various stormwater pollutants.

Temperature

The temperature of stormwater runoff may be of interest depending on assessment goals and downstream conditions (e.g., temperature-sensitive trout streams). Unlike most water quality parameters, such as phosphorus or suspended solids, temperature can be easily measured with *in situ* or on-site techniques. One method is to collect a stormwater sample and measure the temperature on site with a thermometer immediately after the sample is collected. Another method is to use a probe or sensor *in situ* to collect near-continuous temperature data with a data storage device. There are two types of data storage devices that are used for *in situ* temperature measurement: devices that are integrated into temperature probes and devices that are externally attached to them (often called data loggers). Temperature must be measured either *in situ* or on site because water temperature can change rapidly.

For near-continuous *in situ* sampling using a data storage device, the probe or thermocouple must be submerged during a runoff event. The device will continually measure and record temperature at a user-specified time interval until the data storage capacity is exhausted. Most devices can be set such that the oldest data are overwritten with new data when storage capacity is exceeded. For data storage devices that are integrated with the probe, data are usually downloaded directly to a computer through a data-transfer cable or infrared connection. An example of a data storage device integrated with a temperature probe manufactured by Onset is shown in figure 5.2. For data storage devices connected to an external thermocouple, data are typically accessible via modem, cellular connection, or direct download (via serial cable) from the data storage device. An example of a thermocouple that would be

Figure 5.2: Hobo temperature sensor by Onset with infrared data download cable.

externally connected to a data logger is shown in figure 5.3. Some advantages of integrated and external data storage devices are listed below:

Figure 5.3: Thermocouple

Integrated data storage device advantages

- Less expensive than data logger and thermocouple
- Data can be downloaded using infrared wireless connection
- Does not require protective cabinet to store data storage equipment

External data storage device advantages

- Less expensive if a data logger is already in use
- Temporally synchronized with other measurements stored in the data logger (e.g., discharge, rainfall)
- Typically more storage capacity than an integrated device
- Thermocouples respond more quickly to temperature changes
- Data retrieval does not require disturbance of the thermocouple
- Data can be downloaded via modem or cellular connection

The U.S. EPA (U.S. EPA. 2002) notes that some pressure transducers have built-in thermometers so that water depth values can be corrected for temperature. Manufacturers of such temperature probes at the time this manual was written include: Campbell Scientific, Inc.; Onset; and Vemco. Probes are available for different temperature ranges, depths, and prices.

Assessing thermal impacts of stormwater BMPs on downstream water quality and aquatic habitat has been investigated. A simple procedure for developing an assessment program for thermal assessment, including installation guidance and calculation of results, is provided in Appendix E.

pH or hydrogen ions

The acidity or basicity of water is indicated by pH, which is a function of the molar concentration of hydrogen ions in solution ($[H^+]$), pH = $-\log_{10}[H^+]$. Thus, for a water of pH 8, the hydrogen ion concentration is 10^{-8} moles/L. Acidic waters have relatively high hydrogen ion concentrations and therefore low pH values (< 7). Alkaline waters have relatively low hydrogen ion concentrations and high pH values (> 7) and neutral waters have pH values of approximately 7. Federal and state regulations suggest that pH values remain between approximately 6.5

and 8.5 to ensure the quality of water for recreational use, aquatic life, and drinking water (Minnesota PCA 2003, U.S. EPA 2004).

In situ or on-site sampling should be used to measure pH values. Probes are available from several manufacturers for *in situ* or on-site measurement. Manual or grab samples for pH with subsequent analysis in a laboratory are permissible if the samples are transported on ice and analyzed within two hours of collection. pH probes should be calibrated weekly, after every 25 samples (U.S. EPA 1997), or as recommended by the manufacturer to ensure accurate and consistent results.

Conductivity

Conductivity is an indirect measure of the ion concentration in water and is often measured with a probe or meter using *in situ* or manual sampling techniques. Conductivity is often used as a surrogate for total dissolved solids (TDS) or salinity. High concentrations of TDS can be toxic to aquatic life and can reduce habitat.

Conductivity is most often measured *in situ* but can also be measured using manual or automatic sampling techniques. Most 'bundled' probes (multiple probes in one device) include a conductivity probe for *in situ* sampling. An example of a Hydrolab bundle probe is shown in figure 5.4. Manual or automatic samples transported to an analytical lab for conductivity measurements must be analyzed within 28 days of collection and should be kept on ice or refrigerated.

Figure 5.4: Hydrolab Bundle of several probes for *in situ* water quality measurement.

Turbidity

Turbidity is a measure of water clarity and can be measured *in situ* with a turbidity meter. High turbidity values can block sunlight required for photosynthesis by aquatic vegetation and subsequently reduce aquatic life and diversity. Turbidity can be used as a surrogate for suspended solids concentration but requires calibration at each location and for different seasons to ensure accuracy (Stefan et al. 1983). Refer to the turbidity section in Standard Methods (e.g., A.P.H.A. 1998) for details about correlating turbidity and suspended solids.

Turbidity is most often measured *in situ* or on site, but samples collected manually or by automatic samplers can also be transported to an analytical lab for analysis. Some 'bundled' probes include a turbidity meter. Manual or automatic samples transported to an analytical lab for turbidity measurements must be analyzed within 24 hours of collection and should be kept in the dark and on ice or refrigerated.

Dissolved oxygen

Dissolved oxygen (DO) is the amount of oxygen dissolved in water. DO is necessary for the survival of aerobic aquatic organisms such as fish and invertebrates. Minimum dissolved oxygen concentrations in Minnesota are 7 mg/L for Class 2A waters (aquatic life and recreation), and 5mg/L for Class 2B and 2C waters (Minnesota PCA 2003); in Wisconsin, 6 mg/L for Coldwater A & B waters and 5 mg/L for Diverse Fish and Aquatic Life (Wisconsin Department of Natural Resources 2004); in Michigan, 7 mg/L in all Great Lakes, connecting waterways, and portions of stratified lakes and never less than 5 mg/L (Michigan Department of Environmental Quality 2006).

The maximum concentration that the water can sustain at equilibrium with air is termed the saturation concentration. The DO saturation concentration is a function of water temperature, air pressure (specifically the partial pressure of oxygen), and salinity. The DO saturation concentration increases with decreasing temperature, increasing oxygen partial pressure, and decreasing salinity.

DO should be measured using *in situ* or on-site sampling techniques. Manual and automatic sampling for DO measurement is not recommended because DO concentrations can change rapidly. For on-site sampling, DO should be measured immediately after sample collection. Most DO probes require weekly cleaning and re-calibration to ensure accurate measurements. Luminescent DO measurement techniques are available, but their accuracy and stability has not been tested.

Nutrients

Nutrients (e.g., phosphorus and nitrogen) support aquatic vegetation and organisms. Excess nutrients, however, can cause nuisance algae blooms that generate negative aesthetic and eutrophic conditions in receiving lakes and rivers (U.S. EPA 1999). In temperate fresh waters, dissolved phosphorus is typically the limiting nutrient (Schindler 1977, Aldridge and Ganf 2003).

Figure 5.5: *In situ* probe for measuring nitrate concentration manufactured by Unisense (approximately 8 inches (20.32 cm) in length).

Until recently, it was necessary to collect water samples by automatic or manual sampling techniques for subsequent analysis in a labora-

Figure 5.6: MicroLAB *in situ* nutrient measurement system for nitrate, phosphate, ammonia and silicate systems manufactured by Envirotech Instruments.

tory to determine nutrient levels. *In situ* probes, however, are now available for nitrate, ammonia, and phosphate. Two examples of *in situ* nutrient probes are shown in figures 5.5 and 5.6. Nevertheless, the accuracy and stability of these probes for assessing the nutrient removal performance of stormwater BMPs is unknown.

5.2 Automatic sampling equipment

Stormwater sampling equipment is designed to collect samples either manually when triggered by the user or automatically when predefined criteria are met, with the aid of data loggers and computer software. Available equipment is summarized herein and discussed in greater detail in *Urban Stormwater BMP Performance Monitoring* (U.S. EPA 2002). Manual, or grab, sampling equipment is also discussed in Assessment of Storm Drain Sources of Pollutants to Santa Monica Bay, Vol. II (Stenstrom and Strecker 1993).

Automatic samplers, which collect and store water samples until they can be retrieved, are recommended for sampling suspended solids, phosphorus, nitrogen, salts, metals, and other pollutants that do not change or degrade rapidly. For pollutants that may undergo rapid transformation, such as fecal coliforms and organic chemicals, it may not be possible to retrieve and analyze the samples before transformation compromises the sample integrity. For such pollutants, manual samples or rapid retrieval of automatically collected samples followed by prompt analysis are recommended to ensure accurate representation of the pollutant concentration. Alternatively, sample refrigeration or chemical preservatives can be used to reduce the rate at which pollutant transformation occurs. Consult an analytical methods manual (e.g., A.P.H.A. 1998) to determine if refrigeration or preservatives will reduce transformation of pollutants and whether addition of preservatives will interfere with analysis of other pollutants of concern.

Automatic samplers do not require anyone to be present for sample collection; they can be programmed to begin sampling when a user-specified rainfall amount or intensity occurs (electronic rain gauge required), after a predefined depth or quantity of flow is achieved, or after some combination of conditions is met. They can also be programmed to collect varying sample sizes, collect samples at user-specified time intervals (i.e., time-weighted) or flow volume increments (i.e., flow-weighted), or collect samples over an entire runoff event that lasts two days or more.

Some automatic samplers are powered from an external 120-volt AC power source. Many locations, however, do not have an external power source and therefore most monitoring applications use automatic samplers that are powered by a 12-volt battery. Solar panels are also available to recharge the batteries, provided that adequate sunlight is available and the solar panel is free from obstructions (e.g., snow, leaves, etc.). Another option is to use an additional battery as backup to the power supply.

As discussed above, samplers are available to collect discrete samples or composite samples. The sampling portion of an assessment program should be planned before sampling equipment is purchased to ensure the appropriate equipment is available and does not exceed the budget of the program. Automatic samplers with refrigerated sample storage compartments can be used to preserve the integrity of samples that degrade. For example, sample storage for dissolved phosphorus determination recommends refrigeration to reduce the transformation of dissolved phosphorus to particulate phosphorus, or vice versa (A.P.H.A. 1998). Refrigeration units, however, require an AC power supply.

While samples must always be manually retrieved from the storage unit for analysis, some samplers and data loggers have modem or cellular connections that allow measurement data such as flow rate, water depth, and rainfall intensity to be retrieved without physically visiting the monitoring station. Some systems also allow users to remotely determine whether samples have been collected. Manufacturers of automatic samplers at the time this manual was written include: EPIC/Stevens, Hach/Sigma, Isco, and Manning.

5.2.1 Equipment placement and maintenance

Placement of sampling equipment is site-specific and depends on a number of factors, including: equipment type, amount of equipment, availability of protective cabinets, type and design of stormwater BMP. As described in Chapter 4, influent (or effluent) flow measurement and sampling is simplified if all stormwater inflow (or outflow) is routed to a single location. Placing sampling equipment near flow measurement equipment is advantageous because sampling is typically triggered by flow measurement equipment and all instrumentation can be housed in the same enclosure. An example of flow measurement and sampling equipment in the same location is shown in figure 5.7, and a protective cabinet housing automatic sampling equipment is shown in figure 5.8.

Automatic sampling equipment that remains in the field for long periods of time should be maintained at weekly intervals. Sampling equipment maintenance will vary, so the user should follow the manufacturer's recommendations. Additional sampling bottles are available for purchase, and it is recommended to have at least two sets of sample bottles (one for the sampler and one for transporting samples to the analytical lab). More sets of sample bottles may be required, depending on the frequency of storm events and the processing time of the analytical lab.

Figure 5.7: Pressure probe for flow measurement and sampling tube for pneumatic sample collection placed at a weir to measure stormwater inflow.

It is important to recognize that some pollutants adsorb to the surface of collection bottles (organic compounds), degrade over time (coliforms), or may volatize (dissolved gases). These confounding processes can be minimized by choosing sample bottle material properly (e.g., plastic or glass) and cleaning sample bottles appropriately. Consult Standard Methods (e.g., A.P.H.A. 1998) or the analytical lab performing the water quality analysis to determine whether the pollutants of interest for the assessment program will adsorb or degrade and which bottle material or preservation technique is recommended. If analyte degradation is a concern, then sample preservation (e.g., refrigeration), collection followed by rapid analysis, or both, may be necessary.

Figure 5.8: Protective cabinet housing automatic sampling equipment.

Care and cleaning of sampling equipment and bottles will prolong proper functionality and reduce analytical error. Sample bottles should be cleaned according to Standard Methods (e.g., A.P.H.A. 1998). Depending on the pollutant, special procedures may be required to prepare the bottles for sampling. For example, sample bottles for metals or phosphorus should be acid washed, and sample bottles for coliforms should be sterilized (e.g., autoclaved). Refer to the analytical procedure for pollutants of interest, Chapter 6, or the analytical lab that will process the samples.

5.3 Recommendations

Sampling methods will vary based on the goals and budget of the assessment program. In the case of synthetic runoff testing or monitoring, the number of storm events sampled and the number of samples collected during storm events (synthetic or natural) will also vary depending the assessment goals. For most assessment programs that use synthetic runoff testing or monitoring to assess pollutant removal effectiveness, however, it is generally recommended that:

1. *in situ* pollutant sensors be used whenever possible,
2. manual samples or automatic samples be collected promptly for pollutants or characteristics that change rapidly (e.g., temperature, bacteria, DO),
3. flow-weighted composite samples be collected by automatic samplers.

See previous sections in this chapter for details and discussion on sample analysis and preservation, placement of *in situ* probes, number of samples required, and other related details.

5.4 References

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6.
Analysis of Water and Soils

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Hot Links

1. Data quality objectives
2. How to decide what analyses are necessary
3. Descriptions of water quality constituents
4. Descriptions of soil constituents
5. Handling samples
6. Quality assurance program
7. Summary

6.1 Planning

6.1.1 Preliminary steps

Chapter 2 outlines a process assessment framework, which identifies the processes that are needed for a stormwater BMP assessment program. Once the process goals are identified, the next step is to identify the specific type of assessment program that is needed. This is done in chapter 3. Except for visual inspection, each type of assessment program outlined in chapter 3 requires the collection of samples.

The goal of this chapter is to identify specific parameters to be measured and to outline, in a general way, the analytical process that occurs once samples are collected. A key guide for specific methods for sample collection and analysis of water is Standard Methods (APHA 1995). A compilation of EPA methods is available on the web (Nelson 2003). Finally, the American Society of Testing and Materials (ASTM) publishes individual methods, available on its Web site (http://www.techstreet.com/info/astm.tmpl).

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6.1.2 Data quality objectives

A first step in designing an analysis protocol is to establish data quality objectives (DQOs). The following steps are adapted from Standard Methods.

1. What is the assessment question?
2. What decisions will be based on answering these questions (e.g., regulatory action, modification of BMP to improve operation)?
3. What information is needed to address the question?
4. What are the study limits in cost, time, and space?
5. What are the decision rules (i.e. what result would trigger some action)?
6. What are allowable limits for uncertainty?

Answers to these questions (as in example 6.1) guide both the overall monitoring program and the analysis plan.

Example 6.1: Consider a sedimentation basin for which one design goal is removal of phosphorus (P). The original prediction was 70% P removal. Here are the corresponding answers to the DQO questions.

Answer to 1: P removal only because this is part of a permit requirement, which is in turn part of a TMDL implementation plan.

Answer to 2: If 70% P removal is not being achieved, the sedimentation process could be modified or additional control measures, such as source reduction, could be developed.

Answer to 3: What parameters need to be measured, and where? It will probably be necessary to measure both soluble P and particulate P in both the inlet and the outlet.

Answer to 4: Given a budget constraint ($20,000), the study will be limited to a few runoff events, using composite samples. Only suspended solids, total P, and soluble reactive P will be measured.

Answer to 5: Measured P removal < 70% would trigger action, which might include reconfiguring the sedimentation basin (perhaps adding a baffle) or developing an upstream source reduction program.

Answer to 6: For lab P measurements, an acceptable bias would be 5% and an acceptable precision would be 10%. These should be achievable at an expected minimum P concentration of 0.2 mg/L.

6.2 Selecting analytical constituents

Identification of assessment goals and an assessment approach leads to general selection of the types of constituents that need to be analyzed. In some cases, regulatory requirements may specify the exact analysis (for example, total phosphorus), but for other goals, several types of analyses can be used to answer assessment questions.

6.2.1 General considerations in selecting analytical methods

There are nearly always several alternatives for measuring a given constituent in water and soil. The questions below can be used to select an appropriate laboratory method:

1. Will analytical results from your program need to be compared with other sampling programs? If so, sample collection, preservation, and analytical methods must be as similar as possible. This is particularly important for samples that must be compared with prior sampling programs. For side-by-side comparison (for example, a study of multiple detention basins throughout the state, each using its own lab), an inter-lab quality control program may be needed.
2. What is the concentration range of interest? There often are several analytical methods available for a given constituent, with varying limits of quantification. Also, the potential for contamination increases for low-level analysis, so additional care is needed in sampling.
3. Is it necessary to measure just “total” concentrations (dissolved + particulate-bound pollutants), or is it necessary to measure

dissolved and particulate forms of the pollutant separately? For example, in assessing P removal in a stormwater pond, it may be necessary to analyze both particulate and dissolved forms in order to develop an understanding of factors controlling total P removal.

4. Can the constituent be measured as one part of an analytical "sweep"? Some analytical techniques measure multiple constituents, and in some cases there may be benefit in using them. Examples include inductively coupled plasma (ICP) emission, which can measure a suite of metals in one analytical injection, and ion chromatography (IC), which can measure up to a dozen ions with one injection. On the other hand, single-constituent methods may be cheaper if there is need for only the single constituent. For example, nitrate analysis using an automated colorimetric method would probably be cheaper than analysis by IC. If one did not need the analyses provided by IC (for example, chloride and phosphate) the colorimetric method may be preferred because it is cheaper and has a lower detection limit. For many parameters, field test kits can provide fast, inexpensive results.
5. What type of sample handling is needed? Sample handling is extremely important for obtaining meaningful results for a stormwater assessment program. Some constituents are subject to contamination problems and others are reactive, requiring preservation or other special treatment.
6. Is there a need for a standardized method to meet legal requirements? This would certainly be the case for NPDES permit requirements or TMDL program requirements, but there is more flexibility in selecting analytical methods to address questions regarding BMP sustainability.

6.2.2 Constituent groups of water

The section below is divided into constituent groups. Within each group, the appropriate analysis may depend on the exact assessment question, available analytical equipment, cost, and potential for *in situ* analysis.

Suspended solids

Total suspended solids (TSS) is based on filtration of a subsample withdrawn from a larger sample bottle through a glass fiber filter (APHA 2005). This technique is problematic when samples contain significant amounts of sand-sized particles (> 0.062 microns) because larger particles settle quickly and tend to remain in the original sample bottle (Gray et al. 2000, Selbig et al. in press), leading to underestimation of TSS. Gray et al. claim that the TSS method is "fundamentally unreliable" for the analysis of natural water samples.

ASTM (2000) includes three methods for determining suspended-solids concentrations (SSC). For samples with high suspended concentrations, the wet-sieving method (method C) is recommended. This method involves wet sieving through a 62 micron (0.002 inches) sieve followed by filtration through glass fiber filter. In addition to providing better measurement of SSC, this method also provides some information on the distribution of particle size diameter (d; 62 micron d < 62 micron).

For detailed analysis of particle retention, more detailed information on the particle size distribution in stormwater can be obtained by sieving followed by the hydrometer method (ASTM 2000), which yields information on silt and clay distribution. Analysis of volatile suspended solids (VSS) can be used to estimate the contribution of organic matter to TSS.

Salinity-related variables

Salinity is generally defined as the total dissolved solids (TDS), which is the mass concentration (mg/L) of all ions in solution. In practice, about eight ions comprise nearly all of TDS (ALPHA 2005), as in equation 6.1.

There is rarely a need to measure all major ions in a stormwater program. TDS is measured by gravimetric analysis, which is tedious, so it is common to estimate TDS from measurements of specific conductance (SC), which can easily be measured in the field and can readily be automated. A common procedure is to develop a regression relationship between TDS and SC early in a sampling program. This relationship can be established with 25 or so samples collected over a range of TDS values. Once the relationship is determined, SC is measured directly, and the SC-TDS regression relationship is used to estimate TDS. The SC-TDS relationship will change if the ionic composition of the water shifts markedly, as would occur with road salt influence in the wintertime. It would therefore be good practice to develop separate SC-TDS relationships for non-snow and snow months.

Equation 6.1 Total Dissolved Solids (TDS)

$$TDS \approx Ca^{2+} + Mg^{2+} + Na^{+} + K^{+} + Cl^{-} + SO_4^{2-} + HCO_3^{-} + CO_3^{2-}$$

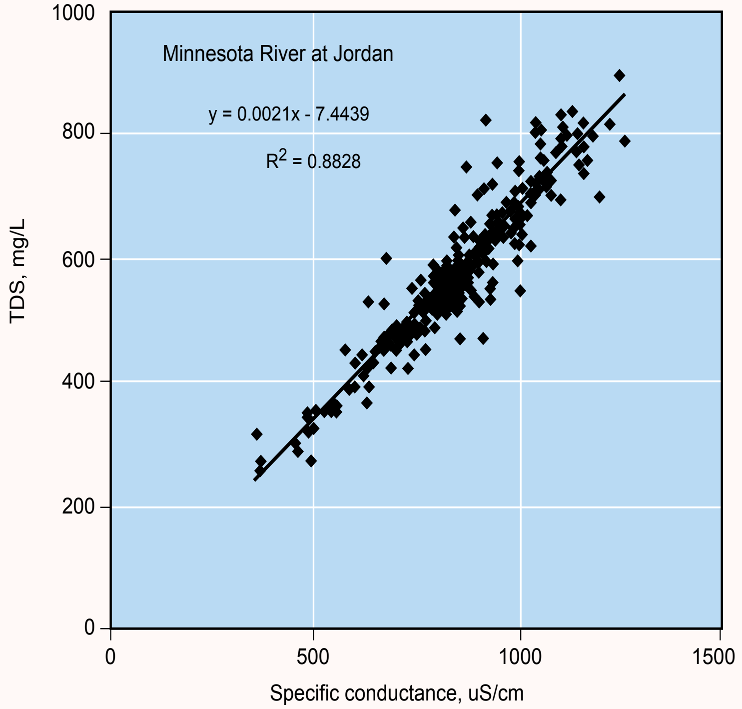


Figure 6.1. An example of the relationship between specific conductance (SC) and total dissolved solids (TDS). Samples are from the Minnesota River at Jordan. Source: USGS water quality database. [One centimeter = 0.394 inches.]

Natural organic matter

In addition to VSS (above), two common metrics of organic matter in water include biological oxygen demand (BOD) and chemical oxygen demand (COD). BOD is a measure of readily decomposable organic matter, generally measured over a period of five days (BOD-5). Measurements of BOD are needed when an assessment goal is to reduce the quantity of oxygen-depleting material entering an urban stream. COD measurements are less expensive, so it is fairly common practice to estimate BOD from COD in wastewater, where the relationship between BOD and COD is fairly constant (~2:1). However, this is not advisable for stormwater because the ratio is higher and more variable.

Phosphorus species

Phosphorus (P) exists in many forms in the environment: as phosphate ions, as polyphosphates, as a component of RNA and DNA, and in phospholipids. Analysis of the exact chemical species of P requires highly specialized analytical techniques that are generally used only in research projects. For stormwater assessment, P species are based on operational definitions based on sample handling and analysis. Typically, separation of species in water samples is based on filtration and type of digestion (figure 6.2). Total P in water is determined for unfiltered samples that have been digested using one of several strong acid digestion techniques. For water samples, the most common is persulfate digestion (APHA 2005). Filtered (dissolved) samples may be digested (total dissolved P) or undigested (dissolved reactive P). Knowledge of P speciation is important because P removal processes are dependent upon speciation. For example, particulate P would likely be removed by sedimentation or filtration, but dissolved P would not.

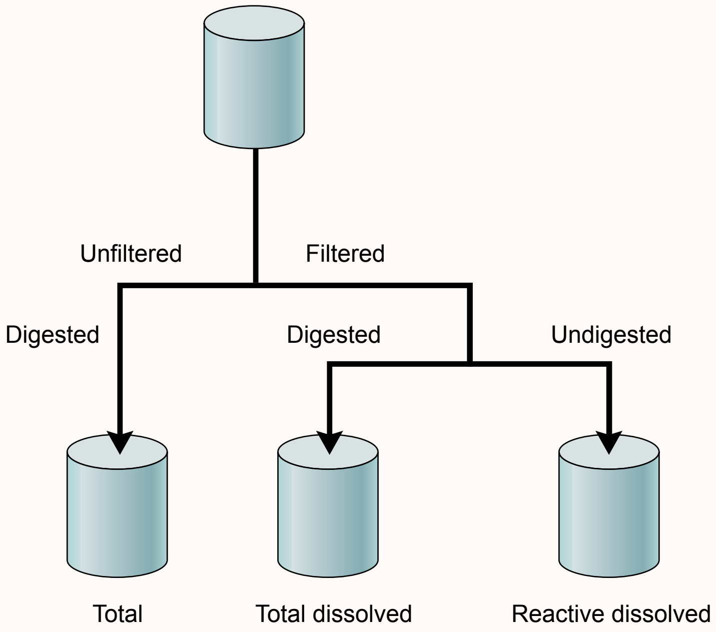


Figure 6.2. Typical separation of P into various species by filtration and digestion.

Nitrogen

Because waters in Minnesota, and particularly stormwater, tend to be P-limited with respect to algae growth, there is generally less emphasis on measurements of N species in stormwater than of P species. Nevertheless, for infiltration practices, there may be concern regarding nitrate leaching to aquifers.

As with P, speciation of N for practical applications is operational, defined by filtration, digestion, and method of final analysis. Major N species in water include particulate N, dissolved organic N (DON), nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+). There is no single method for analyzing total N in water. Instead, the sample is digested using Kjeldahl digestion, which converts organic N (particulate N and DON) to ammonium. The ammonium is then analyzed by one of several methods, depending upon the level of N expected (AHPA 2005). The resulting value, total Kjeldahl nitrogen (TKN), includes organic N plus the original ammonium in the sample. Total N is the sum of TKN + NO_3^- + NO_2^-. For infiltration practices, the total N concentration in stormwater may be a rough indicator of the potential to contaminate groundwater with NO_3^- because organic N and NH_4^+ can be oxidized by bacteria to NO_3^-.

Algae abundance

Measurement of algae abundance may be important in wet ponds for several reasons. Planktonic algae (algae suspended in water) are a form of suspended solids but do not behave like inorganic particles. Whereas the source of inorganic particles is the watershed, algae grow within ponds, essentially forming "new" suspended particles. Algae do not settle like inorganic particles because they have lower density (and some can alter their density with gas vacuoles) and different shapes. High concentrations of algae, particularly blue-green algae, can also become a nuisance and health hazard to homeowners living near a wet pond.

Algal abundance can be estimated from Secchi disk transparency (SDT). Although SDT is closely correlated with algae abundance in lakes, this metric is less useful in stormwater ponds than in lakes because SDT is also affected by concentrations of inorganic suspended solids, which are generally higher in sedimentation ponds than lakes.

Chlorophyll concentrations provide a more accurate measure of total algal abundance, and the lab-based chlorophyll procedure can be modified slightly to yield an estimate of blue-green algae. For most stormwater applications, chlorophyll samples are collected by filtering samples. For analysis, the chlorophyll on the filter is extracted into acetone or another solvent and analyzed. Chlorophyll in the extract is then analyzed in the lab by spectrophotometry or fluorometry (APHA 2005). When samples cannot be analyzed immediately, the filters are frozen for preservation.

Chlorophyll can also be measured *in situ* using fluorescence-based monitors. This enables real-time measurement, which could be an advantage for assessments with a focus on algae problems.

As a rough rule, chlorophyll comprises approximately 1% of algae (dry weight basis). This means that a sample with 0.1 mg chlorophyll/L (a hypereutrophic pond) would have a TSS concentration of approximately 10 mg/L.

Metals

Urban stormwater often contains metals at levels of environmental significance (see Chapter 2). Metals in water are most commonly measured as "total" metals (unfiltered samples) and "dissolved" metals (filtered samples, generally through a 0.45 μm filter). Samples for "total" metals analyses are digested with strong acids and/or oxidants to solubilize metals that are part of particles or bound to particles. Digestion techniques vary with respect to completeness in releasing metals from solution, so the description of "total" is operationally defined by the type of digestion used (AHPA 2005). The most rigorous digestions may involve extremely hazardous materials (such as hydrofluoric acid or perchloric acid), so unless this level of digestion is required, milder, safer digestion procedures are generally used. The analytical lab involved in the assessment project should be consulted regarding digestion procedures.

Once in soluble form, metals are measured by atomic adsorption (AA) spectrometry or inductively coupled plasma (ICP) emission spectrometry. AA measures one element at a time but generally has lower detection limits. ICP has the advantage that it can be used to measure a suite of metals simultaneously.

Metals readily bind to soils, and some accumulation of metals over time would be expected in infiltration-based BMPs. There may therefore be a need to measure changes in the metal content of soils over time. Further discussion, including analysis methods, are discussed in the following section.

6.2.3 Constituent groups of soils

This section addresses the measurement of soil properties and soil constituents that are important to the way stormwater treatment practices operate. There may be several methods available for each analysis; only the most commonly used methods will be discussed. Detailed description of the following analysis can be found in the texts *Methods of Soil Analysis Part 1 and Part 2* (Klute 1986, Black 1965).

Soil properties

Soils are an integral component of a variety of stormwater best management practices and provide numerous functions for the treatment of stormwater runoff. Some of the critical processes that soil facilitates include: infiltration, filtration, absorption, evaporation, adsorption, nitrification, volatilization, thermal attenuation, degradation, and decomposition (Prince George's County 2002). Efficient treatment of stormwater runoff by soil processes requires properly functioning and stable soils. Therefore, measurement and understanding of soil properties are important for the overall assessment of stormwater BMPs. These processes, and the physical properties of the soil, change with soil depth, which should be taken into consideration when examining the soil.

Bulk density

Bulk density is the ratio of the mass of solids to the total soil volume . It is used to gauge the degree of compaction and is needed to calculate soil moisture content and porosity (below). The bulk density of soil, which can change with location, is influenced by soil structure due to its looseness or degree of compaction and by its swelling and shrinking characteristics (Hillel 1998). Bulk density is typically measured using the core method, which involves drying and weighing a soil sample of a known volume. The clod method is a technique in which the total volume is determined by coating a stable clod, or coarse peds, with a water-repellent substance and then weighed in the air and in a liquid (Klute 1986).

Soil texture

Many of the physical and chemical properties of soil are affected by its texture (Pepper et al. 1996). Soil texture is based on the particle size distribution (PSD) of sand, silt, and clay, and soils are assigned different classes based on this ratio. The particle size distribution of soil is measured using particle-size analysis (PSA). According to the U.S. Department of Agriculture (USDA) classification, the particle sizes are divided into three size classes: sand, silts, and clays. (There are, however, other classification systems used by organizations such as the American Society for Testing and Materials (ASTM) and the International Soil Science Society (ISSS).) Pretreatment of the soil prior to PSA is needed to improve the separation and dispersion of aggregates (Klute 1986). There are three methods available for the dispersion of soils: chemical, physical, and ultrasonic. See *Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1—Physical and Mineralogical Methods* for a detailed description of each method. After pretreatment of the soil sample, the sand fractions are separated out using variously sized mesh sieves. The fraction of silts and clays can be determined using the pipet method. The pipet method, a direct sampling procedure, is a sedimentation analysis that relies on the relationship of settling velocity and particle diameter, and it uses Stokes' Law settling times for sampling at a given depth for a particular temperature (Klute 1986). The hydrometer method also applies Stokes' Law and uses a calibrated hydrometer for multiple measurements of the suspended sediment over time. In addition to laboratory analysis for the determination of PSD, there is a field technique based on feel, which is described in Chapter 11.

Porosity

The pore spaces in the soil matrix vary in amount, size, shape, tortuosity, and continuity and are an important physical property of the soil, especially with regard to the retention and transport of solutions, gases, and heat (Klute 1986). Porosity is a term that refers to the volume fraction of pores and typically ranges from 0.3 to 0.6 (Hillel 1998). When the particle density (ρ_s) and the dry bulk density (ρ_b) are known, the porosity (f) can be calculated using equation 6.2. A typical mineral soil has a particle density of 2.65 g/cm^3. Methods for the direct measurement of porosity can be found in *Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1—Physical and Mineralogical Methods*.

Equation 6.2. Porosity

$$f = 1 - \rho_b / \rho_s$$

where

f = porosity

ρ_b = dry bulk density

ρ_s = particle density

If the particle density is not known (e.g., most soils), porosity is determined by saturating a known volume of soil, weighing it, and then drying it at 105 °C (221 °F). Since the bulk density of water = 1.0, the difference in weights is the pore volume and the porosity is the pore volume divided by the original soil volume.

Penetrability

Compaction of soils can occur due to normal stresses and can be induced by machinery. Soils that are highly compacted exhibit low total porosity due to reduced volume and continuity of large pores; low total porosity restricts aeration and impedes root penetration, infiltration, and drainage (Hillel 1998). A direct measure of the level of compaction is done with penetrometers, which measure the ease with which an object can be driven into the soil. The penetration resistance measured is influenced by several soil factors: water content, bulk density, compressibility, soil strength, and soil structure (Klute 1986). Chapter 11 has additional references for measuring compaction.

Water content

The amount of water in the soil influences numerous soil properties, governs the air content and gas exchange of the soil, affects plant growth, influences microbial activity, and dictates the chemical state of the soil (Hillel 1998). The measurement of water content is also necessary for the determination of hydraulic conductivity of the soil when using a Modified Philip-Dunne permeameter, as described in

Appendix C. There are both direct and indirect methods for measuring water content. The traditional method is the gravimetric technique and involves weighing a fresh soil sample, drying the sample in an oven or microwave, and reweighing the sample to determine the amount of water removed. Indirect methods rely on the relationship between water content and certain physical and physical-chemical properties of the soil (Klute 1986). Electrical resistance, capacitance, neutron scattering, gamma-ray absorption, and time-domain reflectrometry (TDR) are indirect methods used to measure water content. There are several capacitance and TDR probes available that can be used in the field either manually or with monitoring equipment.

Hydraulic conductivity

Hydraulic conductivity of soil is a measure of its ability to transmit water and is used in Darcy's Law to calculate flow or infiltration rates (Klute 1986). The terms "permeability" and "hydraulic conductivity" are sometimes used synonymously; however, permeability is an exclusive property of the soil matrix while hydraulic conductivity includes properties of the fluid as well (Hillel 1998). Chapter 4 discusses the theory of infiltration and describes the devices used to measure infiltration in detail.

Cation exchange capacity

The cation exchange capacity (CEC) of soil is a major sorption mechanism for pollutants and is due primarily to the negative charge associated with clay particles and organic particles. Positively charged ions such as heavy metals are attracted to the negatively charged sites on the clay particles and therefore influence the mobility of those cations. As plants and microorganisms utilize these ions in the soil solution, exchanges are made from the negatively charged particles (soil colloids) to the soil solution (Pepper 1996). The CEC is the sum of the exchangeable cations of the soil and is usually expressed as milliequivalents of positive charge per 100 grams of soil (mEq (+) $100g^{-1}$). Common methods for measuring CEC include saturating the exchange complex with a particular cation and then measuring the absorbed cations (Black 1965). Two of these methods can be found in *Methods of Soil Analysis, Part 2–Chemical and Microbiological Properties*.

Soil pH

Soils with high concentrations of organic matter found in areas with high rainfall tend to be acidic (<5.5). The pH of the soil can influence the degree of ionization of compounds, which affects their solubility and may be critical to the transport of pollutants through the soil (Pepper 1996). The measurement of soil pH is split into two methodic groups: the colorimetric methods that utilize dyes or acid-base indicators and electrometric methods that utilize an electrode to measure the hydrogen ions (Black 1965).

Other soil properties

The analysis of other soil properties, such as water potential, evaporation rate (see chapter 4), temperature, and air permeability, may also be desirable for assessment. For detailed standard procedures, see *Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1—Physical and Mineralogical Methods*.

Soil constituents

Stormwater runoff carries various types of pollutants with it as it is conveyed. Measuring the type of constituents and their concentration in the soils can be a useful assessment tool for understanding the soil's capacity to retain those constituents. Retention (or sorption) is one of the major processes influencing the transport of pollutants in soil (Pepper 1996). The retention and transformation of pollutants is desirable to prevent water quality degradation in lakes, streams, and rivers. To ensure that pollutants are being treated properly and that the soil has not reached its capacity for such treatment, analysis of the soils within the practice may be necessary. The mobility of pollutants and the physical properties influencing their transport vary spatially; this should be taken into consideration when collecting soil samples for analysis. This section will discuss some of the key pollutants found in soils of stormwater BMPs.

Organic matter

Organic matter affects physical properties of soil such as bulk density, porosity and infiltration rate. The humic and nonhumic substances in organic matter contribute to the pH-dependent CEC of the soil, which is important for the sorption of pollutants, and these substances can also be important for the chelation of heavy metals. Plant residues are incorporated into the soil surface and are degraded by microorganisms into complex residues that are utilized by plants and microbes for metabolism and also incorporated into macromolecules (Pepper 1996). There are two approaches for determining organic matter content. The first, measurement by loss-on-ignition, volatilizes organic matter (OM), which is determined as the difference between dry weight of the combusted and non-combusted, dried sample. The other approach is to measure organic carbon (OC) content. One of the most common ways to do this is by high-temperature combustion followed by measurement of CO_2 produced during combustion. This is the method used by most carbon analyzers. Organic matter is then estimated using a ratio of C:OM, often approximately 0.5.

Salinity

Soil salinity refers to the concentration of soluble salts. Salinity is important because it harms plants, either by interfering with water uptake or through direct toxicity of ions associtied with salinity (especially chloride). The accumulation of salts in soils also indirectly affects soil properties such as swelling, porosity, water retention, and permeability (Hillel 1998). The major cause of salinity-related problems in stormwater BMPs in this region is road salt (see Chapter 7). A common method for measuring salinity is by electrical conductivity. Electrical conductivity is typically expressed as millimho per centimeter (Black 1965). According to the U.S. Department of Agriculture Handbook 60, a saline soil has an electrical conductivity exceeding 4 mmho/cm at 25 °C (77 °F), (Hillel 1998). A related metric is the sodium exchange percentage, which is the percentage of CEC occupied by sodium. Sodium exchange percentage values > 15% are associated with decreased infiltration in soils with significant clay content.

Phosphorus

Phosphorus poses a particular problem in this region to surface waters as it is often the limiting nutrient restricting algal and plant growth. Phosphorus is retained in soils by adsorption and chemical precipitation. Although phosphate was once thought to be completely immobilized by soils, there is abundant evidence that soils can reach phosphorus saturation. Beyond this point, phosphate leaches through the soil column (see chapter 2). The "active" soil P pool is generally measured by the "Bray" or "Olsen" methods (AES 1988).

For infiltration-based BMPs, there may be a need to quantify build-up of P in soils to assess whether the P sorption capacity of soils has been exhausted. The most commonly used P adsorption metrics are the Bray extraction method (for non-calcareous soils) and the Olsen method (for calcareous soils) (AES 1988). The relationship between extractable P in soil and P leaching is discussed in chapter 2.

Nitrogen

Nutrients such as nitrogen, phosphorus, and potassium are taken up in large quantities by plants and collectively termed macronutrients. As mentioned in the section of constituent groups of water (section 6.2.2, this chapter), nitrogen is found in numerous forms. Plants typically take up nitrogen as ammonium (NH_{4+}) or nitrate (NO_{3-}), which are obtained directly from dissolving salts or indirectly through processes such as nitrogen fixation (conversion of atmospheric nitrogen to ammonia) or nitrification (oxidation of ammonia and ammonium to form nitrate) (Pepper 1996). Nitrate is highly soluble and has the potential to leach into groundwater where high concentrations can result in "blue baby disease." The typical copper content found in soils ranges from 1 to 3 parts per million (ppm) and ranges from 10 to 300 ppm for zinc concentrations (Black 1965). A biological process called denitrification converts nitrate into nitrogen gas (N_2) and is discussed in chapter 2. There are several methods for the analysis of the various forms of nitrogen, and the appropriate technique should be chosen depending on the species of interest.

Metals

Metals commonly found in stormwater are lead, zinc, copper, and cadmium (chapter 2). There is the potential for the accumulation of metals in stormwater BMPs, especially for infiltration-based BMPS (chapter 10). "Total" metal content is determined by rigorous hot-acid digestion of soil samples with one of several strong acids (often nitric), generally with a catalyst. "Extractable" metals are measured using extractions with weaker acids, usually at room temperature. A detailed discussion of metals analyses is found in Standard Methods (APHA 2005).

Microbial populations

Soil contains billions of living organisms that are essential to biochemical transformations and the overall health of the soil. The major groups of organisms found in soils include bacteria, actinomycetes, fungi, algae, viruses, and macro fauna (Pepper 1996). The vital role these microbial populations play in the soil environment make their presence and diversity necessary for the proper treatment of stormwater runoff. Due to the variability in the type of microorganisms present in the soil and the special requirements for each species, it is difficult to measure directly the biological community in the soil. The most-probable-number (MPN) method allows for the estimation of the population density without direct measurement of actual colonies

(Black 1965). There are additional techniques for measuring specific microorganisms that can be found in *Methods of Soil Analysis, Part 2–Chemical and Microbiological Properties*. The abundance of microorganisms in the soil, and therefore pollutant biodegradation, is dependent on oxygen and nutrient availability, organic matter content, pH, redox potential, temperature, and soil moisture texture (Pepper 1996).

6.3 Sample handling

Proper sample handing is essential to meaningful analyses. Some constituents undergo rapid reaction, such as degradation (e.g., BOD), degassing (e.g., oxygen), adsorption to the walls of bottles (many metals and organics) and coagulation (e.g., turbidity). Contamination can be a serious problem for some analyses, notably phosphorus and some metals.

Prior to sampling, sample bottles, filtration apparatuses, filters, and other equipment must be cleaned appropriately. Bottles to be used for collection of nutrient or metals samples generally need to be cleaned with special detergents and acid rinses. Details are provided in Standard Methods (APHA 2005).

Samples for most types of analyses require some time of sample pre-treatment, such as filtration or preservation. An extensive list of sample handing requirements is presented in Table 1060.1 in Standard Methods (APHA 2005). Samples to be analyzed for dissolved constituents should be filtered within a few hours of collection.

Some dissolved gases (e.g., dissolved oxygen) are readily measured *in situ*, using field instruments. If lab analysis is necessary, samples must be analyzed within a few minutes or collected in sample bottles that are filled completely with water (no gas bubbles or headspace) and sealed tightly to avoid gas exchange.

Many types of samples require preservation, such as refrigeration, acidification, or reaction, to form stable storage products. Even with preservation, acceptable holding times vary from a few hours to a few months. Because each type of analysis has its own requirements for sample containers, cleaning, filtration and preservation, it is not unusual to split a sample into half a dozen separate containers when multiple analyses are required.

Because of these requirements, designing a sample collection and handling program is time consuming. It is very important that sample handing procedures are documented and that samplers are properly trained (see Section 6.4.2, Quality assurance, below).

6.4 Quality assurance program

Taylor (1987) defines quality assurance as the “system of activities whose purpose is to provide to the producer or user of a product or a service the assurance that it meets defined standards of quality with a stated level of confidence.”

Most groups involved in stormwater monitoring send samples to commercial or government laboratories. The Minnesota Department of Health maintains a list of certified analytical labs (http://www.health.

state.mn.us/divs/phl/cert/). Contract laboratories nearly always use standardized analytical methods. Standardized methods required by most agencies are generally based on Standard Methods for the Examination of Water and Wastewater (APHA 2005) or specific EPA methods (Nelson 2003).

Contract labs have in-house quality assurance programs, but these assure only the quality of the analytical result for the sample that arrives at the lab. The lab cannot assure that collected samples are representative or complete (see Chapter 5 for discussion of sample collection), that they were collected or handled properly, or that results are verified after leaving the lab.

The entity conducting the sampling program must therefore be responsible for the overall quality assurance (QA) program. The quality assurance program must start with sample collection and proceed through sample processing, lab analysis, and validation of results.

Quality assurance has two components, quality control and quality assessment. Quality control seeks to minimize errors in sample handling and analysis; quality assessment seeks to quantify these errors and determine whether they are acceptable.

6.4.1 Quality control

Quality control is the set of activities that assures quality of the analytical program. In the context of a field sampling program these steps include:

Documentation and archiving of sampling procedures

A guiding principle for documentation is that it should include sufficient detail to allow someone other than the person doing the documentation to replicate the sampling program. Documentation of sampling procedures in the form of a guidance manual should include the following:

- Field sampling methods: sampling locations, sampling methods, field measurements, etc.
- Preparation of samples (pre-cleaning of bottles, filtration, storage, etc.)
- Labeling and chain-of-custody procedures
- Analytical methods used by the contract lab, including any modifications of test procedures from standard conditions
- Overview of the quality assurance program
- Safety protocols to assure safety of field crews.

Documentation of procedures should occur prior to the start of a monitoring program.

Training sampling personnel

Before sampling starts, the sampling team should be trained using the documentation developed for the program. Training will often lead to modifications of the guidance manual as flaws become apparent.

Training is particularly important when multiple field crews are used or when personnel change.

Inspection

The stormwater sampling program should be inspected periodically to assure that procedures are being followed. A very important, but often ignored, part of inspection is sample validation (see Section 6.4.2, Quality assurance). Failing to inspect and validate results can lead to continued use of flawed sampling and/or analytical procedures, yielding unusable results.

6.4.2 Quality assurance

Error in sample analysis is caused by two components, bias and precision. Bias is systematic error in the analytical method that causes sample values to be systematically higher or lower than the "true" value. Precision is a measure of the dispersion of analytical values for the same sample. Figure 6.3 illustrates the interrelationship between the two metrics.

The **Green** values are both unbiased and precise. They are all near the "bulls-eye," (true value) and relatively close together. This is an optimal sampling procedure.

The **Blue** values are unbiased but not very precise. They are near the bulls-eye, but there is substantial variability in their locations.

The **Red** values are precise, but biased. Something causes that sampling methodology to deviate from the true value, but the methodology produces consistent results.

The **Yellow** values are both imprecise and biased. They are off the mark and also demonstrate high variability.

Both accuracy and bias decline as concentrations decrease to levels near the detection limit.

Bias

Mathematically, bias is represented as in equation 6.3. For water or soils analyses, bias can be introduced in the analytical system (e.g., by contaminated reagents) or in field sampling (e.g., by contaminated filters or sample bottles). Laboratory bias is generally determined by analyzing external QC standards (alternatively called "check samples" or "unknowns"). Contracts should be written to specify that QC samples are analyzed along with samples throughout the monitoring program. A typical con-

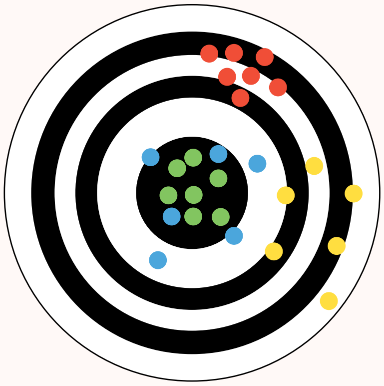


Figure 6.3. Schematic illustrating sample accuracy and precision. Source: Minnesota Pollution Control Agency

Equation 6.3. Bias

$$b = \frac{(C_m - C_T)\ x\,100}{C_T}$$

where

b = bias, %

C_T = true ("known") concentration of QC standard (commercially prepared solution made with pure chemicals)

C_m = average measured value of QC standard.

Example 6.2

Using **equation 6.3**, consider the following analytical results for a QC standard with a known value of 1.6 mg/L :

Measurement	Value
1	1.74
2	1.65
3	2.90
4	1.70
Cm	1.75

$$\text{Bias} = \frac{(1.75-1.6)\ x\ 100}{1.6} = 9.2\%$$

NOTE: This example illustrates a process but may not represent typical results.

Example 6.3: Consider six pairs of samples

First result	Second result	d	d^2
3.4	3.6	-0.2	0.04
4.5	4.4	0.1	0.01
10.3	9.7	0.6	0.36
12.8	13.4	-0.6	0.36
5.0	4.5	0.5	0.25
6.1	5.5	0.6	0.36
Σ			**1.38**

s = [1.38/(2 x 6)]0.5 = 2.03

NOTE: This example illustrates a process but may not represent typical results.

Equation 6.4: Pooled Standard Deviation

$$s = (\sum d^2/2k)^{1/2}$$

where

d = difference of duplicate measurements

k = number of sets of measurements and the number of degrees of freedom

Equation 6.5: Relative Standard Deviation (RSD)

$$RSD = s/Cm \times 100$$

tract should specify the frequency of QC samples to be analyzed (e.g., every 10th sample).

One important QA check for contamination is analysis of field blanks. Field blanks should be high-purity distilled water, generally provided by the analytical lab. Field blanks should be filtered, stored, labeled, and analyzed like normal samples (hence the term “field blanks”). Higher-than-expected values for field blanks indicate contamination in the sampling process.

Precision

Precision is a measure of the dispersion of analytical values for the same sample. Precision is quantified by repeating measurements on samples with similar concentrations. For field sampling programs, a common practice is to run replicate samples for every 10 samples (10% of sample stream) and then determine a pooled standard deviation(s) (see equation 6.4).

Precision is often expressed as a relative standard deviation (RSD), as in equation 6.5.

Detection limit

The limit of detection (LOD) is the lowest concentration that can be reliably distinguished from a blank (high purity distilled water). Operationally, the LOD is determined by repeated analysis of a low-level standard to determine the standard deviation (so). The LOD = 3so. Most analytical labs will provide information on detection limits for various analyses run in their labs. Selection of analytical techniques is sometimes based on detection limits. Most constituents can be analyzed by more than one technique, but as a rough general rule, the technique with the lower LOD will be more expensive than the technique with a higher LOD. Selecting an analytical method is therefore a trade-off between the need for a low LOD and cost. These needs should be discussed with the analytical lab before a sampling program is started.

Implementation and verification

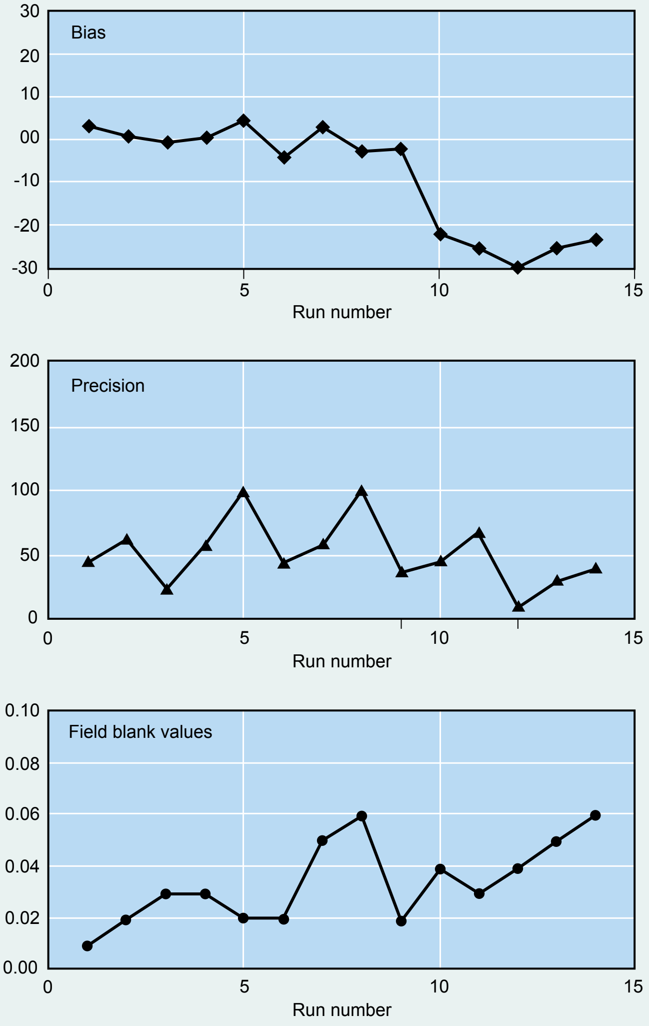
A typical QA program would consist of analysis of field blanks to determine contamination problems, replicates to determine precision, and lab QC check samples to determine bias.

Verification of data quality should be an ongoing process so that problems can be detected early. Control charts are often used to track results from QA samples (blanks, replicates, and QC checks).

Example 6.4 shows an example how control charts are used to track sample QA. Frequent inspection of QA data would have caught the error immediately and would have led to troubleshooting steps to correct the problem. An error of this type might occur as the result of using a contaminated reagent or mis-calibrating an instrument. If it had been caught, the problem could have been readily diagnosed and fixed, allowing the analyst to re-run the stormwater samples. However, in this example, inspection of data was not done in a timely manner, so all data collected in runs 10–12 had to be rejected.

Example 6.4: Control charts

Figure 6.4 shows control charts for a sampling program with the following DQOs: RSD < 10%; field blanks < 0.10 mg/L; bias < 10%. The RSDs hover around 5% (within the DQOs) with no trend upward or downward. Field blanks are consistently below the DQO of 0.10 mg/L. Bias values were consistently between +/- 5% through run 9. An unacceptable bias (-24%) was incurred in run 10 and the negative bias persisted through run 12.



NOTE: This example illustrates a process but may not represent typical results.

6.5 Summary

Planning the analytical program carefully can greatly increase the success of a stormwater assessment program. Careful thought regarding the goals of the program, the type of assessment program, and the DQOs can guide development of an effective yet cost-efficient analytical program to support the assessment effort.

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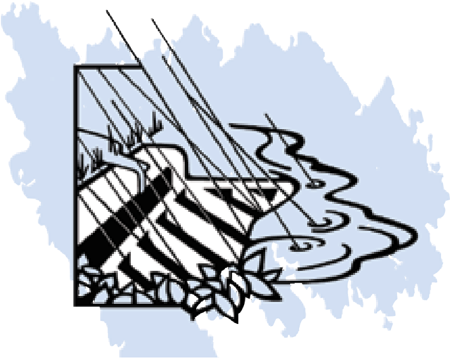

7.

Source Reduction

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7.1 Source reduction

7.1.1 Rationale for source reduction of pollutants in stormwater

Source reduction, or pollution prevention (P2), means reduction in the amount of pollutants entering stormwater conveyances. There are several reasons for employing and assessing source reduction as part of MS4 programs. These include:

1. Most MS4 programs require that municipalities consider the sources of pollutants and the potentially polluting activities being conducted in the watershed. Because source reduction often involves the public, source reduction programs would often also meet the public education requirement (MPCA 2005).
2. Pollutant loading reductions from source reduction could eventually be used to claim credit in Total Maximum Daily Load (TMDL) programs. The MPCA is developing a closer linkage between storm-

Baker, L.A., R.M. Hozalski, and J.S. Gulliver. 2007. Source reduction. In *Assessment of Stormwater Best Management Practices,* ed. J. S. Gulliver and J.L. Anderson. St Paul, MN: University of Minnesota.

water assessment programs and the TMDL program requirements. Concepts from this chapter could be used directly to develop TMDL load reduction credits for source reduction activities.

3. Effective source reduction can decrease overall costs of stormwater programs. For example, reducing erosion and sediment transport to stormwater conveyances would likely reduce operations and maintenance costs for sedimentation basins.
4. Source reduction can be more effective than structural BMPs for some types of pollutants. For example, a large fraction of nutrients in lawn runoff is in soluble form (Waschbusch et al, 1999), which is not efficiently removed in sediment-removal BMPs (e.g., detention basins, etc.).
5. Source reduction may be more equitable. Source reduction shifts the responsibility of reducing urban pollution from the taxpayer, who contributes to municipal stormwater treatment, to the individuals responsible for creating the pollution.
6. The overall reliability of stormwater pollution programs improves when source reduction is part of a multiple-barrier strategy. The multiple-barrier strategy is widely employed for pathogen control for drinking water supplies.
7. Many structural BMPs do not function well during snowmelt periods, when pollutant concentrations are often very high (Novotny et al. 1999).

7.1.2 Goals of chapter

The first part of this chapter examines specific sources of pollutants and methods for assessing their inputs. Specific sources include lawn fertilizer, corrosion inhibitors, erosion, sand and salt added to streets, and atmospheric deposition. The second section addresses the specific issue of street sweeping. The last section develops several example analyses of source reduction impacts.

7.1.3 System boundaries

Definitions of "source reduction" depend upon where the system boundaries are set, which determines what is meant by "source." Three systems are illustrated in Figure 7.1 using phosphorus as an example. The first system of interest is the entire watershed. Sources of nutrients to watersheds in urban or urbanizing landscapes include lawn fertilizer, atmospheric deposition, road sand, human food, pet food, and phosphate compounds used for corrosion control in water distribution systems. All of these are potential stormwater contaminants.

The second system is the network of contributing impermeable surfaces, which means impermeable surfaces that contribute runoff to stormwater conveyances. The boundary of this system extends upstream to the edge of connected impermeable surfaces, the point where they intersect lawns and other vegetated landscapes. The downstream boundary is the curb cut or storm sewer grate. This definition is useful when considering landscape sources such as lawns and construction sites.

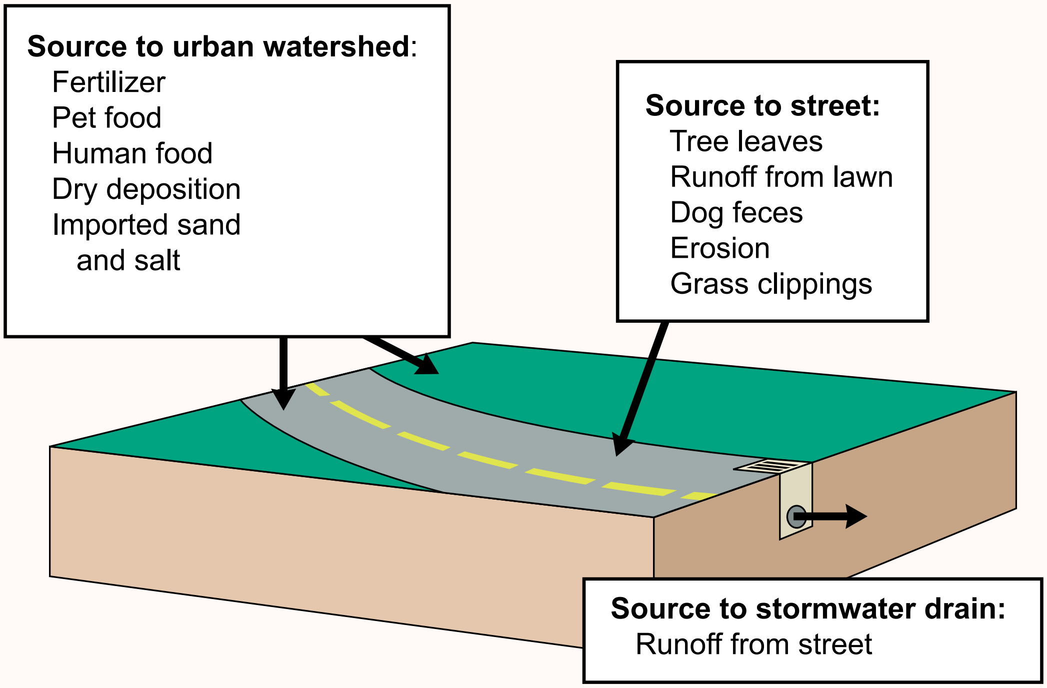

Figure 7.1. System boundaries for source reduction assessment.

The third system is the stormwater conveyance itself. This system extends from the storm sewer grate to the stream. From this perspective, streets are the source of pollution. This is the system definition used for designing end-of-pipe structural treatment systems.

The next sections describe the concept of source reduction in the context of each of these systems.

Reduction of pollutants to watersheds

Reducing inputs to the watershed can be an effective means to decrease pollutant loading to stormwater and surface waters. An excellent example is the nationwide reduction of lead inputs to watersheds resulting from bans on leaded gasoline and paint. The nationwide average “event mean concentration” (EMC) for lead in urban stormwater was 0.144 mg/L in the late 1970s (USEPA 1983) when leaded gasoline and leaded paint were in widespread use. These uses were banned in the late 1970s. A recent synthesis of stormwater data in the Twin Cities area found an average lead EMC of 0.013 mg/L, a 90% reduction (Brezonik and Stadelmann 2002). Other product bans that have had a dramatic impact on the chemical composition of surface waters and aquatic organisms include elimination of phosphorus in laundry detergents and bans on various organochlorine pesticides (Baker 1992, Litke 1999).

Reduction of pollutant transport from landscapes to impervious surface

Further source reduction can occur by altering landscape design and landscape management to reduce the movement of pollutants from landscapes to streets. The loading of pollutants coming from landscapes is the product of runoff volume and pollutant concentrations. The amount of runoff is affected by soil cover, soil compaction, soil type, and slope. Concentrations of pollutants depend on the mass of pollutant accumulation that is available for wash-off, rainfall intensity runoff and total volume, and chemical and biological processes affecting the movement of the pollutant. The variation in pollutant loadings from urban landscapes is large. Phosphorus in runoff from the Twin Cities varies by a factor of three depending on soil fertility and lawn fertilization practices (figure 7.2, Barten and Jahnke 1997).

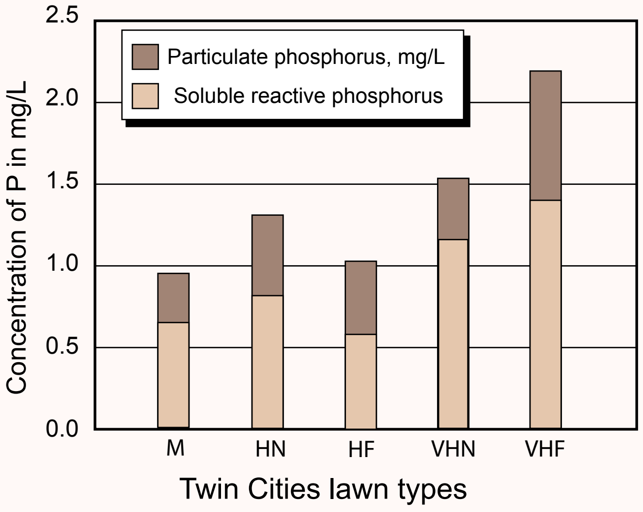

Figure 7.2 Average phosphorus concentrations in lawn runoff (Barten and Jahnke 1997).

Fertility classes on the x-axis are:
M = medium Bray P, not fertilized;
HN = high Bray P, not fertilized;
HF = high Bray P, fertilized;
VHN = very high Bray P, not fertilized;
VHF = very high Bray, fertilized.

Removal of pollutants from streets before they reach stormwater conveyances

Pollutants often sit on street surfaces for some time before precipitation or snowmelt washes them into storm sewers. These deposited materials include tree leaves, grass clippings, road sand, road salt, and atmospheric deposition. To varying degrees, these materials can be removed from streets by street-sweeping during dry periods. The effect of street-sweeping will be discussed in detail later in this chapter.

Removal of pollutants at the end of the pipe

Urban stormwater entering a storm sewer grate is usually conveyed directly either to surface waters or to a structural BMP, such as an infiltration basin or sedimentation basin, located at the end of the conveyance. For this system, the input boundary is the storm sewer grate. Structural BMPs remove pollutants from stormwater by biodegradation, accumulation in sediments and plants, and volatilization.

7.1.4 Pollutants of interest

More than a dozen contaminants cause impairment in Minnesota's lakes and streams. Those most likely to be associated with stormwater include nutrients, sediments/turbidity, and coliforms (MPCA 2004). In addition, salt is an emerging contaminant (Kaushal et al. 2005, SSC 2005). This chapter will therefore focus on these contaminants.

Advanced Discussion

Because Minnesota has enacted a fertilizer P restriction that greatly reduces P inputs to watersheds with large percentages of lawns, it would be useful to estimate the rate of decline of P in lawn runoff in that state. Lawn fertilizer can be a major source of P to residential watersheds. However, this does not mean that the fertilizer P restriction will result in an immediate proportional decline in stormwater P. In fact, the reason that phosphate-containing fertilizer is often not needed is that the soil retains phosphorus so well. The

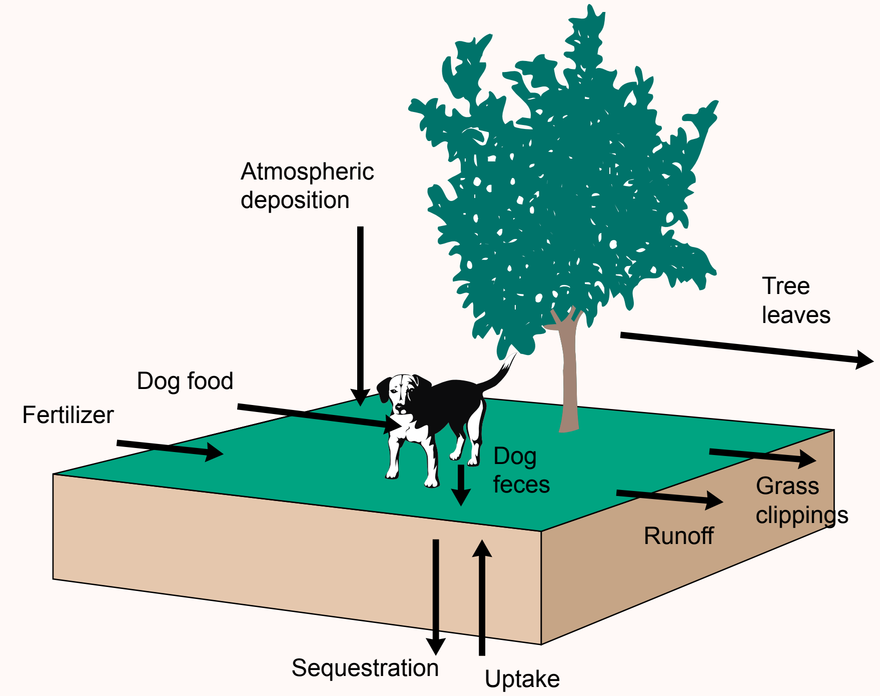

Figure 7.3. Schematic of nutrient flows through a residential lawn (Baker and Brezonik 2006).

drop in phosphorus in runoff will happen gradually after a ban in phosphate fertilizers is instituted. In the studies citied above, immediate losses of applied fertilizer via runoff range from 1% to 20% of applied fertilizer, depending largely on timing relative to irrigation or precipitation events. The P fertilizer restriction should have reduced this source of P to streets. Grass and trees will continue to "mine" stored soil P after cessation of fertilizer P inputs. Most lawn soils in Minnesota are enriched with adsorbed P (as measured by "Bray" or "Olsen" P) (Barten and Jahnke 1997). When grass is cut and left in place, it decomposes, releasing soluble P. This soluble P is either leached into the soil or is exported via runoff, depending on the amount and timing of the next precipitation or irrigation event. Over a period of many years, available soil P ("Bray P") will become depleted, reducing the P content in plants, which in turn will reduce the quantities of P released during decomposition. At some point, soil P could become depleted to the point that plant growth is inhibited, probably at a Bray P level of approximately 10 mg/kg (Hull and Martin 2004). The rate of depletion of soil P depends largely on the magnitude of other P inputs (e.g., animal urine and feces) and the rate at which P is exported via grass clippings and tree leaves. These processes are illustrated in figure 7.3.

7.1.5 Levels of assessment

The types of assessment needed for source reduction are somewhat different that those used to evaluate structural BMPs. Visual inspection (level 1, discussed in Chapter 3) is the major practical approach for evaluating on-site erosion control measures, but it is not very useful for assessing other source reduction BMPs. For the most part, our assessment of the potential for source reduction is based on limited measurement and calculation to estimate the potential for pollutant load reduction. This is very roughly analogous to "capacity testing" (level 2, discussed in Chapter 3). Simulated runoff testing (level 3) would not generally be useful to assessing source reduction BMPs. Finally, monitoring a watershed following implementation of source reduction BMPs would be extremely valuable but has been done in only a couple of studies. One of these, a study done by the Three Rivers Park District to evaluate the effect of a local restriction on lawn fertilizer use, is presented as a case study in appendix A.

7.2 Assessment of specific source reduction BMPs

7.2.1 Lawn and lawn fertilizer management

Background

Lawn and fertilizer management BMPs include (MDA 2004):

- Restricting on the use of P-containing lawn fertilizers
- Matching fertilizer application rate to lawn requirements based on soil testing
- Timing fertilization to avoid excessive runoff following precipitation events
- Watering fertilizers to encourage uptake by plants
- "Good housekeeping" practices, such as keeping grass clippings and fertilizer pellets off streets.

Lawn and fertilizer BMPs have received relatively little attention until recently, in part because there has been relatively little research to demonstrate effectiveness. Studies conducted over the past decade show that lawn fertilizer management can be effective in reducing runoff volume and export of nutrients. These studies are of three types: experiment turf studies (Easton and Petrovic 2004, Shuman 2004, Linde and Watschke 1997) studies of functional lawns (Barten and Jahnke 1997,Waschbusch et al. 1999a, Steuer et al. 1997) and watershed studies (Johnson 2006). In summary, these studies indicate the following:

1. Nutrient concentrations in runoff from private lawns are very high, comparable with levels in effluent from an advanced wastewater treatment plant. Typical concentrations range from 0.5–5 mg/L for total P and 3–6 mg/L for total N. Much of the N and P load in lawn runoff is in the soluble form (Easton and Petrovic 2004, Shuman 2004, Linde and Watschke 1997).
2. Nutrient export in lawn runoff is directly related to nutrient (fertilizer) addition (Barten and Jahnke 1997).
3. Watering in following fertilization reduces export by runoff but may increase downward movement (infiltration) (Shuman 2004).
4. Timing of fertilization relative to precipitation events is important—a worst-case scenario would be fertilization of saturated soils just before a precipitation event (Linde and Watschke 1997).

Equation 7.1: Watershed input rate

$$L_i = R_i \, x \, F_p \, x \, F_f$$

where

L_i = watershed input rate for constituent i, mass/area/yr

R_i = fertilization rate for fertilized landscapes, mass/area/yr

F_p = fraction of watershed that is pervious

F_f = fraction of pervious surface that is fertilized.

5. Nutrient yields from lawns are 7–8 times higher than those from undisturbed forest, mainly due to greater runoff volumes (Graczyk et al., 2003).
6. Reducing soil compaction, either by avoiding initial compaction or by reversing it, may reduce runoff from lawns (Schueler 2000, Kelling and Peterson 1975).
7. For watersheds with large lawn areas, reduction of lawn P fertilizer will probably reduce stormwater P export (Barten and Jahnke, 1997).

Assessment approaches for lawn BMPs

Fertilizer input to watersheds. The main external inputs of N and P to lawns are commercial fertilizers. The input rate of N and P from fertilizer can be calculated from the percentage of pervious surface (= 100 – percentage of impervious surface), the percentage of pervious surface that is fertilized, and the fertilizer application rate.

Table 7.1. Summary of lawn maintenance practices from Minnesota lawn surveys, as % of homes. N/A indicates that the information was not collected.

Study	Respondents	Clippings mulched, left on lawn or composted	Fertilization events per year			Irrigation
			0	1–2	>2	
Creason and Runge 1992	410	N/A	28	N/A	N/A	N/A
Schultz 1995	21	71	13	62	23	N/A
Morris and Traxler 1996	981	81	25	46	24	76
Access 2001	141	69	23	29	39	92
Hudleston 2001	160	N/A	45	55		N/A

Overlays of maps of impervious surface can be used to estimate potentially fertilized surfaces in urban watersheds. For the Twin Cities, both impervious surface and land use GIS coverages are available from Met Council.

Estimating the actual fertilization rate, R_i, and the fraction pervious surface that is fertilized, F_f, is more difficult. Several lawn-care surveys conducted in the Twin Cities over the past decade show that about one-fourth to one-half of homeowners in a given year do not fertilize at all (table 7.1). However, although respondents know how many

Table 7.2 Recommended N fertilization rates (Minnesota Extension Web page).

	Recommended annual application rate	
Lawn management	pounds N/1000 ft^2	kg N/ha
Irrigated, clippings removed	4	168
Irrigated, clippings left on	3	126
Not irrigated, clippings removed	2	84
Not irrigated, clippings left on.	1	42

Example 7.1: Estimating fertilizer N input to a residential neighborhood

Consider a 1.0 km^2 (0.39 mi^2) watershed that is 70% residential land. Assume that 20% of the lot is impervious and that another 20% is never fertilized (i.e., wooded areas, steep slopes, etc). This means that 60% of the residential land is fertilized.

Total fertilized area $= 1.0\ km^2 \times 100\ ha/km^2 \times 0.7 \times 0.8 \times 0.8 = 45\ ha\ (111.2\ acres)$

Assume that the site is located in Minnesota, so non-P fertilizer is used.

Assume one-quarter of households do not fertilize in a given year. Also assume, based on survey of lawn maintenance, that half of the remaining homeowners irrigate but leave clippings on (from Table 7.2, they would use 3 lb N/1000 ft^2, or 126 kg/ha) and half do not irrigate but leave clippings on (from Table 7.2, they would use 1 lb/1000 ft^2, or 42 kg/ha).

Fertilizer N $= (45\ ha - 0.25 \times 45)*(0.5 \times 126\ kg/ha\text{-}yr + 0.5 \times 42\ kg/ha\text{-}yr) = 2{,}822\ kg\ N/yr\ (6{,}221.45\ lbs\ N/yr)$

A more accurate assessment of N fertilizer use could be made by surveying homeowners. The survey would include actual measurements of lawn area, plus questions regarding lawn management. In practice, a more reliable approach may be to use information on lawn management in conjunction with Table 7.3 to estimate N fertilization rates.

To determine trends in fertilizer input rates, lawn surveys repeated over time could be used to calculate the impact of changes in lawn management on watershed N input.

NOTE: This example illustrates a process but may not represent typical results.

Example 7.2: Estimating export of lawn runoff to streets

There are currently no suitable process-based models for predicting export of N and P in runoff from lawns that could be used to evaluate changes in lawn management practices. There are several approaches for estimating runoff volume as a function of vegetation type and cover, soil type, and slope.

As a first approximation, lawn nutrient yield can be roughly estimated as the product of runoff volume and an estimated concentration, as in **equation 7.2**.

Example: P yield from a high fertility lawn.

$P = 0.75\ m/yr\ \ (2.46\ ft/yr)$

$R = 0.1$

$C = 2\ mg/L$ (Waschbusch et al. 1999a)

$Y = 0.75 \times 0.1 \times 2 \times 10 = 1.5\ kg\ P/ha\text{-}yr\ (0.031\ lbs\ P/1000\ ft^2\text{-}yr)$

Nutrient yields from lawns are probably more sensitive to runoff volume than concentration.

To determine trends in fertilizer input rates, lawn surveys repeated over time could be used to calculate the impact of changes in lawn management on watershed N input.

NOTE: This example illustrates a process but may not represent typical results.

$$Y_i = P \times R \times C_i \times 10$$

where

Y_i = yield of substance i, in kg/ha-yr

P = annual precipitation, m

R = runoff coefficient, (= runoff/rainfall), dimensionless

C_i = average concentration, mg/L.

Example 7.3: N and P inputs from tree leaves to streets

As noted above, tree leaves may be a substantial source of N and P to streets. This input can be estimated using equation 7.3.

The biomass of leaves at the time of leaf fall can be estimated using the Urban Forest (UFORE) model developed by the U.S. Forest Service (Nowak and Crane 2000). Modeled results for three key species of landscape trees in the Falcon Heights, Minnesota, neighborhood show that leaf production increases with size, as measured by "diameter at breast height," or DBH (Figure 7.4).

The average nutrient content in leaves for various tree species is about 2% of dry weight for N and 0.3% for P (Baker et al. 2006). About half of the N and P in tree leaves is re-translocated to roots before abscission (leaf fall) so the nutrient content of fallen leaves is 1% for N and 0.15% for P.

Sample calculation: Phosphorus and nitrogen input from leaf fall from a maple tree:

Diameter at breast height: 50 cm (19.69 inches)

Fraction of tree canopy overhanging street: 0.5 (50%)

From figure 7.4, the leaf biomass is 34 kg (74.96 lbs) on a dry weight basis.

P input to street = 34 kg x 0.0015 x 0.5 = 0.026 kg P/yr (0.057 lbs P/yr)

N input to street = 34 kg x 0.01 x 0.5 = 0.17 kg N/yr (0.375 lbs N/yr)

The total N and P input for a given street would then be calculated by summing N and P inputs from individual trees on that street.

NOTE: This example illustrates a process but may not represent typical results.

Equation 7.3: Leaf input

$$L_i = T_L \ x \ F_i \ x \ A_s$$

where

L_i = loading of constituent i for a given tree to the street

T_L = biomass of leaves

F_i = fraction of constituent i in tree leaves at time of abscission (leaf fall).

A_s = fraction of tree canopy that overhangs the street, dimensionless.

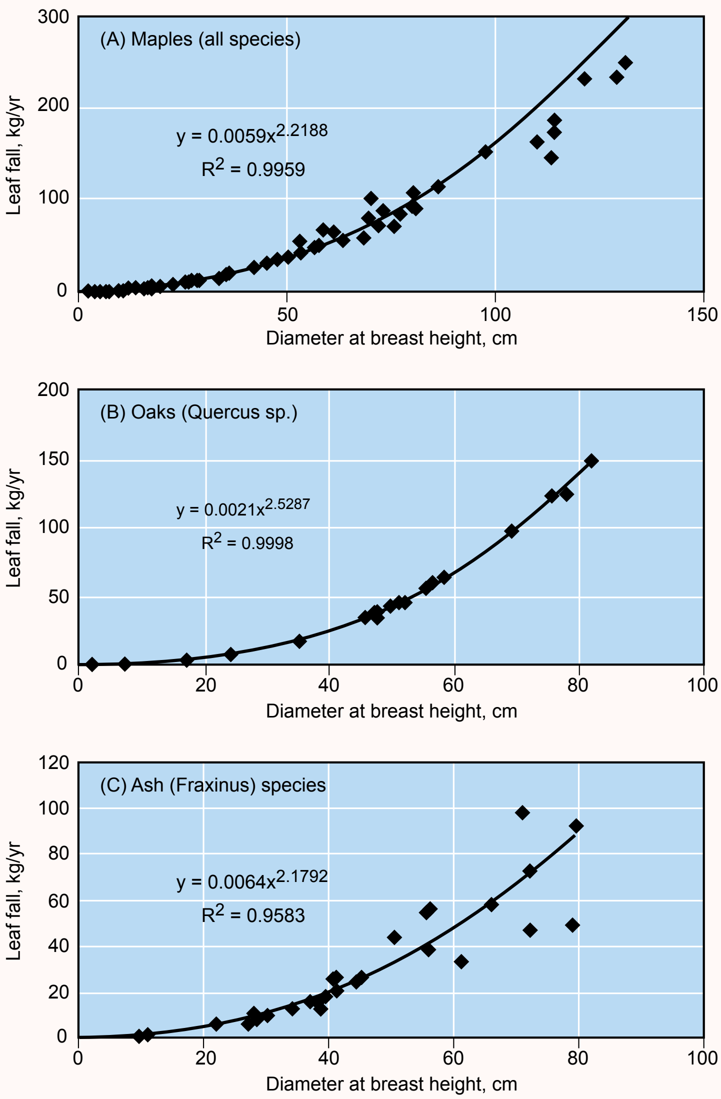

Figure 7.4. Leaf fall (dry weight basis) per tree for (A) all maples, (B) all oaks, and (C) ash in the Twin Cities as a function of diameter at breast height. [One centimeter = 0.394 inches; 1 kilogram = 2.205 pounds.]

Example 7.4: A lawn receives 0.2 m (0.656 ft) of water throughout the summer containing 0.31 mg P/L. Determine annual phosporus added to this lawn using **equation 7.4**.

$L_p = 0.31 x 0.2 x 10 = 6$ *kg/ha-yr (0.123 lbs/1000 ft*^{2}*-yr)*

NOTE: This example illustrates a process but may not represent typical results.

Equation 7.4: Amount of phosporus added to a lawn

$$L_p = C_p x Z x 10$$

where

L_p = phosphorus loading, kg/ha-yr
C_p = concentration of phosphate, mg P/L
Z = depth of irrigation water, m/yr

times they fertilize in a given year, they have little idea of the composition of the fertilizer they use or the actual application rate. The majority of homeowners leave their clipping in place (table 7.1).

Because the use of P in lawn fertilizer is now restricted, one could assume an input rate of zero. For nitrogen, a reasonable approach for estimating fertilization rate would be to assume that homeowners apply N at recommended rates for the type of lawn maintenance being used (table 7.2), and then estimate lawn maintenance from survey information. Lawn maintenance practices in a watershed could be assessed by household surveys of occupants.

7.2.2 Reduction of phosphorus input from corrosion inhibitors

Background

Polyphosphate compounds are added to water supplies of 160 communities throughout Minnesota to reduce lead and copper contamination caused by leaching from pipes. The median concentration is 1.0 mg PO_4/L (0.31 mg P/L; Rezania 2005), with a range of 0.2 mg/L to 0.7 mg/L. This P is transferred to lawns during irrigation. Appropriate BMPs to reduce P inputs from corrosion inhibitors would be:

- Use an alternative method to reduce lead and copper corrosion.
- Inform homeowners about the amount of P entering lawns as polyphophates and advise them to reduce fertilizer P inputs accordingly.
- Take measures to reduce lawn runoff to streets.

Assessment approach

The concentration of polyphosphates added to a particular water supply can be obtained readily from the water supplier or from the state department of health (Rezania, per. comm.). The amount of P added to a lawn can be calculated using equation 7.4.

7.2.3 Management of animal excretion

Background

Excretion by dogs and other animals is an important urban pollutant, a source of both nutrients and pathogens. This section will emphasize dogs because they are the predominant source of excretion in most watersheds. Dog feces contain ~107 fecal coliforms per gram, roughly the same as human feces (Scheuler 2000). There are diseases of dogs, including giardiasis and salmenellosis, that can be passed to humans (CDC 2006). Dog waste may also be a major source of nutrients in urban watersheds, although there are few peer-reviewed studies of dog wastes in urban environments.

The most common BMPs to reduce inputs of dog wastes to stormwater are “pooper-scooper” laws, which require pet owners to pick up their dogs wastes. These are sometimes limited to public areas, but in some cases (e.g., City of Minneapolis), regulations also specify that the pet owner remove feces from their own property. These laws are not always obeyed. Several studies have reported compliance rates of 40–60% among pet owners who walk their dogs (RDEQ 2003).

Table 7.3 Estimated number of dogs, households, dogs per household and average weight of dogs.

	Value	Source
Estimated number of dogs in the United States	61,278,000	(PFI 2003)
Estimated number of households	108,510,000	(PFI 2003)
Average dogs per household	0.56	Calculated
Average weight of dog, pounds	30	Estimated

Assessment approach

The potential effect of pooper-scooper BMPs on nutrient inputs to watersheds and coliform input to streets can be estimated.

Excretion of N and P. N and P excretion can be estimated from dietary inputs because inputs (food) = outputs (waste). An assessment approach follows:

1. Estimate the number of dogs in a watershed. The simplest approach for estimating the number of dogs in a neighborhood is to use national average ownership rates (table 7.3).
2. Estimate the food intake per dog. Recommended caloric consumption is based on dog weight. Purina Corporation (per. comm.) uses the relationship in equation 7.5.

Table 7.4. Estimated composition of dog food.

	Average	Std. dev.
Kcal per 100 g	336	17
Protein, %	23.4	2.8
Fat, %	11.9	2.9
Moisture, %	11.6	1.3
P, %	0.8	0.0
Carbohydrate, %	43	4.9

Equation 7.5:
Recommended caloric consumption (Purina Corp.)

$$ME = 110\ (W)^{0.75}$$

where

ME = metabolizable energy, kcal/day
W = weight

Equation 7.6: Estimate of nitrogen and phosphorus input

$$L_i = N\ x\ F_d\ x\ I_d$$

L_i = loading of nutrient
N = number of houses
F_d = fraction with dogs (from table 7.3, 0.56)
I_d = intake of nutrient *i* per dog, based on figure 7.5.

3. Convert food intake to nutrient intake. Baker et al. (2006) estimated the nutrient contents of dry dog foods through an informal survey of the nutrient contents of a dozen popular dry foods. Protein, fat, fiber, and moisture content were listed on all products, and the P content was listed

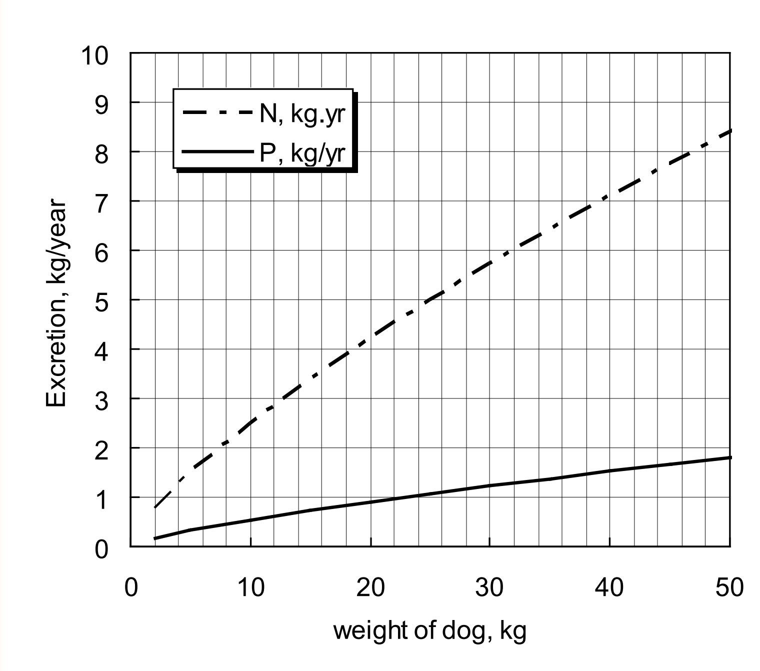

Figure 7.5. Computed nitrogen and phosphorus in dog excretion as a function of dog weight. [One kilogram = 2.205 pounds.]

Example 7.5. Nutrient input from dog food to a residential watershed

Consider the same residential watershed used for our nitrogen fertilizer example. The 1 km^2 (0.39 mi^2) watershed is that is 70% residential, with an average household lot size of 0.1 ha (~ 0.25 acre). The number of households is:

N = 1 km^2 x 100 ha/km^2 x 0.7 /0.101 = 692 households

Assuming 0.56 dogs/household (Table 7.3) and an average-size dog of 30 pounds (14 kg), Figure 7.5 shows that each dog consumes and excretes 3.2 kg (7.05 pounds) N and 0.8 kg (1.76 pounds) P. From **equation 7.6**, the amounts of N and P entering the watershed as dog food are:

P = 692 x 0.56 x 0.8 = 310 kg/yr (683.43 lbs/yr)
N = 692 x 0.56 x 3.2 = 1250 kg/yr (2,755.8 lbs/yr)

This is also the amount of N and P excreted. Most of the nitrogen in dog wastes is in the urine, whereas most of the P is in feces **(table 7.5)**. Removal of dog feces from yards and depositing them to garbage would therefore reduce the potential for P entering stormwater but would have little effect on N.

NOTE: This example illustrates a process but may not represent typical results.

Table 7.5. Distribution of nitrogen and phosphorus in dog excretion (Wood et al. 2004)

	% in urine	% in feces
Nitrogen	85	15
Phosphorus	27	73

Example 7.6: Transfer from landscape to street

For P and coliforms, the input from lawns to streets would depend on a delivery ratio–the ratio between the quantity "delivered" to streets and the amount produced by feces and urine.

The yield of coliforms from dog feces to the street could be estimated using **equation 7.7**.

Example: Fecal coliform input to 1 km of street with 12 dogs.

Assume a delivery ratio of 0.01:

$FC = 0.736 \times 10^7 \times 12 \times 0.01 = 8.8 \times 10^5$

This calculation is very sensitive to the delivery ratio, which has not been well-characterized for urban lawns. The value of 0.01 used in the example above is based on delivery of P from Minnesota feedlots (Barr 2004). We have not been able to find published values for delivery ratios for coliforms from dogs to streets.

NOTE: This example illustrates a process but may not represent typical results.

Equation 7.7: Fecal coliform input to street

$$FC = fc \times ND \times d$$

FC = fecal coliform load, #/length of street

fc = coliform loading per dog = 0.736×10^7/day; from Scheuler 2000a

ND = number of dogs per length of street whose feces is not removed by owners

d = delivery ratio, dimensionless.

on some. The carbohydrate content (not shown) was computed by difference. Metabolic energy (ME) was computed from protein, fat, and carbohydrate contents using the following energy conversion values (kcal/gm) (NRC 1985): protein (3.5), fats (8.46) and carbohydrates (3.5). Carbon content of proteins, fats, carbohydrates, and fiber were taken from (Klass 2004). Table 7.4 shows the typical content of dog food.

Equation 7.5 is used to calculate ME from dog weight, and the calculated ME is used to calculate the intake of total food consumption, protein, fat, carbohydrates, fiber, and P using values in Table 7.4 to yield a nomograph (figure 7.5).

4. Estimate N and P input to the watershed from dogs by assuming national average dog ownership by watershed using equation 7.6.

7.2.4 Reduction of erosion and sediment transport from construction sites

Background

Erosion is an important source of suspended solids to streets. Erosion rates from lawns may be on the order of average erosion from agriculture (table 7.6). Construction

Table 7.6. Sheet and rill erosion from various land covers

	Sheet and rill, Tons/acre-year	Source
Construction	35–45	USEPA (1992)
Cultivated agricultural land in Minnesota	2.1	USDA (2003a)
High fertility lawn	0.08	Calculated from data in Barten and Jahnke (1997)
Medium fertility lawn	0.8	Calculated from data in Barten and Jahnke (1997)

activity can generate at least one order of magnitude higher sediment loading than cultivated cropland or lawns. For a medium fertility soil with a total P content of 0.5 mg P/kg soil, every ton of soil loss would also result in the loss of one lb of P/acre.

BMPs to reduce movement of sediment fall into two categories: erosion control and sediment trapping. The measures below are taken from the Minnesota Stormwater Design Manual (SSC, 2005).

Erosion control. These measures prevent soil detachment during precipitation events. They include vegetated buffers, soil mulching, soil blankets, rapid establishment of vegetation, planning to minimize disturbed area, and diversion of water from exposed surfaces through temporary downdrains.

Sediment trapping. These measures trap sediments after they are detached. They include silt fences, fiber logs, rock entrances to construction sites, grade breaks, floating silt curtains, rock dams, rock or compost bags, filter bags and temporary siltation ponds.

If properly employed and maintained, erosion and sediment control (ESC) measures can reduce sediment export from construction sites by two orders of magnitude (Benik et al. 2000). Construction sites > 1 acre are also regulated by NPDES permits, but smaller construction sites are regulated entirely at the local level. Implicitly, these fall under the MS4 Program.

Assessment approach

Evaluation of erosion and sediment control measures. One of the main problems with ESC practices is that they are not employed effectively. For example, (Paterson 2000) studied ESC practices in North Carolina by (1) surveying ESC administrators and (2) conducting a field investigation at 128 construction sites (table 7.7). The survey of administrators found that although some ESC measures were "technically deficient," the greater problems were poor installation and poor maintenance. For example, only 7% considered "silt fences"

Table 7.7. Results for the most common (n > 40) planned ESC measures in North Carolina (Patterson 2000)

	Percent actually installed	Percent installed correctly	Percent adequately maintained
Storm drain inlet protection	71	72	55
Silt fence	67	58	34
Sediment trap	86	86	58
Vegetation/earth channel	77	98	87
Velocity dissipators	51	86	69
Anti-tracking pad	89	89	67
Sediment basins	84	94	75

to be technically deficient, but 57% reported that they were poorly installed and 36% reported that they were poorly maintained. The field inspection showed that some practices listed on ESC plans were never installed at all. For example, only 67% of planned silt fences and 71% of storm water inlet protection devices were actually installed. Many others were either not installed correctly, or were not maintained.

Chapman and Isensee (2000) evaluated compliance of ESC programs at 545 sites in Dakota County, Minnesota. They found that only nine sites had a person with ESC training, and an additional 72 where at least one individual in the company doing the construction had ESC training. A review of inspections (Figure 7.6) showed that only 2% were fully compliant; the others required maintenance or corrective action.

Many states are tackling the problem of unqualified ESC personnel. The University of Minnesota's ESC certification program has "graduated" 4,000 individuals between 2000 and 2006, and currently trains about one thousand individuals per year, of which about 40% attend for recertification. This expertise is being developed because the Phase II Stormwater Construction Program permits require that a project owner must have a designated ESC staff who are "knowledgeable and experienced" regarding ESC measures. (Chapman 2006).

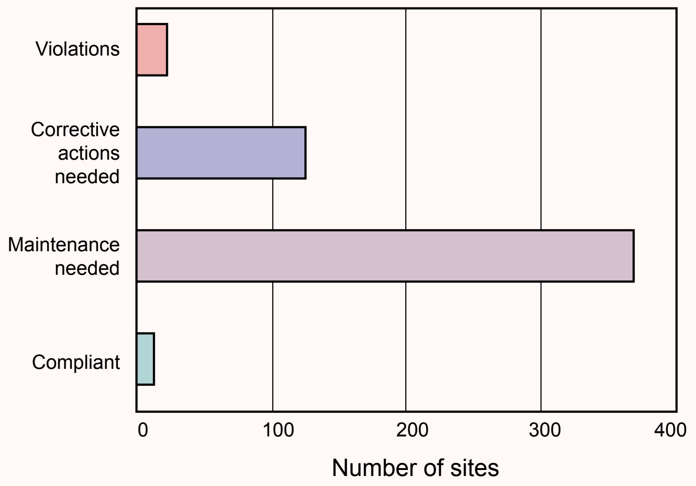

Figure 7.6. Status of ESC measures at 545 sites in Dakota County (Chapman and Isensee 2006).

Given the poor performance of ESC programs, the main assessment tools for evaluating construction sediment production are measuring (1) the adequacy of oversight inspections and (2) the adequacy of implementation of Stormwater Pollution Prevention Plans (SWPPs).

Oversight inspections. Some cities and local units of government have trained inspectors, but most do not (Chapman and Isensee 2006). Given this situation, a key assessment tool would be a continuous survey of ESC-trained inspectors throughout the state, and an accounting of the number of construction site "designated personnel" with ESC training, the number of site inspections actually conducted, and the number of violations.

Site inspections. The second assessment tool is a site assessment program. A site assessment program addresses several questions for each construction site:

1. Is the SWPP plan adequate?
2. Has the plan been implemented?
3. Are ESC measures installed correctly?
4. Are they maintained?

5. Are they inspected?

This survey assessment tool can be used to measure progress in construction erosion programs. It can also be used to identify specific weaknesses to be addressed, and perhaps to provide support to local units of government for the need to hire and train more inspectors.

Modeling sediment movement from landscapes to streets. Sediment loading measures from small construction sites (< 1 acre) may be significant even if they comprise a small percentage of the watershed because sediment yields from construction sites are roughly two orders of magnitude higher than those from other types of land (Table 7.6).

The effect of ESC measures on soil erosion and transport can be modeled using the Revised Universal Soil Loss Equation. The latest version (USDA 2003b) models erosion from individual events using climate profiles for a region and can handle complex topographies. Both erosion control and sediment trapping BMPs can be represented. However, using the soil loss equation requires a thorough understanding of soils and hydrology and is unlikely to be a site assessment tool for smaller construction sites.

7.2.5 Reducing inputs of road salt and sand

Background

Road salt and sand are widely used throughout Minnesota to keep streets and highways passable and safe in winter. Nationwide, use of road salt increased four-fold in the 1960s, was stable over the next two decades, and doubled during the period from the 1990s to the present (Figure 7.7). The use of road sand and other abrasives is apparently declining. At least one county (Washington, in Minnesota) now uses only salt and no sand (Aichinger 2006). Minneapolis, Minnesota, uses nearly twice as much deicer as sand and recovers most of the sand added (table 7.9). The Minnesota Department of Transportation (MNDOT) spends $13 million annually for road salt, so source reduction could potentially result in considerable cost savings.

Table 7.9. Use and recovery of road sand and salt in Minneapolis (Jane Onarati, City of Minneapolis, per. comm.)

	Tons per year
Deicer used	18,500
Sand used	11,150
Sand recovered from streets	16,900
Sand recovered from grit chambers	680

The main deicers are sodium chloride, magnesium and calcium chlorides, and calcium magnesium acetate. All have potentially severe environmental impacts. These include salinization and sodification (for NaCl only) of soil, increased metal leaching and increased toxicity of metals to aquatic organisms, chloride toxicity in surface waters, oxygen depletion in streams (for acetate-containing salts only), and migration of salts to aquifers, leading to increased salts in drinking water. Finally, the ferrocyanide compounds used for anti-caking agents can decompose to release free cyanide. (Novotny et al. 1999, Oberts et al. 2005).

Salt contamination of the urban waters of northern USA is increasing. In a study of 20 lakes in the Twin Cities metropolitan area, Heiskary and Swain (2002) found that changes in chloride concentrations since

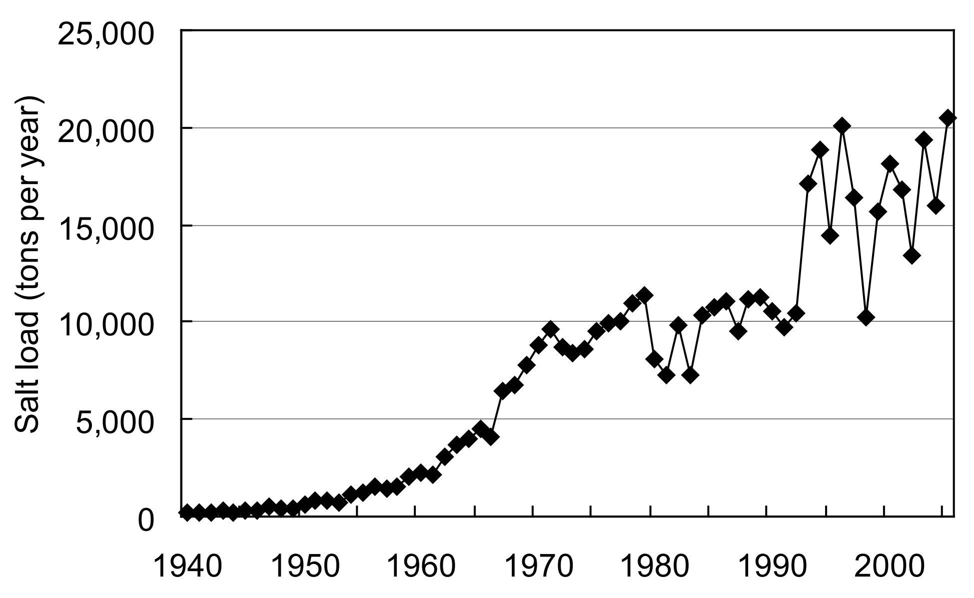

Figure 7.7. Trend in use of road salt in the United States (Salt Institute 2006). [One ton = 0.907 metric tons.]

pre-industrial times were directly correlated with percentages of built-up area in their watersheds. Road salt is likely the largest input of salt into watersheds in Minnesota. For the Shingle Creek Watershed, in Brooklyn Center, Minnesota, which has 45–50% impervious area, salt used on public roads was 90% of total salt input. Shingle Creek is now listed as impaired by chloride, with peak concentrations of 1,000 to 8,200 mg/L in the stream and 340 mg/L in the underlying groundwater (Wenck 2005). For comparison, the chloride standard for protection of aquatic life in streams is 230 mg/L. (MPCA 2005)

An important motivation for reducing use of road sand is high O&M costs associated with street sweeping and cleanout of storm sewer grit chambers. Spring street sweeping is done to remove road sand and other debris, with recovery rates often greater than 100% of sand applied (see Table 7.9). Even with spring street sweeping, cleaning out grit chambers cost the City of Minneapolis $750,000 in 2005. Road sand also contributes to the filling of detention basins and other BMPs. Finally, road sand may also contribute fine particles and phosphorus to stormwater (Oberts 1986). Obert's experiments found that the fine-particle content of road sand was 0.1–0.3% and the P content was 0.3–1.3 mg/kg.

Salinity is not removed by structural BMPs, so source reduction is the only approach for reducing salt loading from urban pavements. Source reduction of salts can be accomplished in a number of ways, (Auditor 1995, Novotny et al. 1999, Wenck 2005) such as the following:

1. Reduced use of "bare-road" policies. The obvious problem with reducing salt application is the potential for increasing accidents. Although a "bare-road" policy is common for highways, many side streets do not necessarily have to be kept bare. A state-wide study of winter road maintenance found that only 28% of cities had a bare-road policy for some or all roads, whereas 64% had a

non-bare-road policy (Auditor 1995). Although there are no data to document trends, total road salt application rates suggest that there may be a trend towards the bare-road policy.

2. Prevention of ice formation (anti-icing). Salt applications can be reduced by spraying brine on roadways before freezing conditions or snowfall occurs. Anti-icing improves safety with less salt by preventing ice from forming on the pavement, rather than melting it after it forms.
3. Use of Roadway Weather Information Systems (RWIS). RWIS stations collect information on weather conditions, including air and pavement temperature. Minnesota now has 80 RWIS stations. These provide information to snowplow operators, allowing them to match salt application rates to weather conditions and reduce salt use.
4. Use of alternative salts. Most road salt is sodium chloride. Ca- or Mg-acetate can be used in areas where chloride is a problem, although the acetate contributes to BOD loading. Where sodium is a problem, $CaCl_2$ or $MgCl_2$ can be used. The alternative salts are more expensive than sodium chloride.
5. Eliminating cyanide-based anti-caking compounds. Ferrocyanide is added to salts to prevent caking. Under some conditions, free cyanide can be formed in receiving waters (Novotny et al. 1999)
6. Housekeeping. Salt piles used by snowplow operators can be a source of salt loading. Enclosing salt piles used by road crews to prevent runoff is now commonly practiced by road-maintenance agencies.
7. Passive barriers. Passive barriers, such as snow fences and hedges, are used to reduce drifting, thereby decreasing pavement clearing needs.
8. Adaptive management with feedback loops. This is both a BMP and an assessment approach because assessment occurs in real time and is used to modify salting operations. Figure 7.8 illustrates the concept of feedback loops. In this approach, road crews send information on salt quantity used, timing, etc., after a salting event to a data analyst, who also compiles data for specific conductance (a proxy for salinity), temperature from remote sensors placed in roadways, and for the stream draining the watershed. This information is processed to develop empirical relationships, which are used to provide specific recommendations to road crews for subsequent events. Recommendations are based on a primary goal of achieving ice-melt on roads and a secondary goal of keeping stream chloride within bounds. The quality of recommendations improves as more events are analyzed, until the minimal amount of road salt needed for each type of event is determined. One likely outcome of this approach would be decreased costs for salt purchases.
9. Education of snowplow operators. Most of the techniques listed above also require education of snowplow operators to utilize them effectively.

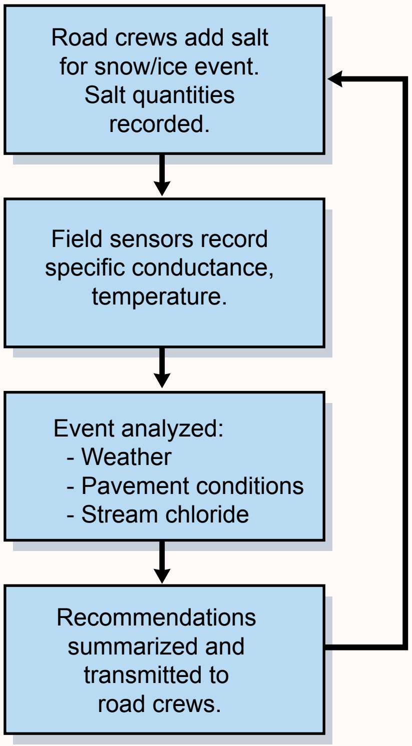

Figure 7.8. Schematic of feedback loop to manage road salt.

Assessment approach

Calculating reductions in watershed salt inputs. Although there are many sources of salts to urban watersheds (e.g., water softener salt, human food, household and industrial chemicals), most of these are not likely to enter stormwater in urban areas with separate sewers. The main source of salt reaching stormwater drains is probably roadways.

Since the main water-quality impairment from road salt in streams is the result of chloride, salt inventories should be converted to chloride equivalents, similar to Table 7.10.

Table 7.10. Calculation of chloride inputs from a hypothetical inventory of road deicing compounds

	Tons used	Chloride, %	Tons Cl^-
Sodium chloride (NaCl)	10	60.6	6.1
Calcium chloride ($CaCl_2$)	5	63.9	3.2
Magnesium chloride ($MgCl_2$)	2	74.5	1.5
Calcium acetate	1	0.0	0.0
Total			10.7

Assessing soil and vegetation impacts. In addition to water impacts, salts impact soil and vegetation. Soils are susceptible to sodification, a process whereby calcium and magnesium ions on soil surfaces are replaced by sodium. It is measured by a metric called the sodium exchange fraction. Values greater than 15% saturation are considered undesirable.

Many plants are also affected by salt along roadways. Evaluating salt damage to plants requires expertise in botany or horticulture. However, the sensitivities of various types of horticultural plants to salt damage are well-documented (TAC 2003) and can guide an assessment of suitable plantings near roadways.

7.2.6 Atmospheric deposition

Background

Atmospheric deposition can be a significant source of pollutants in some environments. Atmospheric deposition includes two components: “wet” deposition (precipitation) and “dry” deposition. The latter is deposition of suspended particles and, for pollutants with a gas phase, adsorption of gases on surfaces.

Measurement of wet deposition is generally done in wet/dry collectors. During dry periods, the “wet” bucket is covered with a moveable plastic cover. Rainfall triggers a sensor, which activates a motor that moves the cover to the “dry” side, leaving the wet bucket open. When rainfall ceases, the motor moves the plastic cover back to the wet bucket. This instrument assures that only wet deposition is trapped in the wet bucket, and that evaporation is minimized (NADP 1999). The “dry side” of the wet/dry collector collects coarse particles but does not measure fine particles or gas deposition well.

Equation 7.9: Dry deposition

$$D_i = C_i \, x \, v_i \, x \, 3.65$$

where

D_i = dry deposition of substance i, kg/ha-yr

C_i = concentration of substance i in the air, g/m^3

v_i = deposition velocity, cm/day.

As an alternative, dry deposition can be inferred from "deposition velocities" and air concentrations, as in equation 7.9.

Air concentrations of various pollutants can be measured reasonably well, but there is considerable uncertainty in the use of assumed deposition velocities.

The Minnesota Phosphorus Study (Barr 2004) estimated wet and dry deposition of P in each region of Minnesota (Figure 7.9). Dry deposition was based on measurements of ambient particulate air concentrations using equation 7.9. Estimated average wet and dry P deposition rates are presented in figure 7.9. A major limitation of the dry deposition estimates is that particulate P was not measured directly, but inferred from calcium:phosphorus ratios.

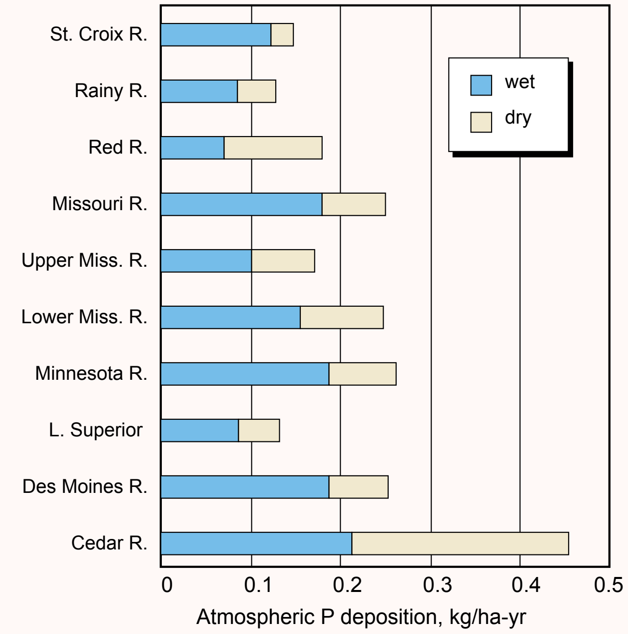

Figure 7.9. Wet and dry deposition estimates for Minnesota's major river basins (Barr 2004). [One kilogram = 2.205 lbs; one hectare = 107,639.1 ft^2.]

Source reduction methods

Reduction of atmospheric deposition of phosphorus could occur by two means: (1) reduction of wind-blown erosion and (2) reduction of the P content of soil particles. The main strategy for reducing atmospheric N deposition would be reduction of NOx emissions, either through control technology or energy conservation. In practice, because these reduction techniques must occur over large regions to be effective, it is unlikely that there is any way to reduce atmospheric deposition inputs to an urban watershed by control measures within that watershed.

Example 7.7: Calculating atmospheric deposition inputs.

For a 10-hectare (24.7 acre) watershed located in the lower Mississippi River basin, the wet + dry deposition rate (**figure 7.9**) is 0.25 kg/ha-yr.

$$L_i = 0.25 \times 10 = 2.5 \text{ kg/yr (5.51 lbs/yr)}$$

NOTE: This example illustrates a process but may not represent typical results.

Assessment approach

Calculating atmospheric deposition inputs to a watershed. Estimating deposition inputs to watersheds is straightforward, as shown in equation 7.10).

A limitation of this approach is that it assumes dry deposition originates outside the watershed. Phosphorus is often attached to particles that have short transport ranges (high deposition velocities). This means that some dry deposition—however measured—will likely include air-born particles generated within the watershed. There is no easy way to resolve this uncertainty. However, in an overall watershed assessment, the errors associated with dry deposition are not very important because dry deposition of P will generally be a small input relative to other inputs.

Equation 7.10: Estimating deposition inputs

$$L_i = D_i \times A$$

where

L_i = wet + dry deposition inputs, mass/yr
D_i = atmospheric deposition rate, mass/area/yr
A = area of watershed

7.2.7 Street sweeping

Background

Nearly all of Minnesota's cities sweep their streets at least once a year. The most common practice is to sweep twice, once in the spring, to remove winter sand and accumulated debris, and once in fall, to remove leaves. In a survey of local governments regarding their street-sweeping practices, Schilling (2005) found that all 58 municipalities that responded reported that their entities swept streets at least once per year. Most swept at least twice a year, and many swept areas near lakes, sediment accumulation areas, and central business districts more often (Figure 7.10). Downtown Minneapolis is swept nightly (Onorati 2006).

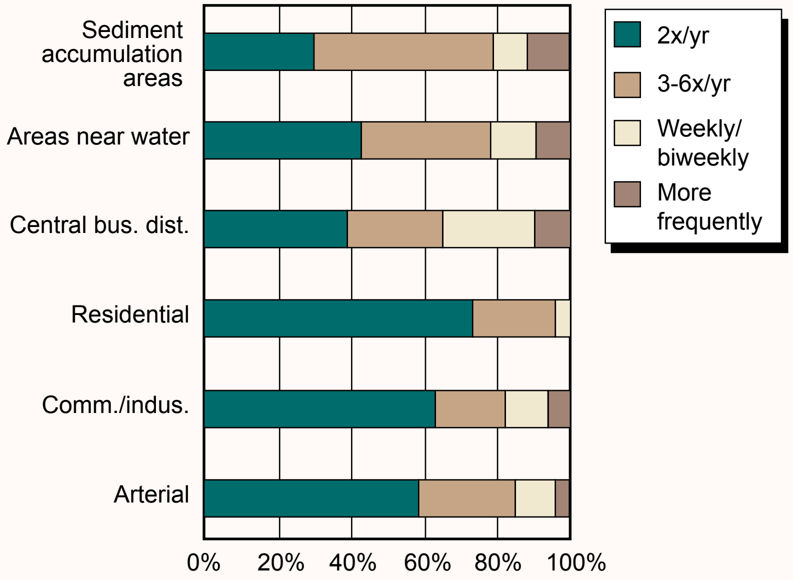

Figure 7.10 Street sweeping frequency for various surfaces (Schilling 2005).

For respondents in Minnesota, "important" or "very important" reasons for street sweeping were: keeping materials out of storm sewers (96%), water quality improvement (91%), aesthetics or cleanliness (91%), maintaining street or roadway safety (90%), and compliance with Phase I or II permits (58%).

The main benefit of street sweeping is to reduce the quantity of material going into storm sewers. Spring street sweeping appears to remove road sand effectively. Material picked up during spring street sweeping often exceeds the amount of road sand added during the winter. For example, Minneapolis applied 11,150 tons of sand in 2005 and removed 16,900 tons of sweepings in the spring (Onorati 2006) [One ton = 0.907 metric tons.] Fall sweeping removed 7,600 tons of leaves. This is material that otherwise would fill grit chambers, storm sewers, and detention basins, or could bypass these devices and flow into public water bodies.

The pollutant removal function of street sweeping is less clear. The effectiveness of street sweeping in removing specific pollutants depends on three factors:

1. Efficiency of street sweepers at removing particles. Brush-type street sweepers are more efficient at removing coarse particles than fine particles. Newer vacuum-type sweepers are more efficient at removing fine particles, with efficiencies > 70% (Schilling 2005). The efficiency of street sweeping is particularly important for fine particles.
2. Distribution of particle sizes. Several studies have examined the size distribution of particles on streets, and some of these have examined the distribution of specific pollutants (mainly phosphorus and metals) on particles within specific size ranges. For example,

Example 7.8 Effect of street sweeping

This example looks at inputs from pervious surfaces to streets to ask the question: how much phosphorus would be removed by repeated fall street sweeping to remove tree leaves?

Consider another residential neighborhood with large maple trees lining a 1-km-long street. The trees have a uniform DBH of 50 cm (19.69 inches) and are spaced 20 m (65.12 feet) apart on both sides of the street. Half of the leaves fall into street, which is 10 m (32.81 feet) wide. Lots are 30 x 30 m (98.43 x 98.43 feet). Assume half of the lots (the front yards, 450 m^2 (4,843.8 ft^2) contribute runoff to the street and assume the runoff coefficient is 0.1.

P input from tree leaves is calculated from **equation 7.3**:

$L_p = T_L \times C_p \times A_s$

T_L can be estimated from Figure 7.3 (A). For a DBH of 50 cm, T_L 34 kg /tree. If leaves are 0.15% P, C_p =0.0015. A_s = 0.5.

$L_p = 34 \times 0.0015 \times 0.5 = 0.026$ *kg P/tree (0.057 lbs P/tree)*

For the 1-km street, there are 50 trees per side, or 100 total, so the total P input is 0.026 kg P/tree x 100 *= 2.6 kg (5.73 lbs)*

Runoff from lawns can be estimated using **equation 7.2**:

$Y_p = P \times R \times Cp$

From **figure 7.2**, the P concentration for a medium-fertility lawn is 1.5 mg/L (C_p = 1.5). For this region, P is generally around 65 cm/yr (25.59 in/yr).

$Y_p = 0.65 \times 0.1 \times 1.5 \times 10 = 0.98$ *kg/ha-yr (0.020 lbs/1000 ft^2-yr)*

So each front yard (0.045 ha) contributes 0.98 x 0.045 = 0.044 kg P/yr. There are 33 lots per side of the street, or 66 total, so the total P input from runoff is 0.044 x 66 = *2.9 kg/yr (6.39 lbs/yr).*

To calculate P inputs from dog feces, assume 0.56 dogs/household, which yields 37 dogs. Assume again that the average dog weighs 30 lb (13 kg) and excretes 0.8 kg P/yr. From equation 7.7, the P load is 66 x 0.56 x 0.8 = 30 kg/yr. Assuming a delivery ratio of 0.1, the P load to the street is *3 kg/yr (6.61 lbs/yr).*

P Input from atmospheric deposition directly to the street is based on the area of the street, which is 1.0 ha. For an atmospheric deposition rate of 0.25 kg/ha-yr, the P input is *0.25 kg/yr (0.551 lbs/yr).*

Figure 7.11 shows that tree leaves comprise 30% of the annual phosphorus input to the street. Complete removal of tree leaves, through repeated fall sweeping, would therefore reduce the total P input from the street by 30%. Presumably most of the P from tree leaves would otherwise have entered the storm sewer system.

NOTE: This example illustrates a process but may not represent typical results.

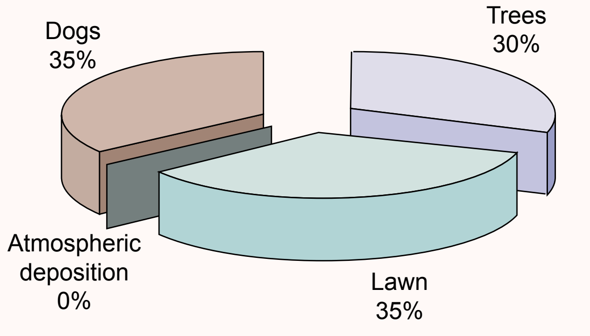

Figure 7.11. Percentage of P inputs to the street in the example in section 7.3.2.

Example 7.9 Efficacy of lawn phosphorus fertilizer restriction

Minnesota enacted a restriction of P use in lawn fertilizer in 2003. What is the predicted effect of the lawn-P fertilizer restriction on the total P input to a hypothetical residential neighborhood?

Consider a 5 km^2 (1.93 mi^2) residential neighborhood. Roads cover 20% of the watershed. House lots are ¼ acre (0.1 ha) with 20% impervious surface. 80% of pervious surfaces are fertilized, at a rate of 1 lb/1000 ft^2. The neighborhood has, on average, 0.56 dogs per household. Lawns are watered at a rate of 0.1 m/yr (0.328 ft/yr), with water containing 1 mg PO_4^{3-}/L (= 0.33 mg P/L). The water supply contains phosphorus corrosion inhibiters at a concentration of 0.33 mg P/L.

In this case, the goal is to compute total phosphorus inputs to the watershed, a level 1 analysis. Inputs to the watershed are fertilizer, atmospheric deposition, dog food, and phosphate in irrigation water. Compute **fertilizer input** from **equation 7.1**. For the pre-fertilizer restriction, fertilizer is applied at 1 lb P_2O_5/1000 ft^2/yr.

$L_p = R_i \times F_p \times F_f$

$R_i = 1 \text{ lb } PO_4^{3-}/1000 \text{ ft}^2/\text{yr} = 22 \text{ kg P/ha-yr} (0.451 \text{ lbs P}/1000 \text{ ft}^2\text{-yr})$

$F_p = 0.8 \times 0.8 = 0.64$

$F_f = 0.8$

$L_p = 9.6 \text{ kg P/ha-yr} (0.197 \text{ lbs P}/1000 \text{ ft}^2\text{-yr})$

P input = 5 km2 x 100 ha/km2 x 9.6 kg P/ha-yr = *5,509 kg P/yr (12,145.3 lbs P/yr)*

For the post-fertilizer restriction period, the phosporus input from fertilizer is 0.

Input of **P from corrosion inhibitors** in lawn irrigation water is computed from **equation 7.4**:

$L_p = C_p \times Z \times 10$

where C_p = 0.33 mg P/L and Z = 0.2 m/yr (0.656 ft/yr)

$L_p = 0.33 \times 0.2 \times 10 = 1.7 \text{ kg P/ha-yr} (0.035 \text{ lbs P}/1000 \text{ ft}^2\text{-yr})$

For the entire watershed, assume that only pervious, fertilized areas are watered (A = 5 km^2 *x* 0.8 *x* 0.8 *x* 0.8 = 2.6 km^2 = 260 ha) P input = 1.7 x 260 = *169 kg P (372.58 lbs P)*

Table 7.11. Phosphorus inputs to our hypothetical residential watershed before and after imposition of the lawn-P fertilizer restriction. [One kilogram =2.205 pounds.]

	Before P restriction		After P restriction	
Source	**total, kg/yr**	**%**	**total, kg/yr**	**%**
Fertilizer P	5,509	73	0	0
Dogs	1,770	23.4	1,770	85.8
Irrigation	169	2	169	8
Deposition	125	2	125	6
Total	**7,573**	**100**	**2,064**	**100**

Example 7.9 continued

P input from dog excrement is calculated using **equation 7.6**:

$L_p = N \times F_d \times I_d$

There are 3,950 households in the watershed. From Table 7.3, there are 0.56 dogs/household. Assume the average weight is 30 lb (13 kg) per dog, and from figure 7.4, each consumes 0.8 kg P/yr (1.76 lbs P/yr).

Lp = 4000 x 0.56 x 0.8 = *1,780 kg P/yr (3,924.2 lbs P/yr)*

Input from **atmospheric deposition** is calculated from **equation 7.9**:

$L_p = D_i \times A$

$D_p = 0.25$ *kg/ha-yr (0.005 lbs/1000* ft^2*-yr)*

A = 5 km^2 *= 500 ha (1,235.5 acres)*

Dp = 0.25 x 500 = *125 kg P/yr (275.6 lbs P/yr)*

Results are summarized in **table 7.11**. Prior to the lawn-P fertilizer restriction, total P inputs to the watershed were 7,573 kg/yr (16,695.6 lbs/yr). After the restriction on phosphorus fertilizer, total phosphorus inputs are 2,064 kg/yr (4,550.3 lbs.yr), a 73% reduction.

NOTE: This example illustrates a process but may not represent typical results.

in a study of two urban watersheds in Madison, Wisconsin, Waschbusch et al. (1999) reported that about 50% of the total P in street-dirt samples was found in the > 250 micron (0.01 inches) fraction, another 30% was in leaves. Less than 10% was found in the fine-particle class (<63 microns (0.002 inches).

3. Frequency of sweeping. The overall efficiency of street sweeping also depends on the number of times sweeping is employed. Assuming continuous inputs of new material to streets, the overall efficiency of street sweeping should increase as the number of sweepings increases, until a plateau is reached. Beyond this plateau, there would be little gain in efficiency because the time between sweepings would be too short to allow much accumulation of particles. The cost-effectiveness of sweeping ($/ton of pollutant removed) would decline before the plateau is reached.

Assessment approach

The simplest method to assess the efficiency of street sweeping for pollutant removal is to analyze the mass of material removed during street sweeping. To do this, subsamples of sweepings are dried and analyzed for chemical and physical composition.

Equation 7.11 calculates the total mass of pollutant removed that would eventually have reached the storm sewer. This analysis has to be done throughout the year because the quantity and composition of material deposited in streets varies throughout the season. In addition, care is needed in obtaining representative sub-samples for chemical analysis.

Equation 7.11: Total mass of pollutant removed

$$M_i = (M_s \times DW \times C_i)/L$$

where

M_i = total mass of pollutant removed
M_s = swept material (wet weight)
DW = dry weight fraction, dimensionless
C_i = concentration of pollutant i on dry particles
L = length of street swept

7.3 Conclusions

Source reduction has numerous merits as an approach for improving the quality of urban stormwater. For some pollutants (e.g. salts), source reduction may be the only feasible stormwater BMP. Source reduction has the potential of adding reliability to stormwater pollution programs and reducing O&M costs of downstream structural BMPs. In some cases, source reduction is likely the most effective stormwater BMP, as in the case of soluble P in residential areas, which should be reduced by the fertilizer P restriction, and salts, which could be reduced by improved application methods. Source reduction may also allocate costs more fairly. This is particularly true for erosion from construction sites.

Because serious interest in source reduction is only now emerging, assessment methods are not as well developed as they are for structural BMPs. As we have illustrated, it is now possible to develop reasonable estimates of total pollutant inputs to urban watersheds, but methods for estimating inputs from permeable surfaces to streets are less well developed. For lawn runoff, better models are needed to simulate the effect of management practices.

Source reduction is particularly amenable to adaptive management approaches. Management of road salting, in particular, is suitable to adaptive management because salinity is easily measured and the audience (road maintenance departments) is well defined.

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8.

Filtration Practices

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8.1 Filtration process

Filtration is defined in Chapter 1 as "the process of removing suspended solids from the stormwater by passing the water through a bed of porous media consisting of sand or soil." In filtration, the solids that are removed from the water are retained by the filter media. The primary retention mechanism is sieving, where solids that are larger than the pore spaces in the sand or soil structure are captured and retained as the stormwater passes through the filter media. Solid deposition or attachment onto filter media or previously deposited solids is another possible solid retention mechanism in filters.

For the same head (i.e., depth of water), the filtration rate is greater for filter media with large pore spaces (i.e., large grain size such as gravel) than for filter media with small pore spaces (i.e., small grain

Hot Links

Erickson, A.J, J.S. Gulliver, R.M. Hozalski, and P.T. Weiss. 2007. Filtration practices. In *Assessment of Stormwater Best Management Practices,* ed. J. S. Gulliver and J.L. Anderson. St Paul, MN: University of Minnesota.

size such as sand or silt). Filter media with large pores, however, allow larger solids, and subsequently more solids, to pass through the filter, reducing solids removal efficiency. Therefore, designing a filtration practice is a balance between filtration rate and solid removal efficiency. While there are currently no effluent or performance regulations other than TMDLs (Total Maximum Daily Loads), the Minnesota Stormwater Manual (Minnesota Stormwater Steering Committee 2005) states that the design storm volume should pass through a filtration practice within 48 hours of a storm event. Additional guidance on filtration practice design and installation can also be found in the Minnesota Stormwater Manual (http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html#manual).

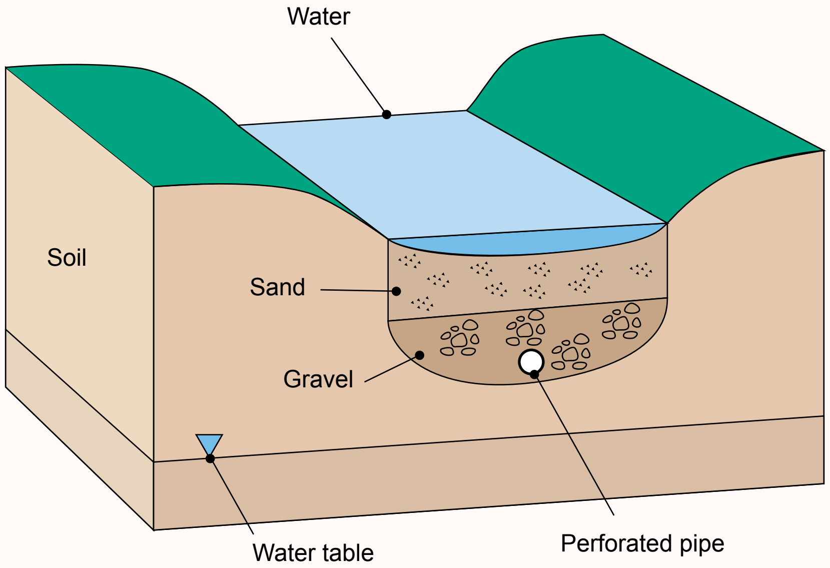

Figure 8.1: Sand filter design cross-section (http://www.pca.state.mn.us/publications/wq-strm8-14ag.pdf)

Dissolved pollutants may also be retained by adsorption onto filter media or previously deposited solids or by chemical precipitation reactions within the filter media. Removal of dissolved pollutants such as phosphorus, however, is typically low for standard sand filters. Harper and Herr (1993) reported that pilot-scale and full-scale sand filters retained 40–50% particulate phosphorus, but only 5% dissolved phosphorus. Similarly, Herrera Environmental Consultants (1995) reported that typical sand filter media had little capacity (0–28% total, 0–38% dissolved) for phosphorus retention. On the other hand, dissolved phosphorous removal can be significantly enhanced if the sand is amended with iron, calcium, aluminum, or magnesium (Arias et al. 2001). Steel wool improved phosphorus retention capacity of ASTM standard C33 sand by 25% to 99% in pilot-scale stormwater filters (Erickson et al. 2007). Other amendments, such as peat and compost, can have the opposite effect by releasing nutrients as stormwater passes

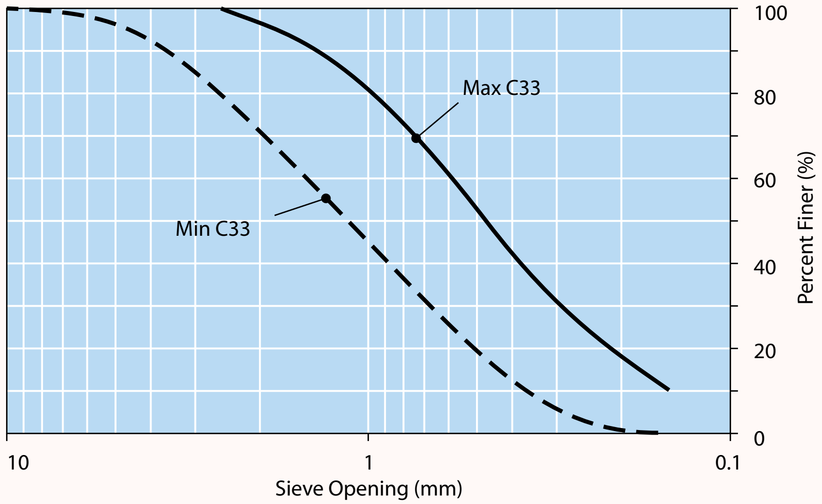

Figure 8.2: American Standard for Testing Materials for C-33 Sand (A.S.T.M. C 33-02a 2002). [One milimeter = 0.039 inches.]

through the filter and subsequently increasing the load of nutrients downstream (Erickson et al. 2007).

The two primary failure mechanisms for filtration practices are clogging and the presence of macropores. Clogging can result in long periods of standing water, flooding of surrounding areas, bypassing of the filter by untreated stormwater, lack of measurable effluent, or any combination thereof. If the clogging occurs at the surface, the practice can often be repaired by removing the top 2 to 5 inches (5.08–12.7 cm) of filter media, roto-tilling the surface, and replacing media with similar or approved alternative media (Minnesota Stormwater Steering Committee 2005). If this procedure does not resolve the problem, the entire filter bed may need to be replaced to restore functionality. Macropores such as wormholes can cause short-circuiting of the filtration practice and subsequently result in reduced solids retention efficiency and less peak flow reduction. Macropore problems can be resolved by mixing the media bed or replacing it entirely.

To prevent clogging or macro pores in filtration practices, routine maintenance is required. Additionally, a pretreatment system such as a sediment fore-bay can significantly reduce the frequency and extent of maintenance by removing settleable solids before the filtration practice. Also, maintenance of sediment fore-bays is easier than maintenance for a filtration practice. For guidance on maintenance and sediment fore-bay design, see the Minnesota Stormwater Manual (Minnesota Stormwater Steering Committee 2005 (http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html#manual).

8.2 Filtration practices

8.2.1. Surface sand or soil filters

Surface sand or soil filters (sometimes called “Austin sand filters”) have a filter mechanism typically made up of a layer of filter media (18–24 inches, 46–61 cm). The filter media is separated from a gravel bed by a layer of geotextile fabric that prevents the filter media from washing through to the gravel bed. The gravel bed contains a perforated pipe collection system that captures filtered stormwater and delivers it either downstream for additional stormwater treatment or directly to receiving waters. These systems are installed in depressions (Claytor and Schueler 1996) as shown in figure 8.1.

The filter media consists of native soils or locally or commercially available sands selected and sieved specifically for filtration purposes. Using native soil as the filter media reduces the overall cost of a filtration practice, but the grain size distribution of native soils is often not appropriate for stormwater filtration (i.e., will not pass the design storm within 48 hours or will not retain sufficient amount of solids). Standard concrete sand (ASTM C 33-02a 2002), as shown in figure 8.2, is a recommended filtration medium that is readily available (Claytor and Schueler 1996). The Minnesota Stormwater Manual (Minnesota Stormwater Steering Committee 2005) can also provide guidance for how to choose filter media.

The surface area typically prescribed for a surface sand filter is 3.0% of the total watershed area (U.S. EPA 1999). Weiss et al. (2005)

reported that on average (± 67% confidence interval), sand (not soil) filters in the United States retain 82% (± 14%) of total suspended solids and 46% (± 21%) of total phosphorus. The U.S. EPA (U.S. EPA. 1999) reported typical ranges of 50%–80% for total suspended solids and 50%–80% for total phosphorus in surface sand filters.

8.2.2. Underground sand or soil filters

Underground sand or soil filters (sometimes called “Delaware sand filters”) consist of a chamber in which stormwater runoff is collected, routed underneath a baffle wall, and directed over a weir. The baffle wall retains floatable pollutants, and the weir creates a pool that allows large dense solids to settle. Once over the weir, stormwater passes through a filter media bed that can capture additional suspended solids. Filter media for underground sand or soil filters consist of native soils or locally or commercially available sands selected and sieved specifically for filtration purposes. Underground sand or soil filters are typically constructed on site or purchased prefabricated from commercial vendors. Some manufacturers produce underground filtration systems and underground sedimentation devices (discussed in Chapter 10).

An advantage of underground sand or soil filters is that they usually do not require surface land area because the entire practice is underground. They may not have the hydraulic capacity of surface filters if subsurface space is limited. A properly designed underground filter, however, is expected to perform similarly to a surface filter with regard to total suspended solids and total phosphorus retention; therefore, the values reported by Weiss, et al. (2005) and U.S. EPA (1999) for surface sand filters that were discussed above also apply to underground filters.

8.2.3. Hybrid filtration practices

Hybrid filtration practices are a combination of filtration and another stormwater BMP process in which filtration is the primary treatment process. An example of a hybrid filtration practice is a detention basin in which a portion of the basin is excavated and replaced with a sand filtration system, including a perforated pipe collection system. In this example, sedimentation and possibly infiltration occurs in the entire basin, but filtration occurs only in the portion of the basin where the filtration media and subsurface collection system exist. Hybrid filtration practices are differentiated from surface filtration practices because infiltration and sedimentation can be significant treatment process in hybrid filtration practices. Design of hybrid filtration practices varies widely, so typical surface land area requirements and pollutant retention estimates are not available.

8.3 Filtration considerations by level of assessment

The purpose of this section is to discuss assessment considerations specific to filtration practices that should be considered when developing and implementing an assessment program. Chapter 3 (Developing

Example 8.1: Estimating filtration time of a filtration practice

Gina, an employee of a state regulatory agency, is reviewing a report for an assessment program that evaluated the retention time of a filtration practice using level 2, capacity testing. The report states that the surface area of a filtration practice is 1000 ft^2 (92.9 m^2). The dimensions of the practice are 25 ft. by 40 ft (7.62 m x 12.19 m). with 2:1 side slopes, and the practice is designed to hold a volume of 10,872 ft^3 at a maximum depth of 6 ft. Based on permeability tests throughout the filtration practice, the filtration rate is estimated to be approximately 1.0 in/hr (7.06×10^{-4} cm/s).

Solution

Gina finds that the authors of the report assume stormwater is only filtering through the bottom of the filtration practice and therefore that the area through which water is filtering is 1000 ft^2 (92.9 m^2). Therefore,

$$\text{Total Flow Rate Infiltrating} = 1.0\,\frac{in}{hr} \times \frac{1\,ft}{12\,in} \times 1000\,ft^2 \times \frac{1\,hr}{3600\,sec} = 0.023\,cfs\ (6.51 \times 10^{-4}\,m^3/s)$$

and,

$$\text{Time to filtrate} = 10{,}872\,ft^3 \big/ 0.023\,cfs = 469{,}670\,sec = 5.4\,days$$

Gina reads the conclusions of the report, which state the filtration practice is expected to filter the design storm volume in approximately 5.4 days, which is longer than the 48-hour (2-day) recommendation for design. Therefore, the filtration practice is NOT functioning as designed and may require repair or replacement to ensure the practice functions as designed.

NOTE: This example illustrates a process but may not represent typical results.

an Assessment Program) provides relevant background information for developing an assessment program.

As discussed in chapter 3, there are 4 levels of assessment for stormwater BMPs: visual inspection, capacity testing, synthetic runoff testing, and monitoring. Determining which levels of assessment should be used in an assessment program for filtration practices will depend on two considerations in addition to those discussed in chapter 3: size of the practice and pollutant removal goals (i.e., suspended solids only or suspended solids and dissolved pollutants).

Visual inspection (level 1) and capacity testing (level 2) are independent of size and therefore can be applied to any filtration practice as long as the conditions discussed in chapter 3 are met. The applicability of synthetic runoff testing (level 3), however, is dependent on the size of the filtration practice and the available water supply (as described in section 8.2.3 below). Monitoring filtration practices is only limited by the site design and accessibility of the practice. As described in chapters 4 and 5, flow measurement and sampling locations are required for monitoring stormwater BMPs, including filtration practices.

One goal for the assessment of filtration practices is to quantify solids removal efficiency, commonly measured as total suspended solids (TSS). As described in chapter 3, visual inspection (level 1) cannot be used to evaluate the removal of solids. Sediment retention tests (level 2) are not applicable to filtration practices because solids are retained within the filter media and not on the surface. Therefore, synthetic runoff testing (level 3) or monitoring (level 4) is required to determine the

Example 8.2: Estimating the Water Quality Volume for an irregularly shaped pond.

Gina, an employee of a state regulatory agency, is reviewing a proposal for an assessment program that will use synthetic runoff testing to evaluate a dry detention pond. The proposal includes a contour map of the irregularly shaped dry pond with a bottom elevation of 612 feet (186.54 m) that was evaluated to determine the area circumscribed by each contour line. Gina used the results from the proposal in the table below to estimate the design WQV of the pond assuming one foot of free board.

Contour (ft)	Area Within (ft^2)
612	0 (pond low point)
613	68
614	159
615	313
616	531
617	744
618	983

Solution

Gina estimates the storage volume available between two adjacent contours by finding the average area circumscribed by the contours and multiplying the average area by vertical distance between the two contours (i.e., one foot in this example). Thus, she determines the estimated storage volume between 612 feet (186.54 m) and 613 (186.84 m) feet to be:

$$\left(\frac{0\ ft^2 + 68\ ft^2}{2}\right) x\ 1ft = 34\ ft^3\ \text{(962.6 liters)}$$

and the storage volume between the 613 foot and 614 foot contours is:

$$\left(\frac{68\ ft^2 + 159\ ft^2}{2}\right) x\ 1\ ft = 113.5\ ft^3\ \text{(3,214 liters)}$$

Gina continues the process for all adjacent contours, and the results are listed below.

Contours	Storage Volume (ft^3)
612–613	34
613–614	113.5
614–615	236
615–616	422
616–617	637.5
617–618	863.5 (freeboard)

Gina estimates the total storage volume of the pond (i.e., the water quality volume) by adding the storage volume available from 612-613 feet up to, but not including, the volume associated with the freeboard (i.e., 617-618 feet). Thus, solving for water quality volume (WQV), Gina determines:

$$WQV = 34 + 113.5 + 236 + 422 + 637.5 = 1443\ ft^3\ \text{(40,804.6 liters)}$$

NOTE: This example illustrates a process but may not represent typical results.

efficiency of a filtration practice for the removal of TSS. The removal of dissolved pollutants can be assessed in conjunction with the suspended solids removal assessment. The results of assessment can indicate whether a filtration practice is clogged or has macropores.

8.3.1. Visual inspection

Visual inspection (level 1) is useful for identifying obvious problems with a filtration practice. Visual indicators that the filter media may be clogged include: standing water more than 48 hours after a storm event, the presence of a visible layer of fine material (i.e., mud) on the surface of the filter, or a lack of vegetation. If standing water is present in a filtration practice 48 or more hours after a storm event, the practice is not functioning as designed. A layer of fine material on the surface of the sand filter is an indication that stormwater was present for an extended period of time such that fine material was allowed to settle out of the stormwater. A lack of vegetation may indicate that stormwater inundates the filtration practice longer than normal dry surface vegetation can withstand. Underground filtration practices will not have vegetation, so this criterion is not indicative of a failing underground filtration practice.

A simple approach for visual inspection of a filtration practice involves inspecting the practice approximately 48 hours following a storm event to look for standing water. A properly functioning filtration practice should filter and treat the maximum volume for which the filtration practice was designed (i.e., design storm) in 48 hours or less (Claytor and Schueler 1996). Thus, the presence of standing water after 48 hours suggests that the filtration system may be clogged. Storms larger than the design storm will likely overflow the filtration practice (e.g., through the emergency spillway), and the amount of stormwater runoff captured by the filtration practice should drain within 48 hours. Smaller storms are expected to drain in less than 48 hours. Visual inspection of filtration practices should be conducted at least annually. See the standard procedures at the end of this chapter for detailed instructions about visual inspection of filtration practices.

8.3.2 Capacity testing

As applied to filtration practices, capacity testing (level 2) involves a series of permeability point measurements. These permeability tests are used to estimate the filtration rate, which can subsequently be used to estimate the amount of time the design storm would require to drain. After the filtration rate is estimated from the point filtration rate measurements, the design storm volume (m^3, ft^3, etc.) can be divided by the filtration rate (m^3/day, ft^3/day, etc.) to determine the amount of time required to drain the design storm volume (hours, days, etc.). See example 8.1.

Permeability tests can also be used to detect the presence of macropores within a filtration practice. Sand filtration design recommends a saturated hydraulic conductivity (k) of 3.5 ft/day (1.07 m/day) (Claytor and Schueler 1996, Minnesota Stormwater Steering Committee 2005). If the results from the permeability tests indicate that the median hydraulic conductivity for the entire practice is larger than 280 ft/day (85.34 m/day), macropores may be reducing the sieving process and thus reducing solids removal efficiency. Additionally, if an area of the filtration practice has a hydraulic conductivity greater than 280 ft/day, macropores may be significantly reducing the sieving efficiency of that area. Filtration rates less than 280 ft/day do not preclude the presence of macropores, but indicate that the amount of macropores is not necessarily significant.

Permeability tests are applicable to surface, underground, and hybrid filtration practices. Permeability tests in hybrid filtration practices, however, should be interpreted differently from permeability tests as applied to surface or underground filtration practices. In areas of the hybrid filtration practice that are used for filtration (sand or soil filtration media, subsurface collection system), permeability tests indicate the rate at which stormwater runoff is filtered. In areas of stormwater storage, infiltration, or both, permeability tests indicate the rate at which stormwater runoff infiltrates into the surrounding soils and therefore the rate at which stormwater runoff volume is reduced by infiltration. The spatial summation of these two components, filtration rate and infiltration rate, is the rate at which stormwater runoff is treated by the stormwater BMP and should be used to determine the drain time for the hybrid filtration practice. If the hybrid filtration practice is not draining the design storm in less than 48 hours, maintenance may be required to increase the filtration rate, or the practice may need to be redesigned to increase the area that is used for filtration.

8.3.3 Synthetic runoff testing

Synthetic runoff tests can be used to measure the filtration rate of filtration practices. The applicability of synthetic runoff testing, however, is dependent on the size of the filtration practice and the volume of water required to fill the practice. The total volume of water and discharge required in relation to the available water supply will determine whether synthetic runoff testing can be used to assess a specific filtration practice. The volume of the filtration basin along with the estimated filtration rate can be used to estimate the water supply requirements. Given accurate contours, drafting software such as AutoCAD can be used to calculate the volume of a stormwater basin, or the volume can be approximated as shown in example 8.2.

Synthetic runoff tests can be used to detect the presence of macropores within a filtration practice. Sand filtration design recommends a saturated hydraulic conductivity (k) of 3.5 ft/day (1.07 m/day) (Claytor and Schueler 1996, Minnesota Stormwater Steering Committee 2005). If the results from the synthetic runoff tests indicate that the hydraulic conductivity for the filtration practice is larger than 280 ft/day (85.34 m/day), macropores may be reducing the sieving process and thus reducing solids removal efficiency. Filtration rates less than 280 ft/day do not preclude the presence of macropores, but indicate that the amount of macropores is not necessarily significant.

For filtration practices, synthetic runoff testing (level 3) may require the same or less effort than capacity testing (level 2). In other words, it may be easier and require less time to fill a filtration practice and measure the change in water level (i.e., ponded depth) with respect to time than to perform multiple point infiltration measurements, as long as the water supply is sufficient. This is especially true of underground filtration practices, which are typically small systems that have limited access. The results of capacity testing and synthetic runoff testing will differ, however, for filtration practices.

The results of capacity testing for a filtration practice will produce more specific information than synthetic runoff testing will and can be used to guide localized maintenance within a filtration practice. For example, synthetic runoff testing of a filtration practice may indicate that the practice is able to drain a synthetic storm event that is equivalent to the water quality volume in less than 48 hours and is therefore functioning as designed. Capacity testing, however, may indicate that 25% of the filtration practice is not filtering water at all and the remaining 75% is filtering all of the incoming stormwater water. Furthermore, capacity testing can indicate where malfunction is occurring in the filtration practice, which allows for localized maintenance to restore the practice to design conditions before the entire filtration practice fails.

8.3.4 Monitoring

Monitoring is the most comprehensive method for assessing filtration practices. Monitoring can assess how well a filter reduces runoff peak flow, reduces runoff volume (by infiltration), and retains pollutants. A successful monitoring program, however, requires accurate and complete water and pollutant budgets. Surface runoff flowing directly into filtration practices that are not measured reduce the accuracy of the water budget and pollutant load budget. The quantity of surface runoff can be estimated with simple runoff models but can become complicated and less accurate for large, complex sites. The pollutant load, however, of unmeasured surface runoff is difficult to model accurately. Surface runoff should be routed (by swale or other means) around the stormwater filter and through a centralized inflow for flow measurement and sampling.

The perforated pipe collection systems that collect stormwater after it passes through a filtration practice are often small (usually 4–8 inch diameter, 10–20 cm). Therefore, measuring and sampling the outflow can be challenging. If using a weir to measure flow from a perforated pipe, it is important to design the weir invert elevations such that the water level in the perforated pipe is below the level of the perforations in the pipe. Back pressure in the perforated pipe will prevent filtered water from entering the pipe. Sometimes, the perforated pipe collection system is connected to a catch basin that has other inflows; therefore, it is difficult to separate the outflow from the filtration practice from the other flows in the catch basin. Thus, it is important to sample and measure flow from the perforated pipe system before it combines with any other surface runoff or conduit flow to ensure an accurate comparison between outflow and inflow for the filtration practice.

Infiltration into the native soil will occur in filtration practices that do not have impermeable liners. Infiltration rates should be measured or estimated to complete the water budget. The amount and rate of infiltration will depend on the stormwater filter design and permeability of the underlying soils. Chapter 4 provides discussion and recommendations for estimating infiltration.

Evaporation and transpiration (also discussed in Chapter 4) will likely not account for a significant (>5%) portion of the water budget because they are slow processes and, water does not remain ponded in properly functioning filtration practices for more than 48 hours. Additionally, vegetation is often limited in filtration practices to ensure adequate filtration by the filter media and to facilitate maintenance of the filter surface. A case study of monitoring a hybrid filtration practice that includes soil infiltration and sand filtration is included in Appendix A.

8.4 Recommendations

Visual inspection is recommended for assessment of all stormwater BMPs at regular intervals. Synthetic runoff testing is recommended for assessment of permeability for small surface filters or underground filters, if an adequate water supply is available. For assessment of permeability on sites too large for synthetic runoff testing, capacity testing is recommended. Pollutant removal performance of surface and underground filtration practices is well established and therefore visual inspection, capacity testing, or synthetic runoff testing is recommended for assessment of pollutant removal performance. Hybrid filtration practices vary in design and installation and therefore can be assessed by visual inspection and either capacity testing, synthetic runoff testing, or monitoring. Monitoring is recommended when capacity testing or synthetic runoff testing do not meet the goals of the assessment program.

8.5 References

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Procedures

for Visual Inspection of Stormwater Best Management Practices using Filtration

Visual inspection is a rapid assessment procedure for qualitatively evaluating the functionality of a stormwater best management practice (BMP). Visual inspections use a set of criteria that, under certain circumstances (described in chapter 3), determine if the stormwater BMP is malfunctioning. Detailed instructions for visual inspection of filtration practices are included below and reproduced in appendix B, part 1, which can be easily printed out and taken to the field.

UNIVERSITY OF MINNESOTA
Stormwater Management Practice Assessment Project

Standard Procedure for Level 1 Assessment: Visual Inspection

Filtration Practices (including soil and sand media filters)

1. Certified Reference:

1.1. None.

2. Application:

2.1. This method is applicable to sand and soil filters as defined in Chapter 8, Filtration Practices.

3. Summary of Method:

3.1. This standard protocol is used as a basis for the visual inspection of sand and soil filters. The questions in section 8.4 below are answered from visual observations of the site and documented with a photographic or video-graphic camera.

4. Interferences:

4.1. Visual inspection requires adequate weather conditions. Fog or other visually limiting weather condition can result in an inaccurate or incomplete visual inspection. Such weather conditions should be avoided whenever possible.

5. Apparatus:

5.1. Camera (digital or film, video or photographic)

6. Materials:

6.1. Field Data Sheet (i.e., this document).

7. Safety:

7.1. This procedure requires field inspection of the site and photographic or video graphic documentation. Caution and appropriate use of safety equipment and traffic controls should be used when walking around and in stormwater BMPs to avoid personal injury.

8. Procedure:

8.1. Print out this Standard Protocol for the visual inspection of sand and soil filters.
8.2. Obtain apparatuses and materials as outlined in sections 5 and 6 above.
8.3. Travel to the sand or soil filter that will be assessed by visual inspection.
8.4. Fill out the attached Field Data Sheet (see below).

9. Calculations:

9.1. None required. See Chapter 12.

10. Quality Control:

10.1. Photographic documentation for the questions answered above (section 8.4) must be provided with this protocol.

11. Additional References:

11.1. None

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Field Data Sheet for Level 1 Assessment: Visual Inspection

Filtration Practices

Inspector’s Name (s): ____
Date of Inspection: ____
Location of the filtration practice
    Address or Intersection: _____________________________________
    Latitude, Longitude: ____
Date the filtration practice began operation: ________________________
Filter size (ft x ft):____
Time since last rainfall (hr): ____________________________________
Quantity of last rainfall (in): ____________________________________
Rainfall Measurement Location: __________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Does this filtration practice utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don't know

3.a) If yes, please describe: ______________________________________

____

____

____

4) Are there multiple inlet structures?

☐ Yes ☐ No

4.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

4.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

4.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

5) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

5.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don’t know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

6) Is there standing water in the filtration practice?

☐ Yes ☐ No

6.a) If yes, does the water have:

☐ Surface sheen (from oils/gasoline)

☐ Murky color (from suspended solids)

☐ Green color (from algae or other biological activity)

☐ Other: ______________________________________

7) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

7.a) If yes, please describe: ______________________________________

____

____

____

8) Is there vegetation in the bottom of the filtration practice?

☐ Yes ☐ No

8.a) What is the approximate vegetation cover?

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

9) Are there indications of any of the following in the bottom of the filtration practice?

☐ Sediment deposition

☐ Erosion or channelization

☐ Excessive vegetation (that needs mowing or removal)

☐ Litter, large debris, solid waste

☐ Other: ______________________________________

☐ No

9.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don’t know

10) Are there indications of any of the following on the banks of the filtration practice?

☐ Erosion or channelization

☐ Other: ____

☐ No

11) Is the bottom of the filtration practice covered with a layer of silts, clays, or both?

☐ Yes ☐ No

12) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

12.a) If yes, what with?

☐ Debris

☐ Sediment

☐ Vegetation

☐ Other: ____

13) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

13.a) If yes, why?

☐ I don’t know

☐ Ice/Frost heave

☐ Other: ____

14) Is there evidence of any of the following downstream of the outlet structure?

☐ Sediment deposition

☐ Erosion, Channelization

☐ Other: ____

☐ No

14.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don’t know

Other observations:

____

____

____

____

____

Inspector’s Recommendations:

15) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

____

____

____

____

____

Maintenance Recommendations:

____

____

____

____

____

Troubleshooting Failure: Visual Inspection

Filtration Practices

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many filtration practices are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessing a filtration practice within 48 hours of a rainfall event may provide additional assessment clues than assessment during a long dry period. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Does this filtration practice utilize any pretreatment practices upstream?

If any pretreatment practices exist they should also be inspected and maintained on a regular basis.

4) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the filtration practice. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the filtration practice.

5) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a filtration practice by means other than those intended by design or prevent stormwater runoff from entering the filtration practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

6) Is there standing water in the filtration practice?

Standing water in a filtration practice is the result of one of three possibilities: (1) rainfall has occurred recently such that stormwater runoff has not had 48 hours to pass through the filter, (2) the filtration rate of the practice is slow such that stormwater runoff does not pass through the filter within 48 hours, but does pass through the filter given enough time, or (3) the filter is clogged and does not filter any stormwater runoff. If it has rained in the last 48 hours (question 2), then the filtration practice may be functioning properly and requires additional assessment (level 2 or higher). If, however, it has not rained in the last 48 hours, it is likely that the filtration practice is either option (2) or (3).

Question 3a provides clues that may determine whether the filtration practice is clogged. Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven not to be illegally discharged into the filtration practice, then a surface sheen may indicate that stormwater runoff is stored in the filtration practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. If this is happening, then the filtration practice is failing. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a high suspended solids concentration that is most likely made up of fine particle sizes such as clays and silts because sand particles settle out of standing water rapidly (as discussed in Chapter 10, Sedimentation). Stormwater runoff with a murky color further indicates that the watershed may be a significant source of fine particle suspended solids, which can clog a filtration practice.

Stormwater runoff with a green color from algae has been stored in the filtration practice for a long period of time such that microorganisms have developed. The filtration practice is not filtering stormwater runoff and is therefore failing.

7) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

8) Is there vegetation in the bottom of the filtration practice?

Vegetation in the bottom of filtration practice can reduce its effectiveness. Plants lose approximately 30% of their root structures annually, which produces macropores. Macropores in a filtration practice often result in short circuiting of stormwater runoff and low sediment removal efficiency. Vegetation does, however, reduce overland flow velocities and can therefore reduce erosion and resuspension of captured solids. It can also maintain or increase filtration rates, because of the macropores, while reducing the effectiveness of filtration. There are both positives and negatives to deep-rooted vegetation in the bottom of the filtration practice. The positives, in general, outweigh the negatives because it is important to maintain filtration capacity.

9) Are there indications of any of the following in the bottom of the filtration practice?

Sediment deposition may indicate that pretreatment devices have reached sediment storage capacity, are not efficiently removing settable solids, or are not present. Sediment deposition may also indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution. Sediment deposition limits the filtration practice surface area available for filtration and therefore can reduce the rate at which stormwater runoff volume is treated.

Erosion or channelization indicates that flow velocities entering, or in, the filtration practice are large or that stormwater runoff is entering the filtration practice by means other than those intended by design. Erosion and channelization can reduce filtration media depth and therefore reduce the practice's effectiveness.

Excessive vegetation, especially with deep roots, can cause short circuiting or damage the subsurface collection system in a filtration practice. If the surface of the filtration practice becomes clogged or sealed, shallow root vegetation can provide pathways for stormwater runoff to reach the filter media below the surface for treatment. Vegetation in filtration practices should be controlled such that deep root vegetation does not damage the collection system or allow stormwater to short-circuit through the practice.

Litter, large debris, and solid waste in a filtration practice are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of filtration practices by reducing the surface available for filtering stormwater runoff.

10) Are there indications of any of the following on the banks of the filtration practice?

Erosion or channelization on the banks of a filtration practice indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the filtration practice with sediment from the bank and subsequently reduce the practice's effectiveness by clogging the media and reducing the volume available for stormwater storage.

11) Is the bottom of the filtration practice covered with a layer of silts, clays, or both?

A visible layer of silts, clays, or both is an indication that the filter media may be clogged. Filtration practices collect particles in the pore spaces of the media. If silts, clays, or both are present on the surface of the filter, the pore spaces within the filter media may be full. Additionally, silts, clays, or both present on the surface of the filter indicates that stormwater runoff is stored in the filtration practice long enough for these fine particles to settle out or for the stored stormwater runoff to evaporate and infiltrate into the surrounding soils.

12) Is the outlet structure clogged?

Like an inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the filtration practice. If the outlet structure is partially or completely clogged, the filtration rate may be limited and stormwater runoff may not pass through the filtration practice in less than 48 hours, as recommended by design (Minnesota Stormwater Steering Committee 2005). Any obstructions should be removed immediately to ensure proper operation of the filtration practice.

13) Is the outlet structure askew or misaligned?

Misaligned outlet structures often allow stormwater runoff to enter or exit a filtration practice by means other than those intended by design or prevent stormwater runoff from entering the filtration practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Outlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact.

14) Is there evidence of any of the following downstream of the outlet structure?

Conditions downstream of a filtration practice can provide evidence of the function of the practice itself. Properly designed and functioning filtration practices remove a large percentage of suspended solids from stormwater runoff. Sediment deposition downstream of a filtration practice indicates that erosion is occurring between the filtration practice and the sediment deposition or that sediments are present in the filtration practice effluent. If sediments are present in the effluent such that downstream deposition is occurring, the geotextile fabric or the subsurface collection system is likely failing. The filtration practice could require complete replacement to repair this problem.

Erosion downstream of a filtration practice indicates that flow velocities are larger than the conveyance channel can withstand. Stormwater runoff filters slowly through filtration practices and therefore downstream erosion is usually only a problem for large filtration practices that treat large volumes of stormwater runoff. Downstream erosion can be mitigated by reconstructing the conveyance such that erosion does not occur (i.e., riprap, concrete), or energy dissipaters should be installed to reduce the flow velocities (i.e., check dams).

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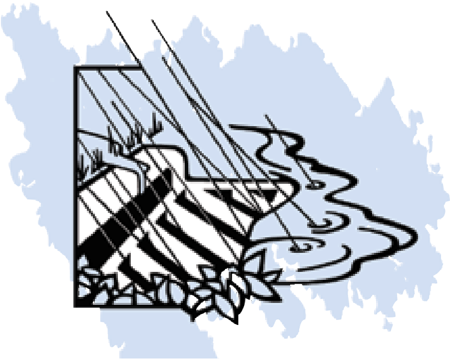

9.
Infiltration Practices

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Hot Links

1. **Infiltration processes**
2. **Types of infiltration practices**
3. **Maintenance of infiltration practices**
4. **Assessment considerations**
5. **Procedures for visual inspection of infiltration BMPs**

9.1 Infiltration practices

Infiltration practices operate by capturing and temporarily storing stormwater, before allowing it to infiltrate into the underlying soil. The infiltrated water stored in the soil is then partitioned into groundwater recharge, discharge through an underdrain (if applicable), and evapotranspiration. By performing this process, these practices provide two fundamental functions in stormwater management: attenuation of runoff volume and treatment of the runoff. These functions may ultimately reduce stormwater pollutants, increase groundwater recharge, decrease runoff peak flow rates, and decrease the volume of stormwater runoff.

Infiltration practices utilize porous materials to facilitate infiltration of stormwater into soils. Stormwater is channeled into infiltration structures where it is stored temporarily before it penetrates the underlying soil. Infiltration into the soil facilitates the removal of pollutants

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through chemical and bacterial degradation, sorption, and filtering. Several studies have documented the effectiveness of pollutant removal in properly functioning infiltration practices. The mechanisms that act to remove pollutants include sorption, precipitation, trapping, straining, and bacterial degradation or transformation. Pollutant removal efficiencies from three studies are shown in table 9.1.

Table 9.1: Pollutant removal from stormwater in infiltration basins and trenches (Schueler 1987, Schueler et al. 1992, Winer 2000).

Pollutant	Winer (2000)	Schueler (1987)	Schueler (1992)
Sediment	95%	99%	90%
Total P	65%	65-75%	60%
Total N	50%	60-70%	60%
Trace Metals	95%	95-99%	90%
Bacteria	ND	98%	90%
BOD	ND	90%	70-80%

ND = Not determined

Infiltration rates in infiltration basins and trenches need to be low enough to promote the retention and treatment of pollutants and nutrients, while high enough to avoid ponded and anaerobic conditions. The Wisconsin Stormwater Manual (University of Wisconsin-Extension 2000) states that soil permeabilities must be at least 0.5 inches (1.27 centimeters) per hour and at most 5.0 inches (12.7 centimeters) per hour. This limits application to soils in Hydrologic Soil Group B, and some soils in groups A and C. Soil infiltration rates can initially be estimated from NRCS soil data but should be confirmed by an on-site geotechnical investigation. For guidance on investigation procedures, see Chapter 12 of the Minnesota Stormwater Manual (http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html#manual). Due to the risk of groundwater contamination, it is required that infiltration practices be designed with a minimum vertical distance of 3 feet between the bottom of the practice and the seasonal high water table or bedrock layer (Minnesota Stormwater Steering Committee 2005).

The effectiveness of infiltration practices is closely tied to maintaining the designed infiltration rate of the structure, which influences the ability of the soil to remove pollutants (Pitt et al. 1996). The infiltration rate should be high enough to promote adequate infiltration, while the drainage rate of water below the soil surface should be low enough to ensure proper treatment of the stormwater in the soil.

Commonly cited reasons for the failure or decreased effectiveness of infiltration structures include surface clogging, poor site selection, and soil compaction (Gregory et al. 2006). As the infiltration capability of the soil is compromised through clogging or compaction, the effectiveness of the structure can suffer severely. Poorly functioning infiltration structures can drastically inhibit infiltration of stormwater, leading to prolonged periods of inundation with minimal or no treatment of stormwater pollutants.

9.2 Infiltration processes

Infiltration is the hydrologic process involving the absorption of rainfall and/or overland flow/ponded water through the soil surface into the underlying soil material. The water that does not infiltrate during a given period of time either remains in detention storage on the surface or drains off the surface to channels or other surface water bodies. The water that does infiltrate will be temporarily stored in the soil profile and will be subject to evapotranspiration, subsurface stormflow back to the land surface at a downslope location, shallow drainage due to installed artificial drainage systems, and deep percolation to ground water.

The rate that water will infiltrate into the soil is dependent on textural characteristic of the soil profile, the condition of the soil surface, and the initial moisture content within the soil profile at the time of the infiltration event. The soil's textural characteristics determine the saturated hydraulic conductivity of the soil and the water retention or storage characteristics of the soil. Naturally, soils that are a coarser textured will tend to have higher saturated hydraulic conductivity than finer–textured soils, and so these coarser-textured soils will tend to have much higher infiltration capacities. The condition of the soil surface is very important because effects such as compaction of the surface layers or deposition of fine particulates onto the surface can drastically reduce the hydraulic conductivity of the surface and thereby drastically reduce the infiltration capacity of the soil. The initial moisture content of the soil is an important factor in determining infiltration capacity: the drier the soil is at the beginning of an infiltration event, the more capacity the soil has to absorb the water available at the soil surface. The factors determining infiltration capacity are described in chapter 4.

It should be clearly understood that the infiltration capacity of soil varies with time during the infiltration event. It is higher at the very beginning of the event and decreases (usually exponentially) with time during the event. If the soil profile is deep, and low-permeability layers within the profile are not present, the lower limit of infiltration will be equal to the saturated hydraulic conductivity of the soil profile.

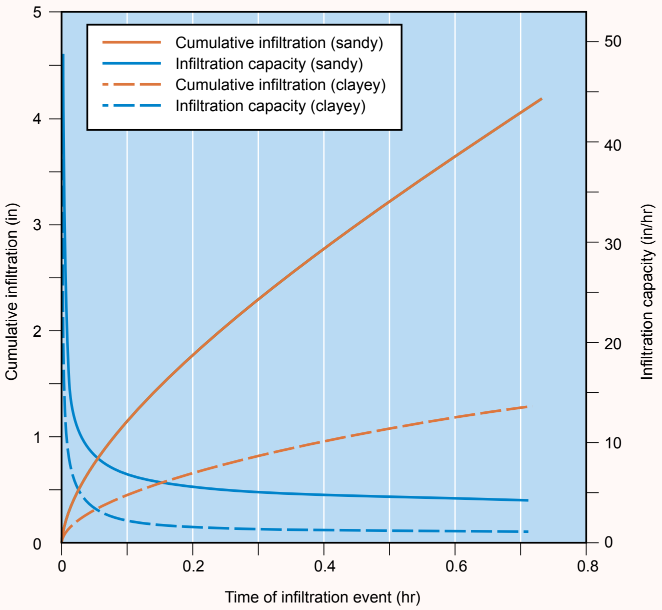

Figure 9.1. Infiltration capacity and cumulative infiltration for two soil textures, a sandy texture and a clayey texture, for an infiltration event that lasts about 20 minutes. [One inch = 2.54 cm; one in/hr = 7.06 x10^{-4} cm/s.]

Advanced Discussion

The effect of soil texture on infiltration capacity is illustrated in figure 9.1, which compares the infiltration capacity and cumulative infiltration for two soil textures, a sandy texture and a clayey texture, for a period of about 20 minutes. These plots were created using **equation 9.1 for the infiltration capacity and equation 9.2** for the cumulative infiltration. It is seen from the graph that the sandy textured soil has a much higher infiltration capacity than the clayey soils; therefore, the cumulative infiltration during the 20-minute infiltration event is much higher for the sandy texture (5 inches (12.7 centimeters) compared to 1.2 inches (3.05 centimeters)).

The infiltration capacity is seen to decrease exponentially for each of the soil textures, with the capacity approaching the saturated hydraulic conductivity for each soil. For the sandy soil, the saturated hydraulic conductivity is 3 in/hr (0.002 cm/s), while for the clayey soil the saturated hydraulic conductivity is 0.2 in/hr (1.41 x 10^{-4} cm/s). For each of the cases shown, the lower limit of infiltration capacity is not reached, though the leveling off of the infiltration capacity does indicate that the lower limit is being approached.

Equation 9.1: Green-Ampt equation (Green and Ampt 1911)

$$f = K_s \left[1 + \frac{(H + h_{wf})(\theta_s - \theta_i)}{F} \right]$$

where

H= depth of water standing on the soil surface
θ_s = saturated water content of the soil
θ_i = antecedent (or initial) moisture content
h_{wf} = wetting front suction
F = cumulative infiltration

Equation 9.2: Cumulative infiltration

$$t = \frac{F - \left[(\theta_s - \theta_i)(H + h_{wf})\right] \ln \left[1 + \frac{F}{\left[(\theta_s - \theta_i)(H + h_{wf})\right]} \right]}{-K_s}$$

where

F = cumulative infiltration
h_{wf} = wetting front suction
$\Delta\theta = (\theta_s - \theta_i)$ is the difference between the saturated water content and the antecedent water content of the soil
K_s = saturated hydraulic conductivity
H= depth of water standing on the soil surface
t = time

9.3 Types of infiltration practices

9.3.1 Infiltration basins

An infiltration basin is a natural or constructed impoundment that captures, temporarily stores, and infiltrates the design volume within an acceptable time period. Infiltration basins contain a flat, densely vegetated floor situated over naturally permeable soils. Nutrients and pollutants are removed from the infiltrated stormwater through chemical, biological, and physical processes. Infiltration basins are well suited for drainage areas of 5 to 50 acres (2.03–20.25 hectares) with land slopes that are less than 20 percent, with typical depths in the basin ranging from 2 to 12 feet (0.61–3.66 meters). A typical infiltration basin is shown in figure 9.2.

9.3.2 Infiltration trenches

An infiltration trench is a shallow excavated trench, typically 3 to 12 feet deep (0.91–3.66 meters), that is backfilled with a coarse stone aggregate allowing for the temporary storage of runoff in the void space of the material. Discharge of this stored runoff occurs through infiltration into the surrounding naturally permeable soil. Infiltration

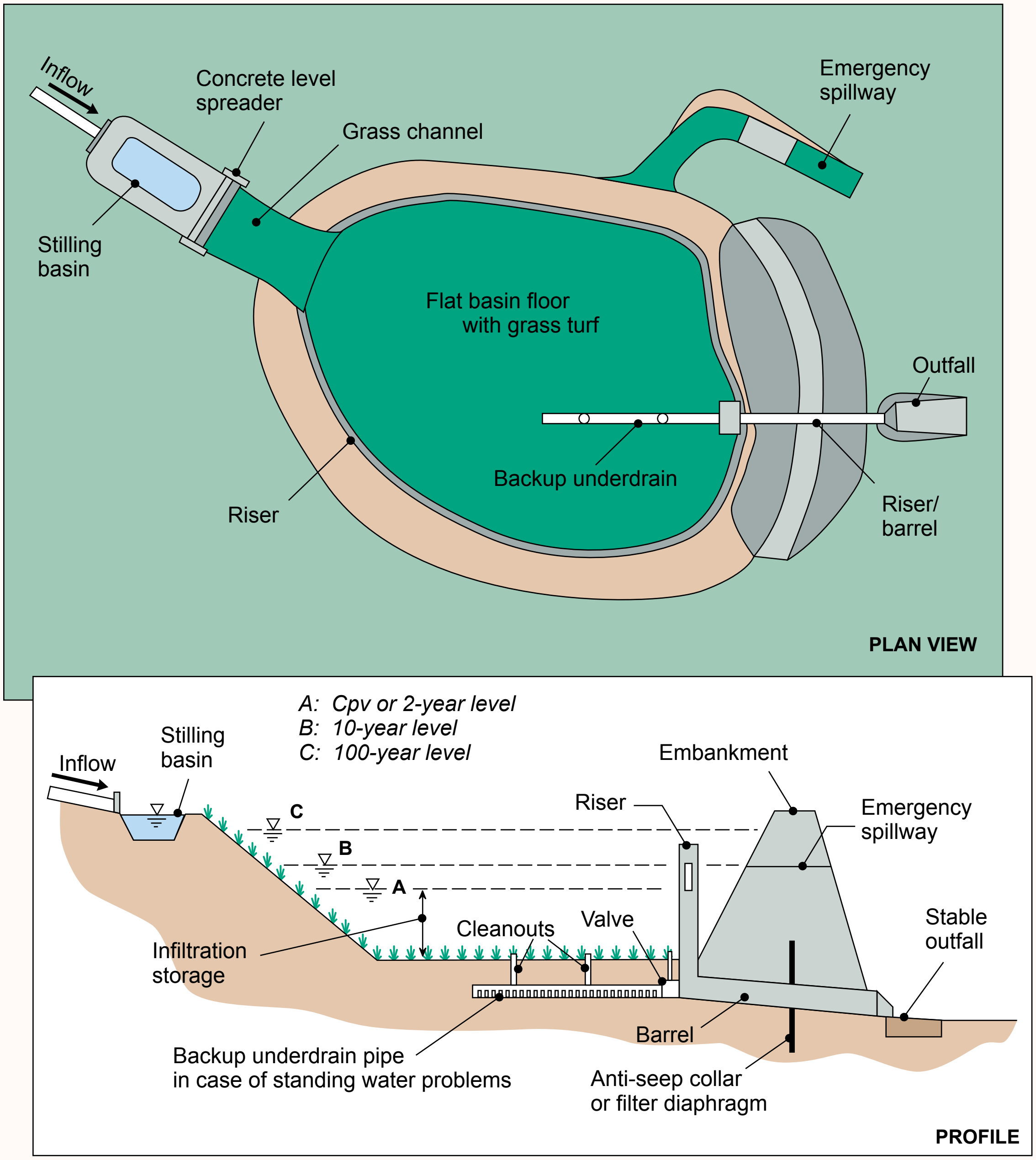

Figure 9.2: Typical Infiltration Basin (Maryland Department of the Environment 2000).

trenches are well suited for drainage areas of 5 acres (2.03 hectares) or less. A typical infiltration trench is shown in figure 9.3.

9.3.3 Porous pavements

While most would consider porous pavements to be composed of either asphalt or concrete materials, there are actually nine categories of materials that fall within the definition of porous pavement (Ferguson 2005). These include porous aggregate, porous turf, plastic geocells, open-jointed paving blocks, open-celled paving grids, porous concrete, porous asphalt, soft porous surfacing, and decks.

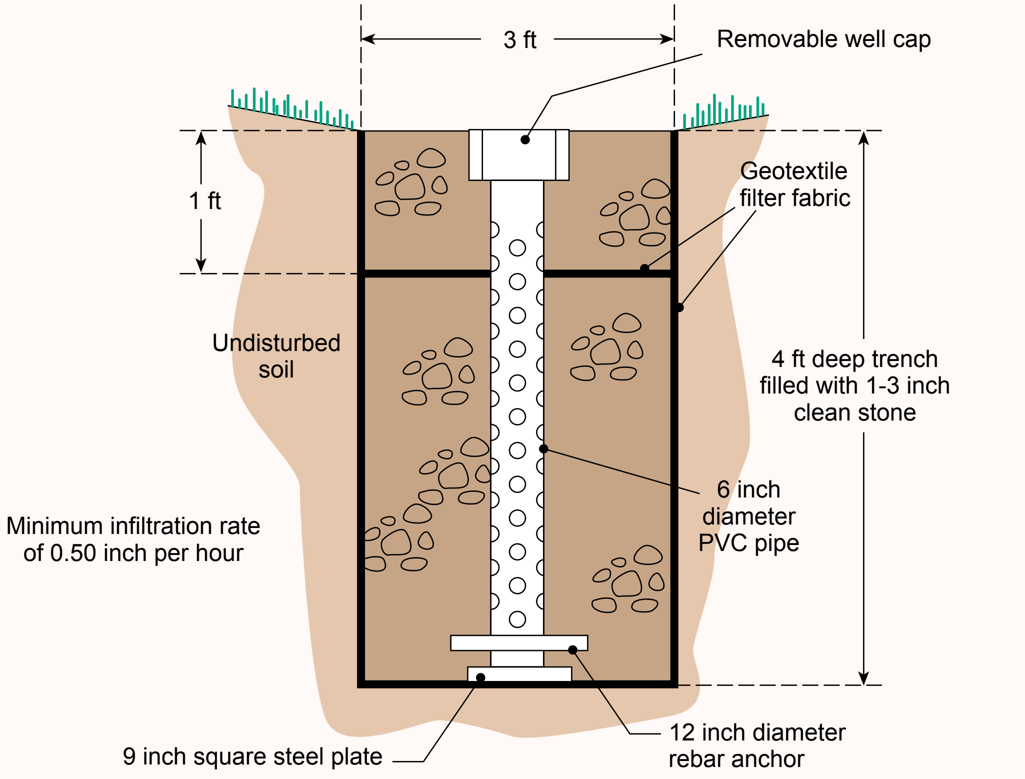

Figure 9.3: Typical Infiltration Trench Design (U.S. EPA 1999b). [One inch = 2.54 centimeters; one foot = 0.305 meters.]

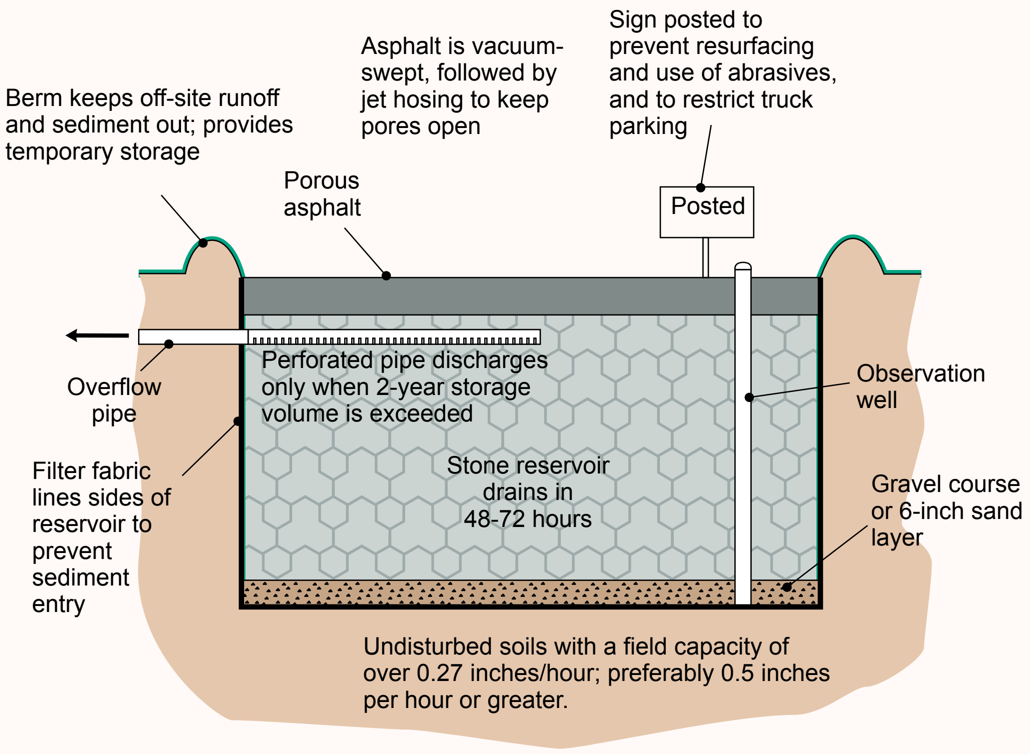

Figure 9.4: Typical Porous Pavement Installation (U.S. EPA 1999c). [One inch = 2.54 centimeters.]

For the case where the porous pavement is either asphalt or concrete, the pavement system is designed so that storm water infiltrates through the porous upper pavement layer and then into a reservoir of stone or rock below. Water from the reservoir then either percolates into the soil beneath, eventually recharging groundwater, or is collected by a perforated pipe underdrain system and carried to a surface discharge location. An illustration of a vertical section through an asphalt porous pavement is presented in figure 9.4.

9.4 Maintenance of infiltration practices

In the past, infiltration structures have been shown to have a relatively short lifespan. Over 50 percent of infiltration systems either partially or completely failed within the first 5 years of operation (U.S. EPA. 1999a). In a Maryland study on infiltration trenches (Lindsey et al. 1991), 53 percent were not operating as designed, 36 percent were

Table 9.2: Typical maintenance activities for infiltration basins and trenches (Adapted from Watershed Management Institute (WMI) 1997).

Activity	Schedule
◆ Remove sediment and oil/grease from pretreatment devices and overflow structures ◆ Mow and remove litter and debris ◆ Stabilize of eroded banks, repair undercut and eroded areas at inflow and outflow structure	Standard Maintenance (As Needed)
◆ Inspect pretreatment devices and diversion structures for signs of sediment buildup and structural damage ◆ If dead or dying grass is evident at the bottom or the basin/trench, check to ensure water percolates within 2-3 days following significant rain events	Semi-Annual Inspection
◆ Disc or otherwise aerate bottom ◆ De-thatch basin bottom	Annual Maintenance
◆ If bypass capability is available, it may be possible to regain or increase the infiltration rate in the short term by providing an extended dry period.	5-year Maintenance
◆ Total rehabilitation of the trench to maintain storage capacity within 2/3 of the design treatment volume and 72-hour exfiltration rate ◆ Excavate trench walls to expose clean soil	Upon Failure

clogged, and 22 percent showed reduced filtration. In a study of 12 infiltration basins (Galli 1992), none of which had built-in pretreatment systems, all had failed within the first two years of operation.

Common reasons cited for failure of infiltration trenches and basins include:

- Clogging of the soil
- Compaction of soil
- Improper maintenance of appropriate surface vegetation
- Poor site selection
- Improper soil textures
- Lack of pretreatment structures

The most commonly cited reason for failure of infiltration structures is clogging due to sediment and organic debris. Due to the high susceptibility of clogging, pretreatment of stormwater prior to its introduction to an infiltration basin or trench is required to remove sediments and debris. Pretreatment structures, such as a plunge pool, sump pit, filter strip, sedimentation basin, grass channel, or a combination of these practices, should be installed upstream of the infiltration practice.

In order to maintain proper function and maximum pollutant removal, infiltration practices require regular maintenance and inspection. table 9.2 provides guidance on typical maintenance practices and time frames.

9.5 Assessment considerations

The infiltration capacity of stormwater BMPs can be evaluated by several different approaches. These approaches vary in level of difficulty, ranging from simple to complex, and in level of resource demand, from inexpensive to expensive. The methods identified here, listed in order of increasing difficulty, are: visual inspection (level 1), capacity testing (level 2), synthetic runoff testing (level 3), and monitoring (level 4). Each of these will now be discussed in detail.

9.5.1 Visual inspection

With this approach, the inspector of the stormwater BMP will make observations of the stormwater BMP to look for indicators of inadequate infiltration capacity. The scope of inspection to perform depends on the type of stormwater BMP involved. See the standard procedures at the end of this chapter for detailed instructions about visual inspection of infiltration practices.

Infiltration basins

Visual inspection is useful for identifying obvious problems with an infiltration basin. Visual indicators that the basin may be failing include: standing water more than 48 hours after a storm event, the presence of a visible layer of fine material (i.e., mud) on the surface of the basin, and the presence of wetland vegetation. Standing water in an infiltration practice 48 hours after a storm event indicates that stormwater runoff is not infiltrating at a rate recommended by design (Minnesota

Stormwater Steering Committee 2005). A layer of fine material on the surface of the sand filter is an indication that stormwater was held for an extended period of time such that fine material was allowed to settle out of the stormwater. The presence of wetland vegetation suggests that the stored stormwater drains so poorly that wetland vegetation can develop.

Infiltration trenches

Infiltration trenches do not promote the growth of vegetation over the trench itself, so visual inspection for vegetative health will be different for trenches than for infiltration basins. One of the main indications of poor infiltration capacity for a trench is a crust or layer of fine sediment that lies over the surface of the trench. If a crust is present, even if it shows signs of desiccation cracking, the crust could easily become a barrier to infiltration upon rewetting. The best practice is to clean the surface of crust and sediment.

While it might not be obvious during visual inspection, the pores of the trench material could be clogged below the surface of the trench, even if the surface is clear of sediments. Closer examination by poking just beneath the surface of the trench with a trowel or shovel might reveal this clogging.

Although no vegetation will grow in the trench material, an indication of poor infiltration in the trench could be poor vegetative growth in the area surrounding the trench. If infiltration is low through the trench, water will pond around the trench for a longer period of time, increasing the chances that resident vegetation will suffer.

Porous pavements

The exact procedure for application of visual inspection of porous pavements depends on the type of porous pavement. If the pavement is a vegetated porous pavement, then the approaches used for other vegetated stormwater BMPs also apply to the porous pavement. Some indicators of inadequate infiltration capacity include dead or unhealthy vegetation during the growing season, or standing water or saturated surface soil more than 48 hours following a significant runoff event.

More involved observations would include examining the soil profile for signs of persistent wet conditions in the surface soil or shallow subsurface soil. Such wet conditions would indicate poor drainage conditions, which mean that infiltration capacities are lower than designed. Signs of persistent wet conditions in the soil are discoloration of the soil to a grayish tone and soil mottling. Mottling is an indication of anaerobic conditions resulting from persistent saturated or very wet conditions.

For asphalt or concrete pavements, the situation is different. For these two types of porous pavement, indicators of poor infiltration performance are persistent standing water on the pavements following rainfall or evidence of sediment deposition on the surface.

9.5.2 Capacity testing

Infiltration basins

Testing the infiltration capacity of infiltration basins involves a series of point measurements of permeability. Measurements made in only one location within the stormwater BMP lead to an estimate of infiltration capacity at only the location where the measurement is conducted. To obtain an estimate for the infiltration capacity of the entire stormwater BMP, it is necessary to make numerous measurements. There are many techniques available for measuring the infiltration capacity (Dane and G.C. Topp, eds, 2002), as described in chapter 4.

Infiltration trenches

Infiltration trenches are generally filled with coarse gravel or even crushed rock. Therefore it is not appropriate to use infiltrometers or permeameters for infiltration trenches. Synthetic runoff testing (section 3.2.3) should be used to evaluate the infiltration rate of infiltration trenches.

Porous pavements

It is not possible to use soil infiltration measurement devices for porous pavements because of the structure of the pavement material. Synthetic runoff testing (section 3.2.3) should be used to evaluate the infiltration rate of porous pavements.

9.5.3 Synthetic runoff testing

For synthetic runoff testing, the infiltration practice is flooded with water as a simulation of a natural runoff event. Careful planning is required for this approach because the volume of water required to fill the stormwater BMP can be significant and might far exceed the capacity of the nearby fire hydrant or available tanker trucks. Assuming that one is able to gather together the required water resource volume for this testing approach, the procedures for performing the test on several infiltration stormwater BMPs are described in the following.

Equation 9.3: Saturated hydraulic conductivity for synthetic runoff testing of infiltration practices

$$K_s = \frac{\frac{\Delta E}{\Delta t}}{(\frac{D}{L}+1)}$$

where:

K_s = saturated hydraulic conductivity,
ΔE = drop in water surface elevation in *(length)* in time interval Δt
Δt = time period
A = the area flooded at any instant of time
D = depth of water at any instant of time
L = thickness of the stormwater BMP soil

Infiltration basins

To conduct a synthetic runoff test of the infiltration capacity of an infiltration basin, the basin is filled with water and the rate with which the water infiltrates is measured based on the rate of drop of the water surface. If the volume of water required to fill the basin is significantly more than is available, then it is possible to delay the experiment until an actual runoff event of sufficient magnitude fills the basin. The saturated hydraulic conductivity can be estimated from equation 9.3.

Example 9.1: Saturated hydraulic conductivity

Consider an infiltration basin that is ponded to an initial depth of 12 inches (30.48 cm). It is seen that the rate of drop of the surface decreases with time, indicating a slowing of the infiltration rate. Using the drop in the water surface toward the end of the experiment where *D = 5 in (12.7 cm)*, the drop in the water surface elevation is 3 inches (7.62) in 1 hour. Using the soil thickness, *L = 30 in (76.2 cm)*, we get with **equation 9.3**:

$$K_s = \frac{\left(\frac{3\ in}{hr}\right)}{(\frac{5}{30}+1)} = 2.57\ in/hr\ \ (0.002\ cm/s)$$

NOTE: This example illustrates a process but may not represent typical results.

Infiltration trenches

For infiltration trenches, the synthetic runoff testing approach is conducted by filling the depressional area with a sufficient volume of water to bring the ponded surface up over the surface of the trench, thereby initiating infiltration into the trench. The water surface should be brought to at least 1 foot (0.305 meters) above the surface of the trench to provide enough height for the measurement of water level drop during infiltration.

Conducting a synthetic runoff test for a trench requires planning because the volume of water required for the test can be significant and depends on the volume-elevation characteristics of the depression. A depression with steeper side-slopes will require less water than a depression with less steep sides. While the soil surrounding the trench will also facilitate some infiltration, infiltration trenches are used in areas where the surface soil has very low infiltration capacity, and therefore it is generally valid to neglect this additional infiltration capacity.

To determine the hydraulic conductivity of the trench, the drop of the ponded water surface is tracked over time. Over any given time interval, the volume of water that flows into the trench can be computed as with equation 9.4a.

The hydraulic conductivity of the trench can then be computed from equation 9.4b.

Again, this method assumes that the outflow from the depression is mostly from the trench alone, and that the flow through the soil surrounding the trench is negligible.

Equation 9.4a Flow volume

$$Q_{trench} = \frac{\Delta H}{\Delta t} A_{sb}$$

where

ΔH = drop in the water surface elevation (*length*) over a time interval Δt

A_{sb} = average surface area of the basin during that time interval

Q_{trench} = discharge

Equation 9.4b: Hydraulic conductivity

$$K_{trench} = 12 \frac{Q_{trench}}{A_{trench}}$$

where

A_{trench} = the surface area of the trench

K_{trench} = hydraulic conductivity of the trench

Q_{trench} = discharge

Porous pavements

Synthetic runoff testing of porous pavements is feasible if water can be stored on the surface of the porous pavement to a measurable depth (> 6 inches (15.24 centimeters)) for a length of time necessary to measure the infiltration (> 1 minute). Generally the pavement surface will be planar and sloped on a uniform grade, so curbs or some form of berm around the boundaries of the pavement will be required to store and infiltrate a measurable depth of water. The base layer underlying the porous pavement is generally very porous, so it is necessary to measure only the saturated hydraulic conductivity of the pavement layer itself. Knowing the thickness of this layer and the rate of drop of the infiltrating ponded water, it is possible to compute the saturated hydraulic conductivity from equation 9.3.

Alternately, water can be applied at a metered rate through a sprinkler onto a specified area of the pavement surface. The sprinkler may be simply a hand-held device, or it may be held in a frame structure. The idea behind the water applicator is to determine the rate of application that causes runoff to occur in the application area. The flow rate through the applicator is increased to the point where runoff just begins to occur. The runoff will be evident by water flowing over the surface to the side of the application area. At the point where runoff just starts to occur, the flow rate should be reduced again until runoff stops. The infiltration capacity is, then, just the rate of water application.

9.5.4 Monitoring

Infiltration basins

To measure flow into the infiltration basin, a weir, flume, or area-velocity meter can be placed at the inlet location as described in Chapter 4. If the inflow is through a pipe directly into the basin, the flow-area meter is the best choice of flow measurement device. If the inflow is via an open channel, the flow can be measured with a weir, a flume, or an alternative depth-discharge relationship for the channel.

At the outlet of the basin, if there is one, the flow is typically controlled by a drop inlet structure. The hydraulics of that structure can be determined from weir and orifice formulae based on the geometry of the outlet. When the hydraulics are known, outflow through the structure can be estimated by measuring the elevation of the water in the basin. Measurements of the water level should continued as the water level drops below the outlet. The infiltration rate can then be determined using a water balance for the basin. That water balance is represented by equation 9.5.

Equation 9.5: Water balance for monitoring an infiltration basin.

$$Q_{in} - Q_{out} - IA = \frac{A\Delta H}{\Delta t}$$

where:

Q_{in} = discharge through the inlet to the basin during time period

Q_{out} = discharge through the outlet structure during time period, Δt

I = infiltration rate during time period

A = water surface area at any given elevation of the water surface

ΔH = change in water surface elevation during the time period, Δt

Δt = time period

If the basin is underlain by a drain pipe, it is necessary to measure the discharge from the drain pipe as well. The magnitude of the expected discharge from the drain pipe, which is dependent on the size of the structure, will determine the type of flow measurement device. For small flows, a tipping bucket device will work well, while for larger flows, a weir, flume, or area-velocity meter will be necessary.

Infiltration trenches

Infiltration trenches function by storing water on the surface of the trench and then permitting the water to infiltrate through that surface. If the inflow into and any outflow from the submerged area can be measured, the flow capacity of a trench can be estimated by monitoring. If both the inflow and outflow points are well-defined, the flow can be measured with a weir, flume, area-velocity meter, or a suitable stage-discharge relation. The water level in the submerged area also needs to be measured over time.

Assuming that the inflows, outflows, and submerged surface elevation can be measured, the discharge into the trench can be determined from a water balance given in equation 9.5. Applying this water balance assumes that the infiltration into the soil surrounding the trench is negligible. Infiltration trenches are used in areas where the surface soil has very low infiltration capacity and therefore this assumption is generally valid.

Porous pavements

The infiltration performance of porous pavements can be assessed by monitoring incident rainfall with a rain gage and runoff at an appropriate outlet point for the pavement. For porous pavement parking lots, the edges of the parking lot will usually be bounded by curbs or other berm-like conditions. The discharge (runoff) from the pavement can be measured at the pavement overflow location. The rainfall depth minus the depth of runoff from the pavement will be equal to the infiltrated water.

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Acknowledgements

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Procedures

for Visual Inspection of Stormwater Best Management Practices using Infiltration

Visual inspection is a rapid assessment procedure for qualitatively evaluating the functionality of a stormwater best management practice (BMP). Visual inspections use a set of criteria that, under certain circumstances (described in chapter 3), determine if the stormwater BMP is malfunctioning. Detailed instructions for visual inspection of infiltration practices are included below and reproduced in appendix B, part 2, which can be easily printed out and taken to the field.

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Stormwater Management Practice Assessment Project

Standard Procedure for Level 1 Assessment: Visual Inspection

Infiltration Practices (including infiltration basins, infiltration trenches, and porous pavements)

1. Certified Reference:

1.1. None.

2. Application:

2.1. This method is applicable to infiltration practices as defined in Chapter 9.

3. Summary of Method:

3.1. This standard protocol is used as a basis for the visual inspection of an infiltration practice. The questions in section 8.4 below are answered from visual observations of the site and documented with a photographic or video-graphic camera.

4. Interferences:

4.1. Visual inspection requires adequate weather conditions. Fog or other visually limiting weather condition can result in an inaccurate or incomplete visual inspection. Such weather conditions should be avoided whenever possible.

5. Apparatus:

5.1. Camera (digital or film, video or photographic)

6. Materials:

6.1. Field Data Sheet (see attached).

7. Safety:

7.1. This procedure requires field inspection of the site and photographic or video graphic documentation. Caution and appropriate use of safety equipment and traffic controls should be used when walking around and in stormwater BMPs to avoid personal injury.

8. Procedure:

8.1. Print out this Standard Protocol for the visual inspection of infiltration practices.
8.2. Obtain apparatuses and materials as outlined in sections 5 and 6 above.
8.3. Travel to the infiltration practices that will be assessed by visual inspection.
8.4. Fill out the attached Field Data Sheet (see below).

9. Calculations:

9.1. None required. See Chapter 12.

10. Quality Control:

10.1. Photographic documentation for the questions answered above (section 8.4) must be provided with this protocol.

11. Additional References:

11.1. None

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Field Data Sheet for Level 1 Assessment: Visual Inspection

Infiltration Basins and Trenches

Inspector's Name (s): ____
Date of Inspection: ____
Location of the infiltration practice
    Address or Intersection: ____________________________________
    Latitude, Longitude: _______________________________________
Date the infiltration practice began operation: _____________________
Size of the infiltration practice (ft x ft):____________________________
Time since last rainfall (hr): ____________________________________
Quantity of last rainfall (in): ________________________________
Rainfall Measurement Location: ________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don’t know

1.a) If yes, when? ______________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don’t know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don’t know

3) Does this infiltration basin or trench utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don’t know

3.a) If yes, please describe: ____

____

____

____

4) Are there multiple inlet structures?

☐ Yes ☐ No

4.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

4.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

4.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

5) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

5.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don't know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

6) Is there standing water in the infiltration basin or trench?

☐ Yes ☐ No

6.a) If yes, does the water have:

☐ Surface sheen (from oils/gasoline)
☐ Murky color (from suspended solids)
☐ Green color from (algae or other biological activity)
☐ Other: ____
☐ No

7) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

7.a) If yes, please describe: ____
____
____
____

8) Does the infiltration basin or trench smell like gasoline or oil?

☐ Yes ☐ No

9) Is there vegetation in the bottom of the infiltration basin or trench?

☐ Yes ☐ No

9.a) What is the approximate vegetation cover?

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

10) Are there indications of any of the following in the bottom of the infiltration basin or trench?

☐ Sediment deposition
☐ Erosion or channelization
☐ Excessive vegetation (that needs mowing or removal)
☐ Litter, large debris, solid waste
☐ Other: ____
☐ No

10.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice
☐ Erosion or channelization outside the practice
☐ Construction site erosion
☐ Other: ____
☐ I don't know

11) Are there indications of any of the following on the banks of the infiltration basin?

☐ Erosion or channelization
☐ Other: ____
☐ No

12) Is the bottom of the infiltration basin or trench covered with a layer of silts, clays, or both?

☐ Yes ☐ No

13) Is the overflow structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

13.a) If yes, what with?

☐ Debris
☐ Sediment
☐ Vegetation
☐ Other: ____

14) Is the overflow structure askew or misaligned?

☐ Yes ☐ No

14.a) If yes, why?

☐ I don't know
☐ Ice/Frost heave
☐ Other: ____

Other observations:

Inspector's Recommendations:

15) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

Maintenance Recommendations:

Troubleshooting Failure: Visual Inspection

Infiltration Basins and Trenches

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many infiltration practices are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessing a infiltration practice within 48 hours of a rainfall event may provide additional assessment clues than assessment during a long dry period. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Does this infiltration basin or trench utilize any pretreatment practices upstream?

If any pretreatment practices exist they should also be inspected and maintained on a regular basis.

4) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the infiltration practice. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system, or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

5) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit an infiltration practice by means other than those intended by design or prevent stormwater runoff from entering the infiltration practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

6) Is there standing water in the infiltration basin or trench?

Standing water in an infiltration practice is the result of one of three possibilities: (1) rainfall has occurred recently such that stormwater runoff has not had 48 hours to infiltrate, (2) the infiltration rate of the practice is slow such that stormwater runoff does not infiltrate within 48 hours, but does infiltrate given enough time, or (3) the infiltration practice is clogged and does not infiltrate any stormwater runoff. If it has rained in the last 48 hours (question 2), then the infiltration practice may be functioning properly and requires additional assessment (level 2 or higher). If, however, it has not rained in the last 48 hours, it is likely that the infiltration practice is either option (2) or (3).

Question 3a provides clues that may determine whether the infiltration practice is clogged. Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven not to be illegally discharged into the infiltration practice, then a surface sheen may indicate that stormwater runoff is stored in the infiltration practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. If this is happening, then the infiltration practice is failing. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a high suspended solids concentration that is most likely made up of fine particle sizes, such as clays and silts, because sand particles settle out of standing water very rapidly (as discussed in Chapter 10: Sedimentation). Stormwater runoff with a murky color further indicates that the watershed may be a significant source of fine particle suspended solids, which can quickly clog an infiltration practice.

Stormwater runoff with a green color from algae or biological activity has been stored in the infiltration practice for a long period of time such that microorganisms have developed. The infiltration practice is not infiltrating stormwater runoff and is therefore failing.

7) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

8) Does the infiltration basin or trench smell like gasoline or oil?

If an infiltration practice smells like gasoline or oil it is possible that hydrocarbon substances such as automotive oil or gasoline are being illicitly discharged into the practice or upstream in the watershed. If hydrocarbons are proven not to be illegally discharged into the infiltration practice, then an oil/gasoline smell may indicate that stormwater runoff is stored in the infiltration practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. For more information on identifying, locating, and eliminating illicit discharges, refer to a manual such as Brown *et al.* (2004).

9) Is there vegetation in the bottom of the infiltration basin or trench?

Vegetation in the bottom of an infiltration basin can increase the infiltration effectiveness. Plants can lose 30% of their root structures annually, which produces macropores. Macropores in a infiltration practice can increase the infiltration rate of the basin or trench so that more stormwater runoff is infiltrated. Additionally, vegetation can reduce overland flow velocities and can therefore reduce erosion and resuspension of captured solids. Infiltration trenches typically have a larger grain size so that vegetation cannot grow without clogging of the pores.

Vegetation can also be an indication of the drain time of an infiltration basin. Terrestrial vegetation often cannot withstand long periods of inundation, and some cannot withstand short periods of inundation. If an infiltration practice has an abundance of terrestrial vegetation, it is likely that the practice infiltrates stormwater runoff quickly (< 48 hours) and is therefore operating properly. If, however, the infiltration practice has signs of aquatic vegetation, the practice may not be infiltrating stormwater runoff and is therefore failing.

10) Are there indications of any of the following in the bottom of the infiltration basin or trench?

Sediment deposition may indicate that pretreatment devices have reached sediment storage capacity, are not efficiency removing settable solids, or are not present. Sediment deposition may also indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution. Sediment deposition reduces the surface area available for infiltration and therefore can reduce the stormwater runoff volume that is infiltrated.

Erosion or channelization indicates that the velocity of flow entering, or in, the infiltration practice is large or that stormwater runoff is entering the infiltration practice by means other than those intended by design. Erosion or channelization indicates that the velocity of flow entering, or in, the infiltration practice is large or that stormwater runoff is entering the infiltration practice by means other than those intended by design. In either case, stormwater runoff is not stored such that significant infiltration is occurring in the areas where erosion and channelization are present.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in infiltration basins and trenches. If the surface of the infiltration practice becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils. Vegetation in infiltration practices is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in an infiltration practice are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of infiltration practices by reducing the surface available for infiltrating stormwater runoff.

11) Are there indications of any of the following on the banks of the infiltration basin or trench?

Erosion or channelization on the banks of an infiltration practice indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the practice with sediments from the bank and subsequently reduce effectiveness by clogging the soil or sealing the surface and reducing the volume available for stormwater storage.

12) Is the bottom of the infiltration basin or trench covered with a layer of silts, clays, or both?

A visible layer of silts, clays, or both is a likely indication that the infiltration practice is clogged. Infiltration basins collect particles on the surface and in the pore spaces of the soil. Silts, clays, or both present on the surface of the basin or trench indicates that the pore spaces within the soil are likely filled or that stormwater runoff is stored in the basin or trench long enough for these fine particles to settle out or for the stored stormwater runoff to evaporate. The infiltration practice is not likely infiltrating stormwater runoff in less than 48 hours as recommended by design guidelines (Minnesota Stormwater Steering Committee 2005).

13) Is the overflow structure clogged?

Infiltration basins and trenches typically have overflow structures instead of outlet structures. Outflow for an infiltration practice is intended to go into the soil such that deep percolation or evaporation occurs. The overflow structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the infiltration practice in the event of a large storm event. If the overflow structure is partially or completely clogged, surrounding areas may be flooded by stored stormwater runoff. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

14) Is the overflow structure askew or misaligned?

Misaligned overflow structures often allow stormwater runoff to enter or exit an infiltration practice by means other than those intended by design or prevent stormwater runoff from entering the infiltration practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Overflow structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned overflow structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

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Field Data Sheet for Level 1 Assessment: Visual Inspection

Porous Pavements

Inspector's Name (s): ____
Date of Inspection: ____
Location of the porous pavement
    Address or Intersection: ______________________________________
    Latitude, Longitude: ____
Date the porous pavement began operation: ___________________________
Size of the porous pavement (ft x ft):__________________________________
Time since last rainfall (hr): ____
Quantity of last rainfall (in): ____
Rainfall Measurement Location: ________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ____________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Is there standing water on top of the porous pavement?

☐ Yes ☐ No

4) Are there indications of any of the following on top of the porous pavement?

☐ Sediment deposition

☐ Erosion or channelization

☐ Litter, large debris, solid waste

☐ Other: ____

☐ No

4.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

Inspector's Recommendations:

5) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

____

____

____

____

____

Maintenance Recommendations:

____

____

____

____

____

Troubleshooting Failure: Visual Inspection

Porous Pavements

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Porous pavement is designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) immediately (Minnesota Stormwater Steering Committee 2005). Assessing a porous pavement within 48 hours of a rainfall event may provide additional assessment clues than assessment during a long dry period. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Is there standing water on top of the porous pavement?

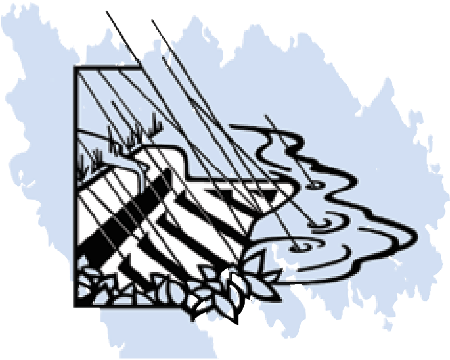
For any runoff volume that does not exceed the design storm, porous pavement should not have any standing water. Standing water on top of porous pavement is the result of two possibilities: (1) substantial rainfall above design has occurred recently such that the stormwater has not been able to infiltrate, (2) the porous pavement is clogged and does not infiltrate sufficient stormwater.

4) Are there indications of any of the following on top of the porous pavement?

Sediment deposition may indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution. Sediment deposition limits the porous pavement surface area available for infiltration and therefore can reduce the stormwater runoff volume that is infiltrated.

References

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html



10.

Sedimentation Practices

P.T. Weiss, A.J. Erickson, J.S. Gulliver (gulli003@umn.edu), R.M. Hozalski

Hot Links

10.1 Sedimentation process

Sedimentation is defined in chapter 1 as the process by which solids are removed from the water by settling out of the water column. Sedimentation practices (e.g., dry ponds, wet ponds, wet vaults, and commercially available proprietary devices) consist of engineered surface basins or underground vessels that decrease the flow velocity, provide temporary storage of stormwater runoff, or both, to allow suspended solids to settle out and be retained by the stormwater BMP. Pollutants that are integrated into or sorbed onto the settled solids will also be retained. The retained solids must be periodically removed from the sedimentation practice to maintain effective solids removal performance. This chapter includes discussion on dry ponds, wet ponds, wet vaults, and proprietary devices. Sedimentation practices in which solids retention is enhanced by vegetation are discussed in chapter 11, Biologically Enhanced Practices.

Weiss, P.T., A.J. Erickson, J.S. Gulliver, and R.M. Hozalski. 2007. Sedimentation practices. In *Assessment of Stormwater Best Management Practices,* ed. J.S. Gulliver and J.L. Anderson. St Paul, MN: University of Minnesota.

Solid settling in stormwater applications can be described by Stokes' law, given in equation 10.1 (Stokes 1851). Stokes law is applicable to clay, silt, and fine sand in stormwater and can be applied up to fine sand (Reynold's Number, $Re = Vd/\nu < 10$) with a maximum error in settling velocity of 25%.

The settling velocity of solids in a fluid is dependent on the size and density of the solids and the properties of the fluid (i.e., density and viscosity) in which the solids are entrained. The size of silica-based particles is given in table 10.1. For stormwater applications, the fluid in which solids are immersed is assumed to be water, for which density is nearly constant and viscosity varies only with temperature. The dependency of settling velocity on sediment size and density as well as water temperature is shown in figure 10.1. Using Stoke's Law, the settling velocity of solids in water at 0 °C (32 °F) is approximately 43% of settling velocity of the same solids in water at 40 °C (90 °F).

Equation 10.1: Stoke's Law for settling solids (Stokes 1851)

$$V = \frac{g\left(\rho_1/\rho - 1\right)d^2}{18\upsilon}$$

where:
V = settling velocity of the solid
g = acceleration of gravity
ρ_1 = mass density of the solid
ρ = mass density of the fluid
d = diameter of the solid (assuming spherical)
υ = kinematic viscosity of the fluid

Table 10.1: Sediment Grade Scale (adapted from Lane 1947)

Class Name	Millimeters	Microns	Inches	Sieve # (openings per inch)
Very Coarse Gravel	64–32		2.5–1.3	
Coarse Gravel	32–16		1.3–0.6	
Medium Gravel	16–8		0.6–0.3	
Fine Gravel	8–4		0.3–0.16	5
Very Fine Gravel	4–2		0.16–0.08	10
Very Coarse Sand	2–1	2000–1000		
Coarse Sand	1–0.5	1000–500		18
Medium Sand	0.5–0.25	500–250		35
Fine Sand	0.25–0.125	250–125		60
Very Fine Sand	0.125–0.062	125–62		120
Coarse Silt	0.062–0.031	62–31		230
Medium Silt	0.031–0.016	31–16		
Fine Silt	0.016–0.008	16–8		
Very Fine Silt	0.008–0.004	8–4		
Coarse Clay	0.004–0.002	4–2		
Medium Clay	0.002–0.001	2-–1		
Fine Clay	0.001–0.0005	1–0.5		
Very Fine Clay	0.0005–0.00025	0.5–0.24		

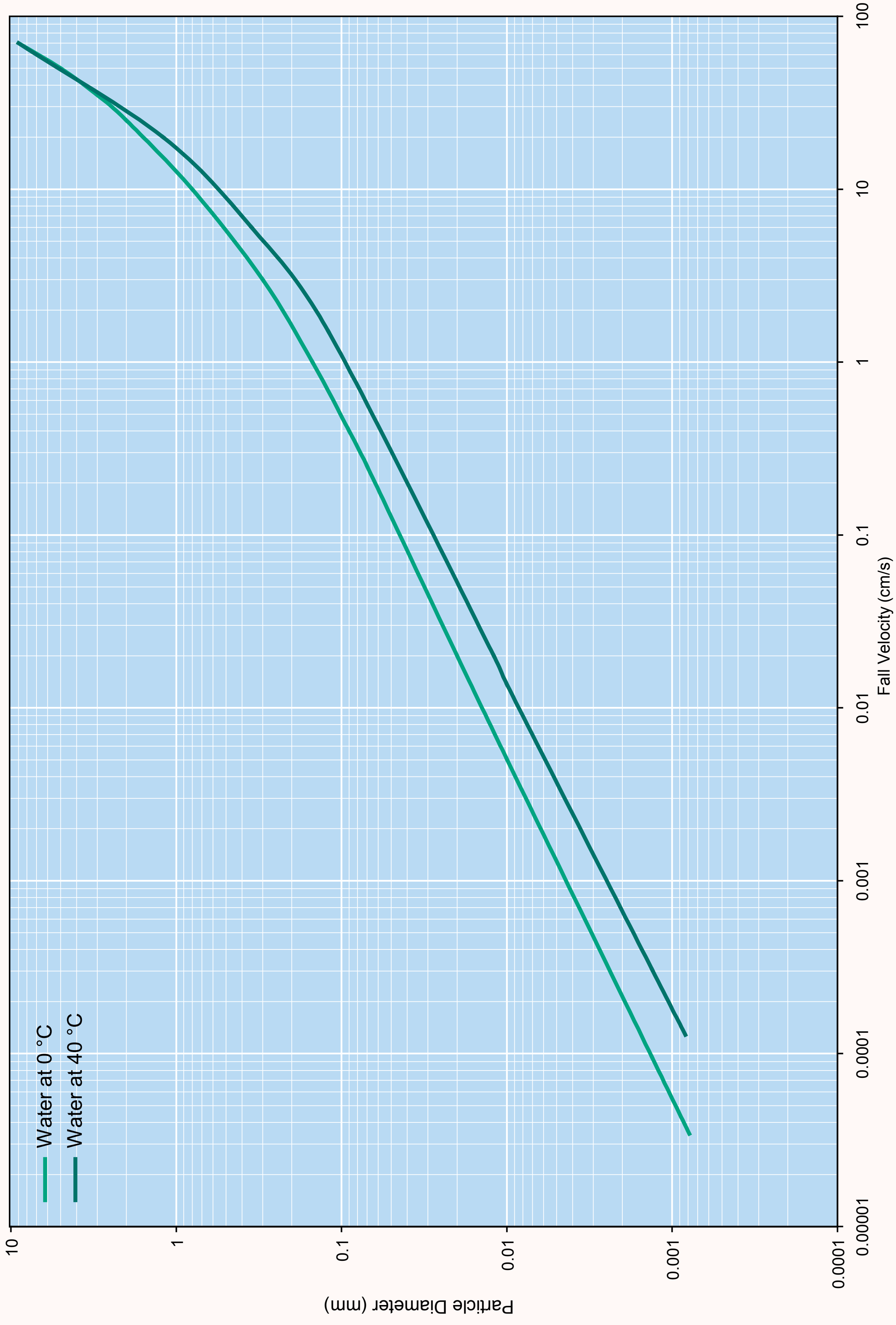


Figure 10.1: Fall velocity of quartz spheres in water (adapted from Rouse 1937). [One cm/s = 0.394 in/s; on millimeter = 0.0394 inches.]

It is evident from equation 10.1 that larger solids will settle faster than smaller solids of the same density. It is also apparent that solids with a large density will settle more quickly than less dense solids of the same size. Therefore, it can be concluded that more solids of varying sizes and densities will settle out of water when more time (i.e., residence time) is allowed. Sedimentation practices can be designed to optimize settling; design guidelines for sedimentation practices are provided in the Minnesota Stormwater Manual (http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html#manual).

10.2 Sedimentation practices

10.2.1 Dry ponds

Dry ponds are unlined depressions in the ground surface fitted with inlets and outlets to manage the collection and release of stormwater. Dry ponds are also called dry detention ponds or detention basins. Dry ponds (figure 10.2) temporarily store stormwater runoff and release the water through a designed outlet structure at a slower rate than if the dry pond were not present. Infiltration and evapotranspiration may occur, but these processes are usually not the primary modes of water transport out of the pond. Dry ponds are designed to drain completely

Figure 10.2: Dry pond (Minneapolis, MN)

and therefore do not maintain a pool of water between runoff events. Dry ponds also remove suspended solids from stormwater via sedimentation, which is the primary mechanism for pollutant retention in dry ponds.

The prescribed surface area for a dry pond is typically 0.5% to 2.0% of the total watershed area (Urban Drainage Flood Control District 1992). Historically, the primary function of dry ponds has been to reduce the peak runoff flow rate and reduce the risk of flooding downstream due to urbanization of the upstream watershed. More recently, the pollutant-retention mechanisms that occur within dry ponds have been investigated. Weiss et al. (2005) reported that on average (± 67% confidence interval), dry ponds in the United States retain 53% (± 28%) of total suspended solids and 25% (± 15%) of total phosphorus. The U.S. EPA (1999) reported typical ranges of 30%–65% for total suspended solids and 15%–45% for total phosphorus in dry ponds.

10.2.2 Wet ponds

Wet ponds are depressions in the ground with elevated outlet structures that allow water to pond and be stored between runoff events. Stormwater runoff remains in a wet pond because it has an impermeable liner or because the groundwater table is too high for the water to infiltrate directly into the soil. Wet ponds (figure 10.3) store runoff

Figure 10.3: Wet pond (Minneapolis, MN)

temporarily and release the water through a designed outlet structure elevated above the pond bottom at a slower rate than if the wet pond were not present. The elevated outlet structure allows a pool within the wet pond to remain until the next runoff event displaces it. The purpose of storing water in a wet pond is to allow time for solids to settle out of the water column. Wet ponds are typically designed with a surface area of 2% to 3% of the impervious watershed area (U.S. EPA. 1999) and are sometimes called retention ponds or wet basins.

On average (±67% confidence interval), wet ponds in the United States retain 65% (±32%) of total suspended solids and 52% (±23%) of total phosphorus (Weiss et al. 2005). The U.S. EPA (1999) reported typical ranges of 50% to 80% for total suspended solids and 15% to 45% for total phosphorus in wet ponds.

10.2.3 Wet vaults

Wet vaults are underground vessels used to store stormwater runoff temporarily. A simple wet vault design consists of large diameter corrugated metal pipes placed underneath a parking lot. Parking lot and rooftop runoff is routed into the underground pipes for temporary storage and subsequent release to the storm sewer. Some wet vaults are designed with perforations, which, given the proper underground conditions, can slowly release water into the ground. Wet vaults are often used in place of dry ponds or wet ponds in urban areas because wet vaults are typically underground and therefore do not consume land surface area. A typical wet vault is shown in figure 10.4

INFILTRATION PRACTICES

Lino Lakes City Hall - Infiltration trench
Lino Lakes, MN

Bradshaw Celebration of Life Center - underground storage & infiltration
Stillwater, MN

Definition:

Natural or constructed depressions located in permeable soils that capture, store and infiltrate the volume of stormwater runoff associated with a particular design event.

Figure 10.4: Installation of an underground stormwater storage vault (wet vault)

10.2.4 Proprietary devices

Proprietary devices are compact, engineered stormwater BMPs designed for underground installation in urban areas. Proprietary devices differ from wet vaults in that they are designed to remove solid pollutants from the stormwater but do not provide water storage to reduce peak flows. Examples of proprietary devices are shown in figures 10.5 and 10.6.

Sedimentation is the primary stormwater treatment process used by proprietary devices, but other processes such as filtration and floatation may also be used to remove pollutants, including suspended solids, nutrients (nitrogen and phosphorus), heavy metals, and fats/oils/greases. Proprietary devices are compact and are usually placed underground, conserving land area.

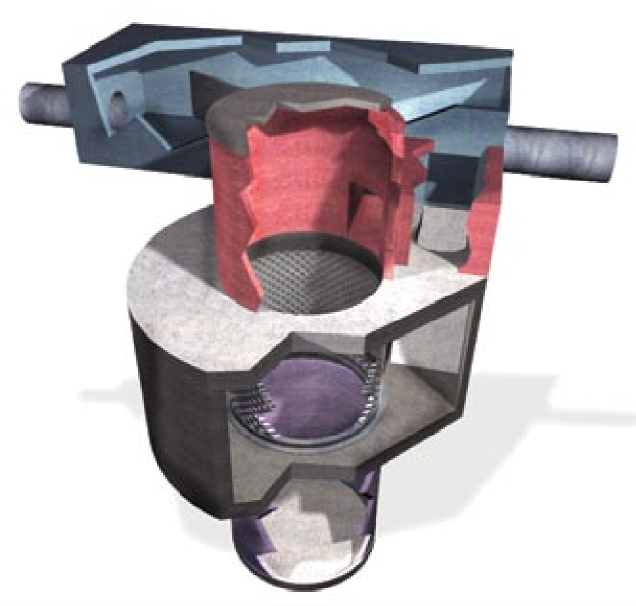


Figure 10.5: Offline Stormwater Treatment Unit supplied by CDS Technologies, Inc.

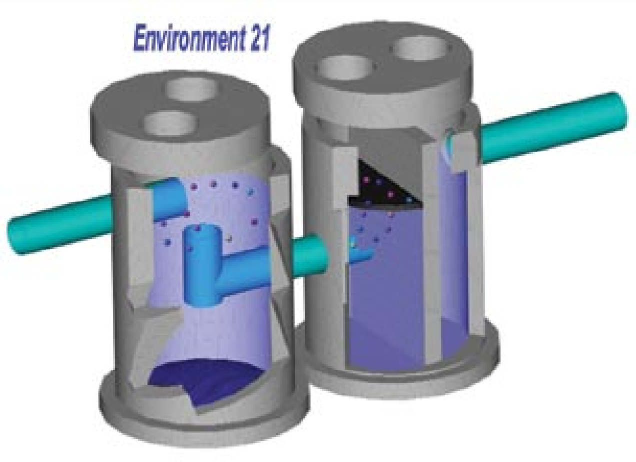


Figure 10.6: Underground proprietary device (V2B1) by Environment 21.

10.3 Sedimentation considerations by level of assessment

When developing and implementing a sedimentation assessment program, topics specific to sedimentation should be considered for each level of assessment. Chapter 3 (Developing an Assessment Program) should be reviewed prior to, or concurrently with, this section because chapter 3 provides relevant background information.

Sedimentation practices are designed to retain solids by settling, but other pollutants (e.g., phosphorus, hydrocarbons, and metals) attached to retained solids (by adsorption, etc.) are also retained by sedimentation practices. Therefore, a topic of concern for sedimentation practices is the analysis of pollutants that may be sorbed to (and subsequently desorbed from) retained solids. Measuring and comparing the solid-bound pollutant concentrations at the influent and in the retained solids, or the dissolved pollutant concentrations at the influent and effluent, may give insight into processes occurring within the device, such as sorption or desorption of pollutants.

10.3.1 Visual inspection

As outlined in chapter 3, visual inspection should be included in all stormwater assessment programs, including those for sedimentation practices. Visual inspection of sedimentation practices should include inspection and documentation of the amount and distribution of retained solids. For example, a large deposit of solids at the inflow location of a dry pond may alter the inflow conditions or increase re-suspension of solids. See the standard procedures at the end of this chapter for detailed instructions about visual inspection of sedimentation practices.

10.3.2 Capacity testing

Capacity testing (i.e., level 2 assessment through permeability or sediment retention tests) can be applied to sedimentation practices to estimate sediment storage capacity. All sedimentation practices can be assessed with sediment retention tests if adequate access is available. Dry ponds can also be assessed with permeability tests.

Dry ponds

Permeability testing of dry ponds is used to estimate the rate at which stored water infiltrates into the soil, which can be used to estimate the runoff volume reduction by infiltration as described in chapter 3. A single point measurement with a Philip-Dunne permeameter (see Appendix C) can take between 30 seconds and several hours, depending on the soil characteristics of the dry pond. As shown in chapter 3, level 2 assessment for a single dry pond can require one day to one week to complete. Permeability tests should be performed shortly after construction to establish a baseline for future tests and to investigate or identify construction impacts on infiltration capacity.

Sediment retention tests are used to estimate the depth and, subsequently, volume of sediment retained in a BMP. Surface elevations in a dry pond are measured either with a level and level rod or a total station (i.e., surveying equipment), and the corresponding longitude and latitude are recorded either with GPS or with a total station. Using the basin topography and the original topography (from as-built plans or design drawings), the amount of sediment retained in the stormwater BMP can be estimated. The amount of retained sediment can be compared to the design capacity to determine the available sediment retention capacity and to estimate when the BMP will require maintenance (i.e., sediment cleanout). One to three days are typically required for each dry pond to perform sediment retention assessment.

Wet ponds

Sediment retention tests can be performed on a wet pond to estimate the depth and subsequently volume of sediment retained in the stormwater BMP. Bottom elevations in a wet pond are measured either with a level and level rod (from a boat) or with a sonar depth measurement device. The water surface can be used as a local elevation standard if a staff gauge has been installed in the pond to measure water surface elevation. Sonar depth measurements can be made in the winter when the wet pond is covered with sufficient ice to traverse or in the summer from a boat or while using waders. Corresponding longitude and latitude are recorded either with GPS or with a total station. Using the basin topography and the original topography (from as-built plans or design drawings), the amount of sediment retained in the stormwater BMP can be estimated. The volume of retained sediment can be compared to the design capacity to determine the available sediment retention capacity and to estimate when the BMP will require maintenance (i.e., sediment cleanout). As with dry ponds, it is recommended that these tests be performed soon after construction is complete to develop as-built plans as a benchmark for future assessment.

Wet vaults and proprietary devices

If the sediment collection area can be accessed, staff gauges or visual benchmarks and as-built plans can be used to determine the volume of sediment collected. These measurements can be used with estimates or measurements of sediment inflow rates to develop a maintenance or cleanout schedule. When the collected solids volume meets or exceeds the solids storage capacity of a wet vault or proprietary device, solids will no longer be removed effectively. Furthermore, resuspension of retained solids can result in negative pollutant removal efficiencies.

10.3.3 Synthetic runoff testing

Synthetic runoff testing can be used to estimate the infiltration rate (and subsequently runoff volume reduction), pollutant removal efficiency, or both, in sedimentation practices such as dry ponds, wet ponds, wet vaults, and proprietary devices (provided adequate access and water supply is available). Synthetic runoff test results can be used to develop an accurate characterization of pollutant retention or removal that can be used with natural runoff in numerical models for total daily maximum load (TMDL) assessments. The primary constraint for synthetic runoff testing is the available water volume and discharge: fire hydrants can typically produce between 2 and 4 cfs for up to approximately 30 minutes and a water truck can produce up to approximately 1 cfs (0.028 m^3/s). Most commercial water trucks hold approximately 500 ft^3 (14,160 liters) of water, but a large water truck can hold up to 1000 ft^3 (28,320 liters). As demonstrated in example 10.1, synthetic runoff testing is not generally possible for the larger stormwater BMPs.

Example 10.1: Simulated runoff testing flow requirement calculation

A 41 ft by 46 ft dry pond with 3:1 side slopes is designed for a water quality volume of 3,864 ft^2 (358.98 m^2) at a maximum depth of 6 ft Based on data from a previous simulated runoff test, the infiltration rate is expected to be around 1.0 in/hr (7.06×10^{-4} cm/s). Determine the required flow rate and total volume of water that must be supplied if the pond is to be filled to its WQV in one hour.

Solution

Determine the approximate overall volumetric flow rate of water that will infiltrate into the ground when the stormwater BMP is being filled. If the 41 ft by 46 ft (12.50 m x 14.02 m) dimensions of the pond are the water surface dimensions when the pond contains the water quality volume (i.e., at 6 ft. depth), then the average surface area of the pond can be estimated by determining the surface area when the pond is 3 ft (.914 m) deep. At a depth of 3 ft and not accounting for the corners, the water surface dimensions are (41 – 3(3)(2)) by (46 – 3(3)(2)), where each dimension is reduced by the change in depth (i.e., 3 ft) multiplied by the side slope (i.e., 3:1) and the 2 accounts for there being two opposing sides in each dimension. This gives a water surface area of 23 ft by 28 ft (7.01 m x 8.53m), which is equal to 644 ft^2 (59.83 m^2).

$$\text{Total Flow Rate Infiltrating} = 1.0\ \frac{in}{hr} \times \frac{1\ ft}{12\ in} \times 644\ ft^2 \times \frac{1\ hr}{3600\ sec} = 0.015\ cfs\ (4.25 \times 10^{-4}\ m^3/s)$$

As the stormwater BMP is being filled, it can be assumed that 0.015 cubic feet of water per second will be leaving the stormwater BMP through infiltration. Performing a mass balance on water in the stormwater BMP gives:

$$\Delta \text{Storage within BMP} = (\text{Rate of Flow In})\Delta t - (\text{Rate of Flow Out})\Delta t$$

Where the ΔStorage within the stormwater BMP is the design water quality volume (if the stormwater BMP is initially empty), Δt is the desired fill time, the Rate of Flow Out is the total flow rate infiltrating (i.e., 0.015 cfs), and the Rate of Flow In is the required flow of the water supply. Substituting the appropriate numerical values gives:

$$3{,}864\ ft^3 = (\text{Required Flow})(3600\ sec) - \left(0.015\ \frac{ft^3}{s}\right)(3600\ sec)$$

Solving for the only unknown, the Required Flow is 1.09 ft^3/s (0.031 m^3/s).

The total water volume required is (1.09 ft3/s) x (3600 sec) = 3924 ft^3 (111,115.3 liters).

NOTE: This example illustrates a process but may not represent typical results.

Dry ponds

Synthetic runoff testing of dry ponds can be used to estimate the runoff volume reduction (by infiltration) and the removal of pollutants. Filling a dry pond with synthetic stormwater runoff and measuring the rate at which the stored runoff infiltrates into the soil can provide information used to estimate the runoff volume reduction for past or future natural runoff events. Synthetic runoff testing, however, requires that the synthetic water source (e.g., fire hydrant, water truck) can fill the dry pond with the design volume at a rate faster than water infiltrates into the soil. Expected infiltration rates are best determined with permeability tests (level 2 assessment) on the same stormwater BMP or from other relevant information about the BMP (e.g., soil type, surface characteristics). If no information is available, however, estimates may be made from literature when possible. Example 10.1 illustrates how the required discharge and total volume of water for synthetic runoff testing is determined.

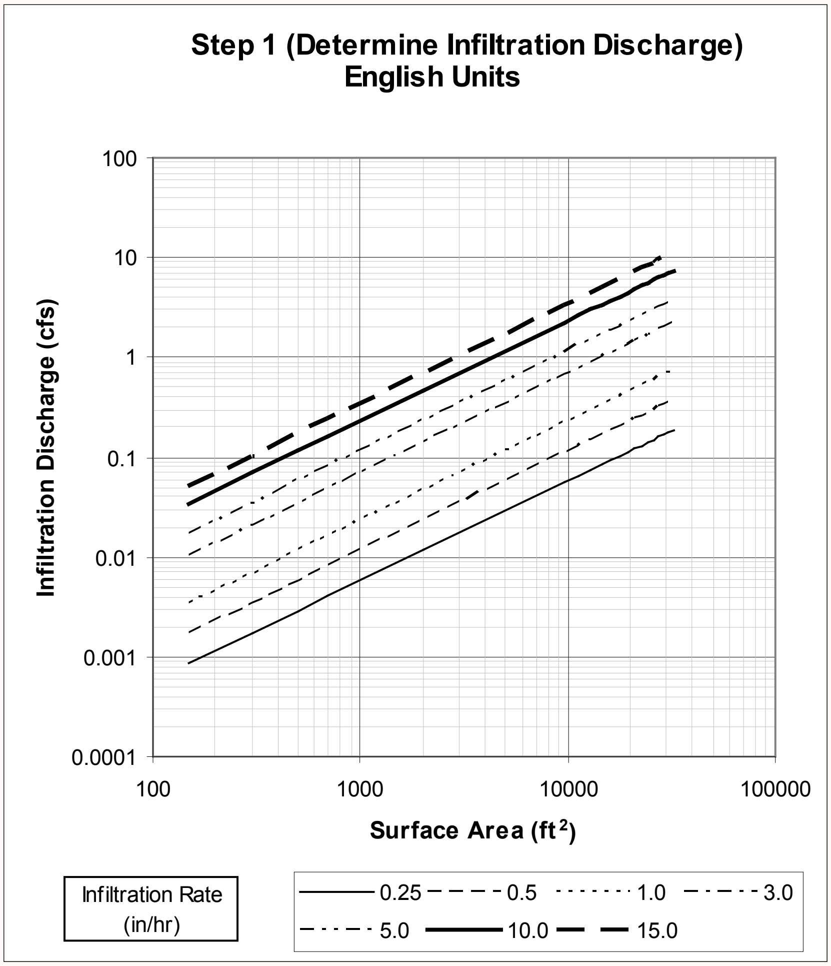


Figure 10.7: Determining infiltration discharge. [One cfs = 0.028 m^3/s; one square foot = 0.093 square meters.]

Figure 10.7 is a graph of the relationship between total infiltration discharge (cfs) and stormwater BMP surface area (ft^2) for various infiltration rates (in/hr). Figure 10.8 is a graph of the relationship between the required synthetic runoff discharge (cfs) and infiltration discharge (determined from figure 10.7) for various ratios of water quality volume (ft^3) and desired fill time (hr). Figures 10.7 and 10.8 can be used together as a graphical solution to estimate the required water supply discharge (i.e., synthetic runoff flow).

Returning to example 10.1, a graphical solution can be obtained using figures 10.7 and 10.8. Using figure 10.7, a pond with an infiltration rate of 1.0 in/hr (7.06×10^{-4} cm/s) and an average surface area of 644 ft^2 (59.83 m^2) will infiltrate approximately 0.015 cfs (4.25×10^{-4} m^3/s). From figure 10.8, an infiltration discharge of 0.015 cfs and a water volume to desired fill time ratio of 3,864 ft^3/hr (109.42 m^3/hr) (i.e., WQV/t_{fill} = 3,864 ft^3/hr) would require a synthetic runoff discharge slightly higher than 1 cfs (0.028 m^3/s). Estimation of the total volume of water required can be determined as demonstrated in the last calculation of example 10.1.

If the water supply used for synthetic runoff testing cannot produce the required flow, the fill time may need to be increased. The calculations in example 10.1 can be reversed and the amount of time required to fill the stormwater BMP can be calculated from the available water supply flow rate. A longer fill time, however, requires a larger total volume of water, which may exceed the limitations of the available water source.

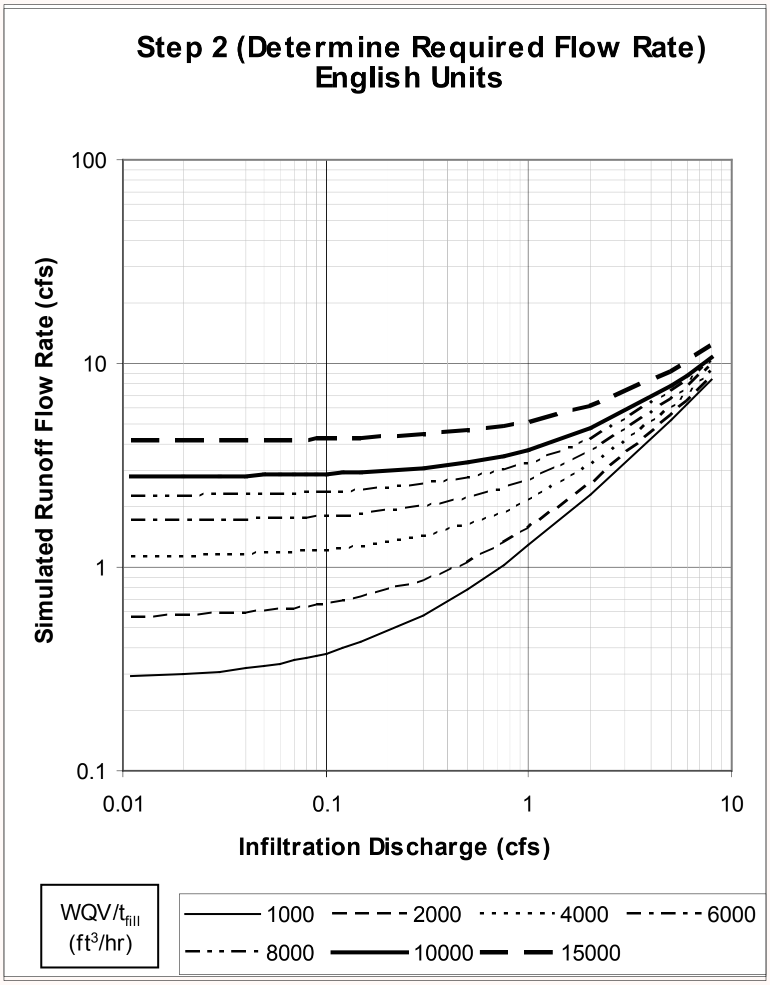


Figure 10.8: Determining required flow rate. [One cfs = 0.028 m^3/s.]

Pollutant removal efficiency can be estimated by adding a well-characterized pollutant (e.g., sediment) to the synthetic stormwater and measuring the change in concentration with respect to time of the pollutant in the effluent of the dry pond. The accuracy of synthetic runoff tests for pollutant removal efficiency may be limited by difficulties in achieving a representative suspended-solids concentration through sampling (see chapter 6). For this type of synthetic runoff testing, the water source must be able to provide the design discharge for a period of time that allows flow through the sedimentation practice to fully develop and equilibrate. A simple comparison of the maximum flow rate of the sedimentation practice and the available water source can be used to determine if the water source is adequate.

Level 2 assessment (sediment retention tests) of dry ponds estimates the amount of solids captured by sedimentation in the dry pond and, if measured with respect to time, can be used to estimate the sediment accumulation rate. Level 3 assessment (synthetic runoff tests), however, can estimate the infiltration rate, the pollutant removal efficiency, or both, and therefore determines very different stormwater BMP parameters than level 2 assessment. As described in chapter 3, level 3 assessment of dry ponds requires more relative effort than level 2 assessment.

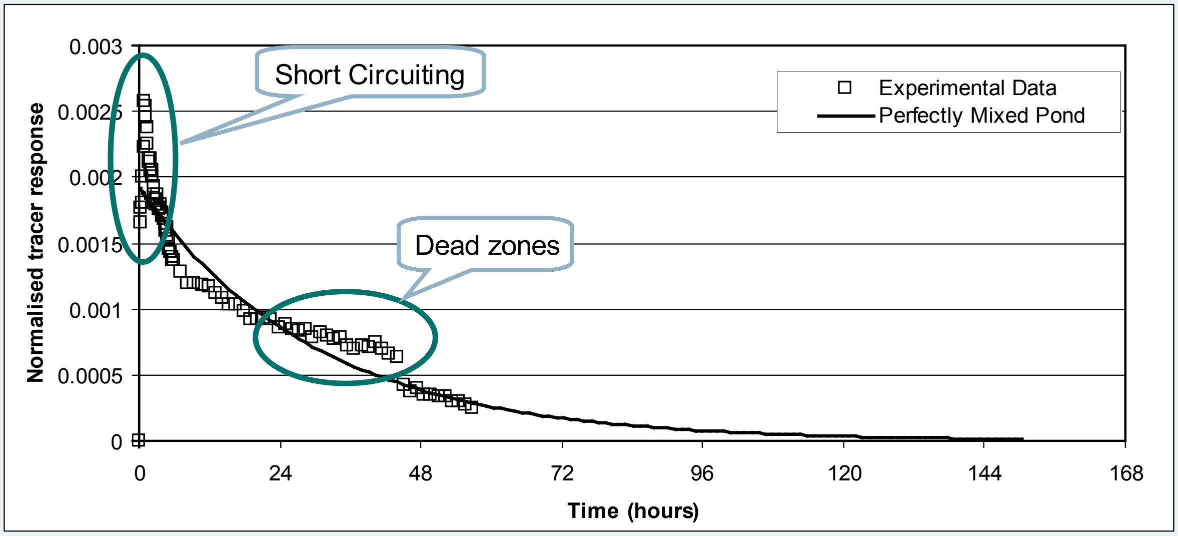
Wet ponds

Synthetic runoff testing of wet ponds can be used to estimate the retention of pollutants. Wet ponds do not infiltrate stored runoff and therefore do not reduce runoff volume except by evaporation. Pollutant removal efficiency can be determined by spiking the synthetic stormwater with a pollutant and then measuring the concentration of pollutant exiting the wet pond. The accuracy of these tests could be limited by difficulties in achieving a representative suspended-solids concentration through sampling (see chapter 6).

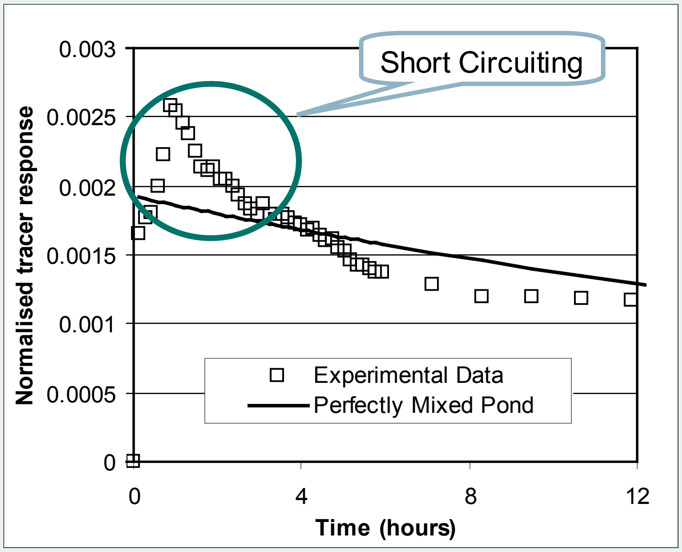
Synthetic runoff tests using a conservative tracer (e.g., chloride, rhodamine) can be used to investigate the hydraulic behavior of a wet pond. Tracer studies involve spiking the influent with the tracer

Example 10.2: Tracer Study of a wet pond (data modified from Shilton et al. 2000)

Alan, the director of the county environmental services department, is reviewing the results of a tracer study that was performed on a stormwater wet pond to examine the hydraulic conditions of the pond. In the study, a perfectly mixed wet pond was modeled ($C = C_0e^{-kt}$) for the same residence time (represented by k) and initial tracer concentration (C_0), as shown in the figure below:



Alan notices two important conclusions that can be made from the above graph. First, there is evidence of short-circuiting in the system in the early stages of the tracer study, which is enlarged and shown in the second graph. Alan concludes that short-circuiting is occurring because the trend in the tracer study data rises sharply in the beginning of the experiment, up to 38% higher than the perfectly-mixed pond. This indicates that some of the tracer is exiting the pond more quickly than expected, which is a result of some tracer short-circuiting to the exit. Second, Alan concludes that dead zones are present in the stormwater wet pond because the experimental tracer response is larger than the perfectly-mixed pond after 24 hours following initiation of runoff. This could indicate that some tracer is temporarily captured in dead zones and released at a later time. The presence of dead zones is confirmed by the sudden drop in tracer response that occurs after approximately 44 hours, which indicates that any tracer that had been retained in dead zones was flushed out.



and measuring the tracer concentration in the effluent as a function of time during a synthetic runoff event. Results from tracer studies can be used to determine if stormwater is short-circuiting through a stormwater BMP or if there are dead zones present. Short-circuiting in stormwater treatment occurs when stormwater passes through a stormwater BMP with minimal or no treatment because of incomplete mixing in the stormwater BMP. A poorly located inlet and outlet may result in a portion of the influent bypassing the treatment available in the pond. Another cause of short circuiting occurs during the winter in northern climates, when wet ponds freeze. Runoff or snowmelt that enters a frozen wet pond may flow over the top of the ice directly to the outlet structure. Short-circuiting can result in poor pollutant removal efficiency and is a common cause of wet pond failure. Dead zones are areas in a stormwater BMP where water becomes trapped and does not pass through the stormwater BMP as intended. For example, an underground proprietary device may have areas where stormwater circulates but is not released until the storm event is over or nearly over. Pollutants in the trapped water may or may not be removed by the proprietary device and, if not removed, may appear in the effluent samples towards the end of the runoff event. Pollutants can become trapped in dead zones between storm events and be released during subsequent storm events, which may result in negative removal efficiency (i.e., effluent pollutant > influent pollutant). Results from a tracer study are analyzed in example 10.2.

Level 2 assessment (sediment retention testing) of wet ponds is used to determine the amount of solids captured by sedimentation. If repeat measurements are made over time, the sediment accumulation rate can be estimated. Level 3 assessment (synthetic runoff tests), however, can estimate hydraulic behavior (via conservative tracer), the pollutant removal efficiency, or both.

Wet vaults and proprietary devices

Synthetic runoff testing can be used to estimate the retention of solids in a wet vault or proprietary device. Typically, proprietary devices neither infiltrate stored runoff nor have sufficient storage volume to reduce peak flow; thus, flow reduction testing of these devices is not relevant. In synthetic runoff testing, the synthetic runoff can be dosed with sediment to assess solids removal performance. The solids removal performance is determined either by collecting and measuring sediment concentrations in effluent samples or by extracting and measuring the sediment retained by an initially clean device. The latter method is likely to be more accurate as all of the solids are collected and weighed, whereas the former analyzes only the sediment in discrete effluent samples from water exiting the device. See Appendix C for a discussion of solids sampling.

Level 2 assessment (sediment retention testing) of wet vaults and proprietary devices is used to determine the amount of solids captured by sedimentation. If repeat measurements are made over time, the sediment accumulation rate can be estimated. Level 3 assessment (synthetic runoff tests), however, can estimate hydraulic behavior (via conservative tracer), the pollutant removal efficiency, or both, and therefore determines very different stormwater BMP parameters than level 2 assessment. As described in chapter 3, level 3 assessment does require more relative effort than level 2 assessment for wet vaults and proprietary devices. A case study of synthetic runoff testing of a proprietary device is given in Appendix A.

10.3.4 Monitoring

Some sedimentation practices may be too large for synthetic runoff testing and therefore require monitoring to achieve the assessment goals. Guidelines for monitoring can be found in chapter 4 (Water Budget Measurement), chapter 5 (Sampling Methods), and chapter 6 (Analysis of Soil and Water).

Dry ponds

By monitoring dry ponds, one can assess the peak flow reduction and pollutant removal efficiency. Measuring and comparing inflow and outflow hydrographs for a dry pond can give an estimate of the reduction in peak flow for a given storm event and, therefore, an estimate of the hydraulic effectiveness of the stormwater BMP. Results from sampling and analyzing stormwater samples from the inflow and outflow can be used to estimate the pollutant removal effectiveness. See chapter 12, Data Analysis, for guidance on analyzing data collected from monitoring studies.

Wet ponds

Monitoring of wet ponds (also known as wet detention basins) is well documented (Wu et al. 1996, Comings et al. 2000, Koob 2002, Mallin et al. 2002). Short-circuiting within a wet pond can be estimated by monitoring the movement of a naturally occurring conservative tracer, such as chloride, as it moves through a wet pond. Comparing the inflow and outflow tracer concentration versus time curves can determine if, and to what extent, short-circuiting may be occurring (see example 10.2).

Wet vaults and proprietary devices

Monitoring wet vaults and proprietary devices for hydraulic performance or water quality treatment is not recommended because wet vaults and proprietary devices are typically designed for small sub-watersheds and are located underground with limited access. Monitoring these systems can be costly, labor-intensive, and result in little, if any, conclusive data.

10.4 Recommendations

Visual inspection is recommended for assessment of all stormwater BMPs at regular intervals. Capacity testing is recommended for assessment of permeability in dry ponds or for the assessment of sediment accumulation in wet ponds. Synthetic runoff testing can be used in dry ponds, wet ponds, wet vaults, and underground proprietary devices for assessment of permeability or pollutant retention performance, if an adequate water supply is available. Monitoring is recommended when capacity testing or synthetic runoff testing do not meet the goals of the assessment program.

10.5 References

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Procedures

for Visual Inspection of Stormwater Best Management Practices using Sedimentation

Visual inspection is a rapid assessment procedure for qualitatively evaluating the functionality of a stormwater best management practice (BMP). Visual inspections use a set of criteria that, under certain circumstances (described in chapter 3), determine if the stormwater BMP is malfunctioning. Detailed instructions for visual inspection of sedimentation practices are included below and reproduced in appendix B, part 3, which can be easily printed out and taken to the field.

UNIVERSITY OF MINNESOTA
Stormwater Management Practice
Assessment Project

Standard Procedure for Level 1 Assessment: Visual Inspection

Sedimentation Practices (including Dry Ponds, Wet Ponds, Wet Vaults, and Proprietary Devices)

1. Certified Reference:

1.1. None.

2. Application:

2.1. This method is applicable to sedimentation practices as defined in Chapter 10, Sedimentation Practices.

3. Summary of Method:

3.1. This standard protocol is used as a basis for the visual inspection of sedimentation practices. The questions in section 8.4 below are answered from visual observations of the site and documented with a photographic or video-graphic camera.

4. Interferences:

4.1. Visual inspection requires adequate weather conditions. Fog or other visually limiting weather condition can result in an inaccurate or incomplete visual inspection. Such weather conditions should be avoided whenever possible.

5. Apparatus:

5.1. Camera (digital or film, video or photographic)

6. Materials:

6.1. Field Data Sheet (see attached).

7. Safety:

7.1. This procedure requires field inspection of the site and photographic or video graphic documentation. Caution and appropriate use of safety equipment and traffic controls should be used when walking around and in stormwater BMPs to avoid personal injury.

8. Procedure:

8.1. Print out this Standard Protocol for the visual inspection of sedimentation practices.
8.2. Obtain apparatuses and materials as outlined in sections 5 and 6 above.
8.3. Travel to the sedimentation practice that will be assessed by visual inspection.
8.4. Fill out the attached Field Data Sheet (see below).

9. Calculations:

9.1. None required. See Chapter 12.

10. Quality Control:

10.1. Photographic documentation for the questions answered above (section 8.4) must be provided with this protocol.

11. Additional References:

11.1. None

UNIVERSITY OF MINNESOTA
Stormwater Management Practice Assessment Project

Field Data Sheet for Level 1 Assessment: Visual Inspection

Dry Ponds

Inspector's Name (s): ____
Date of Inspection: ____
Location of the Pond
    Address or Intersection: ___________________________________
    Latitude, Longitude: ______________________________________
Date the dry pond began operation: _____________________________
Size of the dry pond (ft x ft):__________________________________
Time since last rainfall (hr): ___________________________________
Quantity of last rainfall (in): __________________________________
Rainfall Measurement Location: _________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Are there multiple inlet structures?

☐ Yes ☐ No

3.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

3.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

3.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

4) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

4.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don’t know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

5) Is there standing water in the dry pond?

☐ Yes ☐ No

5.a) If yes, does the water have:

☐ Surface sheen (from oils/gasoline)

☐ Murky color (from suspended solids)

☐ Green color (from algae or other biological activity)

☐ Other: ______________________________________

☐ No

6) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don’t know

6.a) If yes, please describe: ______________________________________

____

____

____

7) Are there indications of any of the following in the bottom of the dry pond?

☐ Sediment deposition

☐ Erosion or channelization

☐ Excessive vegetation (that needs mowing or removal)

☐ Litter, large debris, solid waste

☐ Other: ______________________________________

☐ No

7.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ______________________________________

☐ I don’t know

8) Are there indications of any of the following on the banks of the dry pond?

☐ Erosion or channelization
☐ Other: ____
☐ No

9) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

9.a) If yes, what with?

☐ Debris
☐ Sediment
☐ Vegetation
☐ Other: ____

10) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

10.a) If yes, why?

☐ I don't know
☐ Ice/Frost heave
☐ Other: ____

11) Is there evidence of any of the following downstream of the outlet structure:

☐ Sediment deposition

☐ Erosion or channelization

☐ Other: ____

☐ No

11.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

Other observations:

____

____

____

____

____

Inspector's Recommendations:

12) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

Maintenance Recommendations:

Troubleshooting Failure: Visual Inspection

Dry Ponds

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many dry ponds are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessing a dry pond within 48 hours of a rainfall event may provide additional assessment clues than assessment during a long dry period. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the dry pond. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system, or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the dry pond.

4) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a dry pond by means other than those intended by design or prevent stormwater runoff from entering the dry pond at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the dry pond.

5) Is there standing water in the dry pond?

Standing water in a dry pond is the result of one of three possibilities: (1) rainfall has occurred recently such that stormwater runoff has not had 48 hours to pass through the dry pond, (2) the treatment rate of the dry pond is slow such that stormwater runoff does not pass through the dry pond within 48 hours, but does pass through the dry pond given enough time, or (3) the outlet structure is clogged and does not allow any stormwater runoff to exit the dry pond. If it has rained in the last 48 hours (question 2), then the dry pond may be functioning properly and requires additional assessment (level 2 or higher). If, however, it has not rained in the last 48 hours, it is likely that the dry pond is either option (2) or (3).

Question 3a provides clues that may determine whether the outlet structure of the dry pond is clogged. Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven not to be illegally discharged into the dry pond, then a surface sheen may indicate that stormwater runoff is stored in the dry pond such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. If this is happening, then the dry pond is failing. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a large suspended solids concentration that is most likely made up of fine particle sizes, such as clays and silts, because sand particles settle out of standing water very rapidly (as discussed in Chapter 10, Sedimentation). Stormwater runoff with a murky color can indicate that the watershed is a significant source of fine particle suspended solids, which can quickly clog a dry pond. Murky stormwater runoff in a dry pond may indicate that stormwater runoff has recently entered the dry pond such that fine particles have not had time to settle out.

Stormwater runoff with a green color from algae or biological activity has been stored in the dry pond for a long period of time such that microorganisms have developed. Stormwater runoff is not passing though the dry pond properly and therefore the practice is failing.

6) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

7) Are there indications of any of the following in the bottom of the dry pond?

Sediment deposition may indicate either a significant source of sediment in the watershed that may require remediation to prevent downstream pollution or that the dry pond has not been recently maintained. Sediment deposition reduces the stormwater storage volume of a dry pond and can allow sediments to become resuspended during subsequent storm events.

Erosion or channelization indicates that flow velocities entering, or in, the dry pond are large or that stormwater runoff is entering the dry pond by means other than those intended by design. Erosion and channelization can reduce treatment by sedimentation within a dry pond by reducing the retention time within the pond. Additionally, previously captured sediments can become entrained by poorly or untreated stormwater and pass through the dry pond with the effluent.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in dry ponds that do not have impermeable surfaces (e.g., concrete). If the surface of the dry pond becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the dry pond. Vegetation in dry ponds is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in a dry pond are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of a dry pond by reducing the stormwater storage volume and therefore the retention time.

8) Are there indications of any of the following on the banks of the dry pond?

Erosion or channelization on the banks of a dry pond indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the dry pond with sediments from the bank and subsequently reduce the dry pond's effectiveness by reducing the volume available for stormwater storage and treatment.

9) Is the outlet structure clogged?

Like an inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the dry pond. If the outlet structure is partially or completely clogged, the treatment rate may be limited and stormwater runoff may not pass through the dry pond in less than 48 hours, as recommended by design (Minnesota Stormwater Steering Committee 2005). Any obstructions should be removed immediately to ensure proper operation of the dry pond.

10) Is the outlet structure askew or misaligned?

Misaligned outlet structures often allow stormwater runoff to enter or exit a dry pond by means other than those intended by design or prevent stormwater runoff from entering the dry pond at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Outlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the dry pond.

11) Is there evidence of any of the following downstream of the outlet structure?

Conditions downstream of a dry pond can provide evidence of the function of the pond itself. Properly designed and functioning dry ponds should remove most sand-sized particles (0.125 to 2 mm) from stormwater runoff. Sediment deposition downstream of a dry pond indicates that erosion is occurring between the dry pond and the sediment deposition or that sediments are present in the dry pond effluent. If sediments are present in the effluent such that downstream deposition is occurring, the dry pond is likely failing.

Erosion downstream of a dry pond indicates that flow velocities are larger than the conveyance channel can withstand. The conveyance channel should be resized to accommodate the amount of flow exiting the dry pond, or the channel should be augmented with energy dissipaters or riprap to reduce or eliminate the impact of erosion.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

UNIVERSITY OF MINNESOTA
Stormwater Management Practice Assessment Project

Field Data Sheet for Level 1 Assessment: Visual Inspection

Wet Ponds

Inspector's Name (s): ____
Date of Inspection: ____
Location of the Pond
    Address or Intersection: ___________________________________
    Latitude, Longitude: ______________________________________
Date the wet pond began operation: ____________________________
Size of the wet pond (ft x ft x ft): ___________________________
Time since last rainfall (hr): _________________________________
Quantity of last rainfall (in): ______________________________
Rainfall Measurement Location: _______________________________
Water Surface Elevation: _____________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Are there multiple inlet structures?

☐ Yes ☐ No

3.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

3.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

3.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________

4) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

4.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don't know					
Other					

If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________

5) Is the wet pond a multi-cell system?

☐ Yes ☐ No

5.a) If yes, how many cells are present?

☐ 2 cells ☐ 3 cells ☐ 4 or more

6) Does the water in the pond have:

☐ Surface sheen (from oils/gasoline)
☐ Murky color (from suspended solids)
☐ Green color (from algae or other biological activity)
☐ Invasive, tolerant fish species such as carp or shiners
☐ Other: ____
☐ No

7) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

7.a) If yes, please describe: ____
____
____
____

8) Does the wet pond smell like gasoline or oil?

☐ Yes ☐ No

9) Are there indications of any of the following in the bottom of the wet pond?

☐ Sediment deposition
☐ Excessive vegetation (that needs mowing or removal)
☐ Litter, large debris, solid waste
☐ Other: ____
☐ No

9.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice
☐ Erosion or channelization outside the practice
☐ Construction site erosion
☐ Other: ____
☐ I don't know

10) Are there indications of any of the following on the banks of the wet pond?

☐ Erosion or channelization

☐ Other: ____

☐ No

11) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

11.a) If yes, what with?

☐ Debris

☐ Sediment

☐ Vegetation

☐ Other: ____

12) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

12.a) If yes, why?

☐ I don't know

☐ Ice/Frost heave

☐ Other: ____

13) Is there evidence of any of the following downstream of the outlet structure?

☐ Sediment deposition

☐ Erosion or channelization

☐ Other: ____

☐ No

13.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don’t know

Other observations:

____
____
____
____
____

Inspector’s Recommendations:

14) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

____
____
____
____
____

Maintenance Recommendations:

____
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Troubleshooting Failure: Visual Inspection

Wet Ponds

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many wet ponds are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) and return to normal water surface level within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessing a wet pond within 48 hours of a rainfall event may provide additional assessment clues than assessment during a long dry period. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the wet pond. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system, or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the wet pond.

4) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a wet pond by means other than those intended by design or prevent stormwater runoff from entering the wet pond at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment, or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the wet pond.

5) Is the wet pond a multi-cell system?

Wet ponds are often designed as multi-cell systems to increase treatment and retention time. It is important to recognize multi-cell systems and perform this visual inspection on *each* of the cells in the system to ensure the entire practice is functioning properly.

6) Does the water in the pond have:

Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven to not be illegally discharged into the wet pond, then small amounts of hydrocarbons typically found in stormwater runoff are accumulating and remediation may be necessary to maintain the water quality of the stored runoff and prevent downstream pollution. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a high suspended solids concentration that is most likely made up of fine particle sizes, such as clays and silts, because sand particles settle out of standing water very rapidly (as discussed in Chapter 10, Sedimentation). Stormwater runoff with a murky color also indicates that the watershed may be a significant source of fine particle suspended solids or that erosion is suspending fine sediments from within the wet pond. Murky color in a wet pond further indicates that significant turbulence may be preventing suspended particles from settling. If a rainfall event has occurred in the last 48 hours, this may not be a problem. If rainfall has not occurred in the last 48 hours, murky color may be an indication of illicit discharge.

Stormwater runoff with a green color from algae or biological activity is not uncommon in a wet pond. Wet ponds with excessive algal or biologically activity may require maintenance to prevent pollution of downstream receiving waters.

Invasive, tolerant fish species like carp (*Cyprinus carpio*) or shiner minnows (*Notropis cornutus*) are indications of poor water quality in the wet pond (low dissolved oxygen, turbid, limited habitat) such that tolerant and invasive species are present. More information should be gathered to determine the cause of the poor water quality, and remediation should be performed.

7) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

8) Does the wet pond smell like gasoline or oil?

If a wet pond smells like gasoline or oil it is possible that hydrocarbon substances such as automotive oil or gasoline are being illicitly discharged into the practice or upstream in the watershed. If hydrocarbons are proven not to be illegally discharged into the wet pond, then an oil/gasoline smell may indicate that small amounts of hydrocarbons typically found in stormwater runoff are accumulating in the wet pond. For more information on identifying, locating, and eliminating illicit discharges refer to a manual such as Brown *et al.* (2004).

9) Are there indications of any of the following in the bottom of the wet pond?

Sediment deposition may indicate either a significant source of sediment in the watershed that may require remediation to prevent downstream pollution or that the wet pond has not been recently maintained. Sediment deposition reduces the stormwater storage volume of a wet pond and can allow sediments to become resuspended during subsequent storm events.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in wet ponds that do not have impermeable surfaces (e.g., concrete). If the surface of the wet pond becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the wet pond. Vegetation in wet ponds is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in a wet pond are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of wet pond by reducing the stormwater storage volume and therefore the retention time.

10) Are there indications of any of the following on the banks of the wet pond?

Erosion or channelization on the banks of a wet pond indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the wet pond with sediments from the bank and subsequently reduce the volume available for stormwater storage and treatment.

11) Is the outlet structure clogged?

Like an inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the wet pond. If the outlet structure is partially or completely clogged, the treatment rate may be limited and stormwater runoff may not pass through the wet pond in less than 48 hours, which can result in flooding or untreated stormwater runoff passing as overflow. Any obstructions should be removed immediately to ensure proper operation of the wet pond.

12) Is the outlet structure askew or misaligned?

Misaligned outlet structures often allow stormwater runoff to enter or exit a wet pond by means other than those intended by design or prevent stormwater runoff from entering the wet pond at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Outlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the wet pond.

13) Is there evidence of any of the following downstream of the outlet structure:

Conditions downstream of a wet pond can provide evidence of the function of the pond itself. Properly designed and functioning wet ponds should remove most sand-sized particles (0.125 to 2 mm) from stormwater runoff. Sediment deposition downstream of a dry pond indicates that erosion is occurring between the wet pond and the sediment deposition or that sediments are present in the wet pond effluent. If sediments are present in the effluent such that downstream deposition is occurring, the wet pond is likely failing.

Erosion downstream of a wet pond indicates that flow velocities are larger than the conveyance channel can withstand. The conveyance channel should be resized to accommodate the amount of flow exiting the wet pond, or the channel should be augmented with energy dissipaters or riprap to reduce or eliminate the impact of erosion.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

UNIVERSITY OF MINNESOTA
Stormwater Management Practice Assessment Project

Field Data Sheet for Level 1 Assessment: Visual Inspection

Wet Vaults and Proprietary Devices

Inspector’s Name (s): ____
Date of Inspection: ____
Location of the Pond
    Address or Intersection: ______________________________________
    Latitude, Longitude: ____
Date the device began operation: __________________________________
Size of the device (ft x ft x ft): ____________________________________
Time since last rainfall (hr): _____________________________________
Quantity of last rainfall (in): _____________________________________
Rainfall Measurement Location: ___________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ____________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Are there multiple inlet structures?

☐ Yes ☐ No

2.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

2.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

2.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

3) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

3.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don’t know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

4) Is a significant amount of water entering the wet vault or proprietary device?

☐ Yes ☐ No

5) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don’t know

5.a) If yes, please describe: ______________________________________
____
____
____

6) Are there excessive amounts of solids, debris, vegetation, or other objects that could be hindering performance or be re-suspended and exit the system during subsequent runoff events?

☐ Yes ☐ No

7) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

7.a) If yes, what with?

☐ Debris

☐ Sediment

☐ Vegetation

☐ Other: ______________________________________

8) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

8.a) If yes, why?

☐ I don’t know

☐ Ice/Frost heave

☐ Other: ______________________________________

9) Is there evidence of any of the following downstream of the outlet structure:

☐ Sediment deposition

☐ Erosion or channelization

☐ Other: ______________________________________

☐ No

9.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don’t know

Other observations:

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Inspector’s Recommendations:

10) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

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Maintenance Recommendations:

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Troubleshooting Failure: Visual Inspection

Wet Vaults and Proprietary Devices

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the wet vault or proprietary device. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the wet vault or proprietary device.

3) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a wet vault or proprietary device by means other than those intended by design or prevent stormwater runoff from entering the wet vault or proprietary device at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact.

4) Is a significant amount of water entering the wet vault or proprietary device?

Water entering a wet vault of proprietary device can be an indication that either (1) rainfall has occurred recently and the device is treating stormwater runoff or (2) water is entering the stormwater conveyance system from a leak, spill, or surface application (e.g., lawn watering, etc.).

5) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

6) Are there excessive amounts of solids, non-floating debris, vegetation, or other objects that could be hindering performance or be re-suspended and exit the system during subsequent runoff events?

Excessive amounts of solids, debris, vegetation, or other objects in a wet vault or proprietary device can reduce storage volume and subsequently treatment efficiency. Maintenance should be preformed to remove these obstructions.

7) Is the outlet structure clogged?

Like an inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the wet vault or proprietary device. If the outlet structure is partially or completely clogged, the treatment rate may be limited and stormwater runoff may not pass through the wet vault or proprietary device quickly, resulting in potential flooding of surrounding areas or conveyance systems, or untreated stormwater runoff bypassing the wet vault or proprietary device. Any obstructions should be removed immediately to ensure proper operation of the wet vault or proprietary device.

8) Is the outlet structure askew or misaligned?

Misaligned outlet structures often allow stormwater runoff to enter or exit a wet vault or proprietary device by means other than those intended by design or prevent stormwater runoff from entering the wet vault or proprietary device at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Outlet structures can become misaligned for several reasons, including frost heave of the soil and geotechnical failure. Misaligned outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact.

9) Is there evidence of any of the following downstream of the outlet structure:

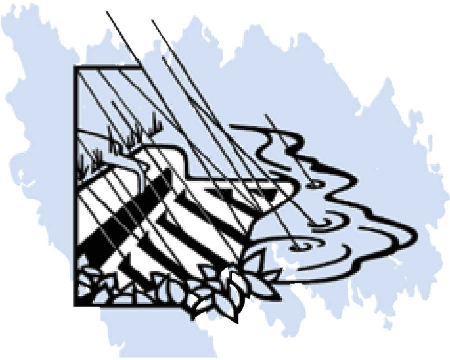
Conditions downstream of a wet vault or proprietary device can provide evidence of the function of the practice itself. Properly sized and functioning wet vaults or proprietary devices should remove most sand-sized particles (0.125 to 2 mm) from stormwater runoff. Sediment deposition downstream of a wet vault or proprietary device indicates that erosion is occurring between the wet vault or proprietary device and the sediment deposition or that sediments are present in the wet vault or proprietary device effluent. The sediment storage capacity of the wet vault or proprietary device may have been reached and maintenance may be required to remove captured sediments.

Erosion downstream of a wet vault or proprietary device indicates that flow velocities are larger than the conveyance channel can withstand. The conveyance channel should be resized to accommodate the amount of flow exiting the wet vault or proprietary device, or the channel should be augmented with energy dissipaters or riprap to reduce or eliminate the impact of erosion.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html



11.

Biologically Enhanced Practices

A.J. Erickson, B.C. Alseson, J.S. Gulliver (gulli003@umn.edu), R.M. Hozalski

Hot Links

11.1 Biologically Enhanced Processes

Biologically enhanced practices are stormwater BMPs in which vegetation, microbiological activity, or both, play a significant role in pollutant removal. Plants enhance removal of pollutants via uptake (e.g., of nutrients) or by providing surfaces for sorption (e.g., of organic chemicals) and deposition (e.g., of particles). Microorganisms remove pollutants such as petroleum hydrocarbons primarily by biodegradation. Nevertheless, the physical-chemical processes of filtration, sedimentation, and sorption are typically significant contributors to pollutant removal in biologically enhanced practices. In addition to removing pollutants, the vegetation in biologically enhanced practices may aid in reducing peak flow and runoff volume through transpiration. Biologically enhanced practices include bioretention practices (rain gardens), constructed wetlands, filter strips, and swales.

Erickson, A., B. Alseson, J. S. Gulliver, and R. Hozalski. 2007. Biologically enhanced practices. In *Assessment of Stormwater Best Management Practices,* ed. J. S. Gulliver and J.L. Anderson. St Paul, MN: University of Minnesota.

11.2 Biologically Enhanced Practices

11.2.1 Bioretention practices (rain gardens)

Bioretention practices or rain gardens are low lying areas, natural or excavated, that are planted with vegetation and receive stormwater runoff from nearby impervious surfaces via stormwater conveyances, such as curb cuts, as shown in figures 11.1, 11.2 and 11.3. The collected stormwater exits the rain garden primarily via infiltration, reducing runoff volume and recharging groundwater. Some rain gardens, however, are equipped with underdrains. Such rain gardens are constructed by excavating the soil, placing a drain tile or perforated pipe collection system at the bottom, backfilling with high permeability soil, and then planting with vegetation (figure 11.4). Underdrains are typically required in a rain garden if the infiltration rate of the underlying soil is too low to drain the design storm

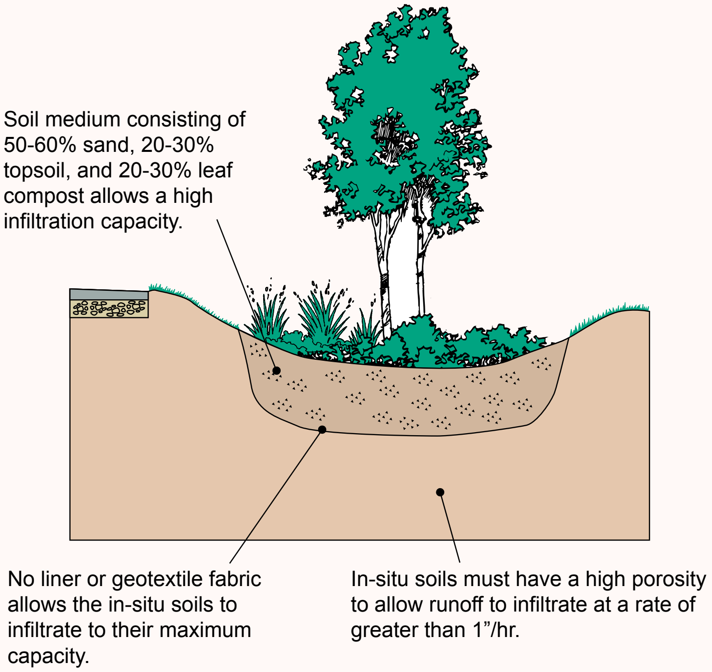


Figure 11.1: Typical rain garden cross-section. (Prince George’s County 2002)

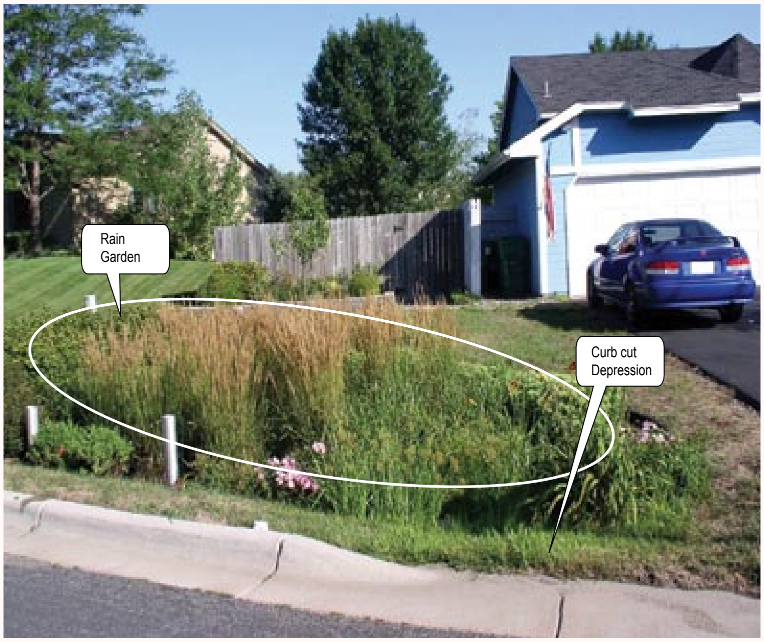


Figure 11.2: Example of rain garden with curb cut. (Burnsville, MN)

Figure 11.3: Example of a rain garden. (Cottage Grove, MN)

volume within 48 hours (Minnesota Stormwater Steering Committee 2005) or if infiltration is not desired. In rain gardens with underdrains, the filtered water captured by the drain tile or perforated pipe collection system is then delivered to a subsequent stormwater BMP (e.g., wetland or pond) or directly to receiving waters.

Rain garden vegetation is selected to tolerate intermittent submergence and to be aesthetically pleasing. In EPA Region 5 (Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin), most rain gardens will typically contain vegetation listed in the publication "Plants for Stormwater Design: Species Selection for the Upper Midwest" (Shaw and Schmidt 2003). For more detailed information on bioretention practices and variations in design, see The Minnesota Stormwater Manual (Minnesota Stormwater Steering Committee 2005) or The Prince George's County Bioretention Manual (Prince George's County 2002).

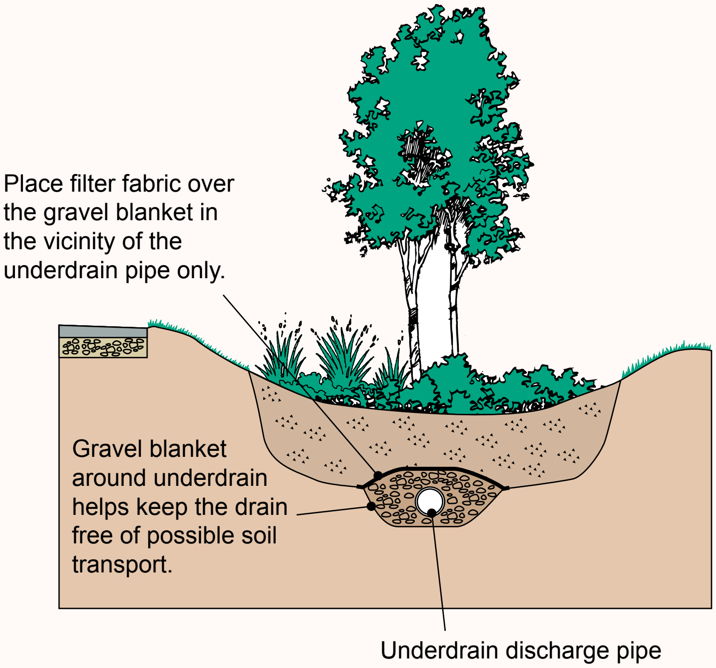


Figure 11.4: Typical engineered bioretention system cross-section. (Prince George's County 2002)

11.2.2 Constructed wetlands

Wetlands are lowland areas where the groundwater level is higher than the ground surface elevation such that persistent shallow pools are present. Constructed wetlands are stormwater BMPs designed to mimic natural wetlands. Shallow pools, vegetation, and microorganisms remove pollutants from stormwater runoff through sedimentation, filtration, and biodegradation, respectively. Plants can also take up pollutants such as nutrients and store them in the wetland by converting them to plant biomass. Constructed wetlands are typically designed with a surface area of 3 to 5 % of the watershed impervious area (U.S. EPA. 1999).

Constructed wetlands reduce runoff peak flow by temporarily storing stormwater runoff. Runoff volume is reduced by evapotranspiration, but due to the high water table, infiltration is usually not significant. On average, constructed wetlands in the United States retain 68% of total suspended solids (67% confidence interval of ± 25%) and 42% of total phosphorus (± 26%, Weiss *et al.* 2005). These average values fall within the ranges reported by the U.S. EPA. (1999) of 50%–80% for total suspended solids and 15%–45% for total phosphorus.

Constructed wetlands require regular maintenance to remain effective. For example, constructed wetlands can lose their capacity to remove phosphorus over time (Oberts 1999) which may be attributable to vegetation reaching a maximum density (Faulkner and Richardson 1991) or to the soils reaching a maximum sorption capacity. Furthermore, overabundant and decaying vegetation can become a source of soluble and particulate phosphorus that may be released with the effluent. While regularly harvesting wetland vegetation to 'remove' phosphorus from the wetland system appears to be the logical solution, research has shown that only minimal amounts of phosphorus are removed when wetland vegetation is harvested (Kadlec and Knight 1996). Eventually, reconstruction may be required for the constructed wetland to remain effective at retaining pollutants.

11.2.3 Swales and filter strips

Swales are vegetated canals or trenches used to convey stormwater runoff while allowing solids to settle, and to filter suspended solids with vegetation. During conveyance, infiltration into the swale side and bottom may also occur. Swales may also be called ditches, grassed channels, dry swales, vegetated swales, wet swales, biofilters, or bioswales. Permeable structures (e.g., check dams) are sometimes installed in swales to reduce flow velocities, which increases filtration by vegetation and settling. Filter strips and grassed swales are typically designed with a surface area of 10 to 20 % of the watershed impervious area. Refer to the Minnesota Stormwater Manual (Minnesota Stormwater Steering Committee 2005) for guidance on design and installation of swales.

Filter strips are vegetated areas specifically designed and positioned for overland sheet flow conveyance of stormwater runoff. The vegetation filters particulate pollutants and reduces runoff velocities, which allows for more infiltration to occur. Filter strips may also be called buffer strips or buffers. Sheet flow is required for filter strips to effectively treat stormwater runoff. See the Minnesota Stormwater Manual (Minnesota Stormwater Steering Committee 2005) for guidance on design and installation of filter strips.

On average, filter strips/grassed swales in the United States retain 75% of total suspended solids (67% confidence interval of ± 20%) and 41% of total phosphorus (± 33%, Weiss *et al.* 2005). The average value reported by Weiss et al. (2005) for total suspended solids falls within the range of 50%–80% reported by the U.S. EPA. (1999), but the mean value for total phosphorus is lower than the range of 50%–80%.

11.3 Biological considerations by level of assessment

The purpose of this section is to discuss assessment considerations specific to biologically enhanced practices. Chapter 3 (Developing an Assessment Program) provides relevant background information.

11.3.1 Visual inspection

Visual inspection, or level 1 assessment, of biologically enhanced practices primarily focuses on the vegetation (species, condition, abundance, etc.). The species found in the BMP and their condition and abundance can provide visual clues as to the functionality of the practice. For example, abundant terrestrial vegetation in a rain garden indicates adequate soil moisture and quick drainage of stored runoff. Conversely, standing water and wetland vegetation (cattails, water lilies, etc.), or no vegetation at all in a bioretention practice shows that stormwater runoff does not infiltrate in the amount of time for which the BMP was designed, if at all. See the standard procedures at the end of this chapter for detailed instructions about visual inspection of biologically enhanced practices.

Bioretention practices (rain gardens)

According to the Minnesota Stormwater Manual, bioretention practices are required to drain within 48 hours. This requirement should be considered along with the time of the last rain event when conducting a visual inspection of the site. When standing water is observed more than 48 hours after the last rain event, further evaluation of the site should be conducted to determine potential causes of failure. Vegetation specified in the design of the bioretention practice should be documented in the original plant design plan with photographs or videos, if possible. After the vegetation has become established, it should cover most of the basin. Annual photo or video records of the vegetation can be used to keep track of changes in health and migration of the plant species with respect to time. Annual photo or video records can also be used to document effects of channelization, sedimentation, and erosion. Plant guides are available that identify vegetation appropriate for stormwater practices, such as “Plants for Stormwater Design: Species Selection for the Upper Midwest” (Shaw and Schmidt 2003). The vegetation present in the rain garden should be evaluated based on health, density, abundance, and location. Observations should also be made about the presence of weeds or invasive plants and wetland plant species, as these plants are undesirable for rain gardens. If the bioretention practice does not sustain vegetation, the reason may be that the soils are retaining water for excessive periods of time, the vegetation is not getting sufficient water, the soil has been compacted and is limiting root growth, or that the plants were killed by introduction of toxic substances (e.g., road salt, herbicides). When the evaluation of the vegetation indicates unsuccessful vegetation, the ideal conditions for each species should be examined and the soil properties (i.e., texture, compaction, sediment accumulation) should be investigated to determine the cause. If, after completion of the visual inspection, the potential cause(s) of failure are not determined, then further assessment (i.e., level 2 or higher) may be required.

It is also recommended that the soil profile be inspected for soil properties, including texture, color, moisture, and bulk density. Standard procedures for determining these parameters can be found in Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1— Physical and Mineralogical Methods (Klute 1986).

The soil comprises three phases: the soil matrix (solid phase), the soil solution (liquid phase), and the soil atmosphere (gaseous phase). The volume and mass relationships among these phases, along with some basic parameters, are useful to characterize the physical characteristics of the soil. The most common parameters used to understand the soil matrix are porosity, bulk density, and water content (Hillel 1998). The porosity, or amount of pore space present in the soil, is important for the soil's capacity to infiltrate water. The textural class of a soil, although not a direct measure of soil porosity or permeability, allows for the estimation of both porosity and bulk density. Soil texture is based on the particle size distribution of sand, silt, and clay, and soil is assigned to a class based on the relative amounts of each. Sieving can be used to determine the amount and distribution of sand particles, and pipetting or hydrometer analysis can be used to separate silts and clays. For more information on particle size analysis, refer to Methods of Soil Analysis (Klute 1986). The classification of a given soil can be determined by finding the intersection of the percent of sand, silt, and clay lines in the USDA textural triangle, as shown in figure 11.5. Alternatively, a field procedure for determining soil texture based on feel (Wheeler and Wittwer undated) is provided in figure 11.6. Over the last 15 years, there have been several efforts to classify saturated hydraulic conductivity of the soil according to textural classes (Rawls et al. 1998). Table 11.1 is a table of saturated hydraulic conductivity based on USDA soil texture from various authors. Please note that each textural class has a range of possible values, and this table represents the average.

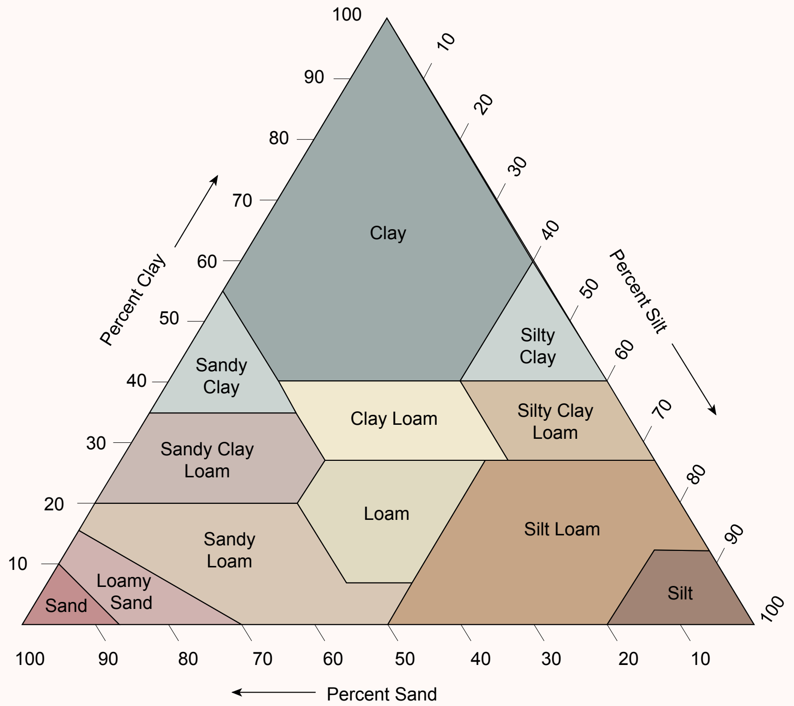


Figure 11.5: The percentage of sand, silt, and clay in the basic textural classes. (Source: USDA Soil Textural Triangle courtesy of United States Department of Agriculture, Natural Resources Conservation Service).

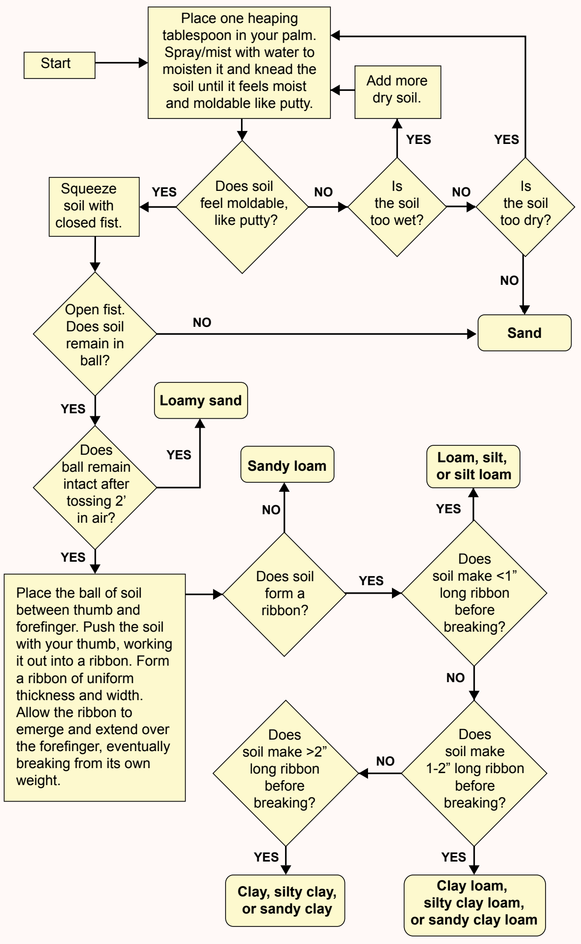


Figure 11.6: Field Method for Soil Texturing (Thien 1979)

Table 11.1. Ranges of saturated hydraulic conductivity (K_{sat}) and porosity for the USDA soil textural classes (Clapp and Hornberger, 1978; Rawls et al., 1998; Saxton and Rawls, 2005)

	(Saxton and Rawls 2005)[1]		(Rawls *et al*. 1998)		(Clapp and Hornberger 1978)	
USDA Soil Textural Class	K_{sat} (ft/h)	Porosity (m^3/m^3)	K_{sat} (ft/h)	Porosity (m^3/m^3)	K_{sat} (ft/h)	Porosity (m^3/m^3)
Sand	0.5091–0.3058	0.48–0.46	0.5965–0.3000	0.44–0.39	0.9732	0.40
Loamy Sand	0.4464–0.1638	0.47–0.44	0.4039–0.1358	0.45–0.37	0.4783	0.44
Sandy Loam	0.3553–0.0744	0.47–0.42	0.1831–0.0425	0.47–0.37	0.1453	0.44
Loam	0.0271–0.1538	0.48–0.46	0.0130–0.0201	0.47–0.39	0.0331	0.45
Silt Loam	0.0402–0.2126	0.48–0.46	0.0472–0.0106	0.49-0.39	0.0083	0.49
Silt	0.0425–0.1068	0.49–0.47	–	–	–	–
Sandy Clay Loam	0.0128–0.0653	0.45–0.42	0.0248–0.0094	0.44–0.37	0.0296	0.42
Clay Loam	0.0122–0.0256	0.50–0.45	0.0142–0.0024	0.48–0.40	0.0083	0.48
Silty Clay Loam	0.0183–0.0252	0.53–0.49	0.0118–0.0165	0.50-0.43	0.0024	0.48
Sandy Clay	0.0003–0.0088	0.46–0.43	0.0035	0.39	0.0035	0.43
Silty Clay	0.0115-0.0118	0.55–0.50	0.0059	0.53	0.0012	0.49
Clay	0.0103–0.0056	0.56–0.46	0.0071–0.0060	0.48-0.40	0.0071	0.48

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[1] *Assuming 2.5% organic matter content and normal compaction*

The soil profile should be examined for hydric soils, degree of saturation, compaction, and sediment accumulation because each will negatively impact infiltration. Hydric soils are formed when anaerobic conditions develop in the root zone due to flooding or ponding during the growing season (Richardson and Vepraskas 2001); they are often found in constructed wetlands or wet ponds. Hydric soils can be identified in the field by the gray color of the soil and the presence of mottles. The gray color indicates a process of "gleying," which includes the chemical reduction of iron or manganese. Mottles, also called redoximorphic features, consist of small areas that differ in color (gray, red, yellow, brown, or black) from the soil matrix because of water saturation and chemical reduction. Reddish mottles, for example, are due to the accumulation of iron oxides in root channels or large pore spaces, and black mottles indicate the accumulation of manganese oxides (Richardson and Vepraskas 2001). Hydric soils are evidence of prolonged water saturation, indicating that stormwater runoff is not infiltrating. For more information on identifying hydric soils, refer to "Wetland Soils: Genesis, Hydrology, Landscapes, and Classification" (Richardson and Vepraskas 2001).

Soil moisture can be measured using the gravimetric method (Klute 1986) or with a capacitance probe. Alternatively, visual (and tactile) assessment of the soil moisture can be made and the soil described as dry, moist, saturated, or inundated. Prolonged saturation of the soil promotes the formation of hydric soils, while overly dry soils can inhibit plant growth. Bulk density is the ratio of the mass of solids to the total soil volume and is used to convert gravimetric moisture content to volumetric moisture content, to calculate porosity and void ratio for a known particle density, and to gauge the degree of compaction (Hillel 1998). Methods for measuring bulk density can be found in Methods of Soil Analysis (Klute 1986). Soil compaction reduces infiltration rates by reducing the pore space available for water transmission. Soils in bioretention practices can become compacted during construction. Post-construction soil compaction does not typically occur in bioretention practices unless heavy machinery is used for maintenance or redevelopment of the practice or surrounding areas. The degree of soil compaction is reflected in its bulk density, which can be measured directly using digital or analog soil penetrometers, the sand cone test (ASTM D1556-90), nuclear density meters (ASTM D2292-91), or other means.

Adverse sediment accumulation is evidenced by "sandbars," areas in which sediment deposition covers or chokes out established or developing vegetation. Sediment accumulation can reduce infiltration rates and stormwater storage capacity. The site should also be examined for erosion occurring near inlets or along the side slopes, as this material will likely be deposited in the bioretention practice. A detailed visual inspection checklist for bioretention practices can be found at the end of this chapter and in appendix B.

Constructed wetlands

Vegetation in constructed wetlands should be well established and diverse unless the wetland has been operating for less than two growing seasons. Visual inspection of constructed wetlands should include the areas around the inlet and outlet structures to ensure that vegetation is not being damaged by high velocity flows or by clogging. If there is a lack of vegetation or if vegetation is "washed over" at the inlet, installing riprap or another energy dissipater may allow vegetation to become established near the inlet, which will increase the treatment area within the wetland. Additionally, if solids are rapidly accumulating in the wetland, maintenance should be scheduled to remove the solids to maintain the desired stormwater residence time and corresponding pollutant removal efficiency. Alternatively, level 2 (capacity testing for sedimentation) or level 3 (synthetic runoff testing with a conservative tracer) assessment could be used to assess sediment accumulation in a constructed wetland.

Filter strips and swales

Vegetation in filter strips and swales should be well established and consistent throughout the filter strip or swale. The flow will find the path of least resistance, which will likely occur at gaps in the vegetation. Erosion and channelization are visual clues that the filter strip or swale is not functioning properly and requires maintenance or repair. Additionally, excess solids deposited in filter strips or swales can choke out vegetation, prevent new growth, and become resuspended during large storm events. If excess deposition occurs, pretreatment systems could be installed, or a periodic maintenance schedule could be established, to remove excess solids.

11.3.2 Capacity testing

Capacity testing, or level 2 assessment, can be used to assess infiltration rates or available sediment storage capacity of biologically enhanced practices. Permeability tests for biologically enhanced practices are applicable to bioretention practices, filter strips, and most swales. Sediment retention tests are applicable to constructed wetlands because they are often designed to remove large quantities of sediment. Simple visual evidence of sediment accumulation in rain gardens, filter strips, or swales indicates that the practice needs maintenance. A pre-treatment system, such as erosion control, street sweeping, or a sedimentation forebay could also be considered. Annual sediment retention tests for constructed wetlands, however, are useful for determining the sediment accumulation rate and the remaining capacity available for sediment storage.

Bioretention practices (rain gardens)

The Minnesota Stormwater Manual (Minnesota Stormwater Steering Committee 2005) states that bioretention facilities should be designed to draw down their storage volume (design storm volume) in less than 48 hours. If a bioretention practice does not infiltrate the design storm volume in less than 48 hours, the soil media may be clogged. Clogged media may cause flooding of surrounding areas or force untreated stormwater to bypass the bioretention facility. Conversely, if the design storm volume drains in less than six hours, macropores or preferential flow paths may be present. Macropores can short-circuit the filtration process, passing untreated (or minimally treated) stormwater directly to the effluent structures or to groundwater.

Permeability testing throughout the bioretention practice can be used to asses the spatial range of infiltration rates and to identify areas of low or high permeability. A permeameter should be chosen and used throughout the bioretention practice (appendix B) to estimate its permeability. Measured permeability for the rain garden should be compared to design specifications to determine if the rain garden is performing effectively. If the design specifications are not available, the measured infiltration rate should be used to estimate the drain time of the design storage volume to see if it is less than 48 hours, as demonstrated in example 11.1. The infiltration rate should be measured periodically (e.g., annually) to determine if the rain garden performance is stable or decreasing significantly.

Constructed wetlands

Sediment retention tests can be performed on a wetland to estimate the depth, and subsequently, volume, of sediment retained in the BMP. Sediment surface elevations in a wetland are measured either with a level and level rod (from a boat) or with a sonar depth measurement device. The water surface can be used as a local elevation standard if a staff gauge has been installed in the pond to measure water surface elevation. Sonar depth measurements can be made in the winter when the wetland is covered with a layer of ice that is strong enough to walk on safely, or in the summer using waders or a boat. Corresponding longitude and latitude are recorded either with GPS or a total station. The amount of sediment retained in the stormwater BMP can be estimated from the measured basin topography and the original basin topography (from as-built plans or design drawings). The amount of retained sediment can be compared to the design capacity to determine the available sediment retention capacity and to estimate when the BMP will require maintenance (i.e., sediment cleanout). These capacity tests should also be performed following construction to develop as-built plans.

Filter strips and swales

Filter strips and swales rarely maintain standing water because they are designed for stormwater conveyance and not stormwater storage. Nevertheless, perme-

Example 11.1: Estimating drain time for a rain garden without design specifications

A bioretention practice was installed ten years ago in a residential park and receives stormwater runoff through a curb cut in the adjacent street. A municipal engineering intern, Rob, has been asked to determine whether the rain garden is functioning appropriately, but he does not have any of the design specifications. Rob visits the site and determines that the rain garden is approximately 25 feet long by 10 feet wide (7.62m x 3.05 m) at the top and can hold a maximum depth of 15 inches (38.1 cm) of stormwater runoff. Rob assumes the shape of the depression can be approximated by a prism. Rob also uses a modified Philip-Dunne permeameter to estimate the overall saturated hydraulic conductivity of the rain garden to be 0.379 ft/day (0.00013 cm/sec).

Back at the office, Rob calculates the stormwater storage volume to be approximated by the volume of a prism (*V = 1/2 x b x w x h, where V = volume, b = base, w = width, and h = height*) with a base of 25 ft, width of 10 ft, and a height of 1.25 ft (.381 m). Therefore, the storage volume of the rain garden is approximately 156 ft^3 (4,417.4 liters). Rob assumes the infiltrating surface area of the rain garden is the same as the top surface area *(25 ft x 10 ft = 250 ft^2 (23.22 m^2))* and that infiltration rate is equal to the saturated hydraulic conductivity. Therefore, the infiltration discharge rate (volume/time) is simply the product of the surface area (*length*^{2}) and the infiltration rate (length/time). The infiltration discharge rate is *250 ft^2 x 0.379 ft/day = 95 ft^3/day (2.69 m^3/day).*

Rob can then develop a rough estimate of the rain garden drain time by dividing the stormwater storage volume (*156 ft^3*) by the infiltration discharge rate (*95 ft^3/day*), which results in 1.6 days. Design recommends that rain gardens drain within 48 hours and the rain garden drains the maximum storage volume in 1.6 days. Therefore Rob concludes that the rain garden is functioning properly.

NOTE: This example illustrates a process but may not represent typical results.

ability tests can be used on filter strips and swales to determine the stormwater infiltration rate. Some filter strips and swales have berms or check dams to reduce flow velocities and store stormwater runoff temporarily, which increases sedimentation and infiltration. Permeability tests should be focused on the locations where infiltration occurs, or is likely to occur based on the design, such as upstream of a berm or check dam.

11.3.3 Synthetic runoff testing

Synthetic runoff testing, or level 3 assessment, involves the application of synthetic stormwater runoff to biologically enhanced practices to assess stormwater infiltration rate, pollutant removal efficiency, or both. The reductions in peak flow and runoff volume can be estimated from the infiltration rate, specified storm intensity and duration, and watershed characteristics. Synthetic runoff testing can be applied to bioretention, constructed wetlands, filter strips, and swales (provided adequate access and water supply is available).

Bioretention practices (rain gardens)

Synthetic runoff testing of bioretention practices to determine the drain time involves filling the bioretention practice with synthetic stormwater and measuring the change in head (i.e., water level) with respect to time. If underdrains and a suitable outlet structure are present, pollutant removal efficiency can be determined by adding a pollutant (or multiple pollutants) to the synthetic stormwater and measuring the pollutant concentration in the effluent (i.e., from the subsurface underdrain or collection system). For drain time testing, the flow rate of the water source (e.g., fire hydrant, water truck) should be significantly greater than the rate water infiltrates into the soil so that the bioretention practice can be filled to the design storm volume in less than 1 hour. If, however, the flow rate of the water source is not sufficient to fill the bioretention practice in a reasonable amount of time, pollutant removal efficiency can still be determined. In this case, it can be assumed that the infiltration rate (units = length/time) is equal to or greater than the water source discharge rate (units = volume/time) divided by the infiltration area.

Determination of the required flow rate and total volume of water for synthetic runoff testing is given in example 11.2. In order to determine the flow rate and volume of water needed for level 3 testing, an estimate of the infiltration rate is needed. Infiltration rates are best determined from permeability tests on the same stormwater BMP (level 2 assessment) or can be estimated from other relevant information about the BMP (e.g., soil type, surface characteristics). Typical saturated hydraulic conductivities for unconsolidated sediments, which can be used to approximate infiltration rates, range from 30–3000 ft/day (0.01 to 1 cm/s) for well-sorted gravels, to 0.3–0.003 ft/day (10^{-4} to 10^{-6} cm/s) for silt, sandy silts, clayey sands, and till (Fetter 2001).

The relationship between total infiltration discharge (cfs) and stormwater BMP surface area (ft^2) for various infiltration rates (in/hr) is shown in figure 11.7. The relationship between the required synthetic runoff flow rate (cfs) and the infiltration discharge for various ratios of water quality volume (ft^3) and desired fill time (hr) is shown in figure 11.8.

Figures 11.7 and 11.8 can be used together to estimate the required water supply flow rate for synthetic runoff.

Example 11.2 can also be solved using figures 11.7 and 11.8. From figure 11.7, a pond with an estimated infiltration rate of 3.0 in/hr (0.002 cm/s) and a surface area of 1634 ft^2 (151.8 m^2) will infiltrate approximately 0.11 cfs (0.003 m^3/s). From figure 11.8, an infiltration discharge of 0.11 cfs and a water volume to desired fill time ratio of 1634 ft^3/hr (i.e., WQV/t_{fill} = 3,864 ft^3/1.0 hr) would require a synthetic runoff flow rate of approximately 0.5 cfs (0.014 m^3/s). For comparison, a typical fire hydrant can produce between 2 and 4 cfs (0.057–0.113 m^3/s) for up to approximately 30 minutes. If the water supply used for synthetic runoff testing cannot produce the required flow, the fill time

Example 11.2: Synthetic runoff testing flow requirement calculation

A 41 ft by 46 ft (12.50 m x 14.02 m) bioretention practice with 3:1 side slopes is designed for a water quality volume of 1634 ft^3 (46,269.7 liters) at a maximum depth of 1 foot (0.305) m. Based on data from a previous simulated runoff test, the infiltration rate is expected to be around 3.0 in/hr (0.002 cm/s). Determine the required flow rate and total volume of water that must be supplied if the pond is to be filled to its WQV in one hour.

Solution

Determine the approximate overall volumetric flow rate of water that will infiltrate into the ground when the stormwater BMP is being filled. If the 41 ft by 46 ft dimensions of the pond are the water surface dimensions when the pond contains the water quality volume (i.e., at 1 ft depth), then the average surface area of the pond can be estimated by determining the surface area when the pond is 0.5 ft deep. At a depth of 0.5 ft and not accounting for the corners, the water surface dimensions are (41 – 0.5(3)(2)) by (46 – 0.5(3)(2)), where each dimension is reduced by the change in depth (i.e., 0.5 ft) multiplied by the side slope (i.e., 3:1) and the 2 accounts for there being two opposing sides in each dimension. This gives a water surface area of 38 ft by 43 ft (11.58 m x 13.11 m), which is equal to 1634 ft^2 (151.8 m^2).

$$Total\ Flow\ Rate\ Infiltrating = 3.0\ \frac{in}{hr}\ x\ \frac{1\ ft}{12\ in}\ x\ 1634\ ft^2\ x\ \frac{1\ hr}{3600\ sec} = 0.113\ cfs\ (0.003\ m^3/s)$$

As the stormwater BMP is being filled, it can be assumed that 0.113 cubic feet of water per second will be leaving the stormwater BMP through infiltration. Performing a mass balance on water in the stormwater BMP gives:

$$\Delta Storage\ within\ BMP = (Rate\ of\ Flow\ In)\Delta t - (Rate\ of\ Flow\ Out)\Delta t$$

Where the ΔStorage within the stormwater BMP is the design water quality volume (if the stormwater BMP is initially empty), Δt is the desired fill time, the Rate of Flow Out is the total flow rate infiltrating (i.e., 0.113 cfs), and the Rate of Flow In is the required flow of the water supply. Substituting the appropriate numerical values gives:

$$1634\ ft^3 = (Required\ Flow)(3600\ sec) - \left(0.113\frac{ft^3}{s}\right)(3600\ sec)$$

Solving for the only unknown, the Required Flow can be determined to be 0.567 ft^3/s (0.016 m^3/s).

The total water volume required is (0.567 ft^3/s) x (3600 sec) = 2042.5 ft^3 (57,837.2 liters).

NOTE: This example illustrates a process but may not represent typical results.

may need to be increased or the flow augmented (i.e., pump truck or multiple hydrants). The total volume of water required can be determined as shown in the last calculation of example 11.2. The total volume of water required must not exceed the limitations of the available water source. Finally, the amount of time required to fill the stormwater BMP can be calculated from a given water supply flow rate.

The measured drain time for the rain garden should be compared to design specifications to determine if the rain garden is performing effectively. The drain time should be measured periodically to determine if the rain garden performance is stable or decreasing significantly.

The pollutant removal efficiency of a bioretention practice can be estimated by adding a pollutant (e.g., sediment or phosphorus) to the synthetic stormwater and then measuring the concentration of pollutant exiting the bioretention practice (if the practice has a subsurface pipe collection system for sampling). The accuracy of these tests is limited by difficulties in achieving a representative pollutant concentration through sampling. Appendix D indicates that automatic sampling of stormwater for suspended solids analysis is a difficulty for inorganic solids that are the size of coarse silts and larger. After infiltration through the soil, however, the size distribution of the remaining suspended solids may be below the problematic range. Erosion control must be considered prior to synthetic runoff testing of a bioretention practice. Inflow structures (i.e., curb cut or storm sewer outlet) should be used when available and appropriate to reduce erosion while simulating a runoff event. Sandbags, rocks, or other flow dissipation devices should be used to prevent erosion of the soil and vegetation.

As discussed in chapter 3, synthetic runoff testing (level 3) requires more ‘relative effort’ than capacity testing (level 2) for most stormwater BMPs and situations. For bioretention practices, however, it might require less

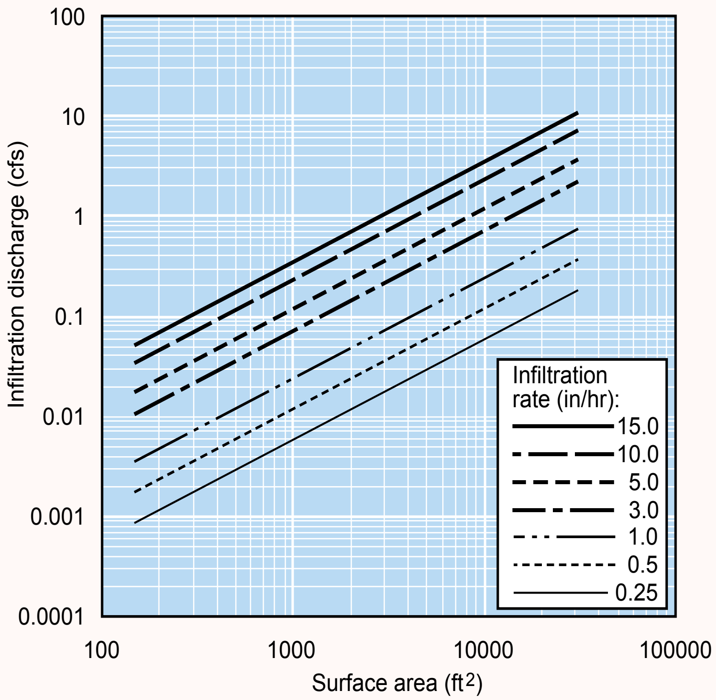

Figure 11.7: Determining infiltration discharge. For a given infiltration rate and surface area, the discharge of infiltration can be determined for use in figure 11.8. [One cfs = 0.028 m^3/s; one foot squared =0.093 meters squared; one in/hr = 7.06 x 10^{-4} cm/s.]

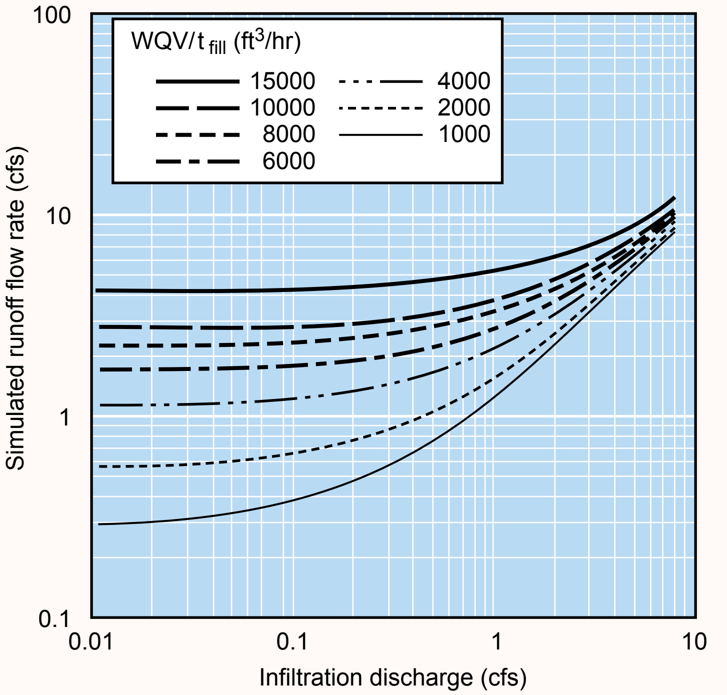

Figure 11.8: The required flow rate for simulated runoff testing can be calculated by taking the water quality volume and dividing by the desired fill time to determine the correct line. The intercept with the infiltration discharge from figure 11.7 will provide the required simulated runoff flow rate. [One cfs = 0.028 m^3/s; one ft^3/hr = 0.028 m^3/hr.]

relative effort to perform a level 3 assessment than a level 2 assessment, as long as a water source is available. In other words, in many cases it may be easier and less time consuming to flood a bioretention practice and measure the change in water level (i.e., ponded depth) with respect to time than to perform multiple point infiltration measurements.

The results of a level 2 assessment of a bioretention practice will, however, produce more specific information than a level 3 assessment because level 2 assessment can be used to guide localized maintenance within a bioretention practice. For example, level 3 assessment of a bioretention practice may indicate that the practice is able to drain a synthetic storm event that is equivalent to the water quality volume in less than 24 hours and is therefore functioning as designed. A level 2 assessment, however, may indicate that 40% of the bioretention practice is *not* infiltrating water and the remaining 60% is infiltrating water faster than the overall average infiltration rate determined from the synthetic runoff test. Furthermore, the level 2 assessment would indicate where in the bioretention practice the low permeability areas are located. The organization that is responsible for maintenance of the bioretention practice can then conduct localized maintenance on the areas that are clogged to rejuvenate the practice to design conditions *before* the entire bioretention practice fails.

Constructed wetlands

Synthetic runoff testing of constructed wetlands can be used to estimate the removal of pollutants by adding a pollutant (e.g., sediment or phosphorus) to the synthetic stormwater and then measuring the concentration of pollutant exiting the wetland. The accuracy of these tests is limited by difficulties in achieving a representative pollutant concentration through sampling, which depends upon the size distribution of inorganic solids in the outflow (see appendix D).

Synthetic runoff tests using a conservative tracer (e.g., chloride, rhodamine, etc.) can be used to investigate the hydraulic behavior of a wetland. These studies involve adding a tracer to the influent and measuring the tracer concentration at the effluent during a synthetic runoff event. Results from tracer studies can be used to determine if stormwater is short circuiting through the wetland, if there are dead zones that do not participate in significant pollutant removal, or if the stormwater wetland is operating as designed. Short circuiting is a significant problem that may result in poor pollutant removal efficiency because pollutant removal efficiency is typically proportional to residence time in the system. An example of using a tracer study to determine the hydraulic characteristics of a wet pond is given in chapter 10, example 10.2. The same procedure would be followed in a constructed wetland, with the appropriate tracer.

Filter strips and swales

Synthetic runoff testing is not recommended for swales or filter strips because these BMPs typically lack the inlet and outlet flow structures that would allow for discharge measurement (as described in chapter 4) or pollutant sampling (as described in chapter 5).

11.3.4 Monitoring

Monitoring is applicable to all four types of biologically enhanced practices but may be necessary only for constructed wetlands. Bioretention practices, filter strips, and swales are relatively small in size, and required monitoring equipment may be cost prohibitive. For example, bioretention practices that are located in residential areas on private property (i.e., residents' front yards) can range from 500 square feet (46.5 m^2) down to 20 square feet (1.86 m^2), and may occur on 50% or more of the properties on a given street. Monitoring each bioretention practice in this area would be costly in both materials and labor. Wetlands are large by comparison, and their design typically facilitates monitoring.

Bioretention practices (rain gardens)

Monitoring of bioretention practices requires that the practice have a subsurface pipe collection system to allow for effluent measurement and sampling. The United States Geological Survey monitored rain gardens for pollutant removal efficiency using wells and lysimeters for subsurface sample measurement and collection. After two years of monitoring, the wells and lysimeters yielded ten or fewer subsurface samples (Tornes 2005), demonstrating that monitoring bioretention practices without subsurface collection systems can be cost prohibitive and result in minimal conclusive data.

Constructed wetlands

Numerous studies have been published in the literature concerning the assessment of constructed wetlands with monitoring (Maehlum et al. 1995, Kadlec and Knight 1996, Oberts 1999, Carleton et al. 2000, Laber 2000, Bulc and Slak 2003, Farahbakhshazad and Morrison 2003, Farrell 2003). Monitoring is the most comprehensive assessment technique for measuring the hydraulic and pollutant removal effectiveness of a constructed wetland. Runoff volume reduction (by evapotranspiration) can be estimated by comparing the total influent water volume to the total effluent water volume in the water budget for the constructed wetland. It is important to recognize that constructed wetlands typically do not infiltrate stormwater runoff and may receive substantial (> 5%) inflow from direct rainfall due to their large surface areas. Chapter 4 provides guidance and recommendations for measurement components of the water budget. Monitoring constructed wetlands for pollutant removal effectiveness requires that all stormwater inputs and outputs are measured for volume and water quality. Along with chapter 4 (water budget measurement), refer to chapter 5 for guidance on sampling techniques for gathering stormwater samples and chapter 6 for analysis techniques and recommendations. Data from monitoring should be analyzed according to methods described in chapter 12, Data Analysis.

Filter strips and swales

It is not recommended that filter strips and swales be monitored for water quality or hydraulic performance. Filter strips and swales typically lack the inlet and outlet flow structures that would allow for discharge measurement (as described in chapter 4) or pollutant sampling (as described in chapter 5).

11.4 Recommendations

As with other stormwater BMPs, visual inspection is recommended as the first level of assessment. If, based on assessment goals, an assessment of runoff volume reduction potential or remaining sediment storage capacity is warranted, capacity testing is recommended because, as long as the number of test locations is sufficient, this level of assessment provides accurate and location–specific data. Since capacity testing only assesses infiltration rates or volumes of entrained sediment, synthetic runoff testing is recommended for all biologically enhanced stormwater BMPs, except for swales and filter strips, only when pollutant retainment assessment is desired and there is an adequate available water supply. Only when capacity testing and synthetic runoff testing are not feasible or do not meet desired assessment goals and the stormwater BMP is not a swale or filterstrip, is monitoring recommended. Synthetic runoff testing and monitoring are not recommended for swales and filter strips because these stormwater BMPs do not have well-defined influent and effluent locations, and as a result, it is not possible to determine an accurate water budget or estimation of pollutant load entering and exiting the stormwater BMP.

11.5 References

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Procedures

for Visual Inspection of Stormwater Best Management Practices using Biologically Enhanced Processes

Visual inspection is a rapid assessment procedure for qualitatively evaluating the functionality of a stormwater best management practice (BMP). Visual inspections use a set of criteria that, under certain circumstances (described in chapter 3), determine if the stormwater BMP is malfunctioning. Detailed instructions for visual inspection of biologically enhanced practices are included below and reproduced in appendix B, part 4, which can be easily printed out and taken to the field.

UNIVERSITY OF MINNESOTA
Stormwater Management Practice Assessment Project

Field Data Sheet for Level 1 Assessment: Visual Inspection

Bioretention Practices (including Rain Gardens)

Inspector's Name (s): ______________________________________
Date of Inspection: ____
Location of the Bioretention Practice
    Address or Intersection:____________________________________
    Latitude, Longitude: ____________________________________
Date the rain garden began operation: _________________________
Size of the rain garden (ft^2): _________________________________
Time since last rainfall (hr): _________________________________
Quantity of last rainfall (inches): ____________________________
Rainfall Measurement Location: __________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ______________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action taken and date of action.

____

____

____

____

2) Has it rained within that last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Does this bioretention practice utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don't know

3.a) If yes, please describe.

____

____

____

____

4) Are there multiple inlet structures?

☐ Yes ☐ No

4.a) If yes, how many inlets are present?

2 3 4 5 6 or more

4.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

4.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

5) Is the inlet or outlet structure askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

5.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don't know					
Other					

If Other: ______________________________________

If Other: ______________________________________

If Other: ______________________________________

If Other: ______________________________________

If Other: ______________________________________

6) Is there standing water in the bioretention practice? ☐ Yes ☐ No

6.a) If yes, does the water have:

Surface sheen (from oils/gasoline)

Murky color (from suspended solids)

Green color (from algae or other biological activity)

Other: ______________________________________

7) Is there evidence of illicit storm sewer discharges? ☐ Yes ☐ No

7.a) If yes, please describe: ______________________________

____

____

____

8) Does the bioretention practice smell like gasoline or oil? ☐ Yes ☐ No

9) Is there vegetation in the bottom of the bioretention practice? ☐ Yes ☐ No

9.a) What is the approximate vegetation cover

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

10) Does the current vegetation match the design plan? ☐ Yes ☐ No

10.a) Is there the presence of:

☐ Weeds
☐ Wetland vegetation
☐ Invasive vegetation
☐ None of the above

11) Does the vegetation appear to be healthy? ☐ Yes ☐ No

11.a) If no, please describe: ____________________________________
____
____
____

12) Is the vegetation the appropriate density/size? ☐ Yes ☐ No

12.a) If no, please describe:
____
____
____
____

13) What is the USDA texture of the soil profile and soil color in the basin?

Depth: _____ Texture: ___________ Color: _____
Depth: _____ Texture: ___________ Color: _____
Depth: _____ Texture: ___________ Color: _____
Depth: _____ Texture: ___________ Color: _____

14) Does the soil appear to be saturated? ☐ Yes ☐ No

15) Are there indications of any of the following in the bottom of the bioretention practice?

☐ Sediment deposition
☐ Erosion or channelization
☐ Excessive vegetation (that needs mowing or removal)
litter, large debris, solid waste
☐ Other: ____
☐ None of the above

15.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice
☐ Erosion or channelization outside the practice
☐ Construction site erosion
☐ Other: ______________________________________
☐ I don’t know

16) Does the soil of the bioretention practice appear to be compacted?

☐ Yes ☐ No

16.a) If yes, what is the bulk density of the soil: ________________

17) Is the bottom of the bioretention practice covered with a layer of silts and/or clays?

☐ Yes ☐ No

18) Are there indications of any of the following on the banks of the bioretention practice?

☐ Erosion or channelization
☐ Other: ____
☐ The banks are in good condition

19) Is the overflow or bypass structure clogged?
☐ No ☐ Partially ☐ Completely ☐ Not Applicable

19.a) If yes, what with?
☐ Debris
☐ Sediment
☐ Vegetation
☐ Other: ____

20) Is the overflow or bypass structure askew or misaligned?
☐ Yes ☐ No

20.a) If yes, why?
☐ I don't know
☐ Ice/Frost heave
☐ Other: ____

Other observations:
____
____
____

Inspector's Recommendations:

21) When is maintenance needed?
☐ 5 – Before the next rainfall
☐ 4 – Before the next rainy season
☐ 3 – Possibly after the next season
☐ 2 – Within a year or two
☐ 1 – No sign that any will be required

Additional Comments:
____
____
____
____

Troubleshooting Failure: Visual Inspection

Bioretention Practices

The following sections provide discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within that last 48 hours at this location?

Many bioretention practices are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessment within 48 hours of a rainfall event may provide performance clues. Additionally, rainfall within the last 48 hours at a location will alter the interpretation of answers to other questions.

3) Does this bioretention practice utilize any pretreatment practices upstream?

Pretreatment practices are required by the MPCA in some MS4 construction permits for bioretention practices. If this practice does not have any pretreatment upstream, it may be in violation of this code.

4) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the bioretention practice. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the bioretention practice.

5) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a bioretention practice by means other than those intended by design or prevent stormwater runoff from entering the practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

6) Is there standing water in the bioretention practice?

Standing water in a bioretention practice is the result of one of three possibilities: (1) rainfall has occurred recently such that stormwater runoff has not had 48 hours to infiltrate, (2) the infiltration rate of the bioretention practice is slow such that stormwater runoff does not pass through the bioretention practice within 48 hours, but does pass through the bioretention practice given enough time, or (3) the soil media is clogged and does not allow any stormwater runoff to infiltrate. If it has rained in the last 48 hours (Question 2), then the bioretention practice may be functioning properly and requires additional assessment (level 2 or higher) to determine whether the soil media is clogged. If, however, it has not rained in the last 48 hours, it is likely that the bioretention practice is either option (2) or (3).

Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven not to be illegally discharged into the bioretention practice, then a surface sheen may indicate that stormwater runoff is stored in the bioretention practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. If this is happening, then the bioretention practice is failing. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown et al. 2004).

Stormwater runoff with a murky color is evidence of a large suspended solids concentration that is most likely made up of fine particle sizes such as clays and silts because sand particles settle out of standing water very rapidly (as discussed in Chapter 10: Sedimentation in the *Assessment of Stormwater Best Management Practices Manual*). Stormwater runoff with a murky color can indicate that the watershed is a significant source of fine particle suspended solids, which can quickly clog a bioretention practice. Murky stormwater runoff in a bioretention practice may indicate that stormwater runoff has recently entered the bioretention practice such that fine particles have not had time to settle out.

Stormwater runoff with a green color from algae has been stored in the bioretention practice for a long period of time such that microorganisms have developed. Stormwater runoff is not passing though the bioretention practice properly and therefore the practice is failing.

7) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown et al. 2004) should be consulted for identifying and locating illicit stormwater discharges.

8) Does the bioretention practice smell like gasoline or oil?

If a bioretention practice smells like gasoline or oil it is possible that hydrocarbon substances such as automotive oil or gasoline are being illicitly discharged into the practice or upstream in the watershed. If hydrocarbons are proven not to be illegally discharged into the bioretention practice, then an oil/gasoline smell may indicate that stormwater runoff is stored in the bioretention practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. For more information on identifying, locating, and eliminating illicit discharges, refer to a manual such as Brown et. al. (2004).

9) Is there vegetation in the bottom of the bioretention practice?

Vegetation in the bottom of a bioretention practice is designed to dry out the soil in between storms and to maintain the infiltration effectiveness. Plants can lose 30% of their root structures annually which produces macropores. Macropores in a bioretention practice can increase the infiltration rate of the practice so that more stormwater runoff is infiltrated. Additionally, vegetation can reduce overland flow velocities and can therefore reduce erosion and re-suspension of captured solids.

Vegetation can also be an indication of the drain time of a bioretention practice. Terrestrial vegetation often cannot withstand long periods of inundation, and some cannot withstand short periods of inundation. If a bioretention practice has an abundance of terrestrial vegetation, it is likely that the practice infiltrates stormwater runoff quickly (< 48 hours) and is therefore operating properly. If, however, the bioretention practice has signs of aquatic vegetation or has little vegetation, it is likely the practice is not infiltrating stormwater runoff at all and is therefore failing.

10) Does the current vegetation match the design plan?

Species of vegetation in planting plans for bioretention practices are selected based on desirable characteristics that a particular species of plant may exhibit. During the construction and throughout the operational life of a bioretention practice, the vegetation may deviate from the original design and thus possibly affect the performance of the bioretention practice. If planting designs are available, compare the currently existing vegetation to the vegetation designated in the design plans. Particular things to look for are certain species that are not surviving and/or have disappeared as well as introduction of weeds, wetland vegetation, and/or other invasive vegetation. For guidance on vegetation identification please refer to Plants for Stormwater Design: Species Selection for the Upper Midwest (Schmidt and Shaw, 2003).

11) Does the vegetation appear to be healthy?

The health of vegetation can indicate conditions that may be too wet/dry, too sunny/shady, lack of nutrients, compacted soil, presence of toxic pollutants, etc. The survival of the vegetation is critical to maintaining proper function of a bioretention practice. During the growing season assess the apparent visual health of the vegetation in the bioretention practice. Some indications of unfavorable conditions are: wilted leaves/stem, discoloration of leaves, lack of flowering buds developing, stunted growth, and a decrease in the number of plantings present. For guidance on vegetation identification please refer to Plants for Stormwater Design: Species Selection for the Upper Midwest (Schmidt and Shaw, 2003).

12) Is the vegetation the appropriate density/size?

Under optimal site conditions the vegetation should have an appropriate size and density for that particular species. Under development can be an indication of poor health while over development can hinder the development of other species in the bioretention practice. For guidance on vegetation identification please refer to Plants for Stormwater Design: Species Selection for the Upper Midwest (Schmidt and Shaw, 2003).

13) What is the USDA texture of the soil profile and soil color in the basin?

For bioretention practices to function, hydraulic conditions of the soil must be appropriate. Ideally the soil will have a coarser texture to allow for adequate drainage. Soil texture is determined by the distribution of particle sizes, which are classified as sand, silt, and clay. The USDA Soil Textural Triangle (see Figure 11.5) classifies the soil texture based on the percentage of each particle size class. For a visual inspection of the soil texture it is recommended that the flow chart in figure 11.6 in Chapter 11 of the *Assessment of Stormwater Best Management Practices Manual* be used to classify the soil texture. The texture of subsurface soil layers can influence the hydrology of the bioretention practice and therefore are important to investigate. Color of the soil also aids in the understanding of the subsurface hydrology. When possible use Munsell® Soil Color Charts to accurately determine the soil color. The soil texture can be used to estimate the saturated hydraulic conductivity of the soil by using Figure 11.7.

14) Does the soil appear to be saturated?

More than 48 hours after a storm event surface soil should not be inundated. Soils that are saturated for long periods of time may not be draining properly and creating hydric conditions. Overly dry soils may inhibit plant growth, which is essential to the proper performance of bioretention practices.

15) Are there indications of any of the following in the bottom of the bioretention practice?

Sediment deposition may indicate that pretreatment devices have reached sediment storage capacity, are not efficiently removing settable solids or are not present. Sediment deposition may also indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution. Sediment deposition reduces the bioretention practice surface area available for infiltration and therefore can reduce the stormwater runoff volume that is infiltrated.

Erosion or channelization indicates that flow velocities entering, or in, the bioretention practice are large or that stormwater runoff is entering the practice by means other than those intended by design. In either case, stormwater runoff is not stored in the bioretention practice such that there is significant infiltration in the areas where erosion and channelization are occurring.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in bioretention practices that do not have impermeable surfaces (e.g., concrete). If the surface of the bioretention practices becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the bioretention practices. Vegetation in bioretention practices is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in a bioretention practice are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of bioretention practice by reducing the surface available for infiltrating stormwater runoff.

16) Does the soil of the bioretention practice appear to be compacted?

Heavily compacted soils can inhibit plant root growth as well as restrict water flow through the soil. Visual indications of compaction include visible bare soil that is smooth and hard. For a more accurate indication of the level of soil compaction it is recommended that the soil bulk density be measured. For the standard procedure to measure bulk density see Methods of Soil Analysis, Part 1 – Physical and Mineralogical Methods (Klute, 1986).

17) Is the bottom of the bioretention practice covered with a layer of silts and/or clays?

A visible layer of silts, clays, or both is a likely indication that the bioretention practice is clogged. Bioretention practices collect particles on the surface and in the pore spaces of the soil. Silts, clays, or both present on the surface of the bioretention practice indicates that the pore spaces within the soil are likely filled, or that stormwater runoff is stored in the basin or trench long enough for these fine particles to settle out or for the stored stormwater runoff to evaporate. The bioretention practice is not likely infiltrating stormwater runoff in less than 48 hours as recommended by design guidelines (Minnesota Stormwater Steering Committee 2005).

18) Are there indications of any of the following on the banks of the bioretention practice?

Erosion or channelization on the banks of a bioretention practice indicates that stormwater runoff is entering at a large velocity by means other than those designed. Erosion and channelization on the banks can fill the bioretention practice with sediments from the bank and subsequently reduce the practice's effectiveness by clogging the soil or sealing the surface and reducing the volume available for stormwater storage.

19) Is the overflow or bypass structure clogged?

Bioretention practices typically have overflow structures instead of outlet structures. Outflow for a bioretention practice is intended to go into the soil such that deep percolation or evaporation occurs. The overflow structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the bioretention practice in the event of a large storm event. If the overflow structure is partially or completely clogged, surrounding areas may be flooded by stored stormwater runoff. Any obstructions should be removed immediately to ensure proper operation of the bioretention practice.

20) Is the overflow structure askew or misaligned?

Misaligned inlet or overflow structures often allow stormwater runoff to enter or exit a bioretention practice by means other than those intended by design or prevent stormwater runoff from entering the practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet and overflow structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet or overflow structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

Munsell. 2007. Munsell Soil Color Chart. http://soils.usda.gov/education/resources/k_12/lessons/color/

Shaw, D. and R. Schmidt. 2003. Plants for Stormwater Design: Species Selection for the Upper Midwest. Minnesota Pollution Control Agency, St. Paul, MN.

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Stormwater Management Practice Assessment Project

Field Data Sheet for Level 1 Assessment: Visual Inspection

Constructed Wetlands

Inspector's Name (s): ____
Date of Inspection: ____
Location of the Pond
Address or Intersection: _______________________________________
Latitude, Longitude: ____
Date the constructed wetland began operation: ____________________
Size of the wetland (ft x ft x ft): _____________________________________
Time since last rainfall (hr): ____
Quantity of last rainfall (in): ___________________________________
Rainfall Measurement Location: ___________________________________
Water Surface Elevation____

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____
____
____
____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Does this constructed wetland utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don't know

3.a) If yes, please describe: ____________________________________
____
____
____

4) Are there multiple inlet structures?

☐ Yes ☐ No

4.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

4.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

4.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

5) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

5.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don't know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

6) Is the constructed wetland a multi-cell system?

☐ Yes ☐ No

6.a) If yes, how many cells are present?

☐ 2 cells ☐ 3 cells ☐ 4 or more

7) Is there standing water in the constructed wetland?

☐ Yes ☐ No

7.a) If yes, does the water have:

☐ Surface sheen (from oils/gasoline)

☐ Murky color from suspended solids

☐ Green color from algae or other biological activity

☐ Invasive, tolerant fish species such as carp or shiners

☐ Other: ____

☐ No

8) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

8.a) If yes, please describe: ____

____

____

____

9) Does the constructed wetland smell like gasoline or oil?

☐ Yes ☐ No

10) Is there vegetation in the constructed wetland?

☐ Yes ☐ No

10.a) What is the approximate vegetation cover?

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

11) Are there indications of any of the following in the constructed wetland?

- ☐ Sediment deposition
- ☐ Erosion or channelization
- ☐ Excessive vegetation (that needs mowing or removal)
- ☐ Litter, large debris, solid waste
- ☐ Other: ____
- ☐ No

11.a) If sediment deposition is evident, what is the source?

- ☐ Erosion or channelization inside the practice
- ☐ Erosion or channelization outside the practice
- ☐ Construction site erosion
- ☐ Other: ____
- ☐ I don't know

12) Are there indications of any of the following on the banks of the constructed wetland?

- ☐ Erosion or channelization
- ☐ Other: ____
- ☐ No

13) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

13.a) If yes, what with?

- ☐ Debris
- ☐ Sediment
- ☐ Vegetation
- ☐ Other: ____

14) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

14.a) If yes, why?

☐ I don’t know

☐ Ice/Frost heave

☐ Other: ____

15) Is there evidence of any of the following downstream of the outlet structure:

☐ Sediment deposition

☐ Erosion or Channelization

☐ Other: ____

☐ No

15.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don’t know

Other observations:

____

____

____

____

____

Inspector's Recommendations:

16) When is maintenance needed?

☐ 5 – Before the next rainfall
☐ 4 – Before the next rainy season
☐ 3 – Possibly after the next season
☐ 2 – Within a year or two
☐ 1 – No sign that any will be required

Additional Comments:

Maintenance Recommendations:

Troubleshooting Failure: Visual Inspection

Constructed Wetlands

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many constructed wetlands are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) and return to previous water level within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessing a wetland within 48 hours of a rainfall event may provide performance clues. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Does this constructed wetland utilize any pretreatment practices upstream?

If any pretreatment practices exist they should also be inspected and maintained on a regular basis.

4) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the constructed wetlands. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the constructed wetlands.

5) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit constructed wetlands by means other than those intended by design or prevent stormwater runoff from entering the constructed wetlands at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the constructed wetlands.

6) Is the constructed wetland a multi-cell system?

Constructed wetlands may be designed as multi-cell systems to increase treatment and retention time. It is important to recognize multi-cell systems and perform this visual inspection on *each* of the cells in the system to ensure the entire practice if functioning properly.

7) Is there standing water in the constructed wetland?

Constructed wetlands are designed to have a permanent pool of water. The absence of standing water in constructed wetlands is the result of one of three possibilities: (1) rainfall has not occurred in a length of time such that all stored stormwater runoff has evaporated (i.e., drought conditions), infiltrated, or both, (2) the outlet structure is damaged or malfunctioning such that stormwater runoff is allowed to drain out of the constructed wetlands, or (3) the inlet structure is clogged or misaligned such that stormwater runoff is not entering the constructed wetlands. If it has rained in the last 48 hours (question 2), then the constructed wetlands should have received or will soon receive stormwater runoff and therefore drought conditions are not occurring. If approximately 48 hours has passed since the last rainfall event and standing water is not present in the constructed wetlands, it is likely that possibility (2) or (3) is occurring.

Surface sheen is often caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. Natural and constructed wetlands, however, can produce hydrocarbons through the chemical and biological processes that occur within the wetland. If hydrocarbons are proven not to be illegally discharged into the constructed wetlands, then remediation may be necessary to maintain the water quality of the stored runoff and prevent downstream pollution. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a high suspended solids concentration that is most likely made up of fine particle sizes, such as clays and silts, because sand particles settle out of standing water very rapidly (as discussed in Chapter 10, Sedimentation). Stormwater runoff with a murky color also indicates that the watershed may be a significant source of fine particle suspended solids or that erosion is suspending fine sediments from within the constructed wetlands. Murky color in constructed wetlands further indicates that significant turbulence may be preventing suspended particles from settling. If a rainfall event has occurred in the last 48 hours, this may not be a problem. If rainfall has not occurred in the last 48 hours, murky color may be an indication of illicit discharge.

Stormwater runoff with a green color from algae or biological activity is not uncommon in constructed wetlands. Constructed wetlands with excessive algal or biologically activity may require maintenance to prevent pollution of downstream receiving waters.

Invasive, tolerant fish species like carp (*Cyprinus carpio*) or shiner minnows (*Notropis cornutus*) are indications of poor water quality in the constructed wetlands (low dissolved oxygen, turbid, limited habitat) such that tolerant and invasive species are present. More information should be gathered to determine the cause of the poor water quality, and remediation should be performed.

8) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

9) Does the constructed wetland smell like gasoline or oil?

If constructed wetlands smell like gasoline or oil, it is possible that hydrocarbon substances such as automotive oil or gasoline are being illicitly discharged into the practice or upstream in the watershed. If hydrocarbons are proven not to be illegally discharged into the constructed wetlands, then an oil/gasoline smell may indicate that small amounts of hydrocarbons typically found in stormwater runoff are accumulating in the constructed wetlands. For more information on identifying, locating, and eliminating illicit discharges, refer to a manual such as Brown *et al.* (2004).

10) Is there vegetation in the constructed wetland?

Vegetation in constructed wetlands should be consistent with native or design-specified wetland vegetation. The absence of vegetation anywhere in or around constructed wetlands may be an indication of poor water quality or excessive infiltration that will dry the wetland.

11) Are there indications of any of the following in the constructed wetland?

Sediment deposition may indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution, or that the constructed wetlands have not been recently maintained. Sediment deposition reduces the stormwater storage volume of constructed wetlands and can allow sediments to become resuspended during subsequent storm events.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in constructed wetlands that do not have impermeable surfaces (e.g., concrete). If the surface of the constructed wetlands becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the constructed wetlands. Vegetation in constructed wetlands is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in constructed wetlands are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may reduce the stormwater storage volume and therefore the retention time.

12) Are there indications of any of the following on the banks of the constructed wetland?

Erosion or channelization on the banks of constructed wetlands indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the constructed wetlands with sediments from the bank and subsequently reduce the volume available for stormwater storage and treatment.

13) Is the outlet structure clogged?

Like an inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the constructed wetlands. If the outlet structure is partially or completely clogged, the treatment rate may be limited and stormwater runoff may not pass through the constructed wetlands in less than 48 hours, which can result in flooding or untreated stormwater runoff passing as overflow. Any obstructions should be removed immediately to ensure proper operation of the constructed wetlands.

14) Is the outlet structure askew or misaligned?

Misaligned outlet structures often allow stormwater runoff to enter or exit constructed wetlands by means other than those intended by design or prevent stormwater runoff from entering the constructed wetlands at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Outlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the constructed wetlands.

15) Is there evidence of any of the following downstream of the outlet structure:

Conditions downstream of a constructed wetland can provide evidence of the function of the pond itself. Properly designed and functioning constructed wetlands should remove most sand-size particles (0.125 to 2 mm) from stormwater runoff. Sediment deposition downstream of a constructed wetland indicates that erosion is occurring between the wetland and the sediment deposition or that sediments are present in the wetland effluent. If sediments are present in the effluent such that downstream deposition is occurring, the wetland is likely failing.

Erosion downstream of a filtration practice indicates that flow velocities are larger than the conveyance channel can withstand. The conveyance channel should be resized to accommodate the amount of flow exiting the wet pond, or the channel should be augmented with energy dissipaters or riprap to reduce or eliminate the impact of erosion.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

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Field Data Sheet for Level 1 Assessment: Visual Inspection

Swales and Filter Strips

Inspector's Name (s): ____
Date of Inspection: ____
Location of the Pond
    Address or Intersection: _______________________________________
    Latitude, Longitude: ____
Date the stormwater BMP began operation: __________________________
Size of the practice (ft x ft):_______________________________________
Time since last rainfall (hr): _______________________________________
Quantity of last rainfall (in): _________________________________
Rainfall Measurement Location: _________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Does this swale or filter strip utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don't know

3.a) If yes, please describe: ______________________________________

____

____

____

4) Are there inlet structures associated with this practice?

☐ Yes ☐ No

4.a) If no, proceed to question 7.

5) Are there multiple inlet structures?

☐ Yes ☐ No

5.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

5.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

5.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ____________________
If Other: ____________________
If Other: ____________________
If Other: ____________________
If Other: ____________________

6) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

6.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don't know					
Other					

If Other: ____________________
If Other: ____________________
If Other: ____________________
If Other: ____________________
If Other: ____________________

7) Is there standing water in the swale or filter strip?

☐ Yes ☐ No

8) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

8.a) If yes, please describe: ____

____

____

____

9) Is there vegetation in the swale or filter strip?

☐ Yes ☐ No

9.a) What is the approximate vegetation cover?

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

10) Are there indications of any of the following in the bottom of the swale or filter strip?

☐ Sediment deposition

☐ Erosion or channelization

☐ Excessive vegetation (that needs mowing or removal)

☐ Litter, large debris, solid waste

☐ Other: ____

☐ No

10.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

11) Are there indications of any of the following on the banks of the swale?

☐ Erosion or channelization

☐ Other: ____

☐ No

12) Are there outlet structures associated with this practice?

☐ Yes ☐ No

12.a) If no, proceed to question 15.

13) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

13.a) If yes, what with?

☐ Debris

☐ Sediment

☐ Vegetation

☐ Other: ____

14) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

14.a) If yes, why?

☐ I don’t know

☐ Ice/Frost heave

☐ Other: ____

15) Is there evidence of any of the following downstream of the outlet structure:

☐ Sediment deposition

☐ Erosion

☐ Channelization

☐ Other: ____

☐ No

15.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

Other observations:

____
____
____
____
____

Inspector's Recommendations:

16) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

____
____
____
____
____

Maintenance Recommendations:

____
____
____
____
____

Troubleshooting Failure: Visual Inspection

Filter Strips and Swales

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Assessing a filter strip or swale within 48 hours of a rainfall event may provide additional performance clues. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Does this swale or filter strip utilize any pretreatment practices upstream?

If any pretreatment practices exist they should also be inspected and maintained on a regular basis.

4) Are there inlet structures associated with this practice?

5) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the swale or filter strip. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system, or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the swale or filter strip.

6) Are any of the inlet structures askew or misaligned?

Misaligned inlet or outlet structures often allow stormwater runoff to enter or exit a swale or filter strip by means other than those intended by design or prevent stormwater runoff from entering the swale or filter strip at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet and outlet structures can become misaligned for several reasons including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet or outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the swale or filter strip.

7) Is there standing water in the swale or filter strip?

Filter strips and swales are designed for stormwater conveyance and not stormwater storage. Standing water in a filter strip or swale is an indication of failure by (1) downstream flooding, or (2) blockage that is preventing stormwater runoff from being conveyed downstream. Areas downstream of the filter strip or swale should be inspected for signs of flooding, and the filter strip or swales should inspected for any obstructions.

8) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

9) Is there vegetation in the swale or filter strip?

Vegetation in the bottom of a filter strip or swale can increase the infiltration rate and remove particulates from stormwater runoff. Plants can lose 30% of their root structures annually, which produces macropores. Macropores in a filter strip or swale can increase the infiltration rate of the practice so that more stormwater runoff is infiltrated. Additionally, vegetation reduces overland flow velocities, which reduces erosion, resuspension of captured solids, and increases suspended solids removal.

10) Are there indications of any of the following in the bottom of the swale or filter strip?

Sediment deposition can indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution or that the swale or filter strip has not been recently maintained. Sediment deposition reduces the stormwater storage volume of a swale or filter strip and can allow sediments to become resuspended during subsequent storm events.

Erosion or channelization indicates that flow velocities entering, or in, the swale or filter strip are large or that stormwater runoff is entering the swale or filter strip by means other than those intended by design. Erosion and channelization can reduce treatment by sedimentation within a swale or filter strip by reducing the retention time and treatment area. Additionally, previously captured sediments can become entrained by poorly or untreated stormwater and pass through the swale or filter strip with the effluent.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in swales and filter strips. If the surface of the swales and filter strips becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the swales and filter strips. Vegetation in swales and filter strips is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in a swale or filter strip are indications that pretreatment practices are failing or not present. Litter, large debris and solid waste may limit the effectiveness of swale or filter strip by altering flow paths which may create channelization, erosion, or both.

11) Are there indications of any of the following on the banks of the swale or filter strip?

Erosion or channelization on the banks of a swale indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the swale with sediments from the bank and subsequently reduce the swale's effectiveness by reducing the volume available for stormwater conveyance and treatment.

12) Are there outlet structures associated with this practice?

13) Is the outlet structure clogged?

Like the inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the swale or filter strip. If the outlet structure is partially or completely clogged, the treatment rate may be limited, and stormwater runoff may not pass through the swale or filter strip untreated or flood surrounding areas. Any obstructions should be removed immediately to ensure proper operation of the swale or filter strip.

14) Is the outlet structure askew or misaligned?

Misaligned inlet or outlet structures often allow stormwater runoff to enter or exit a swale or filter strip by means other than those intended by design or prevent stormwater runoff from entering the swale or filter strip at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet and outlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet or outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the swale or filter strip.

15) Is there evidence of any of the following downstream of the outlet structure:

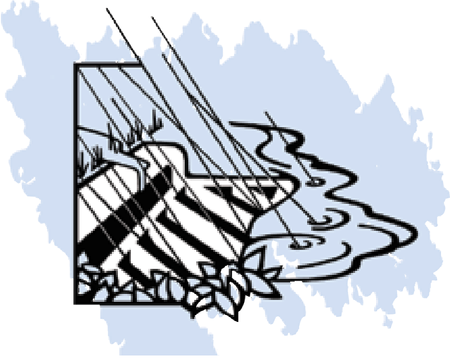
Conditions downstream of a swale or filter strip can provide evidence of the function of the practice itself. Properly designed and functioning swale or filter strip should remove most sand-size particles (0.125 to 2 mm) from stormwater runoff. Sediment deposition downstream of a swale or filter strip indicates that erosion is occurring between the practice and the sediment deposition or that sediments are present in the swale or filter strip effluent. If sediments are present in the effluent such that downstream deposition is occurring, the swale or filter strip is likely failing.

Erosion downstream of a swale or filter strip indicates that flow velocities are larger than the conveyance channel can withstand. The conveyance channel should be resized to accommodate the amount of flow exiting the swale or filter strip, or the channel should be augmented with energy dissipaters or riprap to reduce or eliminate the impact of erosion.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html



12.

Data Analysis

A.J. Erickson, P.T. Weiss, J.S. Gulliver (gulli003@umn.edu), R.M. Hozalski

This chapter discusses how stormwater BMP assessment data should be analyzed. In addition the chapter may be used as standardized methods for data analysis. The chapter is organized in sections according to level of assessment: visual inspection, capacity testing, synthetic runoff testing, and monitoring. Examples using assessment data are provided throughout the chapter, and additional examples can be found in appendix A: Case Studies. Some sections of this chapter require familiarity with mathematical terms and manipulation techniques such as arithmetic averaging, logarithmic functions, and integration.

12.1 Visual inspection

Standard procedures for visual inspection (level 1) vary depending on the category of the stormwater BMP. The final sections of chapters 8–11 and appendix B contain some of these standard procedures. Methods for reporting results from visual inspections are currently in the planning stage.

Hot links

Erickson A.J., P.T. Weiss, J.S. Gulliver, and R.M. Hozalski. 2007. Data analysis. In *Assessment of Stormwater Best Management Practices,* ed. J.S. Gulliver and J.L. Anderson. St Paul, MN: University of Minnesota.

12.2 Capacity testing

The primary function of most stormwater BMPs is either to infiltrate stormwater or capture solids. Capacity testing (level 2) is specifically designed to test these two functions of a stormwater BMP.

12.2.1 Permeability testing

Point measurements of permeability can be used to estimate the saturated hydraulic conductivity at various locations within a stormwater BMP. An example of permeability calculations that provides a case study of capacity testing applied to rain gardens is given in appendix A.

ADVANCED DISCUSSION

The arithmetic mean is an adequate estimation of overall saturated hydraulic conductivity if the measurements are evenly distributed throughout the stormwater BMP, a practice recommended in chapter 3. Most stormwater BMPs for which permeability testing is appropriate will have spatial heterogeneity in saturated hydraulic conductivity due to variations in soil, sediment deposition, and suspended solids capture within the soil. Assuming one–dimensional flow and using Darcy's Law (see equation 12.1 below), at a given water surface elevation it can be shown that the arithmetic mean of hydraulic conductivity will give the proper flow, and thus the proper time, to drain.

12.2.2 Sediment accumulation testing

Point measurements of sediment accumulation depth can be averaged arithmetically to determine the overall sediment accumulation depth. Using software such as AutoCAD or Microstation provides a more accurate estimation of sediment accumulation because the software directly compares the current sediment depth to historical sediment depths. This method of testing can be used to track the change in sediment accumulation over time.

12.3 Synthetic runoff testing

Synthetic runoff testing (level 3) can be used to measure stormwater BMP effectiveness for runoff volume reduction, retention time, and pollutant removal. When performing synthetic runoff testing to assess hydraulic effectiveness of stormwater BMPs, the most important criterion is often whether the stormwater BMP can drain or infiltrate the design storm volume in the required time, which is usually 48 hours (Minnesota Stormwater Steering Committee 2005). The process for estimating the time required for a filtration practice to drain a specified volume of runoff is described in section 12.3.1. Estimating drain times of infiltration practices for volumes other than that used in synthetic runoff testing is discussed in section 12.3.2 but is not recommended because of the complex mathematical modeling required to ensure an accurate estimate.

12.3.1 Assessment of retention time for filtration practices

Water flow through a filter can be modeled with Darcy's Law (equation 12.1), which describes one–dimensional flow through porous media. In the case of a sand filter that is assessed using synthetic runoff testing, equation 12.1 can be integrated after making some assumptions (which will be discussed in example 12.1, Advanced Discussion) to yield equation 12.2. The assessment of a filtration practice for retention time determines if the practice can drain the design storm volume within the design time (i.e., 48 hours). Equation 12.2 can be fit to synthetic runoff testing data to determine the saturated hydraulic conductivity of the filter media. Then, after rearranging equation 12.2 to solve for time (t_1), the saturated hydraulic conductivity can be used in equation 12.3 to estimate the amount of time (t_d) required for a filtration practice to drain a specific depth of stormwater runoff (i.e., the design storm). An example of this process is given in example 12.1.

Equation 12.1: Darcy's Law for one dimensional flow through a porous media (Fetter 2004)

$$Q = -kA\frac{dh}{dL}$$

where:

Q = discharge
k = saturated hydraulic conductivity
A = surface area over which filtration is occurring
h = piezometric head $= p/\gamma + z$
p = water pressure
γ= unit weight of water
z = elevation
l = distance in direction of flow
dh/dl = hydraulic gradient through the porous media (dimensionless)

Equation 12.2: Water level as a function of time for synthetic runoff testing of filtration practices

$$z_w + L_m = (z_0 + L_m)e^{\left(-k/L_m\right)t_1}$$

where:

z_w = water level above the media surface at any time
k = saturated hydraulic conductivity
z_0 = initial water level above the media surface
L_m = length of porous media
t_1 = elapsed time since the start $(t = 0)$ of the synthetic runoff test

Equation 12.3: Drain time as a function of initial water depth, porous media length, and saturated hydraulic conductivity

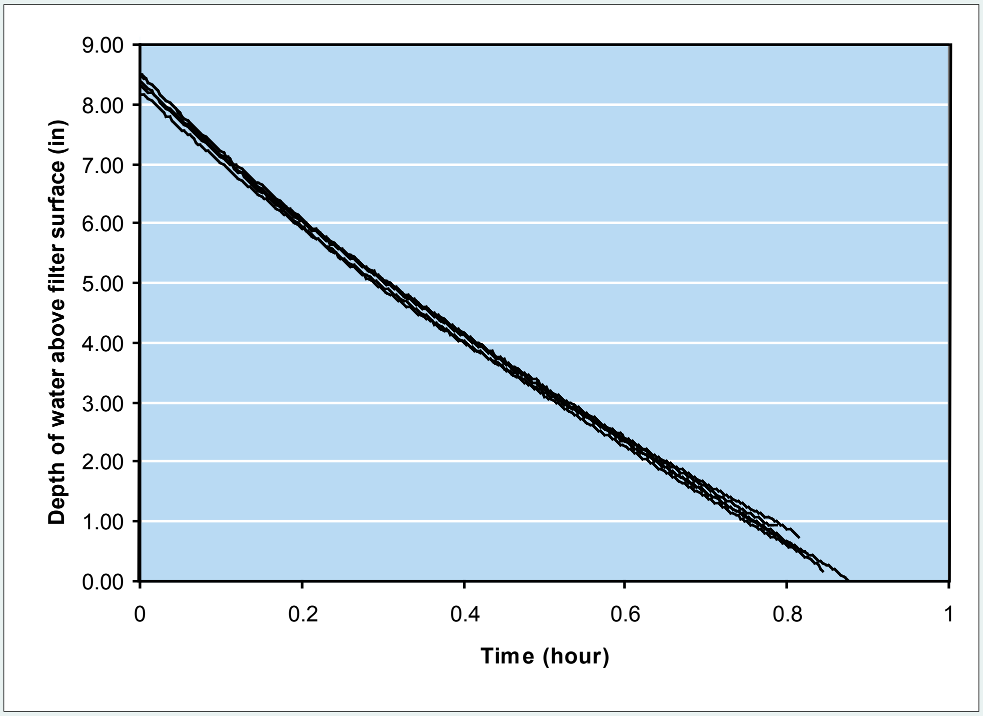
$$t_d = -{L_m}/{k}\left[\ln\left(\frac{L_m}{z_0 + L_m}\right)\right]$$

where:

t_d = drain time
k = saturated hydraulic conductivity
z_0 = initial water level above the media surface
L_m = length of porous media

Example 12.1: Analyzing data from synthetic runoff testing of a filtration practice for retention time

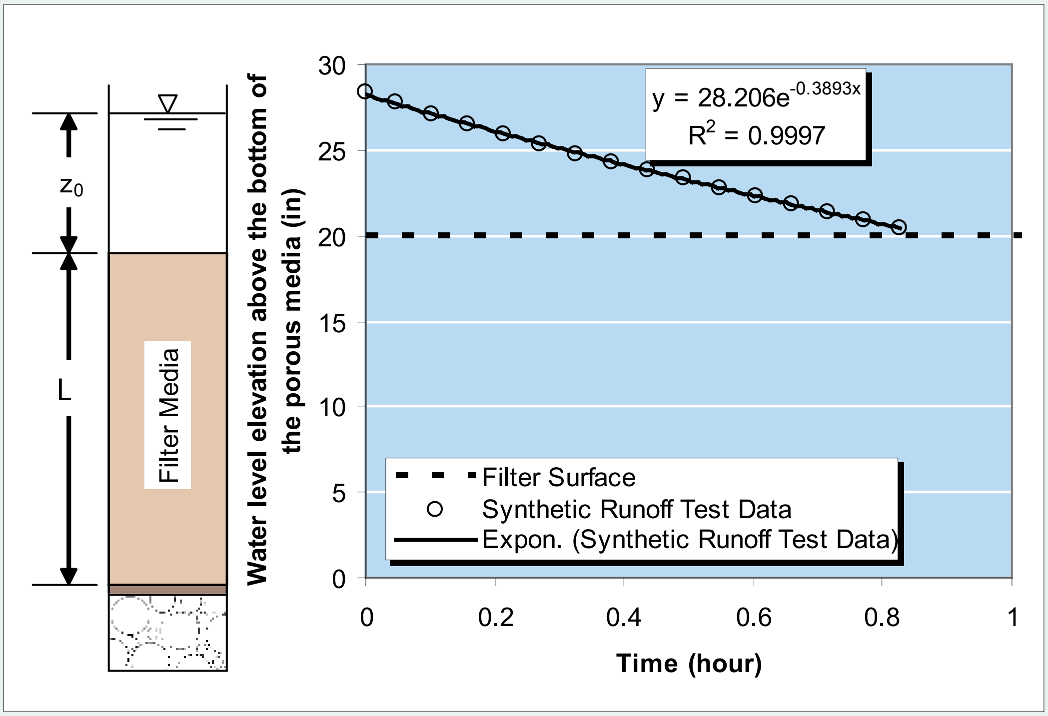
Lana, a watershed district engineer, used synthetic runoff testing to evaluate the retention time of the design runoff volume in a filtration practice. The filter media is 20 inches (0.508 m) thick and the data from five synthetic runoff tests, all of which had significantly less water depth and volume than the design runoff event, are shown below. Note that the data overlap when plotted so that it is difficult to distinguish between the tests. [For graphical representations, one inch = 2.54 cm.]



Lana must determine the saturated hydraulic conductivity of the filter media before she determines the retention time of the design runoff volume. To determine the saturated hydraulic conductivity, Lana adds the porous media length (L_m) to each water level value (z_w) recorded during the synthetic runoff tests and plots all values of this sum versus the corresponding time for each data point in Microsoft Excel™. She then uses the "add trendline" function, chooses an "exponential" function, and changes the options to "Display equation on chart" and "Display R-squared" value on chart to determine and display the best-fit logarithmic function. Lana's results are displayed below.

continued

Example 12.1 *continued*



The best-fit equation matches the form of equation 12.2. Lana determines the saturated hydraulic conductivity by setting the coefficients equal to the corresponding parts of equation 12.2 (i.e., 28.206 = $z_0 + L_m$; -0.3893 = $-k / L_m$). With a porous media length (L_m) of 20 inches (50.8 cm) and rounding to the nearest tenth, Lana calculates the initial water level elevation (z_0) to be 8.2 in (20.8 cm) and, rounding to the nearest hundredth, the saturated hydraulic conductivity (k) to be 7.79 in/hr (0.005 cm/s).

Lana can use the saturated hydraulic conductivity, the porous media length, and a chosen initial water level elevation in equation 12.3 to determine the drain time of other stormwater depths in the filtration practice. Lana knows the design maximum storage depth above the filter surface is 36 in (91.44 cm). Therefore, using equation 12.3, Lana determines the drain time to be 2.65 hours, as follows:

$$t_d = -{}^{L_m}\!/_{k}\left[ln\left(\frac{L_m}{z_0 + L_m}\right)\right]$$

$$t_d = -{}^{20.0}\!/_{7.79}\left[ln\left(\frac{20.0}{36.0 + 20.0}\right)\right]$$

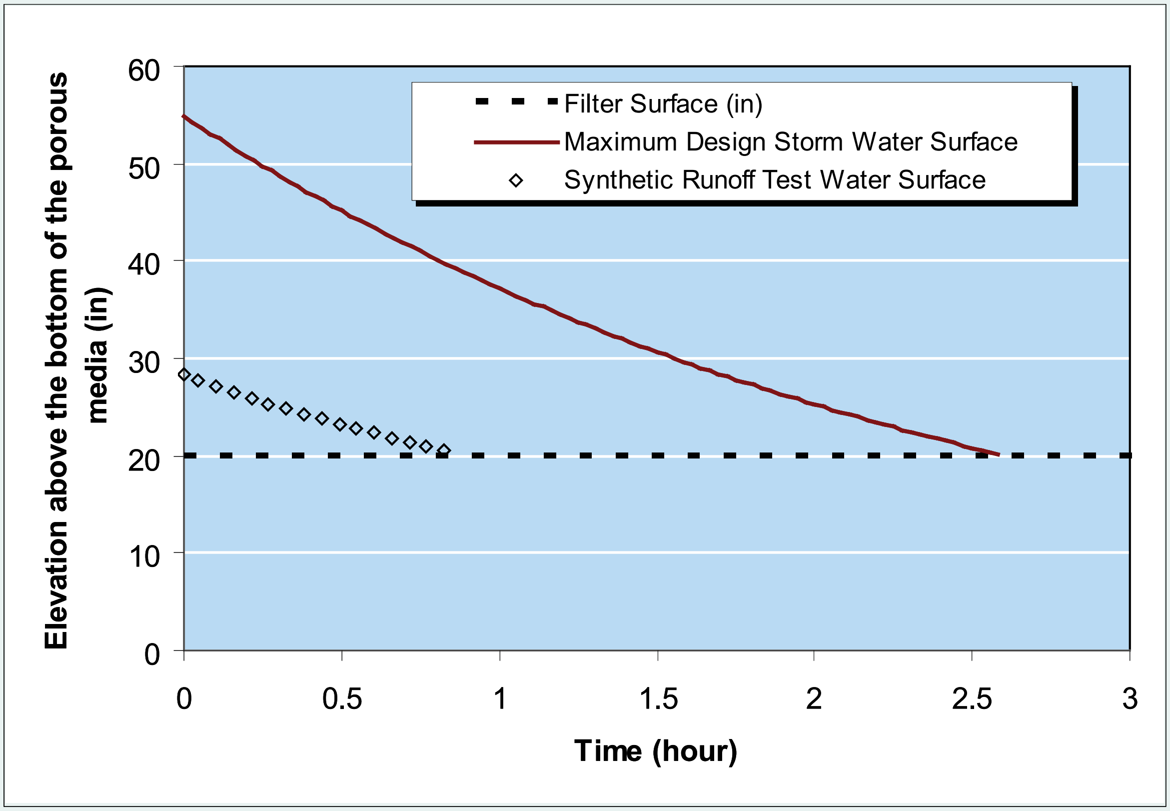
$$t_d = -2.57[ln(0.357)] = 2.65 \text{ hours}$$

The calculated drain time of 2.65 hours is less than the recommended design value of 48 hours and therefore Lana concludes that the filtration practice is functioning adequately.

continued

Example 12.1 *continued*

Lana prepares a graph illustrating the change in water level elevation over time for the maximum storm depth:



NOTE: This example illustrates a process but may not represent typical results.

ADVANCED DISCUSSION

The first assumption for applying Darcy's Law to filtration practices is that both the surface of the stormwater stored above the filtration practice and the subsurface pipe collection system below the filter media, including the gravel sub-base, are exposed to the atmosphere and therefore at atmospheric pressure. This assumption is valid in most filtration practices. Therefore, with an arbitrary datum of z = 0 at the bottom of the filter media, the piezometric head (h) at the filter surface at any point in time is equal to the water level above the filter surface (z_w) plus the length of the porous media (L_m) and varies with time. As a result, the hydraulic gradient across the filter media at any given time is $dh/dl = (z_w + L_m)/L_m$.

The second assumption is that the filter surface area is equally filtering stormwater in one dimension (i.e., vertically downward). For most filtration practices, stormwater will filter one dimensionally unless a layer within a portion of the media is restricting flow. If the second assumption is valid, the total discharge, Q, through the filter is equal to the surface area of the filter (A) multiplied by the change in water level with respect to time (dz_w/dt). Substituting this relationship ($Q = A(dz_w/dt)$) and the previously developed equation for hydraulic gradient through the porous media ($dh/dL = (z_w + L_m)/L_m$) into equation 12.1 and cancelling the area (A) terms results in equation 12.4. Rearranging equation 12.4 in preparation for integration results in equation 12.5.

Equation 12.4: Darcy's Law as applied to synthetic runoff testing data for filtration practices

$$\frac{dz_w}{dt} = -k\frac{z_w + L_m}{L_m}$$

where:

z_w = water level above the media surface at any time
dt = change in time
k = saturated hydraulic conductivity
L_m = length of porous media

The third assumption is that the length of the porous media (L_m) and saturated hydraulic conductivity (k) are constant with respect to both time (t) and water level elevation (z_w). The depth of the filter bed media (L_m) is a physical property of the filtration practice that is based on the design and construction of the practice and is therefore a constant. The saturated hydraulic conductivity (k) is a property of the porous media and the fluid that is passing through the porous media. For homogenous synthetic runoff and non-dynamic porous media, saturated hydraulic conductivity can be assumed to be constant. Therefore, integration of equation 12.5 results in equation 12.2.

As previously discussed, equation 12.2 can be used to determine the saturated hydraulic conductivity of the porous media in a filtration practice. The time required for a filtration practice to drain a specific depth ($z_0 - z_w$) of stormwater runoff can be determined by solving equation 12.2 for time (t), and the total drain time can be determined by setting the final water level equal to zero ($z_w = 0$), which results in equation 12.3.

Equation 12.5: Integration of Darcy's Law for synthetic runoff testing of filtration practices

$$\int_{z_0}^{z_1} \frac{dz_w}{z_w + L_m} = \int_{0}^{t_1} -\frac{k}{L_m} dt$$

where:

z_w = water level above the media surface at any time

k = saturated hydraulic conductivity

z_0 = initial water level

t_1 = elapsed time since the start $(t = 0)$ of the synthetic runoff test

z_1 = water level above the media surface at time t_1

L_m = length of porous media

dz_w = change in water level

dt = change in time *(hour)*

12.3.2 Assessment of volume reduction for infiltration practices

Stormwater infiltrating an infiltration practice is more difficult to model because the length of the filter media is an unknown variable, and the piezometric head gradient (i.e., dh/dl) cannot be easily represented with a single equation, as was the case with filter practices. In fact, infiltration practices cannot be modeled accurately without performing a three-dimensional numerical analysis, which is beyond the scope of this manual. Thus, in order to use synthetic runoff tests to estimate the time required to drain the design runoff volume, the infiltration practice must be filled with the design volume and the drain time recorded directly.

12.3.3 Assessment of pollutant removal

Synthetic runoff tests are a recent technique for stormwater BMP assessment of pollutant removal (Wilson, et al, 2007, Asleson, et al. 2007). Some studies involving synthetic runoff testing are discussed in appendix A: Case Studies. In Case Study two, which describes a proprietary device, sediment load reduction was determined by measuring the amount of sediment captured by the device. The effectiveness of the device was then determined by an application of equation 12.6.

Sediment removal effectiveness was determined for various discharges and various sediment sizes, until a curve of stormwater BMP effectiveness versus a dimensionless parameter incorporating sediment properties could be developed. Alternatively, synthetic runoff testing could be applied to a stormwater BMP for which the influent and effluent runoff volume and pollutant concentrations are measured. Pollutant removal effectiveness would then be estimated using equations 12.7 and 12.8.

Equation 12.6: Removal Efficiency: Mass Load

$$\text{Removal Efficiency (Summation of Loads)} = \frac{M_R}{M_I} \times 100\%$$

where:

M_R = pollutant mass retained by the device

M_I = total pollutant mass input to the device

Equation 12.7: Summation of Loads: Mass Load

$$M = \sum_{i=1}^{n} V_i C_i$$

where:
M = total mass of pollutant
V_i = discharge amount corresponding to sample i
C_i = pollutant concentration in sample i
i = sample number
n = total number of samples collected

Equation 12.8: Removal Efficiency: Mass Load

$$\text{Removal Efficiency (Summation of Loads)} = \left(1 - \frac{M_E}{M_I}\right) \times 100\%$$

where:
M_E = Effluent Pollutant Mass Load as calculated by equation 12.7
M_I = Influent Pollutant Mass Load as calculated by equation 12.7

12.4 Monitoring

Monitoring (level 4) is used to assess stormwater BMP *performance* in a given watershed for natural storm events in which the influent and effluent discharge and pollutant concentrations are not controlled and therefore vary with time. "Urban Stormwater BMP Performance Monitoring" (U.S. EPA 2002) discusses and provides recommendations on ten methods for assessing performance from monitoring assessment data. Two useful methods are (1) summation of loads, and (2) event mean concentration efficiency. The summation of loads method is used to determine the average pollutant mas *load* reduction, and the event mean concentration efficiency method is used to determine the average pollutant *concentration* reduction for a given stormwater BMP. Both methods can be applied to stormwater assess-

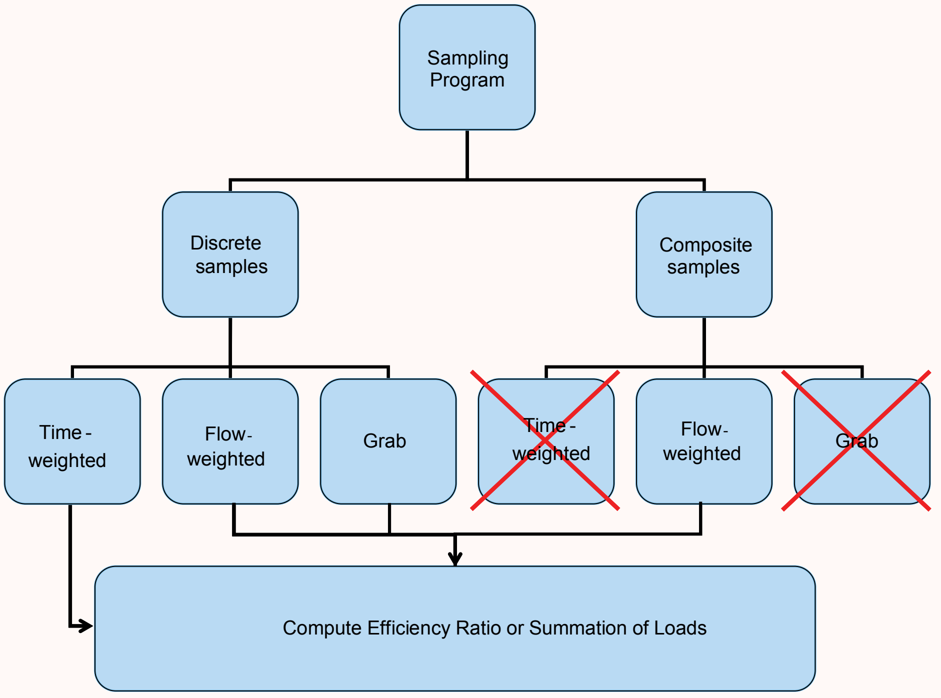


Figure 12.1: Data analysis flow chart for sampling programs

ment data for a single storm event (discussed in analysis of individual storm events, below) or for multiple storm events (in analysis of long-term performance, below) if all water and pollutant import and export processes are accurately sampled or estimated. See chapters 4 and 5 of this manual for more detail on water budget measurement and sampling methods, respectively.

As discussed in chapter 5, there are several methods for collecting and storing stormwater samples. The organizational flow for the rest of section 12.4 is shown in figure 12.1. For more information on collecting and storing stormwater samples, see chapter 5: Sampling Methods.

12.4.1 Assessment of volume reduction

When monitoring a stormwater BMP, one assessment goal may be to determine the performance of the stormwater BMP in order to reduce stormwater runoff volume. This assessment goal may be achieved by a water budget analysis on the stormwater BMP, as discussed in detail in chapter 4: Water Budget Measurement. chapter 4 discusses the theory and details of a water budget, while this section provides water budget recommendations and an example of a water budget analysis as it pertains to a monitored stormwater BMP.

Equation 12.9: Water mass balance

$$\Delta S = \sum V_{in} - \sum V_{ou}$$

where:

ΔS = change in water volume stored in the stormwater BMP
ΣV_{in} = sum of all water volumes that entered the stormwater BMP
ΣV_{out} = sum of all water volumes that exited the stormwater BMP

In order to perform a water budget, the discharge of all open channel and conduit flow entering and exiting the stormwater BMP must be recorded as a function of time. Also, if direct rainfall on the stormwater BMP is significant (> 5% of water budget), the volume of direct rainfall on the stormwater BMP must be calculated by multiplying the depth of rain by the surface area of the stormwater BMP. A water balance for a typical stormwater BMP is given in equation 12.9.

Equation 12.10: Water mass balance

$$V_{loss} = S_1 - S_2 + \left(\sum_{i=1}^{N} Q_i \Delta t_i \right) + P(A_W) - \left(\sum_{k=1}^{Z} Q_k \Delta t_k \right)$$

where:

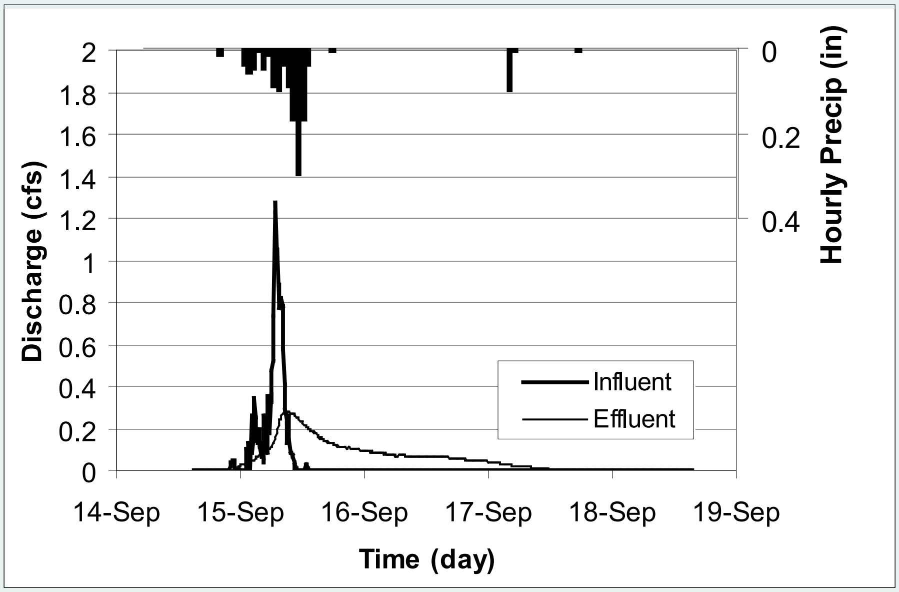
S_i = volume of water stored in stormwater BMP prior to runoff event
S_2 = volume of water stored in stormwater BMP after runoff event
Q_i = influent flow rate data point
i = influent data point number
Δt_i = time duration between data point i and $i + 1$
P = depth of precipitation falling directly into the stormwater BMP
A_W = surface area of the stormwater BMP
Q_k = effluent flow rate data point
k = influent data point number
Δt_k = time duration between data point k and $k + 1$
V_{loss} = volume of water exported by infiltration and evapotranspiration
N = number of influent data points
Z = $n$umber of effluent data points

Water volumes contained within a stormwater BMP can be determined from the depth of water if the stormwater BMP surface geometry is known. Water depth measurement devices are described in detail in chapter 4: Water Budget Measurement. Water depth measurements can usually be stored on the same data logger as flow rate, precipitation, and other data. Otherwise, water depth must be recorded manually during site visits just prior to and immediately after a runoff event. Recognizing that the change in storage within a stormwater BMP is equal to the volume of water in the stormwater BMP after the runoff event minus the initial storage volume, expanding the terms on the right hand side of equation 12.9 to include the water sources and sinks as discussed in chapter 4, and solving for V_{loss}, the water balance equation becomes equation 12.10.

Although the V_{loss} term in equation 12.10 contains the volume of runoff lost through infiltration and evapotranspiration, the losses due to evapotranspiration are small and can be assumed to be zero if the duration of the runoff event is small (i.e., a few days or fewer). Thus,

Example 12.2: Volume reduction effectiveness of a dry pond with underdrains

A 3-acre (1.21 hectare) dry pond with underdrains was monitored for stormwater runoff volume reduction. The inflow, outflow, and hourly precipitation values are plotted in the figure below for a 0.72-inch (1.83 cm) storm event. To determine the stormwater runoff volume reduction, the water balance given in equation 12.10 must be solved. [For graph, one cfs = 0.028 m^3/s; one inch = 2.54 cm.]



The area encompassed by the inflow and outflow hydrographs corresponds to the influent and effluent volumes, respectively. The instantaneous volume is the product of the discharge and the time step for each data point on the hydrograph. The total volume is the summation of the instantaneous volumes for the entire hydrograph. For this dry pond, the influent and effluent volumes were calculated as 12,124 ft^3 and 3,937 ft^3 (343,313 liters and 111,483 liters), respectively. As mentioned above, the total rainfall amount was 0.72 inches over the entire 3-acre dry pond, which contributes 0.18 ac-ft = 7,480.8 ft^3 (211,833 liters) of water. Because the stormwater BMP is a dry pond, it is expected that the storage before and after a storm within the pond is zero, which in fact was the case for this dry pond. Therefore, equation 12.10 simplifies as such:

$$V_{loss} = S_1 - S_2 + \left(\sum_{i=1}^{N} Q_i \Delta t_i \right) + P(A_W) - \left(\sum_{k=1}^{Z} Q_k \Delta t_k \right)$$

$$V_{loss} = 0 - 0 + 12{,}124 ft^3 + 7{,}480.8 ft^3 - 3{,}937 ft^3$$

$$V_{loss} = 15{,}668 ft^3 \text{ (443,668 liters)}$$

Therefore, the volume exported by evapotranspiration and/or infiltration is 15,688 ft^3 (444,234 liters). The effectiveness can be calculated as the volume reduction percentage, which is simply the infiltrated volume divided by the total influent volume = 15,688 ft^3/(12,124 ft^3 + 7,481ft^3) = 79.9% volume reduction efficiency. *NOTE: This example illustrates a process but may not represent typical results.*

the V_{loss} term in equation 12.10 is an estimate of the volume of stormwater runoff that has been infiltrated by the stormwater BMP and can be used to estimate the effectiveness of a stormwater BMP for runoff volume reduction. This analysis is demonstrated in example 12.2.

12.4.2 Assessment of pollutant removal

While reducing runoff volume is important for the integrity of receiving waters, most stormwater monitoring programs are implemented with the goal of assessing pollutants retained by the stormwater BMP. In addition to measuring discharge, assessing the pollutants retained also requires sampling stormwater BMP influent and effluent. As discussed in chapter 5, often several storms continuously spanning two or more rainy seasons are required to accurately assess pollutant removal performance with a low range of uncertainty.

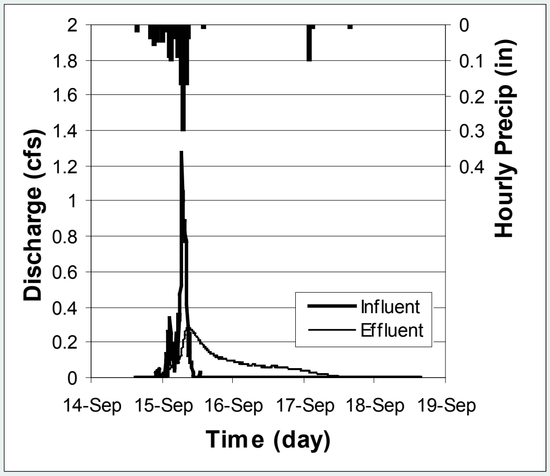
The process for analyzing monitoring data starts with a single storm event. The pollutant concentrations from the samples collected during the storm event are used in conjunction with influent and effluent runoff volumes to determine the pollutant removal efficiency for that storm event. It cannot, however, be assumed that the calculated efficiency from a single storm event is applicable to all storm events. Therefore several storm events representing a range of conditions (e.g., discharge and pollutant concentration) must be monitored to accurately assess the long-term performance of stormwater BMPs.

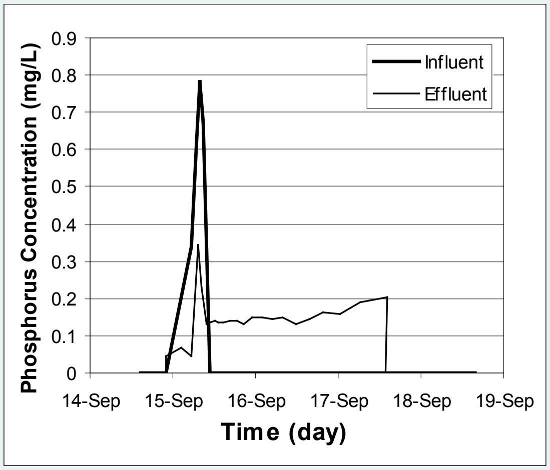
Analysis of individual storm events

Summation of loads. Summation of load for either influent or effluent samples can be calculated using equation 12.7 which is applicable to any number of samples (n) that correspond to discharge data (V) and results in units of mass (e.g., milligrams).

Example 12.3: Storm event analysis by summation of loads method

A dry pond with underdrains was monitored for sediment and phosphorus removal. One method to calculate the pollutant removal efficiency is the Summation of Loads method, using **equation 12.7**. [For graph, one cfs = 0.028 m^3/s; one inch = 2.54 cm.]





continued

Example 12.3: *continued*

Influent Data			
Collection Time (mm/dd hh:mm)	**Volume represented by sample (liters)**	**Pollutant Concentration (mg/L)**	**Sum of Mass Load (g)**
9/15 5:14 AM	62294	0.338	21.1
9/15 6:55 AM	102639	0.617	84.4
9/15 7:45 AM	75768	0.782	143.7
9/15 8:43 AM	56001	0.675	181.5
Effluent Data			
Collection Time (mm/dd hh:mm)	**Volume represented by sample (liters)**	**Pollutant Concentration (mg/L)**	**Sum of Mass Load (g)**
9/14 10:00 PM	0	0.047	0.0
9/15 2:22 AM	10365	0.067	0.7
9/15 5:23 AM	23760	0.045	1.8
9/15 7:16 AM	26797	0.342	10.9
9/15 8:30 AM	31704	0.232	18.3
9/15 9:39 AM	32233	0.132	22.6
9/15 10:49 AM	31519	0.136	26.9
9/15 12:04 PM	30179	0.141	31.1
9/15 1:25 PM	28407	0.137	35.0
9/15 2:54 PM	26699	0.137	38.7
9/15 4:33 PM	25183	0.138	42.1
9/15 6:28 PM	25033	0.138	45.6
9/15 8:36 PM	24415	0.131	48.8
9/15 11:03 PM	25701	0.149	52.6
9/16 1:43 AM	25032	0.149	56.3
9/16 4:46 AM	25286	0.146	60.0
9/16 8:02 AM	23852	0.151	63.6
9/16 11:49 AM	24482	0.132	66.9
9/16 3:26 PM	23008	0.144	70.2
9/16 7:40 PM	24318	0.162	74.1
9/17 12:22 AM	22080	0.156	77.6
9/17 6:23 AM	17460	0.190	80.9
9/17 2:21 PM	6698	0.204	82.3

Example 12.3: *continued*

The summation of loads method requires discharge volume and pollutant concentration data. The first step is to list the pollutant concentrations of each sample with the corresponding discharge volume that each sample represents, as shown in the tables at left. To determine the pollutant load (mass), multiply the pollutant concentration (mass/volume) by the discharge volume. For example:

$$Mass = Conc. \times Volume$$

$$Mass = 0.338 \, {}^{mg}\!/_{L} \times 62294 \, L = 21{,}055 \, mg$$

$$Mass_1 = 21.1 \, g \; (0.046 \, lbs)$$

Then sum the pollutant load for each sample to determine the total pollutant load of the influent and the effluent. For example:

$$Mass_1 = 21.1 \, g$$

$$Mass_2 = 0.617 \, {}^{mg}\!/_{L} \times 102{,}639 \, L = 63{,}328 \, mg$$

$$Mass_2 = 63.3 \, g \; (0.140 \, lbs)$$

$$Mass_1 + Mass_2 = 84.4 \, g \; (0.186 \, lbs)$$

Pollutant removal efficiency can be estimated as (Load in - Load out)/(Load in). Using the results from this monitoring study, the pollutant removal efficiency according to the Summation of Loads method is:

$$Removal = \frac{Load_{in} - Load_{out}}{Load_{in}} \times 100\%$$

$$Removal = \frac{181.5g - 82.3g}{181.5g} \times 100\% = 54.6\%$$

Therefore, the phosphorus removal efficiency of this dry pond with underdrains for a single storm event is 54.6% as calculated by the Summation of Loads method.

NOTE: This example illustrates a process but may not represent typical results.

After the influent and effluent loads have been summed, the stormwater BMP performance can be calculated based on the summation of loads according to equation 12.8. An example of how to apply the summation of loads method to assess stormwater BMP removal efficiency using flow-weighted, discrete-sampled monitoring data is given in example 12.3. The results can be compared to other storm events for the same stormwater BMP, storm events for a different BMP, results obtained from other methods of analysis (e.g., event mean concentration efficiency), or they can be combined with other storm event data for the same stormwater BMP in an analysis of long-term performance, which is discussed later in this section.

The application of equation 12.7 may depend on the type of samples collected for a given monitoring program. Therefore, the summation of loads method is described for each type (e.g., flow-weighted discrete samples, flow-weighted composite samples, etc.).

Flow-weighted discrete samples

When samples are collected based on a user-specified constant incremental volume of discharge (e.g., every 1000, 2000, or 5000 gallons) that passes the sampler, the samples are defined as flow-weighted. Each flow-weighted sample is assumed to represent the average pollutant concentration for the entire incremental volume of water to which it corresponds. Discrete samples are stored in individual containers, and the contents of each container are analyzed separately. Therefore, flow-weighted discrete samples are collected every time a user-specified constant volume of flow passes the sampler and are stored in individual containers that are analyzed separately. Equation 12.7 can be simplified if flow-weighted discrete samples are collected because the volume increment (V_i) is the same for each sample. Therefore, the summation of loads for flow-weighted discrete samples can be calculated using equation 12.11. It is, however, more accurate to use equation 12.7 for flow-weighted discrete samples when the measured volume increment between each sample is not the same, as shown in example 12.3.

Equation 12.11: Summation of Load: Mass load for flow-weighted discrete samples

$$M = V_T \frac{\sum_{i=1}^{n} C_i}{n}$$

where:

M = total mass of pollutant

V_T = total discharge volulme $(V_T = nV_i)$

C_i = pollutant concentration in sample i

i = sample number

n = total number of samples collected

Flow-weighted composite samples

Flow-weighted composite samples are collected every time a user-specified constant volume of flow passes the sampler and are stored in a single container. To determine pollutant concentration, an aliquot is collected from the composite sample, and the concentration is assumed to represent that of the entire composite sample. Equation 12.7 can be simplified if flow-weighted composite samples are collected because the volume increment (V_i) is the same for each sample, and the composite sample concentration is an average of all the individual samples that were taken. Therefore, the summation of loads for flow-weighted composite samples can be calculated using equation 12.12.

Equation 12.12: Summation of Load: Mass load for flow-weighted composite samples

$$M = V_T C_C$$

where:

M = total mass of pollutant

V_T = total discharge volume $(V_T = nV_i)$

C_C = composite sample pollutant concentration

Time-weighted discrete samples

Time-weighted discrete samples are collected at a user-specified, constant time interval (e.g., 30 minutes), and each sample is stored in a separate container that is analyzed separately. Because the magnitude of the discharge during a natural storm event varies over time, each time-weighted sample does not represent a constant volume of discharge. Equation 12.7 cannot be simplified if time-weighted discrete samples are collected because the volume increment (V_i) and concentrations of the discrete samples (C_i) will vary. Therefore, equation 12.7 should be used.

Equation 12.13: Efficiency Ratio: Event Mean Concentration (EMC)

$$EMC = \frac{\sum_{i=1}^{n} V_i C_i}{\sum_{i=1}^{n} V_i}$$

where:

EMC = event mean concentration

V_i = discharge amount corresponding to sample i

C_i = pollutant concentration in sample i

i = sample number

n = total number of samples collected

Time-weighted composite samples

Time-weighted composite samples are collected at equal time increments, and all samples are stored in a single container. Time-weighted composite samples cannot be used to calculate the summation of loads for influent or effluent because the concentration of the composite sample is not representative of the average concentration for the storm event (see chapter 5 for more details). Time-weighted composite sampling is not recommended.

Discrete grab samples

A grab sample is a single sample collected at one location over a relatively short time period, typically sampling the entire cross-section of water. Grab samples have been used to overcome the bias of automatic sampling for sands and silts. If grab samples are collected sporadically, discharge must be accurately and continuously measured and the time of each grab sample must be recorded to assess pollutant removal performance. Discrete samples are stored in individual containers, and the contents of each container are analyzed separately. Equation 12.7 must be used if time-weighted discrete samples are collected because the volume increment (V_i) and concentrations of the discrete samples (C_i) will vary. Discrete grab samples are typically used to obtain an imprecise estimate of stormwater BMP performance and effluent quality, without the effort and expense required to set up an automatic sampler and analyze large numbers of samples.

Composite grab samples

Composite grab samples are typically collected at variable time and volume increments and stored in a single sample storage container. A stop watch may be used to minimize the variability in time intervals between sample collection. Composite grab samples cannot be used to calculate the summation of loads for influent or effluent because the concentration of the composite sample is not representative of the average concentration for the storm event (see chapter 5 for more details). Combining grab samples collected at random time intervals to create a composite sample is not recommended.

Event mean concentration efficiency. Another way to calculate removal efficiency is by using the EMC efficiency method, which relies on the event mean concentration (EMC) from the

Equation 12.14: Event Mean Concentration (EMC) Efficiency

$$\text{EMC Efficiency} = \frac{\text{EMC}_\text{I} - \text{EMC}_\text{E}}{\text{EMC}_\text{I}}$$

where:

EMC_I = influent event mean concentration as calculated by equation 12.13

EMC_E = effluent event mean concentration as calculated by equation 12.13

Example 12.4: Storm event analysis by the event mean concentration (EMC) efficiency method

The Summation of Loads method was used in example 12.3 to estimate the pollutant removal efficiency of a dry pond with underdrains. In this example, the EMC efficiency method is used on the same pond and the same data.

continued

Example 12.4 *continued*

Influent Data			
Collection Time (mm/dd hh:mm)	**Volume represented by sample (liters)**	**Pollutant Concentration (mg/L)**	**Sum of Mass Load (g)**
9/15 5:14 AM	62294	0.338	21.1
9/15 6:55 AM	102639	0.617	63.3
9/15 7:45 AM	75768	0.782	59.3
9/15 8:43 AM	56001	0.675	37.8
Total =	296701		181.5
Effluent Data			
Collection Time (mm/dd hh:mm)	**Volume represented by sample (liters)**	**Pollutant Concentration (mg/L)**	**Sum of Mass Load (g)**
9/14 10:00 PM	0	0.047	0.0
9/15 2:22 AM	10365	0.067	0.7
9/15 5:23 AM	23760	0.045	1.1
9/15 7:16 AM	26797	0.342	9.2
9/15 8:30 AM	31704	0.232	7.4
9/15 9:39 AM	32233	0.132	4.3
9/15 10:49 AM	31519	0.136	4.3
9/15 12:04 PM	30179	0.141	4.3
9/15 1:25 PM	28407	0.137	3.9
9/15 2:54 PM	26699	0.137	3.7
9/15 4:33 PM	25183	0.138	3.5
9/15 6:28 PM	25033	0.138	3.5
9/15 8:36 PM	24415	0.131	3.2
9/15 11:03 PM	25701	0.149	3.8
9/16 1:43 AM	25032	0.149	3.7
9/16 4:46 AM	25286	0.146	3.7
9/16 8:02 AM	23852	0.151	3.6
9/16 11:49 AM	24482	0.132	3.2
9/16 3:26 PM	23008	0.144	3.3
9/16 7:40 PM	24318	0.162	3.9
9/17 12:22 AM	22080	0.156	3.4
9/17 6:23 AM	17460	0.190	3.3
9/17 2:21 PM	6698	0.204	1.4
Total =	534210		82.3

Example 12.4 *continued*

Equation 12.13 can be used to calculate the event mean concentration of the influent (EMC_I) as follows:

$$EMC_I = \frac{\sum_{i=1}^{n} V_i C_i}{\sum_{i=1}^{n} V_i} = \left(\frac{62294L \times 0.338\ mg/L + \ldots}{62294L + 102639L + \ldots} \right)$$

$$EMC_I = \left(\frac{21.1g + 63.3g + 59.3 + 37.8g}{296701L} \right) = 0.611\ {}^{mg}\!/_{L}$$

The dry pond with underdrains has a surface area of 3.0 acres. For this particular storm event a total of 1.38 inches of rainfall was recorded. To adjust the influent EMC for the rainfall that fell directly into the pond, equation 12.16 can be used. Note that equation 12.16 assumes that the pollutant concentration in the rainfall is zero. Using this equation gives:

$$Adjusted\ EMC_I = \frac{M_I}{V_{TI} + PA_W}$$

$$Adjusted\ EMC_I = \frac{181{,}500\ mg}{296701\ L + (1.38in) \times (3.0\ ac) \times \left(\frac{102{,}772\ L}{1\ in\text{ - }ac} \right)} = 0.251\ mg/L$$

Similarly, the effluent event mean concentration (EMC_E) can be calculated using equation 12.13, which results in a value of 0.154 mg/L. EMC efficiency can be estimated using equation 12.14 as follows:

$$Efficiency_{EMC} = \frac{Adjusted\ EMC_I - EMC_E}{Adjusted\ EMC_I} \times 100\%$$

$$Efficiency_{EMC} = \frac{0.251mg/L - 0.154mg/L}{0.251mg/L} \times 100\% = 38.6\%$$

NOTE: This example illustrates a process but may not represent typical results.

influent and the effluent of each runoff event. The purpose of the EMC efficiency method is to determine the reduction in pollutant concentration. EMC in units of mass per volume (e.g. mg/L) can be calculated using equation 12.13, which is applicable to any number of samples. When comparing equations 12.7 and 12.13, it is apparent that EMC can be calculated simply by dividing the total mass of pollutant (equation 12.7) by the total volume of stormwater.

After the influent and effluent EMCs have been calculated, the EMC efficiency of the stormwater BMP can be calculated using equation 12.14. An example of this process for flow-weighted, discrete samples is given in example 12.4. After storm event data have been analyzed, they can be compared to other storm events for the same stormwater BMP, storm events for a different BMP, results obtained from other methods of

Equation 12.15: Event Mean Concentration (EMC): influent pollutant load

$$M_I = EMC_I \times V_{TI}$$

where:

M_I = influent pollutant mass load

EMC_I = influent event mean concentration as calculated by equation 12.13

V_{TI} = total volume of measured influent (excluding rainfall) analysis (e.g., summation of loads), or they can be combined with other storm event data for the same stormwater BMP to analyze long-term performance, which is discussed later in this section.

If precipitation directly on the stormwater BMP is significant, it must be accounted for in the analysis by adjusting the influent EMC. The total influent mass load of the entire runoff event is determined by multiplying the influent EMC by the total influent volume. The adjusted influent EMC is then obtained by dividing the total influent mass load by the sum of the volume of measured influent and the volume of rainfall that fell directly on the stormwater BMP. This procedure assumes that the rainfall contains no pollutant. The equations used are equations 12.15 and 12.16.

Equation 12.16: Event Mean Concentration (EMC): influent pollutant load

$$\text{Adjusted EMC}_I = \frac{M_I}{V_{TI} + PA_W}$$

where:

M_I = influent pollutant load

EMC_I = influent event mean concentration

V_{TI} = total volume of measured influent (excluding rainfall)

P = rainfall depth

A_W = surface area of the stormwater BMP

Note that when the EMC efficiency method (example 12.4) is used to analyze the same data as the summation of loads method (example 12.3), the results are different. The summation of loads method is based on only the total mass of pollutant that enters and exits the stormwater BMP whereas the event mean concentration efficiency method is based on both the mass of pollutants and volumes of runoff entering and exiting the stormwater BMP. The difference arises between the two methods because the volume of runoff entering through monitored inlets is usually different than the volume leaving through monitored outlets, where samples are collected, because of infiltration or evapotranspiration. For example, if an infiltration practice infiltrates half of the influent runoff volume and half of the influent pollutant mass load is retained by the stormwater BMP (e.g., solids filtered at the soil surface), the efficiency would be 50% based on the summation of loads method. This assumes that the water that is infiltrated will be stripped of the pollutant by the soil matrix. In some cases, such as with pollutant metals, hydrocarbons, and phosphorus, this is likely to be true. In others, such as nitrates and chlorides, it is probably not true. With half of the runoff volume infiltrated and half of the pollutant mass retained, the EMC of the effluent would be equal to that of the influent, and the EMC would be zero. Because unmeasured losses such as infiltration and evapotranspiration tend to increase effluent event mean concentrations, the EMC efficiency method will report lower efficiencies than the summation of loads method as long as all inputs into the system, such as direct precipitation on the stormwater BMP, are measured accurately.

Flow-weighted discrete samples

Flow-weighted discrete samples are collected every time a user-specified constant volume of flow passes the sampler and are stored in individual containers that are analyzed separately. Equation 12.13 can be simplified if flow-weighted discrete samples are collected because the volume increment (V_i) is the same for each sample and the summation of the volumes is equal to the total volume.

Therefore, the EMC for flow-weighted discrete samples can be calculated using equation 12.17.

Equation 12.17: Event Mean Concentration (EMC) for flow weighted discrete samples

$$\text{EMC} = \frac{\sum_{i=1}^{n} C_i}{n}$$

where:

EMC = Event Mean Concentration

C_i = pollutant concentration in sample i

n = total number of samples collected

Flow-weighted composite samples

Flow-weighted composite samples are collected at equal volumes of stormwater runoff and stored in a single container. Equation 12.13 can be simplified for flow-weighted composite samples because the volume increment (V_i) is the same for each sample and the composite sample concentration is an average of all the individual samples that were taken. Therefore, the EMC for flow-weighted composite samples is simply the concentration of the composite sample (C_c).

Time-weighted discrete samples

Time-weighted discrete samples are collected at equal time increments, stored in individual containers, and analyzed separately. Equation 12.13 cannot be simplified if time-weighted discrete samples are collected because the volume increment (V_i) and concentrations of the discrete samples (C_i) will vary, and therefore equation 12.13 must be used.

Time-weighted composite samples

Time-weighted composite samples are samples that are collected at equal time increments, and stored in a single container. Time-weighted composite samples cannot be used to calculate influent or effluent EMC because the concentration of the composite sample is not representative of the average concentration for the storm event (see chapter 5 for more details). Therefore, time-weighted composite sampling is not recommended.

Discrete grab samples

Discrete grab samples are typically collected at variable time and volume increments, stored in individual containers, and analyzed separately. A stop watch may be used to minimize the variability in time intervals between sample collection. Equation 12.13 cannot be simplified if time-weighted discrete samples are collected because the volume increment (V_i) and concentrations of the discrete samples (C_i) will vary and therefore equation 12.13 must be used.

Composite grab samples

Composite grab samples are typically collected at variable time and volume increments and stored in a single container. Composite grab samples cannot be used to calculate the EMC for influent or effluent because the concentration of the composite sample is not representative of the average concentration for the storm event (see chapter 5 for more details). This sampling technique is not recommended for the assessment of stormwater BMPs.

Analysis of long-term performance

After assessment data from multiple storm events have been analyzed, the long-term performance of a stormwater BMP can be assessed. Analysis of long-term performance involves first calculating the average removal efficiency based on multiple storm events and then calculating the uncertainty of the removal efficiency. The average stormwater BMP performance represents the period of time encompassed by the storm events (e.g., 3 months, 1 year, 2 years). Analysis of monitoring data from many storms can also be used to investigate relationships between stormwater BMP performance and runoff intensity, pollutant load or concentration, or other variables. In this section, two methods for conducting the analysis of long-term performance are presented: summation of loads and EMC efficiency.

Example 12.5: Analysis of long-term performance by summation of loads

A dry pond with underdrains was monitored for sediment and phosphorus removal. An analysis of long-term performance for multiple storm events allows for statistically significant comparisons between devices, time periods, and other variables.

Storm Event #	Influent TSS Load (kg)	Effluent TSS Load (kg)	Load Based Efficiency (%)
1	194	19.8	89.8%
2	873	76.2	91.3%
3	10.6	0.98	90.8%
4	117	24.9	78.7%
5	15.6	1.32	91.5%
6	4.04	1.29	68.1%
7	29.9	21.7	27.4%
8	6.32	0.69	89.1%
9	9.66	8.1	16.1%
10	2.42	0.5	79.3%
11	4.28	2.28	46.7%
12	0.25	0.01	96.0%
Total =	**1267.07**	**157.77**	**87.5%**

The total suspended solids (TSS) data from the influent and effluent sampling locations were used to determine the pollutant load according to the summation of loads method (see example 12.3) as shown in the table above. The load based efficiency for each storm event and the total influent and effluent loads have been calculated. The long-term removal efficiency can be calculated using equation 12.8:

$$Load_{influent} = 1{,}267.1\,kg\ (2{,}793.5\ lbs) \quad Load_{effluent} = 157.8\ kg\ (347.9\ lbs)$$

$$Removal = \left(1 - \frac{Load_{effluent}}{Load_{influent}}\right) \times 100\%$$

$$Removal = \left(1 - \frac{157.8}{1{,}267.1}\right) \times 100\% = 87.5\%$$

NOTE: This example illustrates a process but may not represent typical results.

Summation of loads. Analysis of long-term performance by summation of loads is similar to analysis of a single storm event (section 12.3.3), except that the data are storm event loads instead of individual sample loads. To do this, influent and effluent loads are calculated separately for each storm event using equation 12.7. Long-term performance can then be calculated using equation 12.8 with the total mass of influent load and total mass of effluent load being the sum of all influent and effluent mass loads, respectively, for all storm events.

Example 12.6: Analysis of long-term performance by efficiency ratio

A dry pond with underdrains was monitored for sediment and phosphorus removal. Analysis of long-term performance for multiple storm events allows for statistically significant comparisons between devices, time periods, and other variables.

Storm Event #	Influent EMC (mg/L)	Effluent EMC (mg/L)	Event Mean Efficiency (%)
1	57.6	10	82.6%
2	790.7	108.7	86.3%
3	19.2	9	53.1%
4	64.8	27.2	58.0%
5	11.5	5.3	53.9%
6	5.6	2.4	57.1%
7	18.4	25.2	-37.0%
8	16.2	4.7	71.0%
9	8.9	8.8	1.1%
10	9.1	8.1	11.0%
11	10.6	11.6	-9.4%
12	2.7	1.8	33.3%
		Average =	**38.4%**

The same total suspended solids (TSS) data from influent and effluent sampling locations used in example 12.5 was used to determine the pollutant removal efficiency according to the efficiency ratio method as shown in the table above. The EMC (see example 12.4) and event mean removal efficiencies (EME) were calculated for each storm event. Long-term removal efficiency can be calculated using equation 12.18:

$$\begin{aligned} Removal &= \frac{\sum_{i=1}^{n} EME_i}{n} \\ &= \left(\frac{82.6\% + 86.3\% + \ldots + 33.3\%}{n} \right) \\ Removal &= 38.4\% \end{aligned}$$

It is important to recognize the difference between calculating the overall removal efficiency from the average of event mean removal efficiencies and averaging the EMC from the influent and effluent. For example, the average influent EMC is 84.6 mg/L and the average effluent EMC is 18.6 mg/L for these 12 storm events. Using the average influent and effluent EMCs, the overall removal efficiency for this stormwater BMP is 78.1% instead of 38.4%. The discrepancy is caused by bias of storm events with large pollutant concentrations that outweigh storm events with negative removal efficiencies. *NOTE: This example illustrates a process but may not represent typical results.*

In the summation of loads method, the pollutant mass entering and exiting the stormwater BMP for each runoff event is summed, and the removal efficiency is computed. Thus, a storm with a relatively small pollutant load will contribute less to the total load than a storm with a relatively large pollutant load, as shown in example 12.5. Therefore, assessment data from a stormwater BMP that is analyzed using the summation of loads method may be biased by storms with large pollutant loads.

Equation 12.18: Analysis of long-term Event Mean Concentration (EMC) efficiency

$$\text{Long - term Efficiency}_{\text{EMC}} = \left(\frac{\sum_{i=1}^{n} \text{Efficiency}_{\text{EMC}\,i}}{n} \right) \times 100\%$$

where:

$Efficiency_{EMCi}$ = event mean concentration of storm number i

n = number of storms monitored

The average pollutant removal from the assessment of a given stormwater BMP's long-term performance can be used to compare different time periods or watershed conditions: for the same stormwater BMP, to other stormwater BMPs of the same type (e.g., dry pond vs. dry pond), or to other stormwater BMPs (dry pond vs. rain garden). Removal efficiencies obtained from the assessment of long-term performance can also be compared with efficiencies obtained from other analysis methods (e.g., EMC efficiency), as shown in example 12.6.

Event mean concentration efficiency. Analysis of long-term performance by the EMC efficiency method involves averaging the event mean removal efficiencies (which were calculated by equation 12.14) to determine the long-term pollutant removal efficiency for a single stormwater BMP. Because EMC is used, the pollutant removal efficiency is independent of the runoff volume for each storm event. Long-term removal efficiency can be calculated using equation 12.18 for all storm events, as shown in example 12.6.

The stormwater BMP pollutant removal efficiency results from examples 12.3 and 12.4 are significantly different. During the 12 storm events that were monitored, 54.6% of the pollutant ***load*** was removed by the stormwater BMP. The pollutant ***concentration***, however, was reduced on average by 38.4%. As discussed in the section Analysis of individual storm events (in this chapter, above), discrepancies between summation of loads and EMC efficiency is caused by significant water budget components, such as infiltration and evapotranspiration, that are not typically accounted for in the analysis methods. For the data shown in examples 12.3 and 12.4, a water budget export (e.g., infiltration) is likely significant. This conclusion is only possible because the data was analyzed by both the summation of loads and the EMC efficiency methods, and a comparison of the two was made. Typically, the load–based removal efficiency is higher that the EMC efficiency.

Estimating uncertainty. The uncertainty of long-term performance analysis is related to the total number and variation of storms assessed, but it is independent of the method chosen to calculate performance. With all other variables held constant, the uncertainty in the average percent removal decreases as the number of analyzed storm events increases. One requirement for calculating uncertainty is that

Equation 12.19: Performance uncertainty of analysis of long-term performance

$$U = \frac{t\sigma}{\sqrt{n}}$$

where:

U = uncertainty

t = Student t value from table 12.1

n = number of storm events

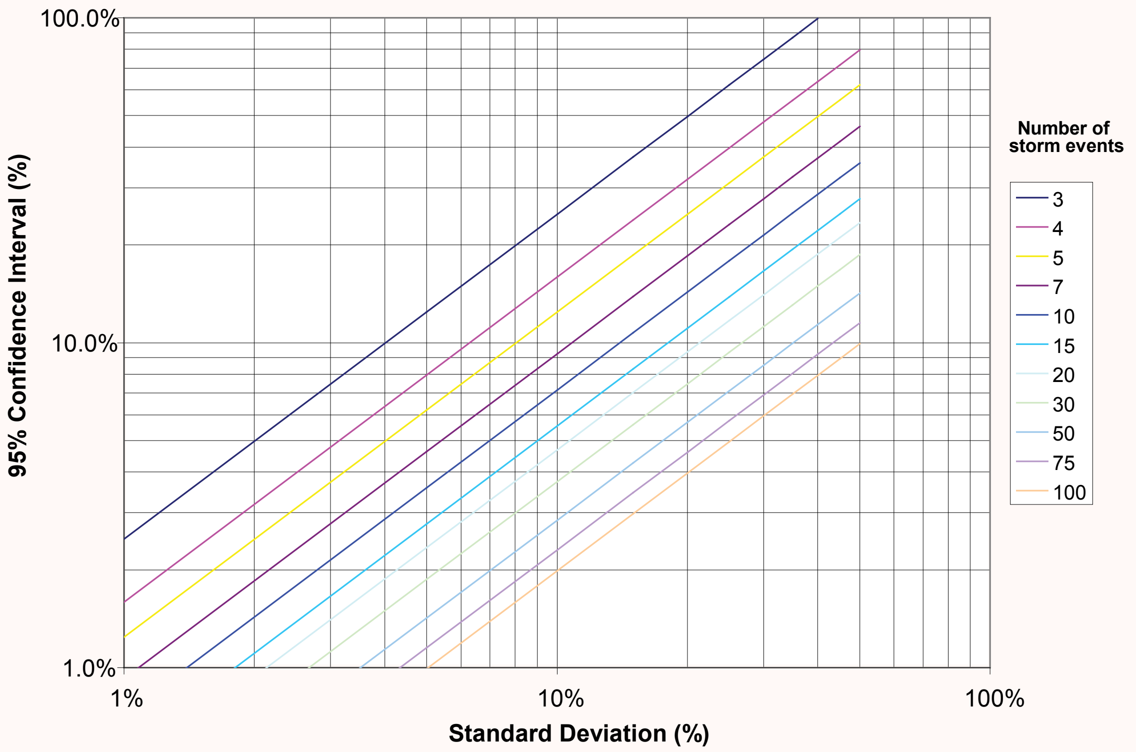


Figure 12.2: Relationship between number of storm events, standard deviation, and 95% confidence interval

a percent removal for all incorporated storm events can be calculated. The 95% confidence interval is recommended to adequately represent uncertainty in mean pollutant removal efficiency because it indicates that there is a 95% probability that the mean value will be within the confidence interval. For example, a stormwater BMP with 72% removal ± 17% confidence interval ($\alpha = 0.05$) means that for 95% (19 out of 20) of monitored storm events, the mean pollutant removal percentage from the runoff of those storm events would fall between 55% and 89%. The range of the confidence interval (in this case, 17%) is dependent on the standard deviation and the number of monitored storm events. The relationship between standard deviation, number of storm events, and 95% confidence interval is shown in figure 12.2.

A simple method (equation 12.19) for calculating uncertainty is based on the Student (Gosset) t-distribution. The Student t-distribution, given in table 12.1 (below), is a probability distribution used to estimate the mean of a normally distributed population from a sample of the population and is more accurate than the similar z-distribution for small ($n < 30$) sample sizes. Thus, the Student t-distribution is used because the number of storms required will likely be fewer than 30. For more information on distributions, consult a statistics text (e.g., MacBerthouex and Brown 1996, Moore and McCabe 2003).

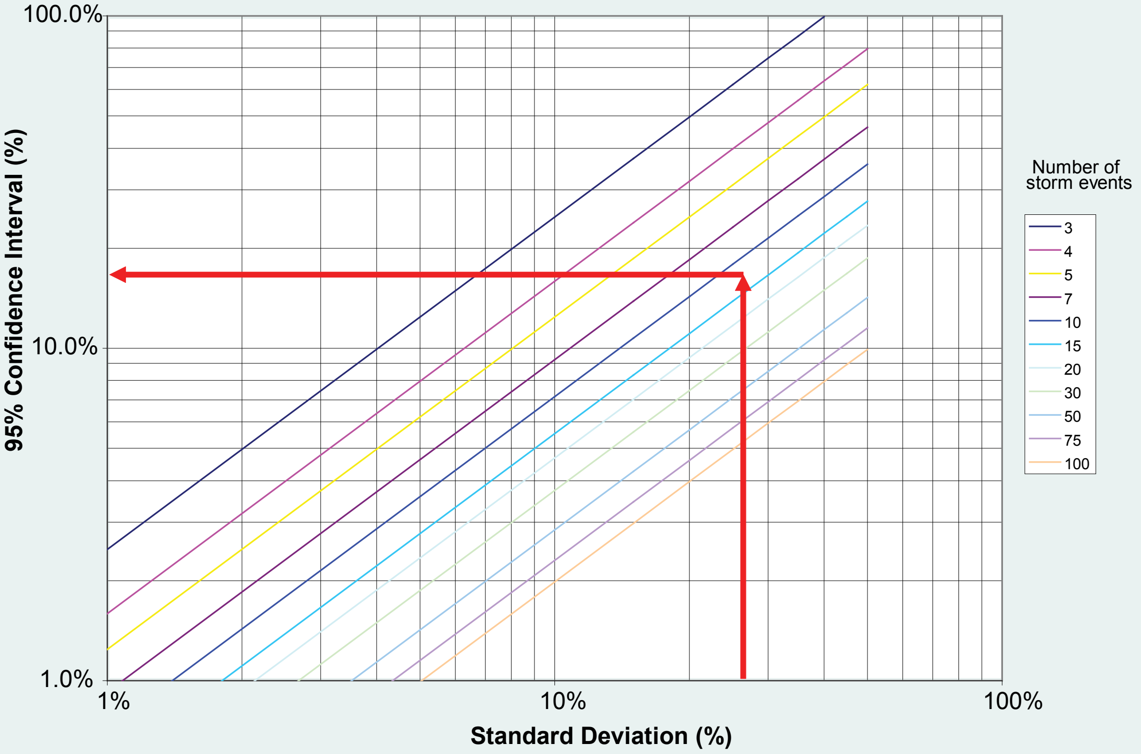
Uncertainty can be calculated by equation 12.19 using the number of storm events, the standard deviation of the performance data, and the Student t value. The standard deviation can be calculated in Microsoft Excel™ (stdev function) or as described in most statistical texts. The Student t value can be obtained in Microsoft Excel™ (tinv function)

Table 12.1: Table of Student (Gosset) t values

	Probability, p							
d.f.	**0.5**	**0.333**	**0.25**	**0.1**	**0.05**	**0.01**	**0.005**	**0.001**
1	1.00	1.73	2.41	6.31	12.7	63.7	127	637
2	0.82	1.26	1.60	2.92	4.30	9.92	14.1	31.6
3	0.76	1.15	1.42	2.35	3.18	5.84	7.45	12.9
4	0.74	1.10	1.34	2.13	2.78	4.60	5.60	8.61
5	0.73	1.07	1.30	2.02	2.57	4.03	4.77	6.87
6	0.72	1.05	1.27	1.94	2.45	3.71	4.32	5.96
7	0.71	1.04	1.25	1.89	2.36	3.50	4.03	5.41
8	0.71	1.03	1.24	1.86	2.31	3.36	3.83	5.04
9	0.70	1.02	1.23	1.83	2.26	3.25	3.69	4.78
10	0.70	1.02	1.22	1.81	2.23	3.17	3.58	4.59
11	0.70	1.01	1.21	1.80	2.20	3.11	3.50	4.44
12	0.70	1.01	1.21	1.78	2.18	3.05	3.43	4.32
13	0.69	1.00	1.20	1.77	2.16	3.01	3.37	4.22
14	0.69	1.00	1.20	1.76	2.14	2.98	3.33	4.14
15	0.69	1.00	1.20	1.75	2.13	2.95	3.29	4.07
16	0.69	1.00	1.19	1.75	2.12	2.92	3.25	4.01
17	0.69	1.00	1.19	1.74	2.11	2.90	3.22	3.97
18	0.69	0.99	1.19	1.73	2.10	2.88	3.20	3.92
19	0.69	0.99	1.19	1.73	2.09	2.86	3.17	3.88
20	0.69	0.99	1.18	1.72	2.09	2.85	3.15	3.85
21	0.69	0.99	1.18	1.72	2.08	2.83	3.14	3.82
22	0.69	0.99	1.18	1.72	2.07	2.82	3.12	3.79
23	0.69	0.99	1.18	1.71	2.07	2.81	3.10	3.77
24	0.68	0.99	1.18	1.71	2.06	2.80	3.09	3.75
25	0.68	0.99	1.18	1.71	2.06	2.79	3.08	3.73
26	0.68	0.99	1.18	1.71	2.06	2.78	3.07	3.71
27	0.68	0.99	1.18	1.70	2.05	2.77	3.06	3.69
28	0.68	0.98	1.17	1.70	2.05	2.76	3.05	3.67
29	0.68	0.98	1.17	1.70	2.05	2.76	3.04	3.66
30	0.68	0.98	1.17	1.70	2.04	2.75	3.03	3.65

Example 12.7: Determining the 95% confidence interval

Based on 12 storm events, a stormwater BMP removed 72% ± 27% (1 standard deviation) of TSS from stormwater runoff. The uncertainty of the removal efficiency can be estimated with 95% confidence using figure 12.2. For a standard deviation of 27% and n = 12 storm events, the uncertainty is approximately 17% (17.30% actual):



NOTE: This example illustrates a process but may not represent typical results.

or from table 12.1 using the degrees of freedom (d.f. = n-1) and the probability of failure (α). For the 95% confidence interval, α = 0.05. For example, if n = 15, the Student t value for the 67% confidence interval would be 1.00 (d.f. = 14, α = 0.33). Alternatively, uncertainty can be estimated using figure 12.2 for a known standard deviation, number of storm events, and an assumed 95% confidence interval, as shown in example 12.7 (below).

12.4.3 Recommendations for monitoring

Summation of loads and EMC efficiency are two methods for estimating stormwater BMP performance. The summation of loads method is used to determine the average pollutant mass ***load*** reduction, and the EMC efficiency method is used to determine the average pollutant ***concentration*** reduction for a given stormwater BMP. Most monitoring studies (e.g., Anderson et al. 1985, Kovacic et al. 2000, Winer 2000, Lin and Terry 2003, Silvan et al. 2004, Bell et al. undated) report pollutant removal or retention efficiencies based on EMC, but regulations (e.g., TMDLs) may require retention calculations to be based on pollutant load reductions. Therefore, both methods should be used to analyze stormwater BMP assessment data.

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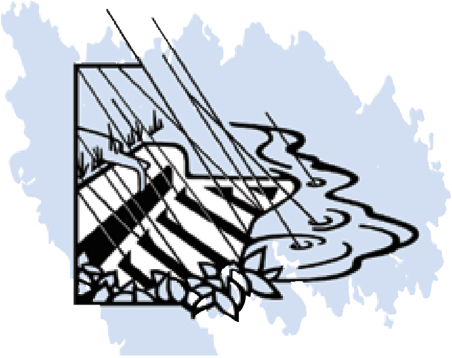
Acknowledgements

This manual, Assessment of Stormwater Best Management Practices, was created with funding provided by the Minnesota Pollution Control Agency, project number 347-6053, with C. Bruce Wilson as Project Manager. Funding for partner projects was provided by the Minnesota Metropolitan Council Environmental Services, project number 347-6054, with Jack Frost as Project Manager, and the Minnesota Local Road Research Board, contract number 81655 Work Order 162, project number 536-6270, with Jon Haukaas as Technical Liaison. In-kind assistance provided by Dakota County through a study funded by the Water Environment Research Foundation was appreciated.



13.

The Future of this Manual

P.T. Weiss and J.S. Gulliver (gulli003@umn.edu)

Hot Links

1. **Expansion of current topics**
2. **Future topics**

This manual emphasizes the assessment of the most common stormwater BMPs in use today. While the assessment methods described are general, the case studies in Appendix A focus on minimizing temperature impacts and reducing stormwater volume, phosphorus, and suspended solids in stormwater runoff for specific practices. A successful watershed management plan will almost certainly involve the assessment of many other factors, such as additional BMPs and target pollutants. It would also be appropriate to include the development and implementation of maintenance plans for each stormwater BMP. Although the current manual does not address all of these issues in detail, it will be expanded in the future to include additional topics and will develop more fully some of the topics included in the current manual. This chapter is intended to communicate the goals of the future expansion of this manual so that those involved in watershed management can look for future editions that will offer help and advice in additional areas as well as provide more details related to some of the current topics.

Baker, L.A., R.M. Hozalski, and J.S. Gulliver. 2007. Source reduction. In *Assessment of Stormwater Best Management Practices,* ed. J. S. Gulliver and J.L. Anderson. St Paul, MN: University of Minnesota.

13.1 Expansion of current topics

The current versions of level 2 and level 3 assessment methods (i.e., capacity testing and synthetic runoff testing) described in this manual focus on the assessment of proprietary devices and bioretention practices. Future versions will include other practices such as infiltration basins, dry ponds, and permeable pavements. The methodologies will describe procedures for successfully carrying out these levels of assessment on other stormwater BMPs.

This document provides background information on topics related to source reduction along with formulas and models that can be used to estimate input loads into the watershed (e.g., fecal coliform from dog feces, phosphorus dry deposition). Future editions of the manual will include a worksheet to help users evaluate and compare different source reduction options. Ultimately, a model will be developed to allow users to estimate the impact of various levels of source reduction and different source reduction practices on the overall runoff quality in the watershed.

Any stormwater management plan requires regular inspection and maintenance of stormwater BMPs. While the current manual focuses on the assessment of stormwater BMPs to determine their level of performance and, ultimately, to indicate if or when maintenance is required, it does not provide information on procedures to restore a stormwater BMP that is not functioning at a satisfactory level. The future manual will list regular maintenance tasks and how often they should be performed for each of the various stormwater BMPs. Also, if any of the four levels of assessment indicates that a stormwater BMP is failing, the manual will provide action steps to restore the stormwater BMP. For example, if visual inspection indicates that a bioretention practice is not adequately infiltrating stormwater runoff, a plan of action to increase infiltration rates to acceptable levels will be provided.

The impact of stormwater runoff on trout streams will be expanded. To complete the model developed in the current manual, it is necessary to incorporate additional potential mitigation measures. The initial mitigation measures were wet ponds, infiltration ponds, and rain gardens. Additional measures, such as stormwater detention vaults, swales, wetlands, and riparian vegetation will also be studied and modeled. The expansion will include instrumentation and data collection, data assembly, data analysis, and, finally, model development. Also, a TMDL study of the thermal pollution of the Vermillion River and of Miller Creek will be conducted using the model components described.

Appendix A will also be expanded to include more case studies. The additional case studies will demonstrate the new methodologies developed for level 2 and level 3 assessments and will expand on methodologies in the current manual.

13.2 Future topics

The current manual mentions some important issues in stormwater management and assessment of stormwater BMPs that could not be addressed in detail. The next edition of manual will include a number of these issues that are relevant to stormwater management in the Upper Midwest.

The key to reducing stormwater runoff volumes, and a focus of the current manual, is to increase infiltration. As the number of infiltration stormwater BMPs increases, their impact on groundwater supplies cannot be ignored. Future versions of the manual will address groundwater pollution that is related to infiltrating stormwater. The impact of infiltration with respect to pollutant concentration levels and temperature will be developed, as will the long-term sustainability of infiltration practices. For example, if an infiltration practice continually removes fine particles and phosphorus from runoff, the future manual will address topics such as how long the process can continue before the practice clogs or becomes a phosphorus source.

The effectiveness of stormwater BMPs that rely on sedimentation as a primary removal method (e.g., wet ponds, dry ponds, proprietary devices) is dependent on the size and density of the settling particles. Thus, in order to design a sedimentation practice properly, the density and size of the solids contained in the runoff must be well characterized. Unfortunately, short–comings in current sampling techniques often prevent representative samples from being collected and, therefore, sediment characterizations of stormwater runoff are often erroneous. With an inaccurate solids characterization, a stormwater BMP cannot be properly designed. The future manual will address this issue by developing a sample collection methodology that will enable the collection of more representative samples, which in turn will provide a more accurate solids characterization with a particle size distribution. This will enable sedimentation-based stormwater BMPs to be designed more optimally.

The future manual will also include more case studies to demonstrate various methodologies. One new case study will be a TMDL analysis on a watershed. This analysis will use a standard computer model (e.g., SWAMM, P8, etc.) to model the impact of a stormwater BMP on a receiving water body. The watershed will include stormwater BMPs upon which assessment of performance can be made. The TMDL analysis will be run with and without the stormwater BMPs to determine their impact on pollutant load.

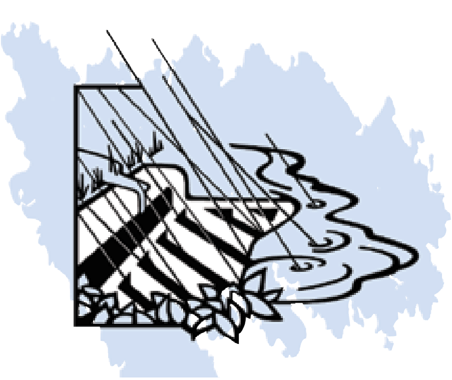
Additional issues to be addressed in future versions of the manual include the effect on infiltration rates of soil compaction by heavy construction equipment, sediment retention capabilities of vegetation, and the quantification of the impact on runoff quality of landscape practices (including low–impact development and phosphorous restrictions). The effectiveness of standard MNDOT manholes as stormwater BMPs will also be investigated.

Future sections of the manual will address cold weather issues such as winter assessment or monitoring of stormwater BMPs, winter salt management strategies (i.e., source reduction) to minimize the impact of salts on receiving water bodies, and the use of porous pavements in cold climates.

A complete watershed management plan will include various strategies, stormwater BMPs, and other items. As the knowledge base and experience with these issues expands, this manual will be revised to provide users with the most current stormwater management information and strategies in existence.

Acknowledgements

This manual, Assessment of Stormwater Best Management Practices, was created with funding provided by the Minnesota Pollution Control Agency, project number 347-6053, with C. Bruce Wilson as Project Manager. Funding for partner projects was provided by the Minnesota Metropolitan Council Environmental Services, project number 347-6054, with Jack Frost as Project Manager, and the Minnesota Local Road Research Board, contract number 81655 Work Order 162, project number 536-6270, with Jon Haukaas as Technical Liaison. In-kind assistance provided by Dakota County through a study funded by the Water Environment Research Foundation was appreciated.



A.

Appendix A

Case Studies

The case studies provided in this appendix cover the range of BMP types and assessment levels, including source reduction, as described in Table A.1. It is understood that this type of description is valuable to practitioners who are applying the Assessment of Stormwater BMPs Manual to various applications. Most of the case studies come from practitioners, and other case studies that fit into the format utilized herein will be welcomed.

Table A.1. Stormwater BMP types and Assessment Levels of the Case Studies

Case Study	BMP Type	Assessment Level(s)	Relevant Chapter
1	Sedimentation practice (Dry pond)	4	10
2	Sedimentation practice (Proprietary underground device)	3	10
3	Biologically enhanced practice (Rain garden)	1-3	11
4	Infiltration practice (Infiltration trench)	4	9
5	Biologically enhanced practice (Multi-cell wetland)	4	11
6	Infiltration practice (Vegetated buffer)	3	9
7	Sedimentation practice (Multi-cell wet pond)	4	10
8	Sedimentation practice (Wet pond)	4	10
9	Source reduction (Fertilizer)	-	7
10	Source reduction (Lawn care)	-	7

Gulliver, J.S. and J.L. Anderson, ed. 2007. *Assessment of Stormwater Best Management Practices.* St Paul, MN: University of Minnesota.

Appendix A: Case Studies

Case Study #1. “Monitoring a dry detention pond with under-drains” provided by C. F. Hussain, J. Brand, A. J. Erickson, J. S. Gulliver (gulli003@umn.edu), and P. T. Weiss at the University of Minnesota.

Case Study #2. “Assessment of a proprietary underground structure for stormwater treatment” provided by M. A. Wilson, J. S. Gulliver, O. Mohseni (omohoseni@umn.edu), and R. M. Hozalski at the University of Minnesota.

Case Study #3. “Assessment of infiltration at a rain garden” provided by B.C Asleson, R.S. Nestingen , J.S. Gulliver (gulli003@umn.edu), R.M. Hozalski and J.L. Nieber at the University of Minnesota.

Case Study #4. “Monitoring a regional infiltration system” provided by Emmons and Olivier Resources (corresponding author: Gary Oberts, goberts@eorinc.com) and the South Washington Watershed District.

Case Study #5. “Water quality benefits of surface stormwater drainage and treatment of parking lot runoff using multi-cell wetlands in parking lot median strips” provided by C.J. Aichinger at the Ramsey-Washington Metro Watershed District.

Case Study #6. “Assessing vegetated buffers using synthetic residential runoff” provided by S.M. Stai (sarah.stai@westwoodps.com) at Westwood Professional Services.

Case Study #7. “Monitoring to test the P8 model at Bass Creek Business Park” provided by Brian Vlach (bvlach@threeriversparkdisrtict.org) and John Barten (jbarten@threeriversparkdistrict.org) at Three Rivers Park District.

Case Study #8. “Monitoring and modeling to improve the management of Eagle Lake golf course” provided by Brian Vlach (bvlach@threeriversparkdisrtict.org) and John Barten (jbarten@threeriversparkdistrict.org) at Three Rivers Park District.

Case Study #9. “Assessment of source reduction due to phosphorus-free fertilizers” provided by Brian Vlach (bvlach@threeriversparkdistrict.org), John Barten, James Johnson, and Monica Zachay at Three Rivers Park District

Case Study #10. “Lawn care impacts on phosphorus load” provided by Brian Vlach (bvlach@threeriversparkdisrtict.org) and John Barten (jbarten@threeriversparkdistrict.org) at Three Rivers Park District.

Appendix A: Case Studies

1. Monitoring a dry-detention pond with under-drains

Provided by F. Hussain, J. Brand, A.J. Erickson, J.S. Gulliver (gulli003@umn.edu), and R.M. Hozalski at the University of Minnesota

CASE STUDY #1: MONITORING A DRY DETENTION POND WITH UNDER-DRAINS

Contributing Authors: F. Hussain, J. Brand, A.J. Erickson, J.S. Gulliver (gulli003@umn.edu), R.M. Hozalski

Carver County dry detention pond is located along Highway 212 and lies one mile west of Cologne, Minnesota in the Carver Creek watershed. It drains a watershed that encompasses the corner of the Carver County's new public works facility site, consisting of 45 acres with impervious area on the site of 10.2 acres. Future construction of County facilities may occur on the remainder of the site.

The dry detention pond is approximately 3 acres with a slope of 1% from inlet to outlet. It is designed to provide storage up to a 100 year – 24 hour event on the site. Stormwater runoff is directed through grass waterways to a small pretreatment pond (forebay) before it enters the pond. After entering the detention pond, the stormwater runoff infiltrates through the soil media. A series of rock-filled trenches holding perforated drain tile acts as an under-drain for the pond into which most of the stormwater runoff drains. Eight sets of 8-inch diameter, perforated polyethylene under-drain pipes (Y-shaped) are joined together with 8 inch by 8 inch by 4 inch polyethylene laterals oriented at 45 degrees. Every set of under-drain pipe consists of two arms, each 30 feet long with a diameter of 4 inches. A total of 140 feet of 8-inch diameter under-drain pipe and 480 feet of 4-inch diameter under-drain pipe were installed within the detention pond as shown in figure 1.

A cross section of the under-drain system is shown in figure 2. The under-drain pipe was surrounded by a mixture of soil and ASTM C33 fine sand, which was used as filter media for the Carver County pond. A filter fabric was used to wrap the soil-sand filter media and under-drain pipe. A layer of 6 inches of native soils (typically tighter clays for Carver County) was used to bury the filter fabric to avoid its exposure at the surface. The under-drains collect the infiltrated storm water and drain it into the outlet structure. The outlet structure of the Carver County dry detention pond is 5 feet in diameter and receives infiltrated runoff through an 8-inch under-drain pipe as shown in figure 3. This large outlet structure was provided so that rainfall in excess of the design storage volume could discharge downstream. An 18-inch (inner diameter) reinforced concrete pipe takes the runoff from the outlet structure and discharges it into the downstream watershed. Native plants were planted on the site, including the grass waterways (ditches) and areas around the parking lot.

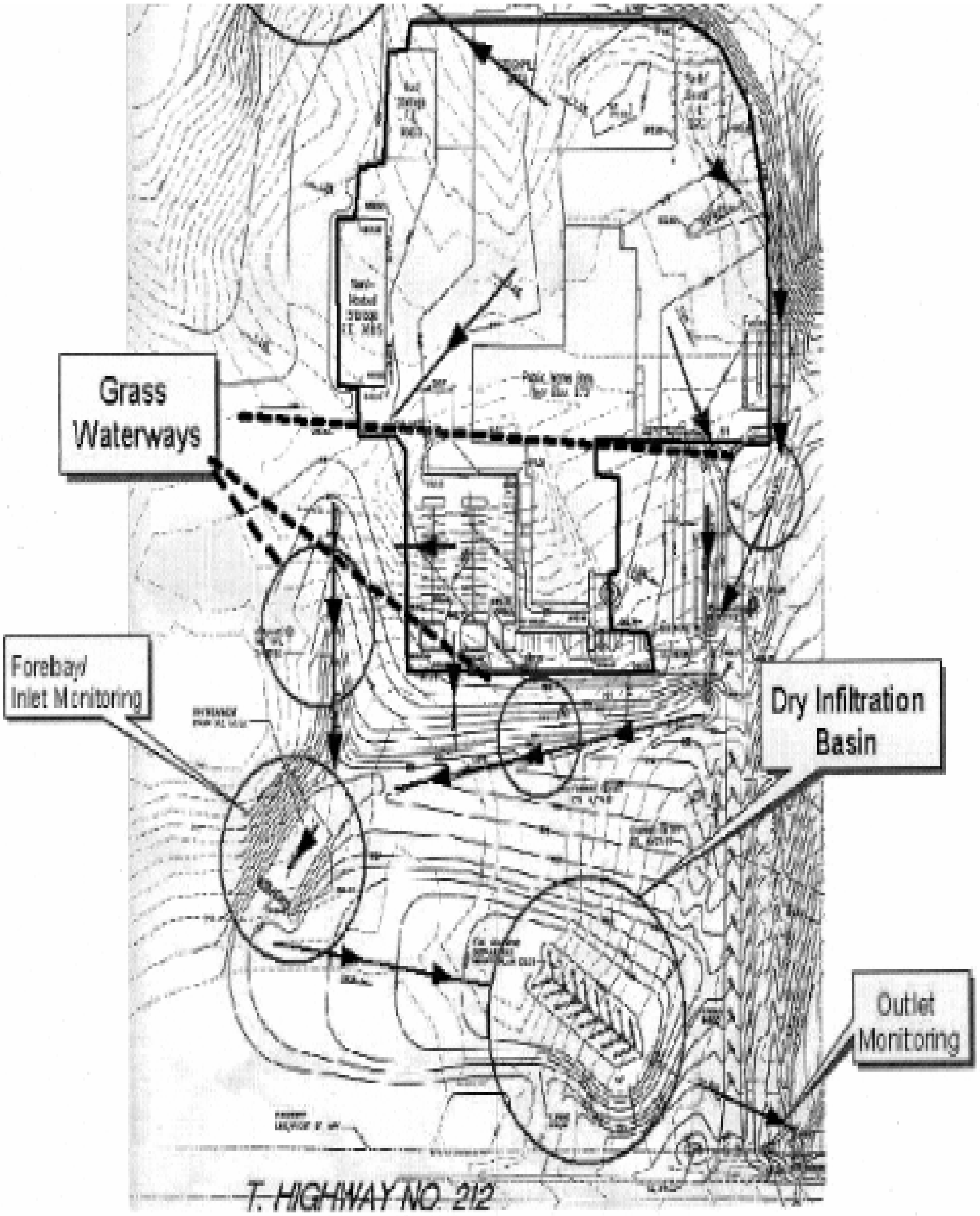


Figure 1: Plan view of Carver County dry detention pond

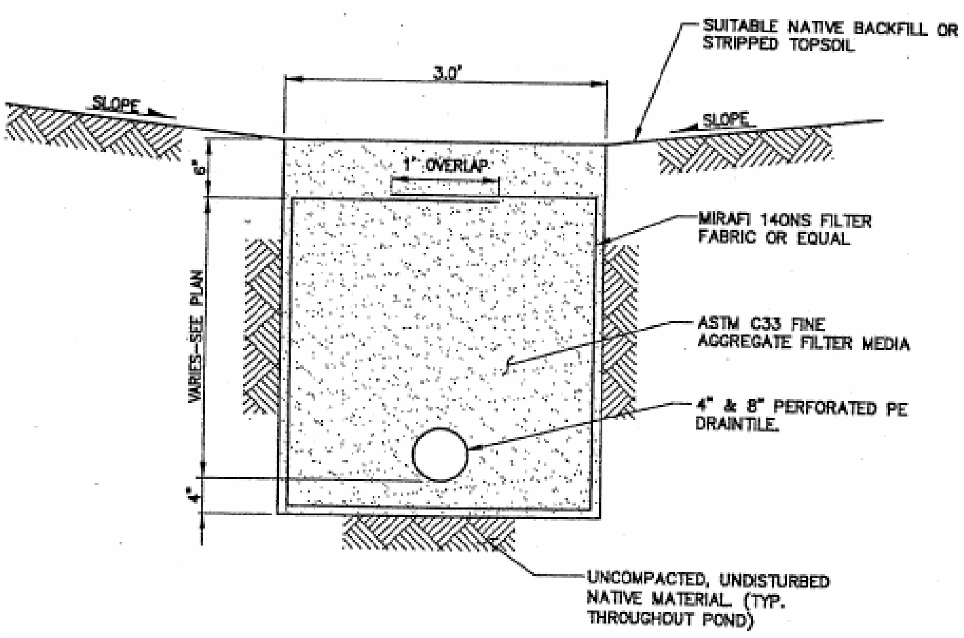


Figure 2: Cross section of Carver County pond under-drain system

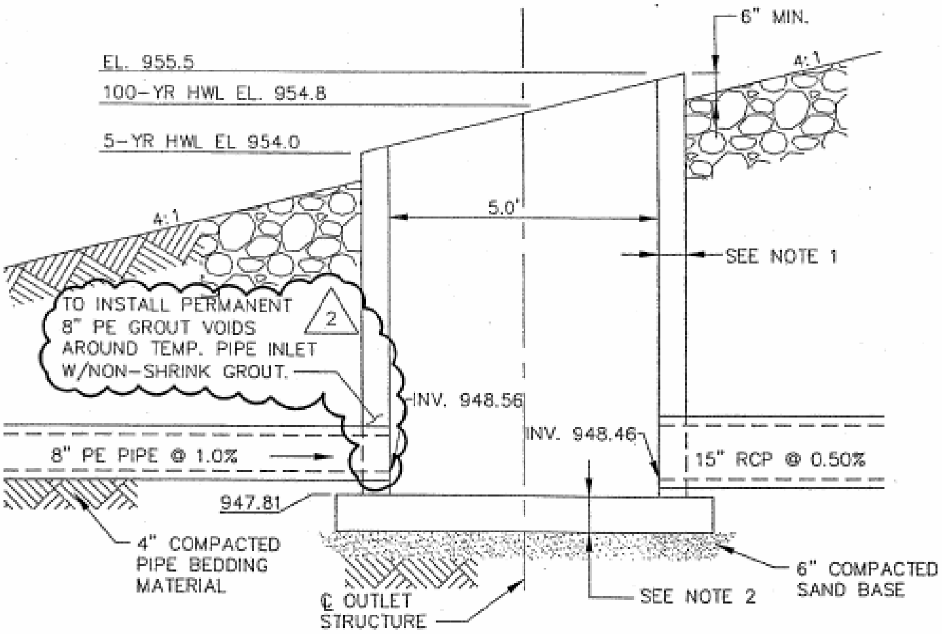


Figure 3: Outlet structure of Carver County dry detention pond

1. Assessment Goals

The goals of this assessment were to (1) assess runoff volume reduction and (2) assess pollutant retention performance of total suspended solids, volatile suspended solids, total phosphorus, and particulate phosphorus. This pond was designed to drain within 48 hours after a runoff event by filtering the stormwater through sand trenches and into a perforated pipe collection system. An elevated outlet structure within the dry pond provided a secondary outlet, which prevented the ponds from flooding. In addition to filtration, a primary treatment process of dry detention ponds with under-drains is sedimentation, which occurs while the runoff is pooled in the pond.

2. Assessment Techniques

To meet the assessment goals, both inflow and outflow had to be measured and sampled at each pond. The pond was chosen for monitoring because it had one influent and one effluent location and limited overland inflow. Thus, only two flow measurement and sampling stations were needed.

A 6700 series portable ISCO water quality sampler, which contained a complete set of 24, 1-liter, wedge-shaped bottles, was installed at the inlet of Pond #3. The unit was programmed to collect flow-weighted samples and to record the depth, velocity, and discharge at 10-minute intervals. A tipping bucket ISCO rain gage was also installed near the inlet of pond to collect data on the total rainfall amount, antecedent dry days, and rainfall intensity for each storm event.

Initially, a 5-foot wide rectangular, sharp-crested weir was installed at the inlet of Pond #3, as shown in figure 4, with an ISCO 710 Ultrasonic Flow Module with a 6700 series sampler. The sensor on the 710 Ultrasonic Flow Module was installed over the water surface just upstream of the weir to measure depth behind the weir. The equipment continuously monitored and recorded the rainfall and water level at the inlet of Pond #3. It also estimated discharge based on the water level.

Results from preliminary monitoring showed that the rectangular weir did not provide accurate estimates of discharge at the relatively low discharge rates that were most common at the site. Therefore, the 5-foot wide rectangular weir was modified by cutting a 3-inch deep, 90 degree V-notch into the middle of the rectangular weir such that the result was a sharp-crested compound weir which could more accurately estimate low discharges.

At the outlet, another 6700 series portable ISCO sampler was programmed to take flow-weighted samples. Using a flexible circular spring ring, a 750 Area Velocity Flow Module was installed on the bottom of the outlet culvert. This type of module uses Doppler technology to measure average velocities at locations across the flow cross-section. A pressure transducer contained within the Module measured water depths and, based on conduit geometry, calculated flow areas. The total discharge was calculated by the ISCO sampler by summing the products of all recorded average velocities and their corresponding flow areas.

Figure 4: Rectangular weir at inlet of Pond #3.

The monitoring systems at both the inlet and outlet of the pond were powered by heavy duty deep-cycle marine batteries and Global Tech (PRO 5W) solar powered battery chargers. Although ISCO 6700 samplers and 700 series modules are water-tight, corrosion resistant, and can be installed without additional protection, all the monitoring equipment was enclosed in lockable wooden environmental cabinets. A laptop PC with ISCO Flowlink 4 software was used to retrieve the data from the 6700 samplers.

An artificial head of water was created in the pipe by installing a 3-inch high plastic circular weir, as shown in figure 5, to ensure that the area velocity sensor used at the outlet had the required 2-inches or more of water depth needed to accurately measure the velocity profile. The area velocity sensor was located inside of the pipe, 6-inches upstream of the circular weir. Due to turbulence created by the weir, the velocity and resulting discharge reported by the area velocity probe were erroneous and could not be used to assess the pond. The depth measurement, however, reported by the probe was correct, and these values were used to calculate the head on the weir and the corresponding discharge.

Figure 5: Circular weir installed in outlet pipe of Pond.

3. Assessment Results

Data and samples were collected for twelve runoff events over two years. The results are presented in tables 1, 2, and 3. The data presented in tables 1 and 2 were used to estimate the performance of the pond for volume reduction and pollutant retention as listed in table 3. There was significant infiltration in the pond. Values ranged from 1/3 of the total influent volume at high discharges to greater than 2/3 of the total volume at lower discharges.

Overall, load-based efficiencies are assumed to be preferred for total load studies. Total load is determined by subtracting the sum of the outflow from the sum of the inflow and dividing by the sum of the inflow. These efficiencies for the twelve monitored storms were 88% for total suspended solids, 81% for volatile suspended solids, 58% for total phosphorus, and 52% for dissolved phosphorus. These load-based efficiencies incorporate infiltration as a treatment mechanism and are therefore less comparable between sites.

The average concentration-based retention efficiencies for the twelve storms at Carver County dry detention pond with under-drainage were 39% for total suspended solids, 32% for total volatile solids, 35% for particulate phosphorus, and 16% for total phosphorus. Retention efficiencies for dissolved phosphorus provided more variation and ranged between negative 18% to positive 60%, with an average retention efficiency of 3%. Dry detention ponds are focused on removing sediment and the associated pollutant concentration, such as particulate phosphorus. The primary retention mechanisms are not designed to retain dissolved phosphorus; thus, dissolved phosphorous retention is minimal.

Table 1: Rainfall amount and duration; total influent, effluent, and infiltration volume for the Carver County pond.

Storm Event	Total Rainfall	Event Duration	Total Influent Volume	Total Effluent Volume	Total Infiltration Volume
	(in)	(hr)	(ft^3)	(ft^3)	(ft^3)
SE 1	4.10	53	119,232	70,062	49,170
SE 2	2.23	2	39,001	24,744	14,257
SE 3	0.70	25	19,488	3,837	15,651
SE 4	2.25	6	63,587	32,281	31,306
SE 5	1.58	13	47,875	8,796	39,079
SE 6	1.39	18	25,487	18,967	6,520
SE 7	1.67	96	57,367	30,420	26,947
SE 8	0.41	23	13,745	5,184	8,561
SE 9	1.16	6	38,206	32,470	5,736
SE 10	0.40	9	9,336	2,158	7,178
SE 11	0.51	16	14,184	6,926	7,258
SE 12	0.18	2	3,207	220	2,987

Table 2: Total influent and effluent pollutant load and concentration of TSS, VSS, TP, and DP for the pond. Load is given in kg and concentration is given in mg/L.

Storm Event	Total Suspended Solids				Volatile Suspended Solids				Total Phosphorus				Dissolved Phosphorus			
	Load In	Load Out	Conc. In	Conc. Out	Load In	Load Out	Conc. In	Conc. Out	Load In	Load Out	Conc. In	Conc. Out	Load In	Load Out	Conc. In	Conc. Out
SE 1	194	20	58	10	18	5	5	3	0.55	0.18	0.16	0.09	0.21	0.10	0.06	0.05
SE 2	873	76	791	109	107	11	97	16	0.27	0.11	0.25	0.15	0.04	0.03	0.04	0.04
SE 3	11	1.0	19	9.0	4.3	0.47	7.8	4.3	0.06	0.01	0.11	0.08	0.04	0.01	0.07	0.06
SE 4	117	25	65	27	24	6.0	13	6.6	0.42	0.19	0.23	0.21	0.25	0.12	0.14	0.13
SE 5	16	1.3	12	5.3	8.8	0.9	6.5	3.8	0.36	0.05	0.27	0.18	0.23	0.03	0.17	0.12
SE 6	4.0	1.3	5.6	2.4	2.1	0.75	2.9	1.4	0.12	0.08	0.17	0.16	0.07	0.05	0.10	0.10
SE 7	30	22	18	25	8.5	7.0	5.2	8.1	0.28	0.19	0.17	0.23	0.18	0.11	0.11	0.13
SE 8	6.3	0.7	16	4.7	2.0	0.3	5.1	2.0	0.08	0.02	0.20	0.13	0.03	0.01	0.08	0.07
SE 9	9.7	8.1	8.9	8.8	2.4	1.9	2.2	2.0	0.29	0.22	0.26	0.24	0.18	0.15	0.17	0.16
SE 10	2.4	0.50	9.1	8.1	1.2	0.22	4.6	3.5	0.04	0.01	0.16	0.14	0.03	0.01	0.10	0.08
SE 11	4.3	2.3	11	12	1.8	1.1	4.6	5.4	0.07	0.03	0.16	0.14	0.03	0.02	0.08	0.08
SE 12	0.25	0.01	2.7	1.8	0.13	0.01	1.4	0.80	0.01	0.00	0.08	0.09	0.00	0.00	0.05	0.08

Table 3: Load-Based and Concentration-Based Removal Efficiencies for the pond.

Storm Event	**Load-Based Removal Efficiencies**				**Concentration-Based Removal Efficiencies**			
	TSS	VSS	TP	DP	TSS	VSS	TP	DP
SE 1	90%	71%	68%	52%	83%	50%	46%	18%
SE 2	91%	90%	61%	31%	86%	84%	39%	-8%
SE 3	91%	89%	85%	83%	53%	45%	22%	14%
SE 4	79%	75%	54%	54%	58%	50%	10%	9%
SE 5	92%	89%	87%	87%	54%	42%	31%	28%
SE 6	68%	64%	33%	31%	57%	52%	9%	7%
SE 7	27%	18%	30%	38%	-37%	-56%	-31%	-18%
SE 8	89%	85%	77%	71%	71%	61%	38%	22%
SE 9	16%	23%	23%	16%	1%	9%	10%	1%
SE 10	80%	82%	80%	81%	11%	24%	13%	19%
SE 11	47%	42%	57%	53%	-9%	-17%	12%	4%
SE 12	96%	96%	92%	89%	33%	43%	-12%	-60%
Mean	72%	69%	62%	57%	38%	32%	16%	3%
Std. Dev.	27%	27%	24%	25%	39%	38%	22%	24%

4. Conclusions and Recommendations

Dry detention ponds have been widely used to temporarily store and treat stormwater runoff, but little is known about their effectiveness in terms of pollutant retention, particularly when they are equipped with under-drains. The Carver County dry detention pond with under-drains was selected and monitored from May 2004 to November 2004 and May 2005 to August 2005 to learn more about their performance. The performance of the pond in terms of pollutant retention efficiencies was estimated by comparing the influent and effluent pollutant concentrations. From the results obtained in this study, the following specific conclusions were reached:

- The measured concentrations of most parameters in stormwater runoff that entered at the Carver County dry detention pond with under-drains were substantially lower than concentrations typically mentioned in other studies throughout the nation and influenced the pollutant retention efficiency of the pond. The lower values found at Carver County dry detention pond site are thought to be related to pre-treatment provided by the small pond near the inlet and also by the two grassy ditches/swales used to transport stormwater runoff to the detention pond site.

- The use of a primary device for flow measurement is strongly recommended, especially in outlet under-drain pipes. These devices (V-notch, rectangular or circular weirs, and flumes) are easy to install and can be used to provide continuous flow hydrographs using measurements of water surface level. The study revealed that an AV sensor cannot measure any velocity unless there is at least 2.5 to 3 inches of water over it, which does not often occur in under-drain outlets.

This research study confirmed that dry detention ponds with under-drains are an effective option for water quality control. The Carver County pond provided moderate stormwater treatment and reduced the concentrations of total suspended solids, volatile suspended solids, particulate phosphorus, and total phosphorus, even with low influent concentrations.

Results from the Carver County dry detention pond with under-drains indicate that influent pollutant concentrations influenced the pollutant retention efficiencies. Higher total suspended and volatile solids influent concentrations for Storm Event 2 resulted in high total suspended and volatile solids retention. Similarly, dissolved phosphorus retention efficiencies were higher at high influent concentrations and lower at low influent concentrations. However, the trend between influent pollutant concentrations and retention efficiencies for all twelve monitored storms at Carver County pond was not consistent.

The filter under-drain system at the pond exhibited poor hydraulic performance and failed to keep the pond dry between the storm events. The runoff residence time in the pond for the twelve storm events monitored ranged from 2 days to 17 days, with an average of 5 days. The filter system requires continual maintenance to ensure that it is functioning properly. Field maintenance activities to maintain the hydraulic performance of the filter media may include replacement of filter media, filter backwashing, or scratching a few inches from the top of the filter media.

Appendix A: Case Studies

2. Assessment of a proprietary underground structure for stormwater treatment

Provided by M.A. Wilson, J.S. Gulliver, O. Mohseni (omohoseni@umn.edu), and R.M. Hozalski at the University of Minnesota

CASE STUDY #2: ASSESSMENT OF A PROPRIETARY UNDERGROUND STRUCTURE FOR STORMWATER TREATMENT

Contributing Authors: M.A. Wilson, J.S. Gulliver, O. Mohseni (omohseni@umn.edu), R.M. Hozalski

Hundreds of proprietary underground structures have been installed in the Twin Cities metropolitan area in recent years to improve the quality of stormwater runoff. One such placement is a V2B1 Model 4 by Environment21, LLC, installed in New Brighton, Minnesota, at the intersection of Rice Creek Road and Long Lake Road, as shown in figure 1. It receives stormwater runoff from a 4.2 acre, residential watershed that is approximately 55% vegetated and 45% impervious. Effluent from the V2B1 device ultimately reaches Long Lake because the lake receives effluent from the watershed.

The V2B1 Model 4 is a dual manhole system consisting of a 5 foot diameter swirl chamber and a 5 foot diameter floatables trap. Stormwater influent is introduced tangentially to the swirl chamber by the 15 inch PVC pipe, inducing a swirling motion inside the manhole. Relatively heavier particulates contained in the stormwater (sands, trash, etc.) settle out of suspension in the swirling chamber. Stormwater escapes the swirling chamber by overflowing an 18 inch diameter PVC standpipe in the middle of the manhole, where the water is conveyed to the floatables trap. The floatables trap manhole contains an underflow baffle wall with a 1 foot by 3 feet rectangular hole at its base. Buoyant material (hydrocarbons, cigarette butts, some organic matter, etc) that passes through the swirling chamber via the overflow standpipe are retained in the floatables trap since water must travel beneath the baffle wall to escape the system through a 15 inch PVC pipe. Downstream of the device, the effluent from the V2B1 discharges into a 36 inch reinforced concrete pipe (RCP), which eventually empties into Long Lake. There is an overall drop of 0.2 feet across the system, from the inlet invert to the outlet invert. The distance between pipe inverts and manhole inverts is approximately 4.5 feet in each treatment manhole. One access point is provided to the swirl chamber, and one access point on each side of the baffle wall in the floatables trap, as illustrated in figure 2.

The unit was designed to accommodate a maximum hydraulic flow rate equivalent to the 10-year event, with an intensity of 4.6 inches/hour, without flooding the street. According to calculations provided by Environment21, this discharge is 6.7 cfs, which serves as the capacity of the storm drain conveyance system around the device. The V2B1 is an in-line system with no bypass provided, meaning the device will receive all flows traveling through the system. However, even though all storm flows travel through the device, treatment is not intended to be provided above the water quality event, defined to be 0.8 inches of rainfall. A runoff coefficient of 0.46 was tabulated for the 4.2 acre watershed. According to calculations provided by Environment21, the water quality flowrate is 1.37 cfs, which corresponds to the maximum treatment rate for performance assessment.

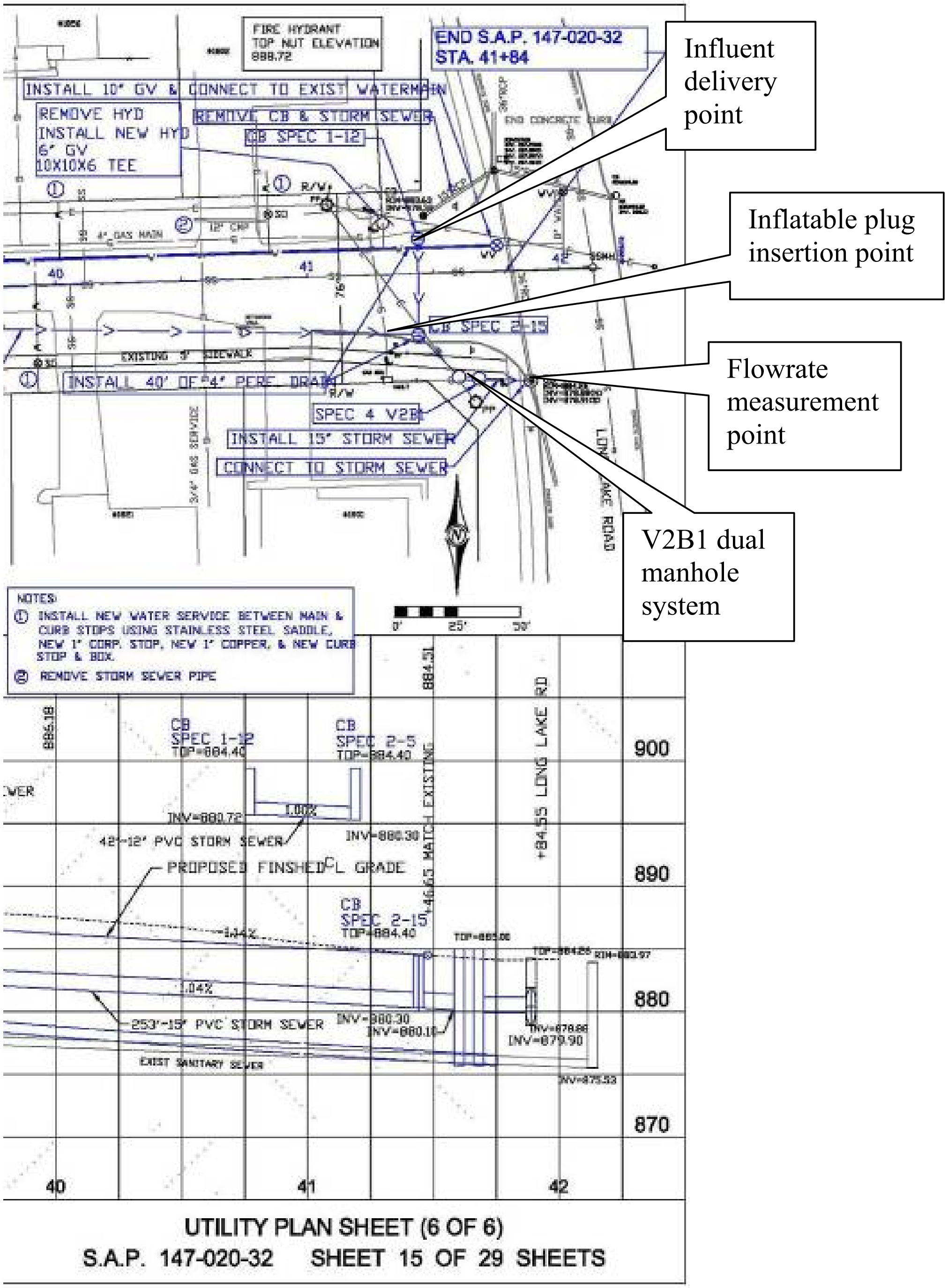


Figure 1: Plan and profile of Environment21 V2B1 Model 4 installation site at intersection of Rice Creek Road & Long Lake Road, New Brighton, MN

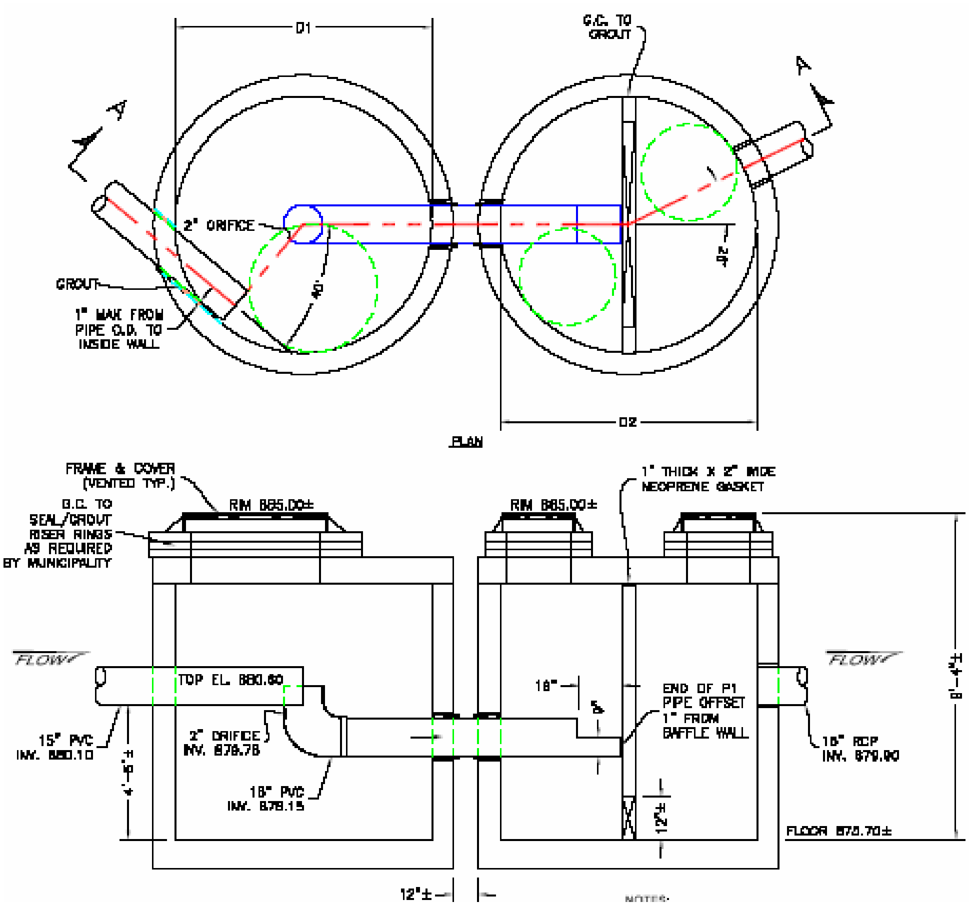


Figure 2: Plan and section of V2B1 Model 4, dual manhole stormwater treatment device installed at Rice Creek Road & Long Lake Road, New Brighton, MN

1. Assessment Goals

The goals of this assessment were twofold: 1) investigate the practicality of controlled field testing as an alternative to field monitoring; and 2) to evaluate the sediment removal capability of the V2B1 Model 4 when subject to field testing with a wide range of sediment sizes and influent flow rates. Another product of the assessment was a performance curve for the V2B1 in which removal efficiency is plotted versus a dimensionless parameter. This performance curve serves as a tool to reliably predict the removal performance for a wide range of V2B1 model sizes, influent flow rates, and pollutant size characteristics. The performance curve can also be used as a tool to accurately size a new stormwater treatment structure, given a target removal efficiency, a target particle size for removal, and a design flow rate.

2. Assessment Techniques

To meet the project goals, a new approach for stormwater facility assessment was developed and refined. Traditionally, stormwater facilities such as detention ponds, bioretention, underground structures, have been evaluated via field monitoring studies. Monitoring studies make use of sampling both upstream and downstream of a treatment facility such that improvement in water quality can be quantified. Upstream-downstream studies offer the advantage of evaluating removal performance of a facility when subject to the often wide variety of actual contaminants in a watershed of interest. However, due to the challenges of obtaining representative samples at both upstream and downstream sampling locations, data obtained are too general to specifically identify the range of performance and tend to have substantial uncertainty.

The concept of synthetic runoff testing for sedimentation devices is specific to performance as a sediment trap and avoids most of the uncertainties associated with monitoring. Using synthetic runoff, rather than actual storm events, utilizes water and sand that is artificially supplied to a clean device. At the completion of a test, personnel enter the device and remove the sediment retained during the test, allowing for a bulk solids analysis on a known quantity of delivered and retained sand. In addition to providing a more certain performance assessment, the synthetic runoff approach enables comparison of results for a particular device across different watersheds, climates, land uses (i.e., different pollutant loading), influent flow rates, and treatment unit size. This comparison can be accomplished by plotting the removal efficiency as the dependent variable versus the appropriate dimensionless parameter, as explained in the following paragraphs. Synthetic runoff testing is thus related to the performance of the device and not to the particular watershed. The runoff from the watershed can then be routed through the device using a computer simulation based on the characteristics of the watershed and the results of synthetic runoff testing.

Prospective sites from throughout the Twin Cities metropolitan area were identified, screened, and evaluated for field testing potential based on a variety of characteristics: 1) location of out-of-vehicle traffic lanes for safety and traffic handling concerns; 2) proximity to a fire hydrant for use as a water source; 3) maximum treatment rate of the BMP device due to finite maximum discharges from hydrants; and 4) device allowing for human access to treatment chamber sump for maintenance. The system to be tested also needed to provide a suitable location within the storm drain system for flow rate measurement using a pre-calibrated weir and pressure transducer. Appropriate permits were obtained from governing agencies.

One of the sites chosen for field testing was the Environment21 V2B1 Model 4 device depicted in figures 1 and 2. Prior to beginning testing activities, the site required several preparation procedures: 1) for real-time flow rate measurement, a pre-calibrated, 15–inch, circular weir and Campbell Scientific CR-10X pressure transducer (figure 3) were installed approximately 20 feet downstream of the floatables-trap manhole depicted in figure 2. The pressure transducer measured water depths, which, based on conduit geometry, were used to calculate flow areas and therefore discharge; 2) the V2B1 manholes were dewatered and several months worth of solids accumulation was removed with the assistance of vacuum trucks provided by the City of New Brighton; 3) a piping system was customized for the delivery of hydrant water as influent test water, using the hydrant's 4 inch connection and a series of fittings, a 4 inch gate valve, and a 6 inch PVC pipe (figure 4); 4) sand was previously sieved into three size fractions for use in each simulated runoff event, with median sizes: 107 μm (ranging from 89 μm to 125 μm), 303 μm (ranging from 251 μm to 355 μm), and 545 μm (ranging from 89 μm to 125 μm), starting with F110 sand (d_{50}~110 μm), AGSCO 40-70 sand (d_{50}~225 μm), and AGSCO 35-50 sand (d_{50}~425 μm) as supply; and 5) an inflatable 15-inch diameter plug was secured from the City of New Brighton to seal off storm drainage upstream of the treatment system but downstream of the influent to prevent nuisance flows in the system from contaminating the controlled influent delivered to the V2B1 and to avoid controlled influent from leaving the test system prematurely.

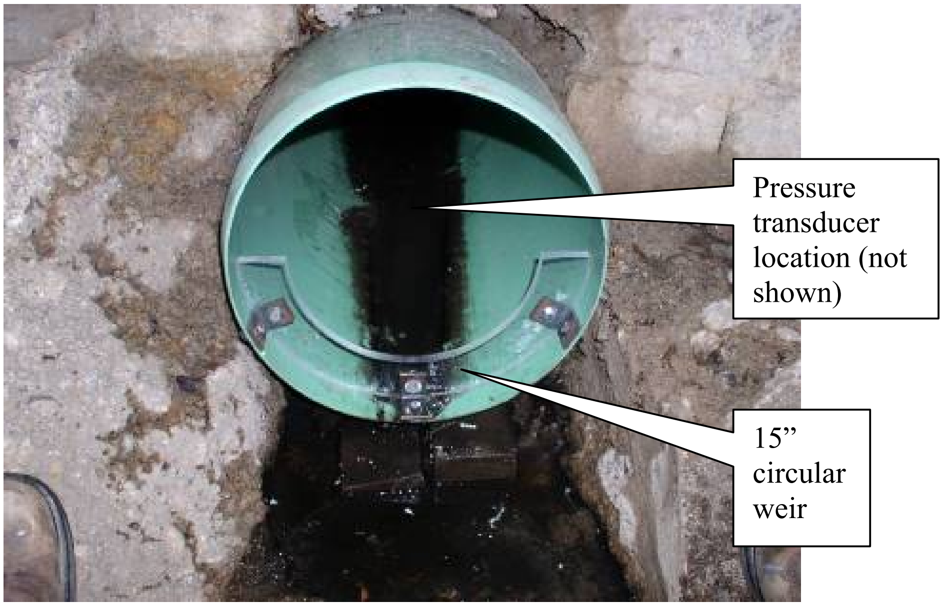


Figure 3: Pre-calibrated 15-inch circular weir installed downstream of the V2B1. Pressure transducer and transducer anchoring not shown. This weir location provided free outfall conditions at all flow rates due to the PVC pipe’s favorable elevation vs. the existing 36-inch RCP it discharged into.

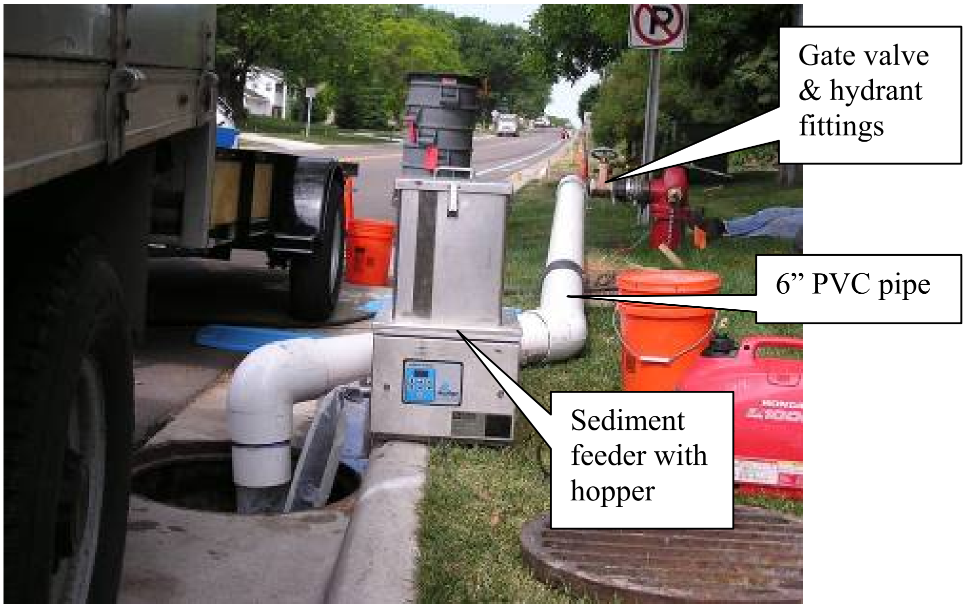


Figure 4: Piping system from hydrant (background) to influent injection point (foreground left) and stainless steel sediment feeder

The procedure for field testing the V2B1 Model 4 includes the following steps:

1) establishing a safe work zone, following confined space entry regulations;
2) installing and inflating with a portable air compressor the 15 inch rubber plug upstream of the V2B1 device to seal off the upstream reaches of the storm drain system (figure 5);
3) connecting piping system from hydrant to influent injection point;
4) flushing clean hydrant water through the system prior to initial device cleanout;
5) dewatering the device with sump pumps and removing solids with a wet/dry vacuum cleaner;
6) establishing an appropriate flow rate through the system using real-time level measurements from a pressure transducer and datalogger, and conditioning the flow with a gate valve on the hydrant. The datalogger recorded 60-second average levels and provided an updated readout every second when connected to a laptop computer loaded with Campbell Scientific's PC200W software;
7) introducing 10-15 kg of pre-sieved sand [equal parts of 107 µm, 303 µm, and 545 µm sands] to the influent hydrant water at 200 mg/L using a pre-calibrated sediment feeder;
8) recording water temperature, mass of sediment delivered, and test duration;
9) following a 20-minute period to allow sand particle settling, dewatering the device with sump pumps, and removing retained solids from each manhole separately with a wet/dry vacuum cleaner;
10) oven drying and sieving the collected sediment into size fractions, and weighing each fraction of retained solids for comparison to the known quantity of each size fraction fed to the V2B1 during the test

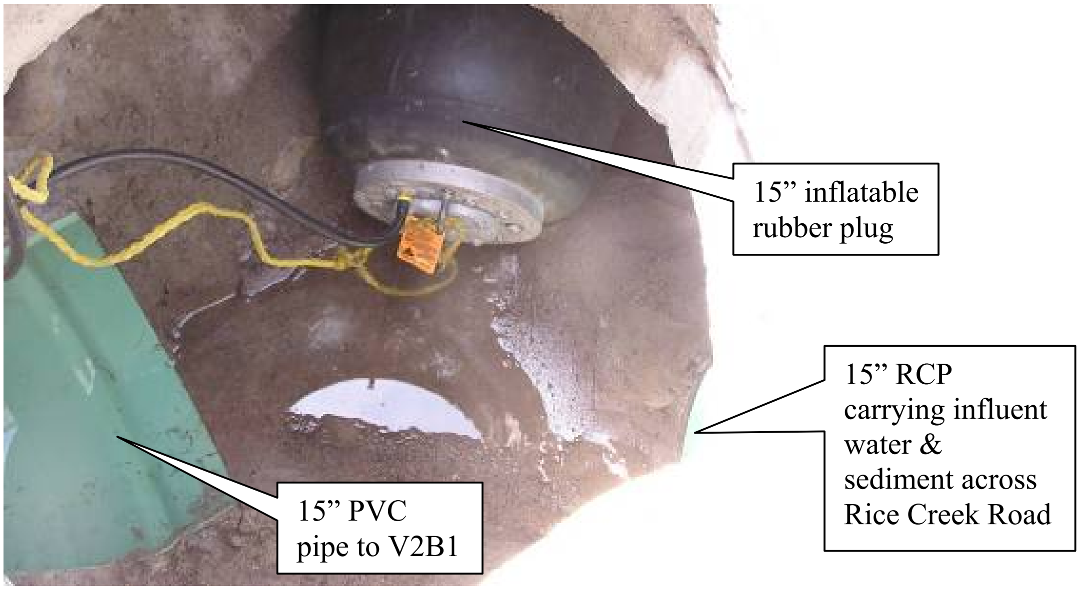


Figure 5: Installation of 15 inch inflatable plug in upstream concrete pipe to seal off nuisance and/or extraneous flows from contaminating test

The data in step 10 above, divided by the known quantity of sand delivered to the V2B1 during the test, provided the removal efficiency of the device for each sand size fraction at a particular flow rate. Thus, each test produced three data points since three discrete sand size ranges were utilized. The testing protocol called for a device to be tested under four flow rate conditions in triplicate, at approximately 25%, 50%, 75%, and 100% of the maximum treatment rate (MTR), for a total of 12 tests. So under ideal test conditions, each device's removal efficiency can be described by 36 data points.

A device's removal efficiency can be plotted as a dependent variable against an appropriate dimensionless independent variable. The dimensionless parameter used as an independent variable was the Peclet Number (Pe), which is the ratio of advection to diffusion (Dhamotharan et al. 1981, Wilson et al. In Press). Advection is calculated as particle settling velocity V_s times a length scale L_1. Diffusion can be simplified to flow rate Q divided by length scale L_2. Putting advection and diffusion together yields Pe = $(V_s * L_1 * L_2)/Q$, where L_1 and L_2 are taken to be a device's treatment chamber diameter and settling depth.

As often as possible, the field team attempted to complete more than one test per day in order to maximize the effort in traveling to the site, setting up equipment, and preparing the device for testing, which were relatively constant 'costs' of testing whether 1 or 3 tests were performed.

Construction activity adjacent to the stormwater quality test site presented difficulty with coordinating field testing. Additionally, a leaking swirl chamber was repaired to ensure proper hydraulics and system operation.

3. Assessment Results

At high Pe Vs (i.e., large particles and therefore high settling velocities), coupled with low flow rate *Qs*, a stormwater treatment device can be expected to be successful removing particles from an influent. If the Pe number was allowed to approach infinity (approximating a large detention pond or lake), very near 100% removal could be achieved. The data appear to exhibit this trend, but the required Pe to such removal is unknown. Conversely, at low Pe Vs (i.e., small particles and therefore low settling velocities), coupled with high flow rate *Qs*, a device can be expected to remove particles from influent with less success. This has been upheld in the results obtained, illustrated by the V2B1 performance curve depicted in figure 6.

The first several tests using the different particle sizes and relatively low flows indicated there was a problem carrying out tests with all of the sands designed for use during the experiment. Under low flow rates, the influent water velocity falls low enough such that it no longer can keep the largest sand particles in suspension for the entire distance from the injection point to the V2B1 (approximately 45 feet). Thus, heavier sands drop out of the water column and settle at the bottom of the pipe, a typical result of which is illustrated in figure 7. The experiment was modified such that the relatively low flow rates were increased (which therefore increased influent water velocities in the pipe) and the largest sand sizes removed from the mixture delivered to the device during these low-flow rate tests, producing a total of 30 data points in figure 6.

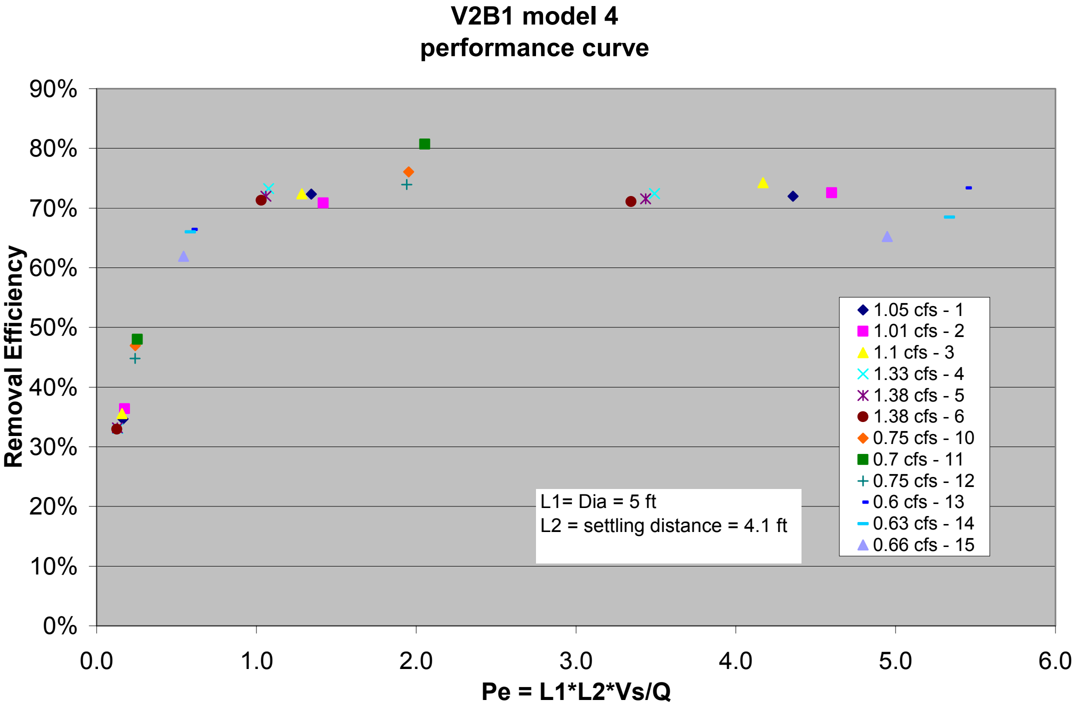


Figure 6: Performance curve of removal efficiency vs. Pe for the V2B1 Model 4 swirl chamber ONLY

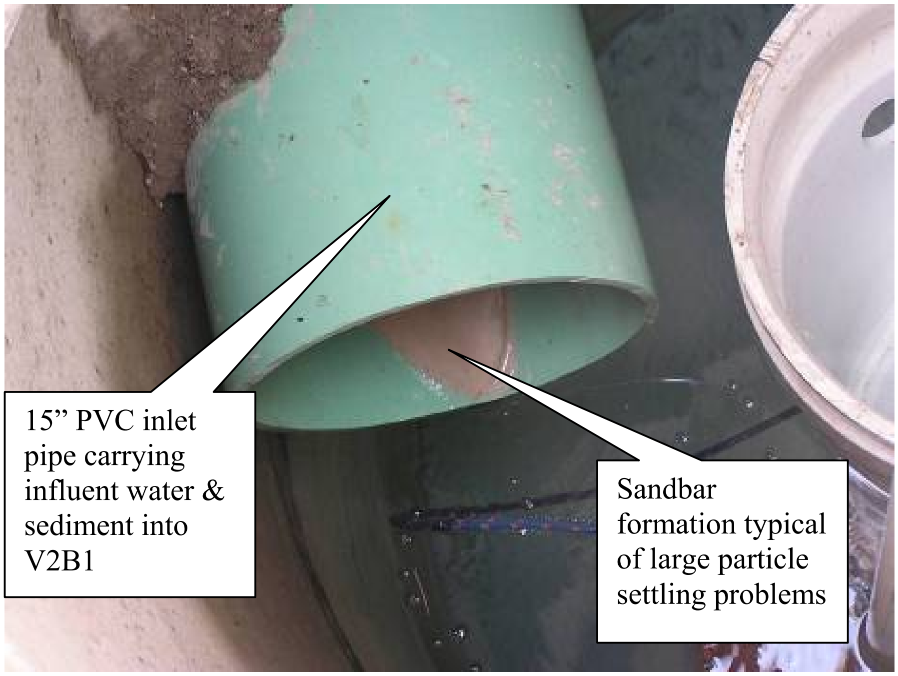


Figure 7: Illustration of particle settling phenomenon inside the swirl chamber’s influent delivery pipe. It is clear that a sandbar has formed, which is believed to contribute to further settling by reducing the vertical settling distance in this pipe.

4. Conclusions and Recommendations

Understanding how devices perform under varying flow rates, sediment sizes, and treatment chamber sizes is important and helpful for consultants, local governments, and state agencies when selecting, designing, and evaluating stormwater treatment technologies for public infrastructure improvement projects. However, the effectiveness of proprietary underground stormwater treatment devices depends upon the settling velocity of influent solids (i.e., solid size and density) in addition to the size and design of the device. That Pe can be used to predict a device's performance over a wide range of V2B1 model sizes, storm events, and pollutant size characteristics is possible because Pe relates two length scales and particle settling velocity to influent flow rate,

This research showed that controlled field tests are a practical, robust and accurate means of determining an underground device's performance, based upon the solid size distribution and influent density, in addition to the water discharge and temperature. The results from this research have been successfully verified on three other devices in field tests and other devices in laboratory tests.

More specifically, these efforts have demonstrated the V2B1 capable of removing coarse solids at a relatively high rate (70% +), but is less efficient at removing fine sands (~32-48%). If the trend is projected to a lower Pe, one would expect that the V2B1 would be even less successful with finer particles such as silt, and remove few, if any, clay particles.

To predict performance and to determine appropriate device sizes, a suspended solid size distribution of typical runoff from the watershed is needed. The next goal is to develop a simple method of determining this size distribution of solids in stormwater runoff.

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Appendix A: Case Studies

3. Assessment of infiltration at a rain garden

Provided by B.C. Asleson, R.S. Nestingen , J.S. Gulliver (gulli003@umn.edu), R.M. Hozalski, and J.L. Nieber at the University of Minnesota

CASE STUDY #3: ASSESSMENT OF INFILTRATION AT A RAIN GARDEN

Contributing authors: B.C. Asleson, R.S. Nestingen, J.S. Gulliver (gulli003@umn.edu), R.M. Hozalski, J.L. Nieber

The University of Minnesota, St. Paul campus rain garden is located on Gortner Avenue and Commonwealth in the Mississippi River watershed. There are five rain gardens located along Gortner Avenue, and three of them are in series. Basins C and B serve as overflow basins and are connected to basin D by two drop structures consisting of bricks. The assessment was conducted on the basin D rain garden. The rain gardens were designed by Barr Engineering and installed in October of 2004. A thorough assessment of basin D was conducted in the summer of 2006.

Basin D rain garden is approximately 716 square feet in size with a ponding depth of 0.5 feet (the design plans indicate 960 square feet with a ponding depth of 2 feet). It is designed to provide storage for the maximum amount of water the space would allow. Stormwater runoff is directed to the rain garden using two inlets, a curb cut-off of Gortner Avenue located along the northwest corner of the rain garden, and an inlet pipe located at the center of the north border of the rain garden, which is connected to the stormwater sewer system. The storm sewer inlet pipe has a 5 inch by 12 inch subgrade of Fond Du Lac wall stone to prevent erosion. The native soil was excavated and filled with a sand trench to a depth of 3-4 feet and a width of 3 feet in the center of the basin. Clean sand with only 5% passing through a 200 micron sieve was used for the sand trench. Basin D rain garden was designed to infiltrate the maximum storage volume within 24 hours at an estimated infiltration rate of 0.5 inches/hour. The basin was then filled with planting topsoil to a depth of 8 inches and planted with selected vegetation. The plant design plan is shown in figure 1.

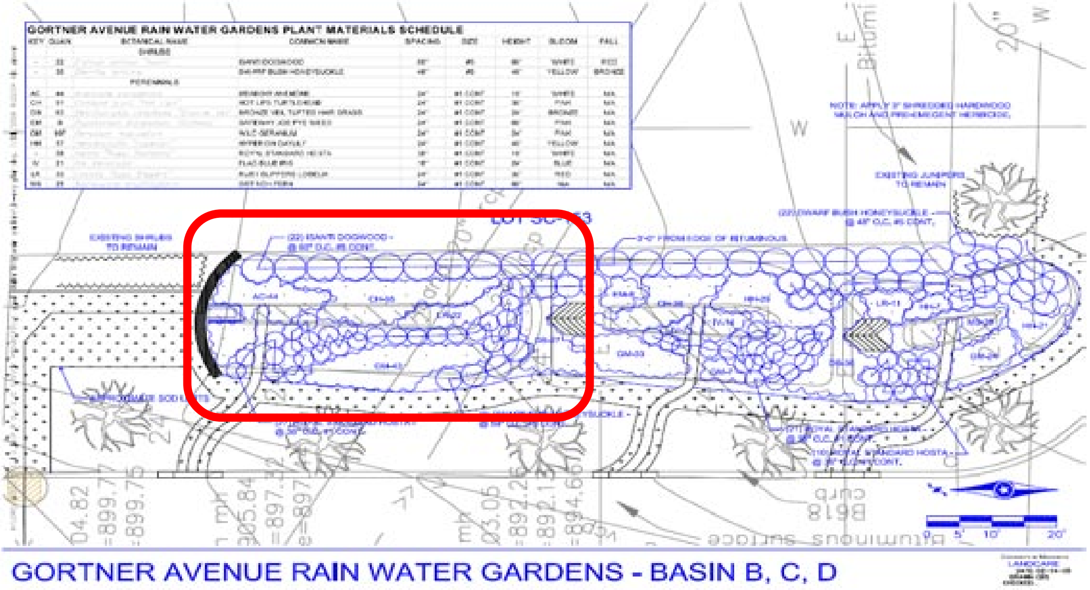


Figure 1: Plant Design Plan

1. Assessment Goals

The purpose of the assessment was to determine if the rain garden had the ability to infiltrate stormwater runoff at the appropriate rate. Rain gardens are typically designed to drain within 48 hours after a storm event. Three of the four levels of assessment as described in Chapter 3 were conducted: visual inspection, permeability tests, and a simulated runoff test.

2. Visual Inspection

2.1. Assessment Techniques

The visual inspection of rain gardens consists of two components: a vegetation analysis and an inspection of the soil. The vegetation analysis examines the species of vegetation present in comparison with the design plans, apparent health of the plants, percent cover of vegetation, and presence of invasive weeds and/or wetland plants. The original plant design was used along with a plant field guide to identify the species present. The leaf color, height, and width of the plants were examined and described as poor, fair, or good. The site was examined for bare spots, and a percent of the vegetation cover was determined. Several photographs of the plants were taken to serve as a record of the vegetation.

The inspection of the soil was conducted by evaluating several soil properties, soil texture and color, soil moisture, and bulk density. These procedures can be found in the Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1-Physical and Mineralogical Methods (Klute 1986). Soil texture can be determined from a sample using sedimentation procedures or in the field using a field guide. The textural flow chart, found in Chapter 11, was used to determine the texture of the soil. Soil color was determined using a Munsell® soil color chart (Munsell 2007) and was done for each new layer (signified by a change in texture or color).

Figure 2 is a photograph of the texture and color of the soil being determined in the field using the USDA textural triangle, textural flow chart, and the Munsell® soil color chart. There are several methods available for measuring soil moisture, or a general wetness can be described. When making general wetness statements, the terms dry, moist, saturated, and inundated are typical descriptions. The soil moisture was measured at this site using two methods: the gravimetric method and with the use of a capacitance probe. Bulk density using the core method was the final soil property measured as part of the assessment. Bulk density can be used to convert gravimetric water content to volumetric water content, calculate porosity, and void ratio when particle density is known and is a useful index of the degree of compaction. Additional observations were made regarding channelization, sediment accumulation, erosion, and condition of inlet structures.

2.2. Assessment Results

The plants in the rain garden matched fairly well to the design plans, although there appeared to have been modifications made to the original design plan. Most of the plants appeared to be healthy with the exception of geraniums along the west edge. They were not filling in the area as they should and their growth was not as lush as expected. There was a fairly large bare area northeast of the center of the basin where the anemones and chelone come together.

Figure 2: Texturing and coloring the soil

The overall percent plant cover of the basin was approximately 70%. There was a large bare area near the inlet and up the side slope next to the curb inlet. Vegetation was sparse in the center of the basin with several large bare areas between plants. There did not appear to be a large number of weeds present, and there was no sign of wetland vegetation. Based on the visual inspection of the vegetation, there appears to be some limitation in plant growth.

The inspection of the soil included soil texture and color, soil moisture, and bulk density. The soil texture and color was as follows:

- 0 – 8 inches: Sandy Loam, 10YR 2/2
- 8 – 19 inches: Silt Loam, 10YR 2/1
- 19 – 47 inches: Sand (non-native), 10YR 6/4
- 47 - ? inches: Silt Loam with coarse Sand, 2.5YR 3/3

The sandy loam topsoil is typical for rain gardens in Minnesota; however, the silt loam layer below is of concern. When comparing the two soils on the USDA Soil Textural Triangle, there is a much higher percentage of silt, which is finer than sand and has a lower K_{sat} than the sandier layer above and below it. The silt loam layer therefore restricts water from flowing downward until the entire soil profile is saturated. The original design plans indicate 3 to 4 feet of the non-native sand directly below the 8 inch layer of topsoil. The soil moisture of the basin was near saturation most of the time. This indicates that there is sufficient water for plant growth with adequate drainage. The mulch layer and canopy cover over the soil surface are likely contributing to the retained moisture during the dry season. The bulk density of the site varied spatially, with an average of 1.18 grams per cubic centimeter. These observations are lower compared to the typical 1.3 grams per cubic centimeter for most mineral soils; however, with the high organic matter content due to the mulch and plant roots, lower-than-expected bulk densities appear to be normal for rain gardens. There were no signs of hydric conditions such as gleying or the presence of mottles. Based on inspection of the soil properties, the infiltration appears to be adequate; however, the restrictive layer of silt loam may pose problems for long-term operation by retaining too much water during large storm events. No signs of erosion or channelization were present near the inlet structure, and both inlet structures were in good condition.

3. Capacity Testing

3.1. Assessment Techniques

The permeability of the soil was measured to determine the rain garden's capacity for infiltrating water. At this site several devices were used to measure the saturated hydraulic conductivity (K_{sat}) of the soil in order to establish the technique. The three devices used to measure K_{sat} were the Double Ring Infiltrometer, Minidisk Infiltrometer, and the Modified Philip-Dunne Permeameter. Locations where point measurements of K_{sat} were to be made were distributed evenly throughout the entire rain garden and marked using orange utility flags. These locations varied in their proximity to the vegetation but were never placed directly over the base of the plant. Additional locations were marked at the low point of the site to better represent the frequently occurring small runoff events. Figure 3 is a photograph of the rain garden with orange utility flags marking test locations.

Figure 3: Flags marking locations of permeability tests

A total of 40 locations were marked in this site to evaluate the spatial variability of K_{sat} within the basin. The data were compiled and used to create a graph to estimate the appropriate number of measurements necessary to obtain an accurate average value of K_{sat} for the entire basin. This graph can be found in Chapter 3 and should be used as a suggestion for conducting capacity tests at other sites. The coordinates of each location as well as the perimeter of the rain garden was logged using a GPS device. At 38 of the test locations a measurement was made using the Modified Philip-Dunne Permeameter, and another measurement was made using the Minidisk Infiltrometer. At the two remaining locations, two measurements were made using the Modified Philip-Dunne Permeameter and two measurements were made using the Minidisk Infiltrometer. The Double Ring Infiltrometer was only used to make measurements at two of the locations due to its bulkiness and lengthy time and water requirements. Each location was allowed to dry out between measurements.

The Double-Ring Infiltrometer is a constant head infiltrometer and requires two sources of water, one for the inner ring and one for the outer ring. The inner ring had a diameter of 8 inches and the outer ring diameter was 16 inches. Constant head was maintained in the inner ring of the double-ring using a Mariotte system. The system used in the field is shown in figure 4. Water levels inside the plastic container (figure 4) and time measurements were recorded once steady state was achieved. For detailed instructions on Double-Ring Infiltrometer procedures see Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1-Physical and Mineralogical Methods (Klute 1986).

Figure 4: Double-ring infiltrometer with Mariotte system

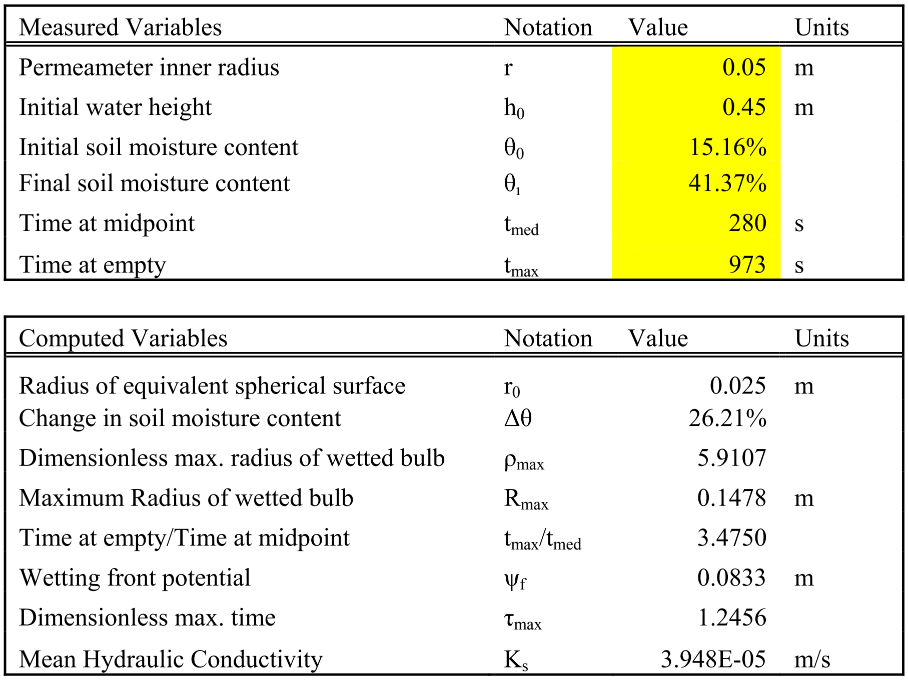
The Minidisk Infiltrometer was purchased through Decagon Devices and is a compact disc infiltrometer. This is a transient flow device in which water is delivered to the soil surface through a porous disc at a negative pressure. This technique is used to prevent water from flowing through large macropores and results in a K_{sat} value representative of the soil matrix itself. This particular device required change in water volume with time measurements to be recorded. These data were then input into a Microsoft Excel ® spreadsheet provided by the manufacturer.

The Modified Philip-Dunne Permeameter is a falling head permeameter constructed specifically for this project; see Appendix C for detailed instructions on the construction. The device was uniformly pounded into the soil to a depth of 2 inches. The initial soil moisture was measured at five locations around the base of the Modified Philip-Dunne Permeameter by two methods: the gravimetric method and using a capacitance probe. Mulch from the rain garden was placed inside the device to prevent erosion; water was then poured into the device to the desired height, which was 17 inches for this site. Two sets of change in water level with time measurements were made for additional data. The first set was the visual method, which requires an initial height of water at time zero, a time at the half way point (approximately 8 inches), and a time at empty. The second method made continuous measurements using an ultrasonic sensor. The soil moisture was then measured from directly inside the device, again at five locations. For more detailed instructions on the use of the Modified Philip-Dunne permeameter, see Appendix C. The original Philip-Dunne equations (Philip 1993), equation 1 below, were modified and the data collected was then used to calculate K_{sat}. A Microsoft Excel ® spreadsheet was developed to input the measured parameters and calculate K_{sat}. An example of the spreadsheet can be seen in table 1; the highlighted cells indicate the necessary input parameters. In depth procedures for calculating K_{sat} using the Modified Philip-Dunne permeameter data can be found in Appendix C. Figure 5 is a photograph of the Modified Philip-Dunne Permeameter being used in the field with an ultra sonic sensor for continuous measurements.

Equation 1: K_{sat} Calculation (Munoz-Carpena et al. 2002)

$$K_s = \frac{\pi^2 r_o \tau_{max}(a)}{8 t_{max}}; \psi_f = \frac{(a^3 - 1) r_o \Delta\theta}{3} - h_o - \frac{\pi^2 r_o}{8}$$

Table 1: Microsoft Excel ® spreadsheet used to calculate K_{sat}



Measured Variables	Notation	Value	Units
Permeameter inner radius	r	0.05	m
Initial water height	h_0	0.45	m
Initial soil moisture content	θ_0	15.16%	
Final soil moisture content	θ_1	41.37%	
Time at midpoint	t_{med}	280	s
Time at empty	t_{max}	973	s

Computed Variables	Notation	Value	Units
Radius of equivalent spherical surface	r_0	0.025	m
Change in soil moisture content	$\Delta\theta$	26.21%	
Dimensionless max. radius of wetted bulb	ρ_{max}	5.9107	
Maximum Radius of wetted bulb	R_{max}	0.1478	m
Time at empty/Time at midpoint	t_{max}/t_{med}	3.4750	
Wetting front potential	ψ_f	0.0833	m
Dimensionless max. time	τ_{max}	1.2456	
Mean Hydraulic Conductivity	K_s	3.948E-05	m/s

Figure 5: Modified Philip-Dunne Permeameter with ultrasonic sensor

3.2. Assessment Results

The 40 locations used for point measurements were positioned using GPS and input into ArcView. Figure 6 is an ArcMap of the measurements made using the Modified Philip-Dunne Permeameter. The results of the measurements made with the other devices as well as the Modified Philip-Dunne Permeameter are shown in figure 7. Both figures illustrate how K_{sat} varies both spatially and among the devices. The average K_{sat} for the double-ring infiltrometer, minidisk infiltrometer, and the Modified Philip-Dunne permeameter were: 0.999 inches/hour, 0.668 inches/hour, and 1.087 inches/hour, respectively. All of the devices used to measure K_{sat} are based on different theories of flow through the soil and different assumptions regarding the system. Currently, none of the devices mentioned have the ability to account for the presence of macropores or other preferential flow paths found in the soil. Chapter 4 presents a detailed discussion of the theories of infiltration as well as the devices used to measure infiltration.

As a result of an evaluation of the devices based on this and previous field work (see table 3.2 in Chapter 3), the Modified Philip-Dunne permeameter was found to be most desirable and is recommended for future assessment of infiltration/filtration practices. For more time-efficient assessment it is recommended to use multiple Modified Philip-Dunne devices. This level of assessment (i.e. level 2) was determined to be the most beneficial technique for understanding the spatial variability of the site and developing a maintenance schedule for the practice.

The time required to drain the design storage volume can be estimated using the measured saturated hydraulic conductivity value of 0.668 inches/hour as a conservative estimate of infiltration rate. With this infiltration rate and the known design depth of 6 inches, the drain time can be estimated by dividing 0.668 into 6 to get 9.0 hours.

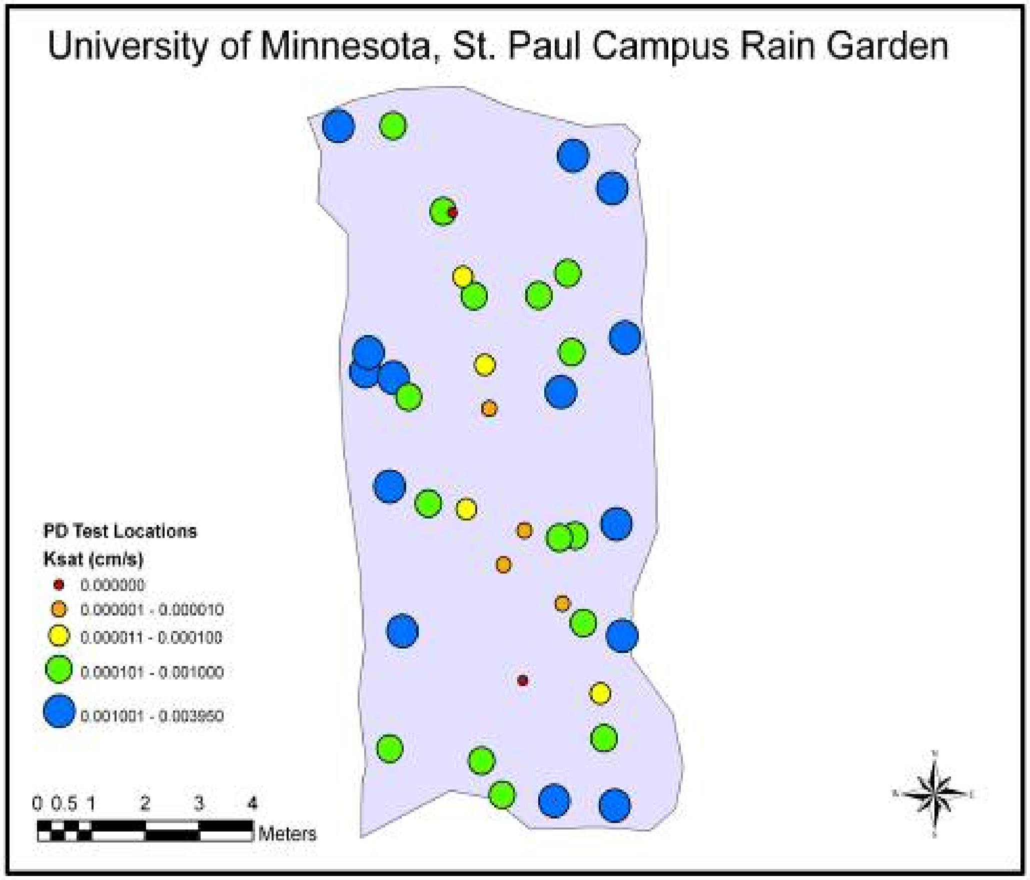


Figure 6: ArcMap of K_{sat} using the Modified Philip-Dunne (MPD) permeameter measurements

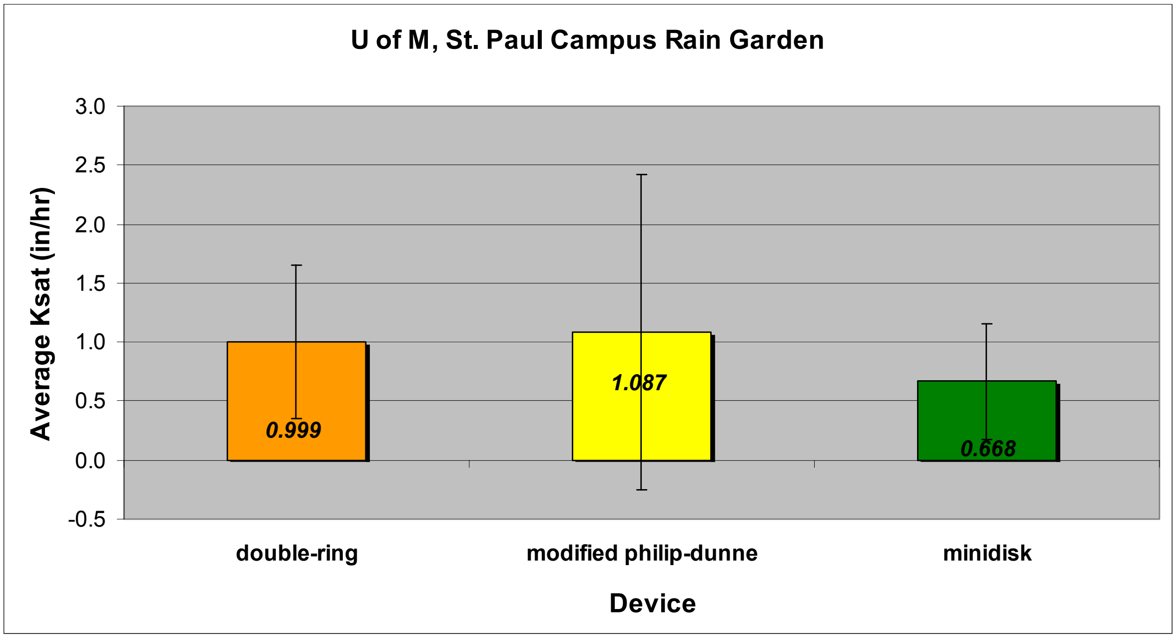


Figure 7: Comparison of measured average saturated hydraulic conductivities using three infiltration devices

4. Synthetic Runoff Test

4.1. Assessment Techniques

A synthetic runoff test was conducted at the site to measure the time required to drain the maximum storage volume. To determine if the nearby fire hydrant could provide the necessary flow, the analysis procedure detailed in example 10.1 was performed. In summary, the water quality volume of the rain garden was estimated by multiplying the surface area of 716 ft^2 by the design depth of 0.5 feet to get 358 ft^3. Assuming the infiltration rate measured with the Modified Philip-Dunne method of 1.087 inches/hour exists when filling the rain garden and that it is desired to fill the rain garden in 30 minutes (i.e. 1800 seconds), the required flow from the hydrant was calculated to be 0.22 ft^2/s by solving the following equation:

$$358 ft^3 = (Q_{req})(1800 \sec) - (1.087 in/hr)(1 in/12 ft)(716 ft^2)(1 hr/3600 s)(1800 \sec)$$

(Q_{req} is the discharge the hydrant must supply if the rain garden is to be filled in 30 minutes.)

Since fire hydrants can typically provide flow up to 3 cubic feet per second (1,500 gal/min), it was determined that the required flow could be obtained from the nearby fire hydrant.

An ultrasonic sensor was positioned directly above the low point of the basin to make continuous water level measurements over time prior to flooding the site. A bare spot within the basin was chosen to provide a good reflective surface for the sound waves. The hydrant was then prepared by connecting a 2.5-inch fire hose to the hydrant using a safety valve to ensure no back flow. The fire hose discharged water into the storm sewer manhole closest to the basin until the rain garden was filled to capacity. Permission was granted by the University of Minnesota facilities management, who also assisted by providing all of the proper connectors, valves, and hoses for the fire hydrant. After the water stopped flowing into the basin, the water level was measured and the timer started. Continuous measurements using the ultrasonic sensor as well as visual measurements with a yard stick were made until the basin was completely drained.

4.2. Assessment Results

Figure 8 is a graph displaying the change in water level with time using the data collected from the ultrasonic sensor. The synthetic runoff test represents the drain time of two hours when the rain garden is filled to capacity. This is about four and one-half times shorter than the conservative estimate of 9.0 hours, which was obtained by assuming the saturated hydraulic conductivity value was equal to the infiltration rate.

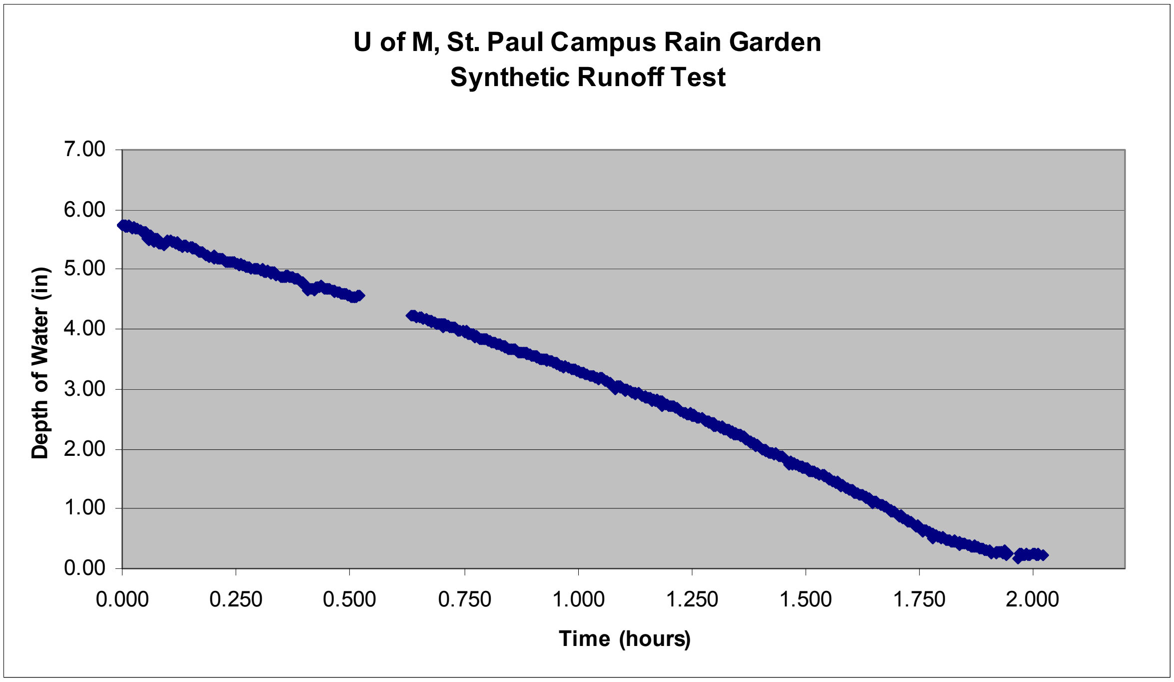


Figure 8: Synthetic Runoff Test results.

5. Conclusions and Recommendations

The overall performance of the basin D rain garden is satisfactory. The results of the visual inspection indicate that there are some concerns for a few of the plant species. These particular species should be further evaluated to eliminate possible causes of growth limitation. Some examples of possible growth inhibitors include improper soil moisture regime, improper sun/shade location, limited oxygen in the soil, high levels of salt in the soil, the presence of invasive species, and a lack of several other plant-specific requirements. The center of the basin had near-saturated soil conditions during the dry season and therefore the plants located in this region should represent a wet meadow plant community. Despite the issues near the inlet and in the center of the basin, the majority of the vegetation was in good health and provided sufficient cover. The soil inspection indicates the potential for problems for large runoff events. The silt loam soil layer just below the topsoil and above the sand trench will result in restricted infiltration to the sand trench due to the smaller pore sizes and increased holding capacity of that particular layer. A more thorough inspection of the soil layers throughout the basin should be conducted to determine the extent of the restrictive layer. The distribution of infiltration rates also indicates that there is a problem with the soil in the center of the basin. All of the very low infiltration rates were located in the center of the basin, which is also where the soil core was taken to characterize the soil layers of the basin. This indicates that the restrictive soil layer could be causing these lower infiltration rates in the center of the basin. The side slopes of the basin had high infiltration rates. Table 2 summarizes the results from the capacity testing and synthetic runoff testing to determine whether stormwater will drain within the specified 48 hours.

To determine the time it will take for the basin to drain using the capacity testing results, first use the dimensions of the basin to calculate the surface area and the storage volume. The infiltration discharge can then calculated by multiplying the surface area by the measured K_{sat}. The time to drain the storage volume can be estimated by dividing the storage volume by the infiltration discharge. An alternative approach that was previously used in section 3 was to divide the design depth by the infiltration rate. As mentioned in section 2.3, each method for measuring K_{sat} of the soil can result in different values due to the theory of flow they are designed for and the scale of the measurements. The results from the measurements made with the Minidisk Infiltrometer would represent the minimum value for the soil, and the synthetic runoff test represents the K_{sat} when the basin is filled to its holding capacity. The Double-Ring Infiltrometer and the Modified Philip-Dunne Permeameter capture a percentage of the macropores present in the soil but cannot account for the total spatial variability of the rain garden. To estimate a conservative drain time, the results from the Minidisk Infiltrometer should be used for this site as it represents the permeability of the soil matrix itself.

Table 2: Comparison of device and synthetic runoff test measurements according to drainage time

Dimensions	**Storage Volume**		
L (ft) = 47.35	WQV (ft^3) = 119.322		
W (ft) = 15.12			
h (ft) = 0.5			
S.A. (ft^2) = 716			
Infiltration Rates			
Double-Ring	Minidisk	Modified PD	
K_{sat} (ft/day) = 1.997	K_{sat} (ft/day) = 1.337	K_{sat} (ft/day) = 2.173	
Infiltration Discharge			
Double-Ring	Minidisk	Modified PD	
I.D. (ft^3/day) = 1429.4	I.D. (ft^3/day) = 956.9	I.D. (ft^3/day) = 1556.2	
Drain Time			
Double-Ring	Minidisk	Modified PD	Flood Test
Time (hrs) = 2.003	Time (hrs) = 2.993	Time (hrs) = 1.840	Time (hrs) = 2.117

The synthetic runoff test indicated very good infiltration when the basin is filled to the maximum storage volume, and the average results of the capacity tests are better estimates for typical rainfall events. Additional synthetic runoff test at varying depths could be conducted to understand how the basin drains for smaller rain events. Although there appear to be some concerns regarding the basin, drainage time is well below the designed 48 hours. The low infiltration and sparse cover of vegetation occurring in the center of the basin should be further evaluated and amended to prevent failure of the basin in the future. A maintenance schedule should be developed based on this evaluation to ensure adequate stormwater treatment efficiency.

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Appendix A: Case Studies

4. Monitoring a regional infiltration system

Provided by Emmons and Olivier Resources (corresponding author: Gary Oberts, goberts@eorinc.com) and the South Washington Watershed District

CASE STUDY: MONITORING A REGIONAL INFILTRATION SYSTEM

The infiltration of runoff water into the ground has been proven to be an effective method of stormwater management in the Minneapolis-St. Paul, Minnesota region. Specifically, the South Washington Watershed District (SWWD - Figure 1) has been using an infiltration system as the backbone of its drainage network and has been monitoring its performance to varying degrees since 1997. Results for two infiltration basins and two infiltration trenches are presented in this case study.

The SWWD is a 54 mi^2 suburban watershed located over very sandy and deep glacial outwash. The watershed is rapidly developing with a 2006 population of about 100,000. The northern two-thirds of the watershed is landlocked. The developed portion is internally drained through a series of ponds, wetlands, and lakes terminating in a large natural depression (CD-P85) that acts as an infiltration basin. CD-P85 contains two constructed infiltration trenches (one monitored) and several dry wells (not monitored). The undeveloped portion consists of two large landlocked subwatersheds that drain to natural depressions that act as infiltration basins referred to as CD-P76 and CD-P82. Land uses within these subwatersheds are predominantly row crop agriculture and rural residential. Figure 2 (a-c) is a collection of photos of the facilities located at the three CD-P sites while they are partially full of infiltrating water.

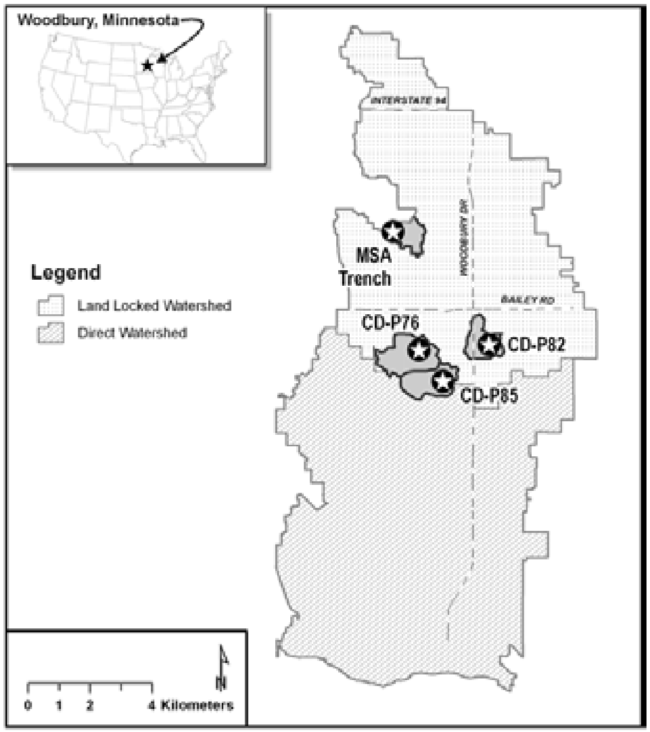


Figure 1. South Washington Watershed District, Minnesota.

Figure 2. SWWD CD-P infiltration facilities during infiltration events.

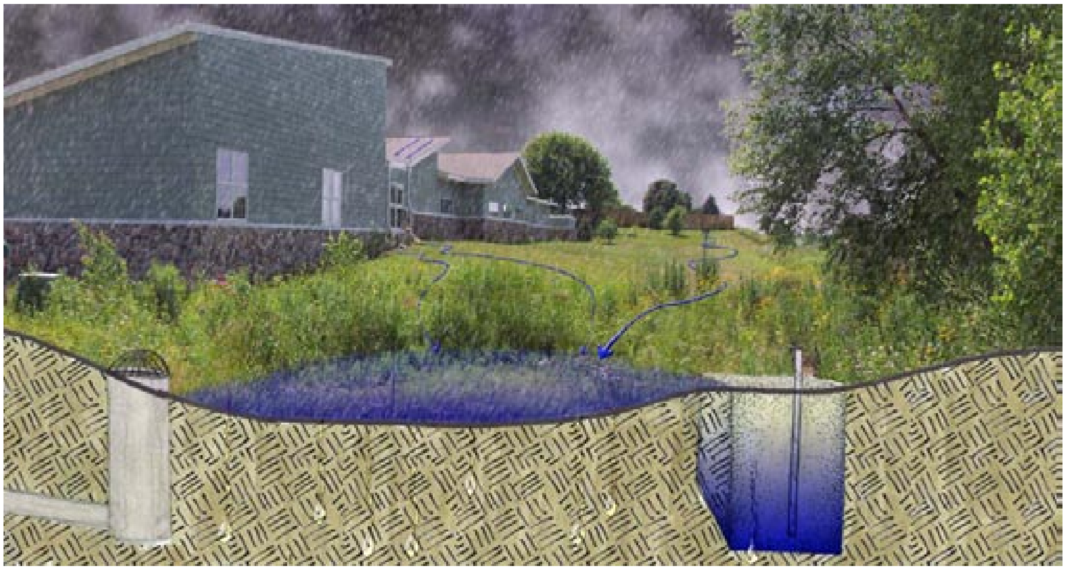
a) CD-P76

b) CD-P82

c) CD-P85

Figure 3 illustrates an SWWD infiltration facility at the Woodbury Math and Science Academy (MSA), which has been monitored since 2001. This infiltration trench measures 15 feet long by 8 feet wide and approximately 13 feet deep and occurs approximately 3 feet off the bottom (on a side slope) of the adjacent basin. The lower portion of the basin was designed as a sedimentation basin to allow sediment to settle prior to runoff reaching the infiltration trench. The basin was planted with deep rooted native vegetation, and has not maintained a permanent pool of water since construction in 1999. The MSA trench drains only 0.4 ha from a portion of the school roof, a swale draining a high traffic county road, and a small amount of open space. Figure 3 illustrates a cross-section view of this facility.

Figure 3. Cross-section of the MSA infiltration trench.



1. Assessment Goals

This case study presents the approach and results of monitoring natural depressions located within CD-P76 and CD-P82 and also constructed infiltration trenches at CD-P85 and MSA (see Figure 1).

Monitoring methods used to evaluate infiltration and potential impacts to groundwater include measuring continuous water levels with the basin or trench, sampling surface and groundwater for water quality parameters, and measuring water level fluctuations responses in the water table.

Data are collected during spring melt conditions, typically beginning in February. Spring melts within Minnesota typically consist of several minor events during mid-winter, followed by a major solar-driven melt event in mid- to late-March. Data are also collected during the summer and fall season in response to rainfall events.

The goals of this multi-year study have been and continue to be: 1) assessment of the long-term performance of a regional infiltration system; 2) understanding the physical mechanisms that promote effective infiltration; and 3) documentation of the water level and water chemistry changes that occur under infiltration facilities.

2. Assessment Techniques

To meet the assessment goals, a monitoring approach has evolved to include measurement of both inflow and outflow quantity and quality, as well as the groundwater level fluctuation under the site. MSA measurements focus on the inflow of water and the infiltration rate, but the lack of a monitoring well means that groundwater behavior under the facility is not currently monitored.

Water quality data have also been collected as part of the overall infiltration monitoring program. Surface water samples are analyzed for the four locations in Figure 1 for dissolved heavy metals (cadmium, lead, nickel, manganese, zinc, copper), volatile and total suspended solids, total phosphorus, ortho-phosphate (as phosphorus), total Kjeldahl nitrogen, nitrate plus nitrite as nitrogen, chloride and hardness. Groundwater samples are collected at CD-P82 and at CD-P85 and analyzed for dissolved heavy metals (cadmium, lead, nickel, manganese, zinc, copper), nitrate plus nitrite as nitrogen, and chloride.

Composite grab samples of ponded surface water in the process of infiltrating are collected using three-foot long polyethylene disposal bailers and poured into individual sample bottles. At MSA, composite flow-weighted samples are collected during overflow events using an automatic sampler and flow meter.

Groundwater samples are collected from monitoring wells using a submersible pump, and a minimum of three well volumes were purged prior to sample collection.

Groundwater level data are collected at eight wells throughout the watershed as part of this program. One well is located adjacent to each of the CD-P82 and CD-P76 basins, and six are located adjacent to or near CD-P85. MSA does not currently have a monitoring well. During construction of the new outlet at CD-P85, the MW-4 well was damaged and later abandoned in early spring 2005. Except for well MW-3w, the peak groundwater mound elevations could not be determined without the use of continuous data loggers in the wells. However, for the discussion on ground water mounding, the periodic hand measure well readings were used to identify the highest observed mounding in each well. Water level readings were taken at each well with the use of an electronic water level sounder, and an automatic data logger was installed in the MW-3w well to record continuous groundwater levels.

3. Assessment Results

Monitoring methods used to evaluate infiltration and potential impacts to groundwater include measuring continuous water levels with the basin or trench, sampling surface and groundwater for water quality parameters, and measuring water level fluctuations responses in the water table.

Data are collected during spring melt conditions, typically beginning in February. Spring melts within Minnesota typically consist of several minor events during mid-winter, followed by a major solar-driven melt event in mid- to late-March. Data are also collected during the summer and fall season in response to rainfall events.

Results – Infiltration Rates

The SWWD drainage system is an ideal geologic system for implementation of infiltration BMPs. The results of five to seven years of monitoring the following sites are summarized in Table 1.

Summaries of each facility follow including example data collected during the spring melt of 2005.

Table 1. Infiltration rate monitoring results (SWWD, 2006)

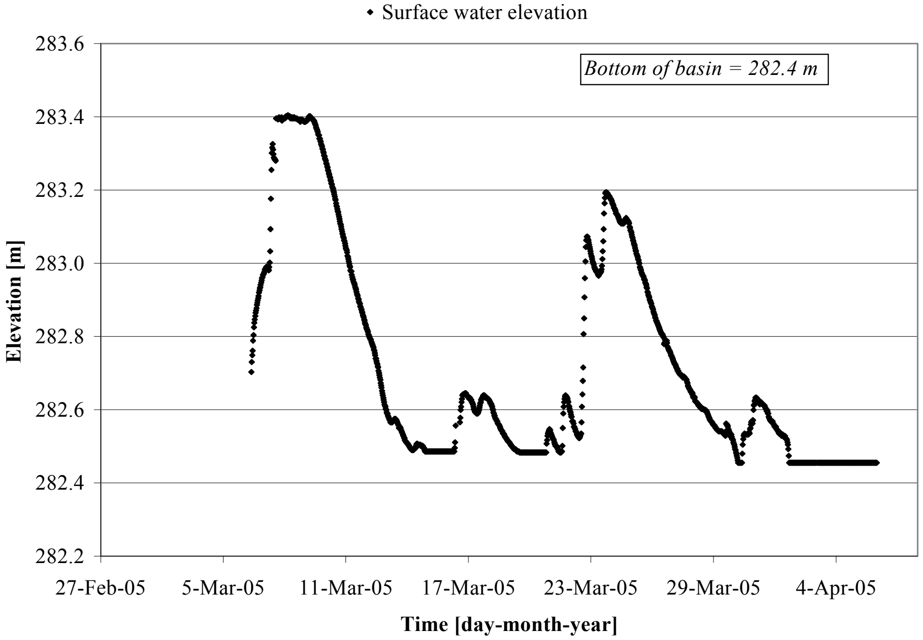
Infiltration Basin (Number of years Infiltration Basin (Number of years monitored)	**Infiltration Rate, mm/hour [inches/hour]**			
	Snowmelt		**Rainfall**	
	Average Rate mm/hour [inches/hour]	**Rate Range mm/hour [inches/hour]**	**Average Rate mm/hour [inches/hour]**	**Rate Range mm/hour [inches/hour]**
CD-P76 (Snowmelt = 7; Rainfall = 2)	8.6 [0.34]	1.4 - 15.2 [0.05 – 0.60]	9.9 [0.39]	4.3 – 27.9 [0.17 – 1.1]
CD-P82 (Snowmelt = 7; Rainfall = 5)	3.3 [0.13]	0.5 – 8.4 [0.02 - 0.33]	2.5 [0.10]	0.8 – 10.4 [0.03 - 0.41]

Infiltration Trench (Number of years monitored)	**Infiltration Rate, mm/hour [inches/hour]**	
	Average Rate	**Rate Range**
CD-P85 Trench (Snowmelt = 4; Rainfall = 6)	15.2 [0.60]	0.4 – 76.2 [0.017 – 3.0]
MSA Trench (Snowmelt = 4; Rainfall = 5)	23.6 [0.93]	0.5 - 172 [0.020 – 6.8]

CD-P76

This infiltration basin receives runoff from a 480 acre watershed consisting of row crop agriculture and rural residential development. The basin typically fills to three feet in depth, with an aerial extent of 5.7 acres. Soils in the basin consist of sandy loam over medium grained sand deposits. Depth to the water table is greater than 60 feet. There is no groundwater monitoring at this site. Figure 4 illustrates the behavior seen in this basin during snowmelt events in 2005 when water level rose within the basin to a maximum depth of two feet. No outflow occurred during these events.

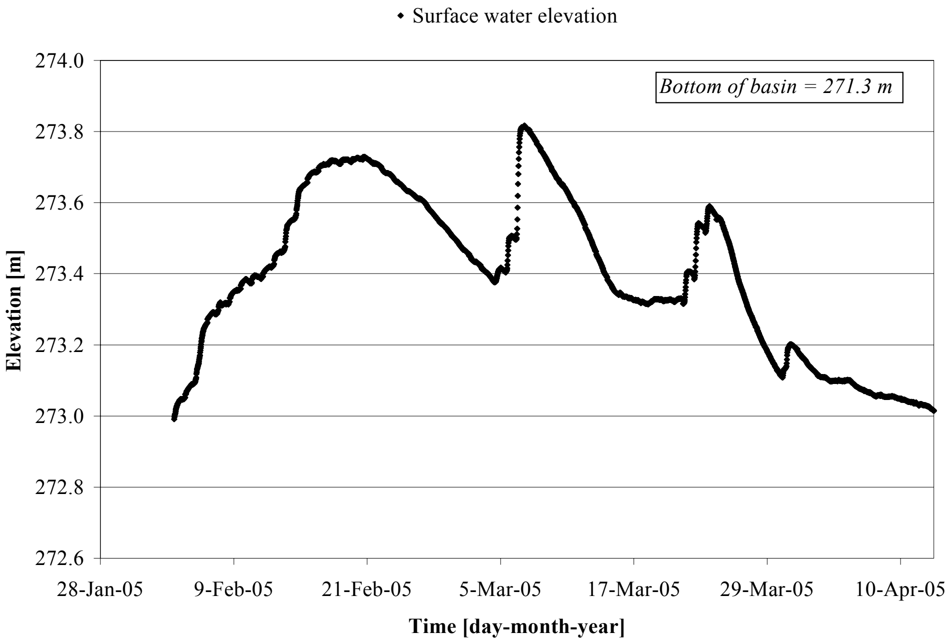
Figure 4. CD-P76 Water Elevation vs. Time, 2005 Spring Melt



CD-P82

CD-P82 receives runoff from a 580 acre watershed comprised predominantly of row crop agriculture and horticulture land uses. The basin typically fills to eight feet in depth, with an aerial extent of 7.5 acres. Soils in the basin and watershed consist of silt and sandy loam over medium grained sand deposits. The silt deposits are found at the bottom of the basin within and surrounding the pond. The basin contains a small sump area at the bottom, which has been sealed over time with fine grained particles. Sandy loam is present on the basin sides and throughout the watershed. Depth to the water table is approximately 30 feet. A groundwater mound typically forms beneath this basin during spring melt conditions, as recorded in an on-site well. During 2005, a groundwater mound formed that was 5.2 feet high. This mound formed and receded over a two month period and likely coincided with a regional water table rise during the spring season. Figure 5 illustrates this basin's behavior during 2005 spring melt conditions, during which no outflow occurred.

Figure 5. CD-P82 Water Elevation vs. Time, 2005 Spring Melt.



CD-P85 (Trench)

CD-P85 is a natural basin within which occur two infiltration trenches and four unmonitored dry wells. Although CD-P85 occurs within a rural, undeveloped area, the largest volumes of water entering the basin are from pumped storage out of the terminal pond in a long chain of urban drainage storage facilities. During spring melt conditions, runoff also enters the basin from the direct drainage area (354 acres) which is comprised predominantly of row crop agriculture land uses. During the spring melt, there is typically very little standing water in the basin. Soils in the watershed consist of very sandy loam over sand and gravel deposits. The basin is a result of a large ice block deposit. At the bottom of the basin, a thick layer of clay is present that is bypassed either laterally into the basin banks or via two infiltration trenches that break through the clay layer. Depth to the water table is typically greater than 50 feet. Six water table wells surround the CD-P85 basin. A groundwater mound does not typically form during spring melt conditions.

Occasionally, runoff enters CD-P85 through a pumped discharge from a large holding pond east of the basin, over a small watershed divide. When this occurs, ponded water depths are as great as 28 feet, with an aerial extent of 25 acres. Groundwater mounding is prevalent during pumped events. The groundwater mound will often intersect the basin.

Two trenches reaching approximately 14 feet into the bottom of the CD-P85 basin were installed during 1999; six years after the basin became operational. These trenches were designed to provide a pathway for ponded water to infiltrate through the clay layer at the bottom of the basin and into the sand material below. The trenches allow for the basin to dry between events, limiting long-term ponded water and allowing the basin and vegetation to recover between events.

Figure 6 illustrates the infiltration behavior of the trench during the 2005 spring melt events. Figure 7 shows the compilation of all data collected since monitoring began. The long-term mean infiltration rate for the trench has diminished slightly over time perhaps due to fines entering the trench, which was placed on the bottom of the basin rather than slightly above that elevation.

Figure 6. CD-P85 Trench Water Depth vs. Time, 2005

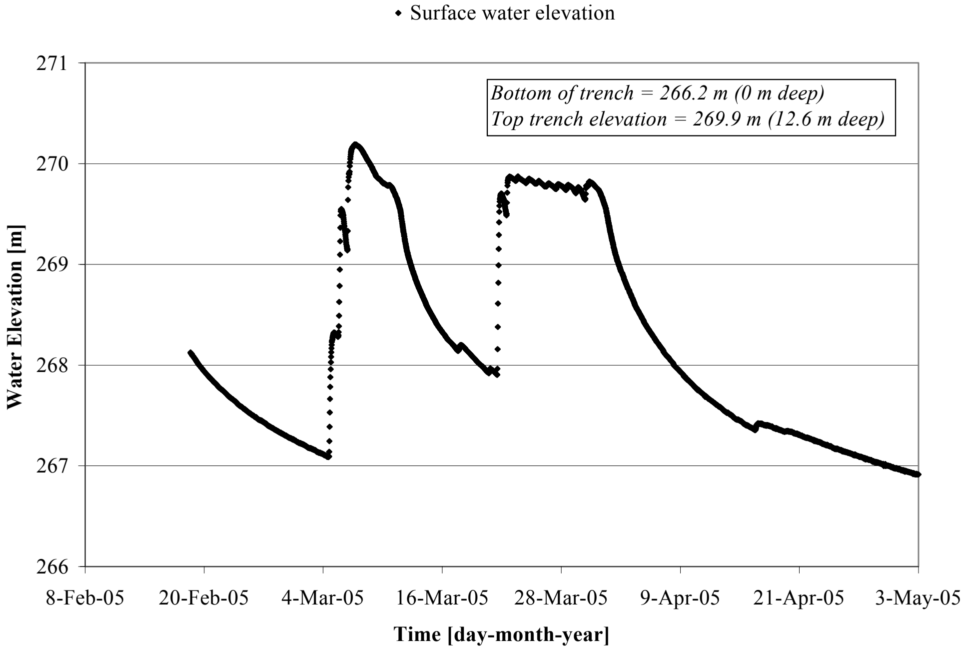
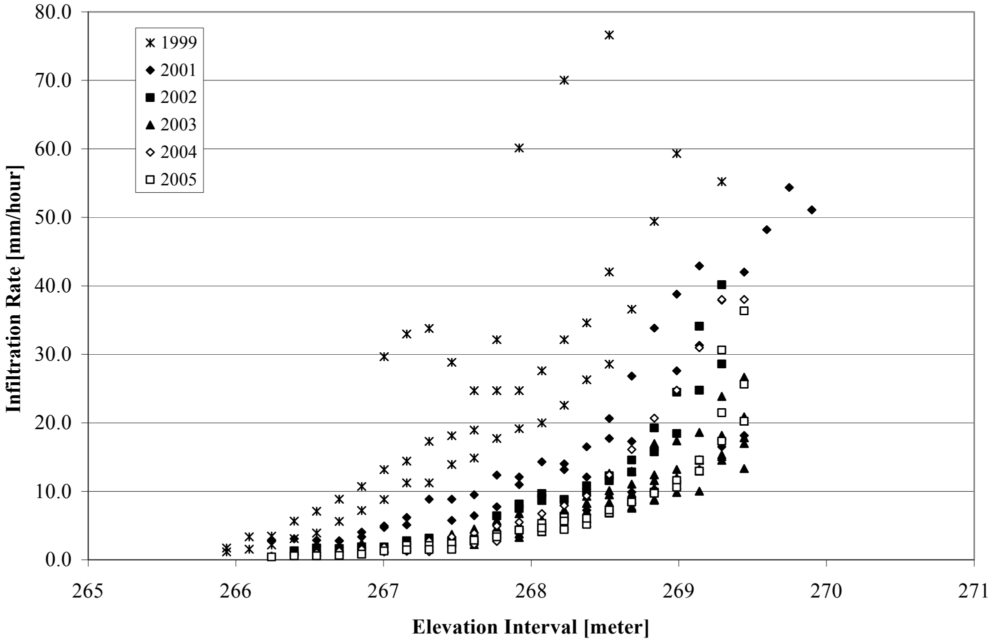


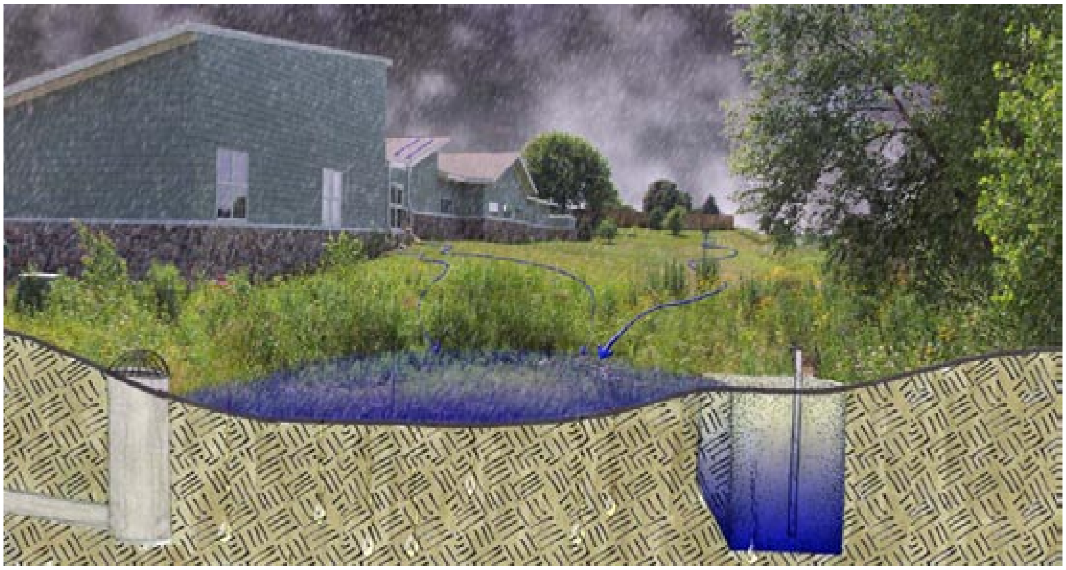
Figure 7. Infiltration Rate vs. Depth for CD-P85 Trench, 1999-2005.



MSA Trench

Perhaps the most interesting of all of the SWWD infiltration facilities is the Math and Science Academy (MSA) trench, which has been monitored since 2001. This trench measures 15 feet long by 8 feet wide and approximately 13 feet deep and occurs approximately three feet off of the bottom (on a side slope) of the adjacent basin. The basin was designed as a detention basin to allow sediment to settle prior to runoff reaching the infiltration trench. The basin was planted with deep rooted native vegetation, and has not maintained a permanent pool of water since construction in 1999. Figure 8 illustrates a cross-section view of this facility.

Figure 8. Cross-section of the MSA infiltration trench



The MSA trench drains only one acre from a portion of the school roof, a swale draining a high traffic county road, and a small amount of open space. Figure 9 shows the numerous snowmelt and rainfall events during spring of 2005 that entered this settling and infiltration facility.

Figure 10 shows how more infiltration is occurring at the same elevation today than earlier years. The rate of infiltration is increasing with each year since monitoring began. Research on the reasons for the improvement has not occurred, but speculation is that it has resulted from very good vegetative growth in the entire basin which has improved conditions through better energy dissipation and solids filtration prior to infiltration, massive root growth downward by the native plants and the insect borings that are visible at the site. The behavior of the MSA Trench is opposite that of the CD-P85 Trench which has decreased in infiltration rate as it ages. The CD-P85 trench is located directly on the bottom of a much larger basin where organic and inorganic fines can gather.

Figure 9. MSA Depth vs. Time and Precipitation, 2005 Spring Melt

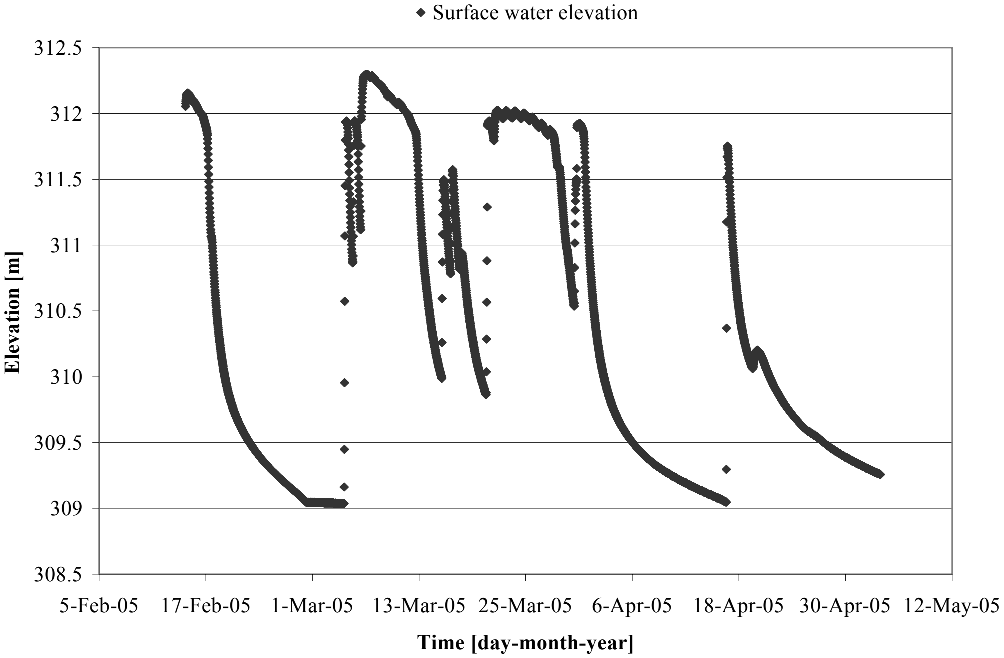
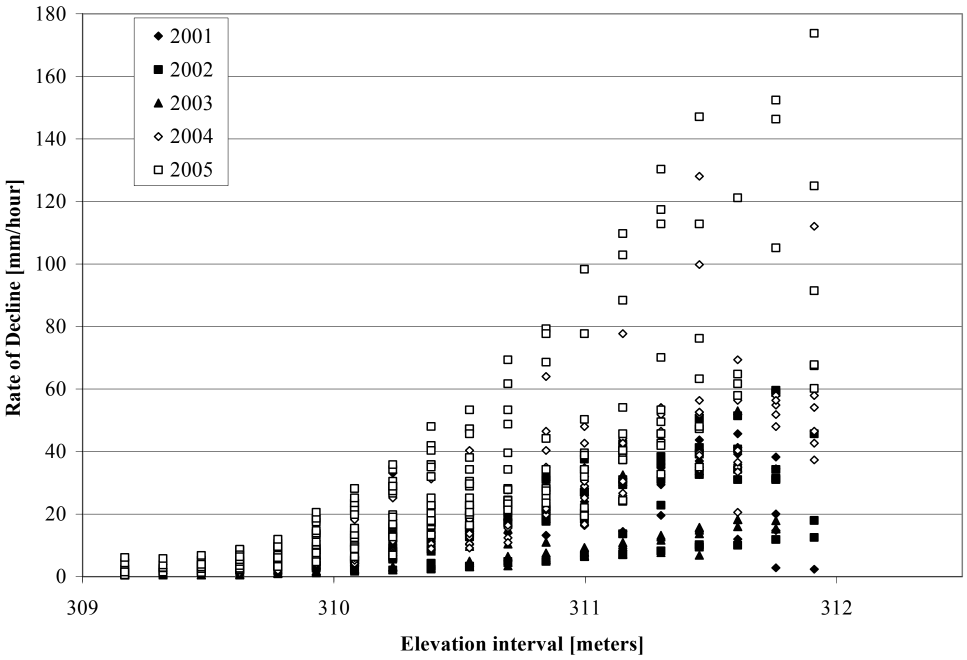
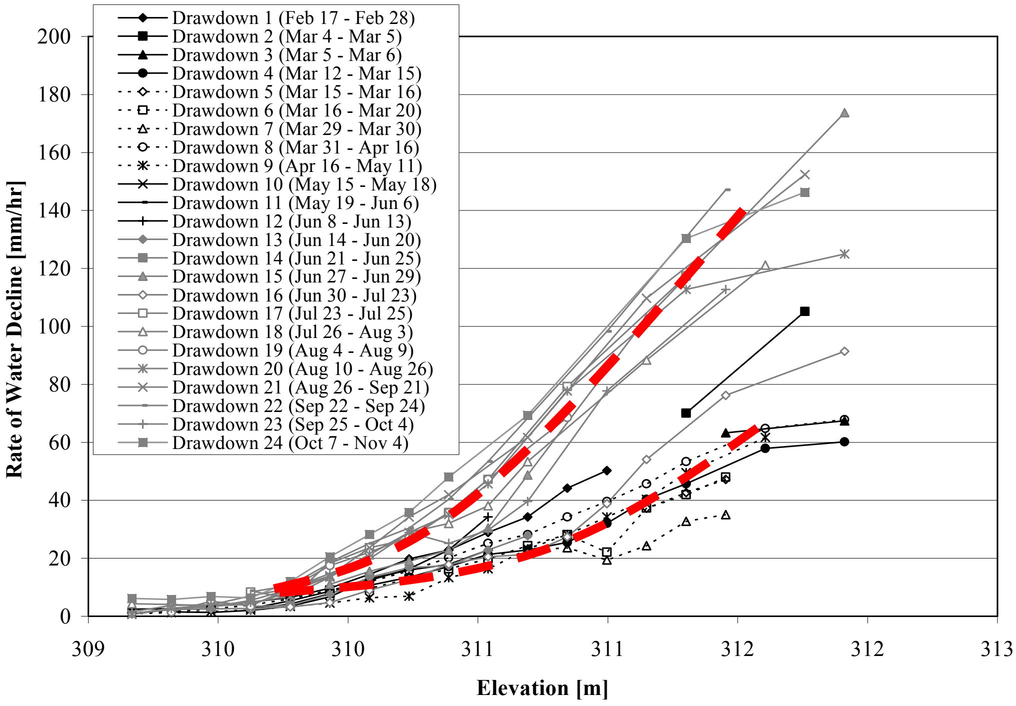


Figure 10. Infiltration Rate vs. Depth for MSA Trench, 2001-2005



Finally, infiltration of snowmelt runoff into the MSA Trench, although very effective, does not appear to be as high as it is for rainfall events. Figure 11 illustrates the monitored infiltration rates for all 2005 events. Note that Drawdowns 1-7 indicate the snowmelt events in the index box. Two separate trend lines were added to the graphic to generally portray the somewhat reduced snowmelt infiltration events (lower line) beginning at about three feet of water depth.

Figure 11. MSA Trench Infiltration Rate Curves, 2005.



Results – Water Quality

Water quality data have also been collected as part of the overall infiltration monitoring program. Surface water samples are analyzed for the locations in Table 1 for dissolved heavy metals (cadmium, lead, nickel, manganese, zinc, copper), volatile and total suspended solids, total phosphorus, ortho-phosphate (as phosphorus), total Kjeldahl nitrogen, nitrate plus nitrite as nitrogen, chloride and hardness. Groundwater samples are collected at CD-P82 and at CD-P85 and analyzed for dissolved heavy metals (cadmium, lead, nickel, manganese, zinc, copper), nitrate plus nitrite as nitrogen, and chloride.

Although water quality data have been collected for many years, the complexity of the flow system has complicated analysis and a detailed water quality model of the system has not been prepared. Table 2 contains meltwater pollutant data for the most recent four years for surface water inflow and four shallow groundwater wells situated around CD-P85 (Table 2a) and a single monitoring well at CD-P82 (Table 2b). The data reflect the range of values observed for snowmelt events only as an example of data collected.

The data for CD-P85 show that groundwater pollutant levels are generally consistent with the surface water samples for most of the metals. The exceptions are Mn and Ni which are higher in the groundwater. The consistent manganese (Mn) groundwater violations are reflective of high ambient concentrations in groundwater in Minnesota. Dissolved nickel (Ni) in MW2 and MW3 could be problematic, although similar high levels are not apparent in the surface water inflow. Nitrate and chloride levels are similarly higher than the pollutant levels in surface water flowing into the infiltration system, This behavior is indicative of regional ambient groundwater quality which is high for NO3 from historic agricultural and septic system inputs.

The chloride (Cl) data paint an unclear picture of how chloride-laden water moves into the CD-P85 system throughout the year. The two possibilities are lateral flow from transportation corridors to the north and the higher concentration of Cl in water pumped in during non-melt periods throughout the year. That is, water from the highly urbanized part of the watershed is gradually routed through the stormwater system and into CD-P85, therefore not reflected in surface water snowmelt monitoring data at CD-P85. The Cl levels, although higher than normal, do not violate any water quality standards, but should be a warning that continued high salt use can lead to groundwater accumulations that could become troublesome. Although some of the pollutants are reflective of high ambient groundwater conditions and warrant attention, it does not appear that the CD-P85 infiltration system is negatively impacting groundwater.

Table 2a. Water quality data for CD-P85 surface water and four groundwater wells, 2002-2005.

Analyte [mg/L]	Surface Water	Monitoring Well-1	Monitoring Well -2	Monitoring Well -3	Monitoring Well -4**
Lead (Pb), dissolved	<0.0001-0.0003	<0.0001-0.0001	<0.0001	<0.0001-0.0002	<0.0003
Cadmium (Cd), dissolved	<0.0002-0.0006	<0.0001-0.0002	<0.0001-0.0003	<0.0001-0.0012	0.00015-0.00018
Manganese (Mn), dissolved	0.0007-0.103*	0.22-0.61*	0.0004-0.46*	0.0017-0.25*	0.031-0.22*
Nickel (Ni), dissolved	0.0013-0.0032	0.003-0.013	0.0026-0.29*	0.0016-0.097*	0.001-0.0015
Copper (Cu), dissolved	0.0034-0.0126*	0.0032-0.0064	0.0007-0.0031	<0.0008-0.0026	0.0024-0.003
Zinc (Zn), dissolved	0.0018-0.0109	0.002-0.0145	0.0024-0.0092	0.0021-0.0086	<0.006
Nitrate (NO3)	<0.05-3.0	0.03-0.44	2.5-13*	2.8-8.3	<0.02
Chloride (Cl)	2-9	29-77	26-53	45-83	35

* MN – EPA Secondary Drinking Water Standard = 0.05 mg/L; Minn. Dept. of Health (MDH) Health Risk Limit = 0.1 mg/L
Ni – MDH Health Risk Limit = 0.1 mg/L; MPCA Chronic 2B Water Quality Standard = 0.283 mg/L
Cu – MPCA Chronic 2B Water Quality Standard = 0.015 mg/L
** Data for 2003 only

CD-P82 monitoring data are collected for surface water and a single well adjacent to the basin. Table 2b shows generally the same kind of metals behavior as CD-P85, with the exception of lower levels of Ni in the groundwater. Nitrate inflows are about the same, but groundwater levels are high enough to have violated standards during one sampling event (February 2002). Chloride levels are higher than naturally occurring groundwater, but not in violation of any standard as yet. As with CD-P85, the impact of the infiltration system on local groundwater does not appear to be significant.

Table 2b. Water quality data for CD-P82 surface water and four groundwater wells, 2002-2005.

Analyte [mg/L]	Surface Water	Monitoring Well
Lead (Pb), dissolved	<0.0001-0.0003	<0.0003-0.0018
Cadmium (Cd), dissolved	<0.0001-0.0041*	<0.0004-0.0019
Manganese (Mn), dissolved	0.0021-0.409*	0.0007-0.14*
Nickel (Ni), dissolved	0.0026-0.0051	0.0009-0.0044
Copper (Cu), dissolved	<0.0008-0.011	0.0015-0.0038
Zinc (Zn), dissolved	0.002-0.071	0.001-0.019
Nitrate (NO3)	0.11-3.8	1.9-11*
Chloride (Cl)	8-88	9-70

* Mn – EPA Secondary Drinking Water Standard = 0.05 mg/L; Minn. Dept. of Health (MDH) Health Risk Limit = 0.1 mg/L

Cd – MDH Health Risk Limit = 0.004 mg/L; MPCA Chronic 2B Water Quality Standard = 0.002 mg/L

NO3 – MDH Health Risk Limit = 10 mg/L

4. Conclusions and Recommendations

1. Large-scale infiltration in cold climates can be an effective management practice if soil and geologic conditions are "suitable", which means adequate soil permeability, dry conditions at the time of freeze-up, and bedrock depths well below (at least six feet) the bottom of the infiltration system. These conditions are common across many parts of the upper Midwest, particularly in glacial outwash plains.

2. Infiltration rates as high as 1.1 in/hr have been documented for snowmelt events within natural infiltration basins. Rates as high as 4 in/hr are documented for an infiltration trench during spring melt and 6.8 in/hour for a summer rainfall event.

3. Although not discussed in this study, a maintenance program to assure removal of fine particulate matter is essential to the proper and long-term operation of any infiltration system. Situating infiltration trenches above the bottom of a detention pool and using deep-rooted native vegetation help to minimize the maintenance need for repeated removal of sediment and reduced infiltration. The accumulation of fine-grained material has had an impact on some of the infiltration facilities, but not enough to warrant extensive maintenance after up to 10 years of operation.

4. Although some elevated pollutants have been detected in groundwater near the infiltration system, monitoring data indicate that infiltrating surface water is not the cause of this problem. The most common violations are for naturally occurring elements in the

soils and are commonly found within surface and groundwater in southern Washington County. Chloride does not currently exceed any water quality standards, but is higher than "non-impacted" water and should be a warning for careful management of salt application.

Appendix A: Case Studies

5. Water quality benefits of surface stormwater drainage and treatment of parking lot runoff using multi-cell wetlands in parking lot media strips

Provided by C.J. Aichinger at the Ramsey-Washington Metro Watershed District

CASE STUDY #5: Water Quality Benefits of Surface Stormwater Drainage and Treatment of Parking Lot Runoff Using Multi-Cell Wetlands in Parking Lot Median Strips

1997 TWIN CITIES WATER QUALITY INITIATIVE GRANT
Final Report

Legal Name of Project Sponsor: Ramsey-Washington Metro Watershed District

Designated Project Representative: Clifton J. Aichinger, Administrator

Mailing Address & Telephone Number of Project Sponsor:
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Project Title: Water Quality Benefits of Surface Stormwater Drainage and Treatment of Parking Lot Runoff Using Multi-Cell Wetlands in Parking Lot Median Strips

Project Summary:

The Ramsey-Washington Metro Watershed District (RWMWD) has a continuing goal of looking at alternative approaches for dealing with stormwater runoff treatment. In 1998 the Ramsey-Washington Metro Watershed District, in cooperation with H.B. Fuller Company, studied the water quality benefits, vegetation management issues, and costs of an alternative parking lot design. The study was a comparison between a traditional curb and gutter parking lot and an alternative lot design, which uses interconnected wetland cells to convey stormwater. The monitoring program was funded with a Twin Cities Water Quality Initiative Grant distributed by the Metropolitan Council.

Methods

Water quality monitoring equipment was set-up to capture stormwater runoff and to log flow at each sampling location for as many storm events as possible throughout the season. The project goal was to sample stormwater runoff from at least 10-12 storm events at both the traditional and alternative parking lot designs. Sampling sites were visited every other day or the day after a storm event. Samples were composited and delivered to the lab within 10-24 hours of collection. Storm samples were analyzed using Standard Methods for total phosphorus, soluble reactive phosphorus, and total particulate matter at the Ramsey County Environmental Services Laboratory. The flows were calculated by using v-notch weir equations and data points entered in ISCO samplers. Precipitation data was collected with an on-site Ramsey County Network rain gage monitored by H.B. Fuller Environmental Services staff.

The RWMWD staff biologist performed a qualitative visual vegetation assessment of the wetland cells. All other vegetation and ground maintenance was performed or contracted out by staff from H.B. Fuller. H.B. Fuller staff also monitored ground maintenance costs and problems.

Site Description

The test and control sites are located about 328 yards apart on the H.B. Fuller headquarters campus in the city of Vadnais Heights. The sites are of similar age: both were constructed between the years of 1994-96. The motor vehicle traffic and use patterns are also very similar at both sites.

The test site (wetland lot) built in 1996 is a 2.6 acre bituminous parking lot which provides parking for 220 vehicles. The lot is broken up into sections by three vegetated infiltration median strips (figure 1). These infiltration strips or "wetland cells" are inter-connected and outlet to an open water wetland at a single point. All stormwater runoff from this lot under-goes some sort o infiltration or filtration treatment before entering the down stream wetland. Eighty percent of the parking lot drains directly into the wetland cells by way of sheet flow. The remaining twenty percent sheet flows overland through woodland and native prairie grasses to the open water wetland down gradient of the wetland cells.

Figure 1: Vegetated infiltration median strips.

The control site (Lab A lot) is a traditional bituminous curb and gutter parking lot with raised, manicured medians. The Lab A lot consists of 80 parking spaces with an impervious surface area of 1 acre. Stormwater from the entire 1 acre is collected by two curb catch basins and routed through a 12-inch concrete pipe to a main storm sewer. The stormwater receives no treatment prior to being discharged to a small stormwater wetland on the shores of Willow Lake.

Sampling Site Description

The District staff took great care during the site selection and sampler placement for this study. Many possible comparison sites, sampler locations, and set-ups were reviewed. After much analysis the District staff chose what it felt was the best possible location and sampling configuration that the study budget would allow.

Figure 2: Multi-cell wetland system collecting parking lot runoff.

The test site (wetland) sampler was located 100 feet down stream of the last wetland cell. A large hole was excavated down to the 8-inch PVC outlet pipe and a section of the PVC pipe was removed and replaced with a clear acrylic pipe fitted with a v-notch weir insert, bubble tube, and a suction screen. The clear pipe was employed as a visual aid in maintenance and in flow calibration. An ISCO 6700 sampler/flow meter was used to record flow readings and to retrieve flow-weighted samples.

The location for the control sampling site (Lab A lot) was selected because of its proximity to the wetland test site, flow characteristics, and its easy access. The Lab A sampler was located at a catch basin just outside the sampled watershed. An inflatable weir insert equipped with a bubble tube and suction screen was placed inside the 12-inch concrete pipe to gage flow and retrieve samples. Flow data and flow-weighted samples were collected with an ISCO 6700s sampler/flow meter.

Results

During the sampling period of April through November, the Watershed District collected flow weighted samples from 27 storm events. H.B. Fuller staff recorded 28.86 inches of rainfall in their on-site rain gage during this sampling period. 1998 rainfall recorded by H.B. Fuller showed nearly 5 inches above the thirty-year average for April through November in this region.

Figure 3: A wetland system that provides depression storage, infiltration, and vegetative filtration.

The test site sampler had much success capturing samples from large storm events. The sampler took samples from 16 storm events with a rainfall depth range of 0.1 inches to 2.12 inches, with a mean depth of 1.0 inches. Fifty percent of the samples were collected from larger storm events (storms > 1 inch). The small storm events (storms< 0.25 inches) were either stored or infiltrated in the wetland cells with little or no runoff recorded at the outlet.

The control/Lab A lot sampler performed remarkably well, collecting samples from 25 storm events. The samples were collected from a wide range of rainfall depths and storm intensities. The storms sampled had rainfall depth ranging from of 0.02 inches to 2.12 inches, with a mean rainfall depth of 0.60 inches. Over 60 percent of the events sampled were from small rainfall events (storms < 0.25 inches).

Total stormwater flow volumes for the sampling period were recorded at both sampling locations. Only flow associated with rainfall events was used in total flow calculation, and this eliminated calculating flow from irrigation. The flow volumes, along with the mean nutrient concentrations from each site, are listed in table 1.

Table 1: Mean Flow Weighted Nutrient Concentration and Flow Volume

Site Name	Total Phosphorus (mg/l)	Soluble Reactive Phosphorus (mg/l)	Total Particulate Matter (mg/l)	Total Flow Volume (cubic ft)
Test/wetland	0.241	0.104	25	20000
Control/Lab A	0.194	0.017	121	*75000

*Corrected for lot size differences (correction factor of 2)

Vegetation Management Issues

The wetland cells were planted with native mesic and wet prairie plant species. The planting of the parking lot cells was started in earnest one year after completion of the lot. During the spring of 1996 the wetland cells were seeded with nearly 50 wetland and prairie species. Seed was again applied in the late fall of 1996 and early spring of 1997 along with some supplemental seedling planting to portions of the cells that received erosion damage. The later seeding and plantings were much more successful than the first 1996 attempt. In the 1998-vegetation assessment, 30 native plant species were recorded in and around the wetland cells. As of the fall of 1998, the wetland cell vegetation appears to be well established, and at this time no further seeding or planting is planned.

The H.B. Fuller ground maintenance staff spent considerable time in 1996-97 establishing and weeding the wetland cells and surrounding upland. The time spent on maintenance was reduced in half for the summer of 1998, and it was projected to be further reduced for the summer of 1999. Table 2 shows a comparison of maintenance man-hours for the two study sites.

Table 2: Maintenance Time Comparison

Maintenance Task	**Test Lot**	**Control Lot**
Watering	0	40
Spreading Wood chips	32	20
Weeding	16	15
Mowing/Trimming	48	40
Sweeping Sand	30	0
Misc.	16	10
Total Hours	**142**	**125**

Discussion

This study demonstrates that the use of small created wetland depressions in parking lot medians can effectively reduce the stormwater runoff leaving the site. Review of the flow and nutrient data indicates that the wetland cells' primary function is infiltration and not nutrient removal. The wetland lot discharged nearly 40 percent less stormwater runoff than an equal size curb and gutter site, which calculates into nearly 55,000 cu-ft of nutrient-laden stormwater. To our surprise, we found that the wetland site may have acted as a nutrient source. The test site had a

Appendix A: Case Studies

6. Assessing vegetated buffers using synthetic residential runoff

Provided by S.M. Stai (sarah.stai@westwoodps.com) at Westwood Professional Services

CASE STUDY #6: ASSESSING VEGETATED BUFFERS USING SYNTHETIC RESIDENTIAL RUNOFF

Contributing Author: S.M. Stai (sarah.stai@westwoodps.com), Westwood Professional Services

Vegetated buffers, also known as wetland buffers, riparian buffers, buffer strips, or vegetated filter strips, are areas of vegetation between developed land and surface water. Buffers are established or protected for many different reasons, including hydrologic event modification, aquatic and wildlife habitat protection, aesthetic value, and open space preservation. The potential for buffers to aid in water quality protection has gained particular attention in Minnesota in recent years.

1. Assessment Goals

The primary purpose of this study was to determine the buffer width that represents the point of "diminishing returns." Specifically, the objective was to assess how a vegetated buffer's sediment and phosphorus retention capacity changes as a function of downslope distance from the point of entry by residential stormwater runoff. A secondary purpose was to determine the effect that buffer slope has on pollutant retention. The focus on residential land use reflected the interest of the project sponsors: the Metropolitan Council, the Builders Association of the Twin Cities, and the National Association of Home Builders.

2. Assessment Techniques

STUDY SITE AND PLOT SET-UP

The study site was located behind a commercial office building in Eden Prairie, Minnesota. The site sloped away from the building for approximately 300 feet (91.4 m) toward Purgatory Creek (Figure 1). A review of historical aerial photography indicated that land use at the site was primarily agricultural until construction of the current building took place in 1997. The site was selected for four main reasons. First, because the sloped area had been seeded with a native prairie mix nine years prior to the study, the vegetation was well established and was representative of mature buffers that would typically be found at residential subdivisions in the Twin Cities Metropolitan Area (TCMA). Second, the site's native soil was the Lester-Malardi complex, a well-drained loam and a state soil common to the TCMA. Third, the site contained slopes at varying degrees up to 50 percent, allowing for examination of buffer effectiveness as a function of slope as well as width. Finally, stormwater runoff generated by the impervious surfaces of the building roof and parking lot was captured and conveyed through pipes to a holding pond, thereby preventing overland flow (and hence interference) of naturally generated commercial runoff into the study area.

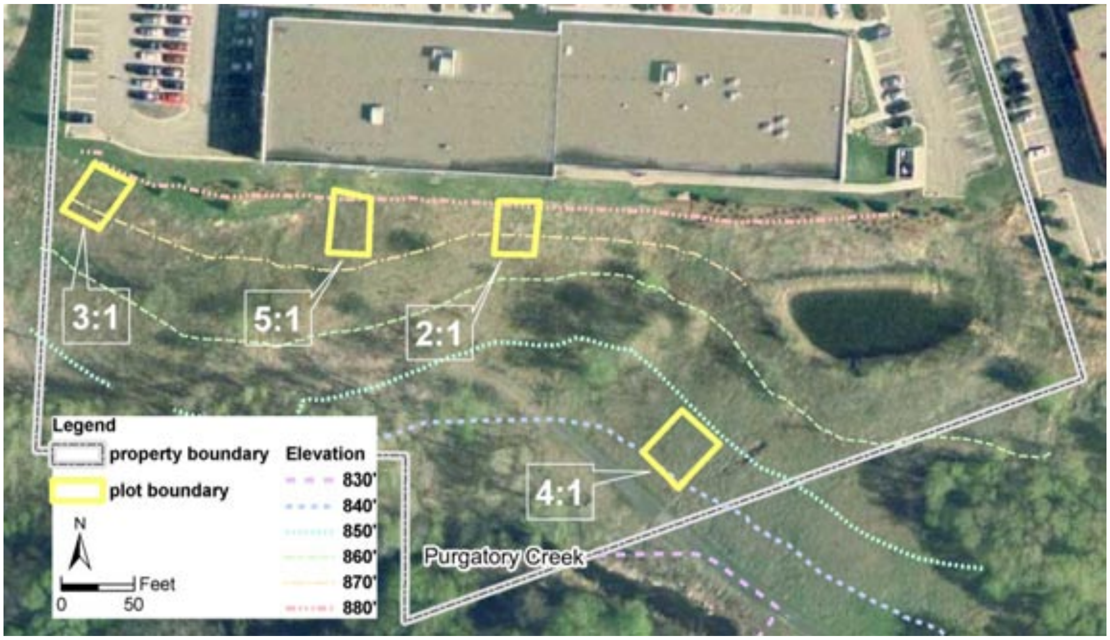


Figure 1. Study site and plot locations.

Four plots were established on the site, with each plot representing a different slope between 2:1 and 5:1 (Figure 1). Each plot consisted of three transects, each of which was 8 feet (2.4 m) wide and separated from adjacent transects by at least 2 feet (0.6 m). Transect locations were selected to meet the slope requirements for the plot, to be at least 40 feet (12.2 m) in length, and to exclude uneven ground and woody vegetation to the maximum extent possible. Each transect was outfitted with a runoff collector at four intervals (5, 10, 20, and 40 feet [1.5, 3, 6, and 12 m]) downslope from the head of the transect (Figure 2). The runoff collector consisted of a 6-inch (15.2-cm) PVC pipe cut to a 2-foot (0.6-m) length, capped at the bottom, and partially submerged in the ground (Figure 3). Each collector received runoff from a 2-foot (0.6-m) wide flow path, and the runoff was directed to the collector by means of a V-shaped piece of lawn edging called the diverter (visible in Figure 3, though mostly obscured by grass). A hole cut in the apex of the diverter was equipped with a mesh screen to prevent passage of debris and with a PVC coupler, which was connected to the runoff collector with Tygon tubing.

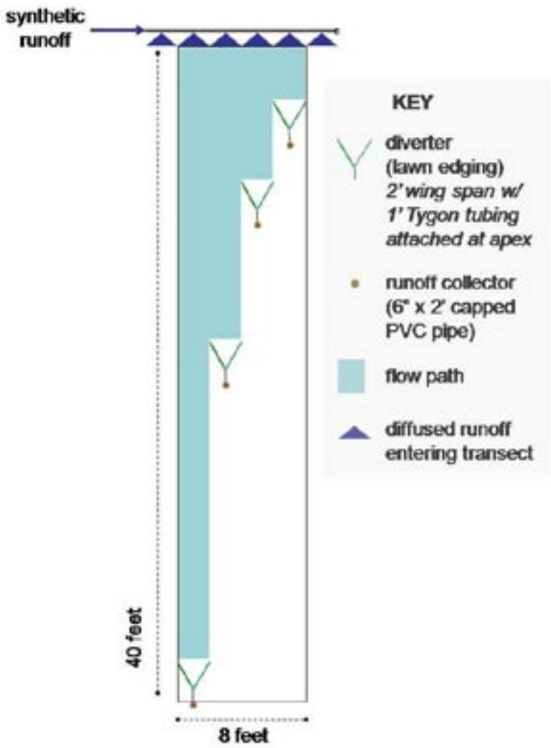


Figure 2. Transect Layout.

Figure 3. Runoff collector.

SYNTHETIC RUNOFF TESTS

Level 3 assessment (synthetic runoff testing) was selected for this study because of its advantages over monitoring. The synthetic runoff could be prepared with known concentrations of phosphorus and sediment and applied in known volumes under controlled, repeatable conditions without reliance on unpredictable natural rainfall.

The synthetic runoff system had three main components (Figures 4-5): a water tank for mixing and holding the synthetic runoff, an eductor manifold installed inside the tank to keep phosphorus dissolved and sediment in suspension during a trial, and a nozzle manifold placed at the head of the transect to deliver runoff in the form of laminar flow. The water tank was a 625-gallon round plastic livestock tank that measured 8 feet (2.4 m) by 2 feet (0.6 m). The eductor manifold consisted of a 2-inch (5-cm) PVC pipe, capped at both ends, and equipped with four polypropylene eductors and a T-joint at the center (Figure 4). A circulating pump was used to cycle water through the eductor manifold, which kept water circulating in the tank. A transfer pump delivered water from the tank to the transect through the nozzle manifold, which consisted of a 2-inch (5-cm) PVC pipe capped at one end and six brass flood-jet nozzles attached via T-joints to the pipe (Figure 5). The fan of water generated by each nozzle was approximately 2 feet (0.6 m) wide, corresponding to the 2-foot (0.6-m) wide flow path of each collector. The four central nozzles were lined up with the center of each flow path during a trial. The two outer nozzles were included to ensure that equal volumes were delivered to each flow path on account of slight overlap by the nozzle fans.

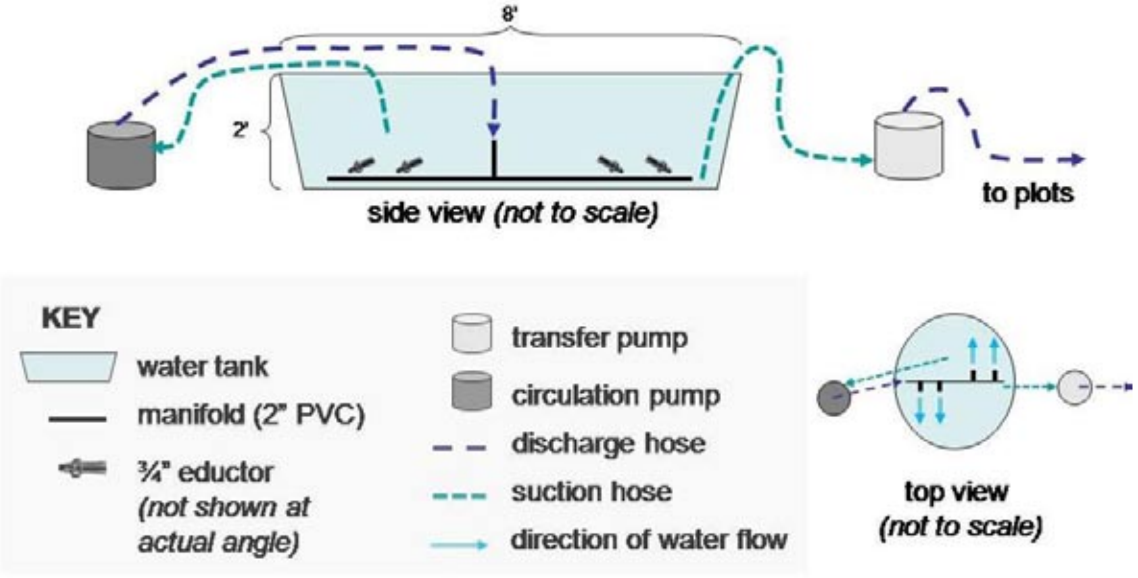


Figure 4. Synthetic runoff system: water tank and eductor manifold.

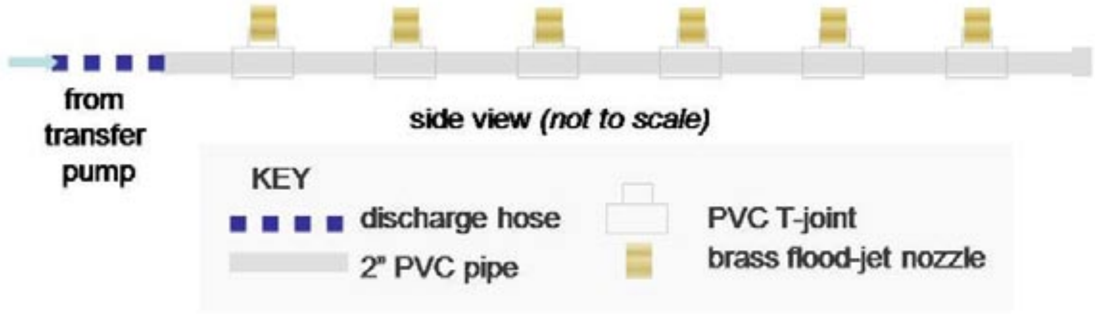


Figure 5. Synthetic runoff system: nozzle manifold.

EXPERIMENTAL DESIGN

The experimental design consisted of three treatments: Control, Two-Year, and 100-Year. The Control and Two-Year treatments represented the runoff volume estimated from a standard residential driveway in a 2.8-inch (7.1-cm) storm event, and the runoff volume of 100-Year treatments was estimated from a 5.9-inch (15-cm) storm event. Controls and Two-Year treatments involved 450 gallons (1700 L) of synthetic runoff applied to a transect during a given trial. The tank was always filled with 600 gallons (2270 L) in preparation for a trial, because an extra 150-gallon (570-L) volume was needed in the tank at all times in order to keep the eductor manifold submerged and operational. The 100-Year trials involved 900 gallons (3400 L) of synthetic runoff applied to a transect in two applications of 450 gallons (1700 L) each, separated by the time it took to refill the tank (approximately 45 minutes).

Synthetic runoff for Control trials consisted of tap water alone. The synthetic runoff for Two- and 100-Year treatments consisted of 0.6 oz (1.8 g) phosphorus (i.e., 0.34 oz [9.5 g] Na_3PO_4) and 4.5 lbs (2,043 g) sediment per 600 gallons (2270 L) of tap water. Sediment was obtained by sifting topsoil from the study site to a size of $\leq 3.9 \times 10^{-5}$ inches ($\leq$ 850 microns).

Trials were conducted from August through October 2006. Each of the three treatments was applied to each of the three transects in each of the four plots and replicated three times for a total of 108 trials.

DATA COLLECTION AND ANALYSIS

Collectors were observed from the beginning of a trial (i.e., the point at which runoff entered the transect) to the end (i.e., when the tank level had reached 150 gallons [570 L], approximately 30 minutes after starting). The volume of runoff reaching each downslope distance was calculated by adding the known volume inside the collector to the estimated volume of collector overflow. The volume of collector overflow was estimated by measuring the duration and rate of overflow through an extra PVC coupler installed on the downslope side of collectors. Whether or not the diverter overflowed upstream of the collector was also noted, in order to indicate cases where the runoff volume calculated for a collector was an underestimate of the actual volume reaching a given distance downslope. Volume reduction was calculated per collector as a percentage based on the runoff volume applied per flow path in a trial (e.g., 1700 L per transect / 6 nozzles = 283 L per flow path for Control and Two-Year trials).

Water samples were analyzed at the Metropolitan Council's water quality lab located at the Metropolitan Wastewater Treatment Plant in St. Paul. Synthetic runoff was sampled from the central four nozzles of the manifold during two different trials in order to determine the actual concentration of total solids and total phosphorus applied to transects during Two- and 100-Year trials (Table 1). A sample of tap water was analyzed in order to estimate the background concentrations of total solids and total phosphorus in Control trials (Table 1). The tap water was also analyzed for total dissolved solids. The background concentration of 170 ppm total solids was made up of approximately 44 ppm total suspended solids and 126 ppm total dissolved solids. The additional ~179 ppm total solids applied to transects was assumed to represent primarily total suspended solids added during synthetic runoff preparation.

Treatment	Total Phosphorus (ppm)	Total Solids (ppm)
Control[1]	0.19	170
Two and 100-Year[2]	1.49	349

[1] concentration in tap water alone (n = 1)

[2] mean concentration in runoff collected upon exit from nozzles (n = 8)

Table 1. Actual concentration of phosphorus and sediment in synthetic runoff

Samples of runoff were collected from each collector receiving runoff and analyzed for total solids and total phosphorus. The samples reported here were collected from the initial volume of runoff to enter a milk jug placed inside the collector. Samples were also collected from the final volume to overflow the collector; differences between "beginning" and "end" samples were not substantial. The level of total solids and total phosphorus in runoff samples at each collector was converted to mass by multiplying the concentration of total solids or total phosphorus by the volume of runoff received at the collector in a given trial. Removal efficiency was calculated per collector as a percentage based on the mass of total solids or total phosphorus applied per flow path in a given trial.

3. Assessment Results

RUNOFF QUANTITY

Collectors typically received about twice the average runoff volume in 100-Year trials as they did in Control or Two-year trials (Table 2).

Treatment	5:1	4:1	3:1	2:1
Control	33.3	31.9	54.5	49.8
Two-Year	35.7	29.7	55.0	47.3
100-Year	65.1	74.1	111.6	116.2

Table 2. Average runoff volume (liters) received per collector, grouped by slope (n = 36 for each cell). Note: Some averages represent underestimates of the runoff volume reaching a collector, because certain diverters consistently overflowed and this overflow volume could not be reliably be estimated and incorporated into the volume calculation.

As expected, average runoff volume was generally related to the steepness of the slope (Table 2). Figure 6 illustrates that there was a slight upward trend in runoff volume as slope increased for Control and Two-Year trials, and a more pronounced upward trend for 100-Year trials.

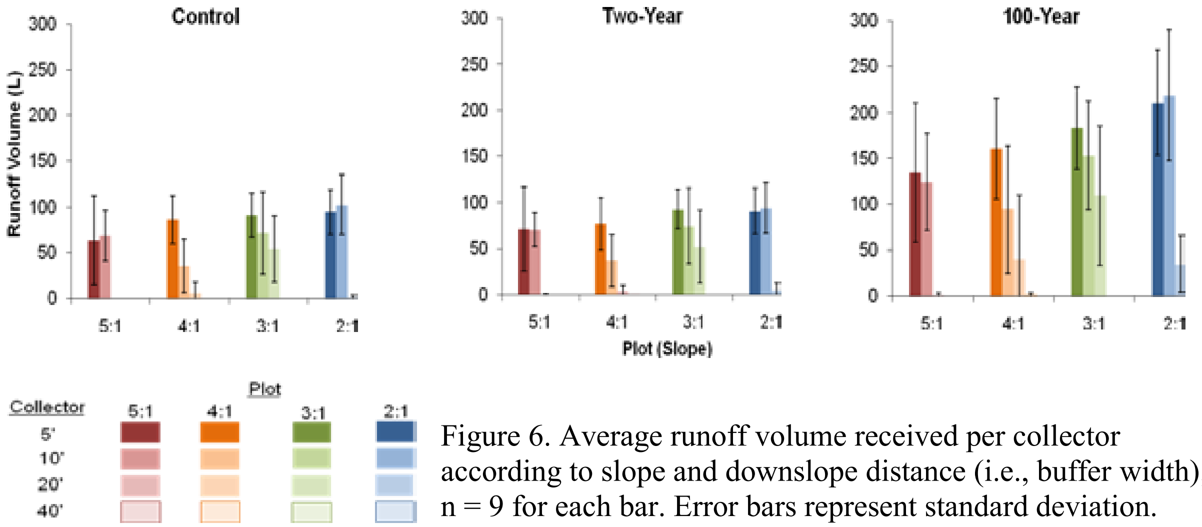


Figure 6. Average runoff volume received per collector according to slope and downslope distance (i.e., buffer width); n = 9 for each bar. Error bars represent standard deviation.

The average reduction in runoff volume was generally related to buffer width (Figure 6). The 4:1 and 3:1 plots showed a relatively consistent decrease in volume between 5’ and 40’ in all three types of trials. For the 5:1 and 2:1 plots, the 5’ and 10’ collectors tended to receive similar volumes, followed by a sharp decrease in runoff at 20’.

The 4:1 plot was the only plot to have runoff that reached the 40’ collector. This happened once during a Two-Year trial and once during a 100-Year trial. Both cases occurred on transect II during the third round of trials toward the end of the experiments. These cases could not be attributed to changes in plot characteristics, errors in trial procedures, or initial soil moisture conditions. Rather, the two occurrences of runoff at 40’ on transect II most likely resulted from gradual trampling of aisle vegetation between transects I and II and repeated flow of runoff through the aisle during trials on transect I. As the experiments progressed, it appeared that excess runoff from transect I began to flow toward the foot of transect II. This most likely increased soil moisture in the aisle and in the downslope portions of transect II. This process seems to have inhibited the infiltration of runoff upslope of the 40’collector on transect II.

RUNOFF QUALITY

Total Solids

As expected, the concentration of total solids in runoff reaching collectors was consistently higher in Two- and 100-Year trials than in Control trials (Figure 7). In some cases the Control total solids was higher than that of the tap water, which suggests that plots may have been contributing solids to the runoff (particularly the 3:1 plot).

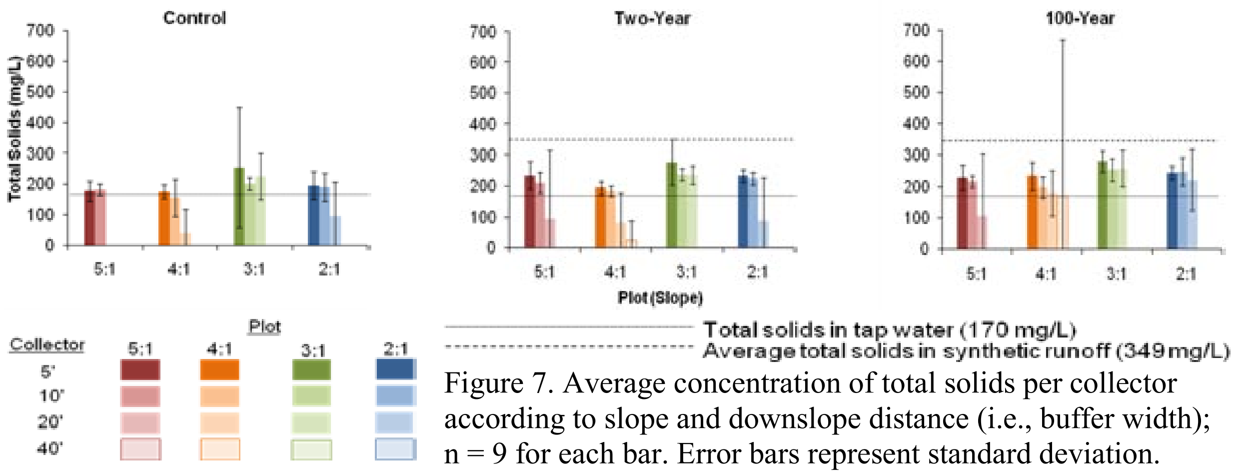


Figure 7. Average concentration of total solids per collector according to slope and downslope distance (i.e., buffer width); n = 9 for each bar. Error bars represent standard deviation.

In the Two- and 100-Year trials, much of the total solids removal (~60-95%) appeared to occur within the first 5' and did not increase substantially between 5' and 20' (Figure 8). The 5:1 and 2:1 plots appeared to be slightly more effective at removing total solids compared to the 4:1 and 3:1 plots. Removal efficiency was generally higher in the Two- and 100-Year trials compared to Control trials. Because the higher level of total solids in treatment trials was presumed to be primarily attributable to total suspended solids, the results suggest that most of the total solids removal occurring in treatment trials was serving to remove suspended solids from the runoff.

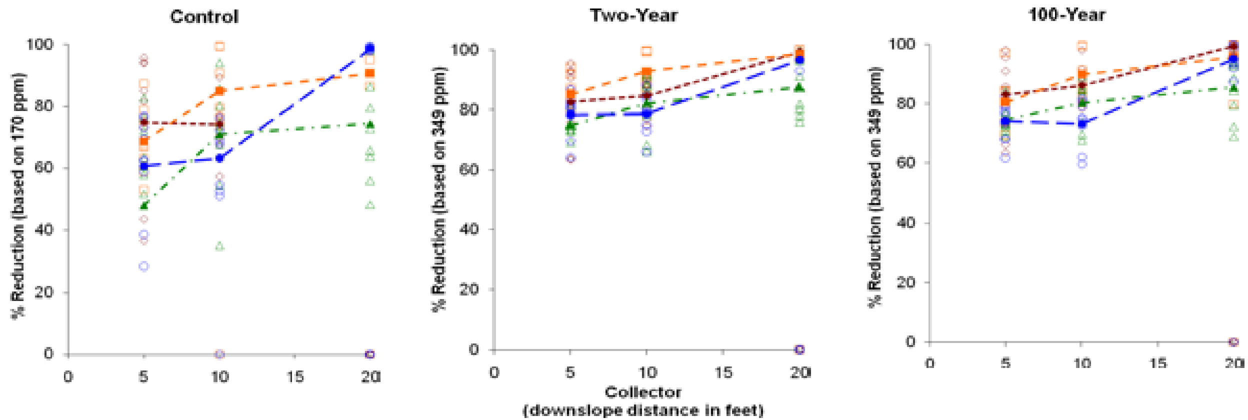


Figure 8. Removal efficiency of total solids as a function of buffer width; n = 9 for each average marker. Hollow markers indicate individual values while solid markers represent averages.

In the only cases where runoff reached 40’ (i.e., on the 4:1 plot), the average total solids concentrations shown in Figure 7 are misleading because a runoff sample was obtained in only one of nine trials for each of the two treatment types. In the 100-Year trial, however, the total solids concentration was an outlier at 1510 ppm. This large value was likely due to runoff from the adjacent transect, as described above.

Total Phosphorus

The concentration of total phosphorus in runoff reaching collectors was consistently higher in Two- and 100-Year trials than in Control trials (Figure 9). The presence of total phosphorus in excess of the background level during Control trials (primarily in the 3:1 plot), in conjunction with the observation made above for total solids in Control trials, suggests that the plots themselves were contributing some sediment-bound phosphorus to the runoff.

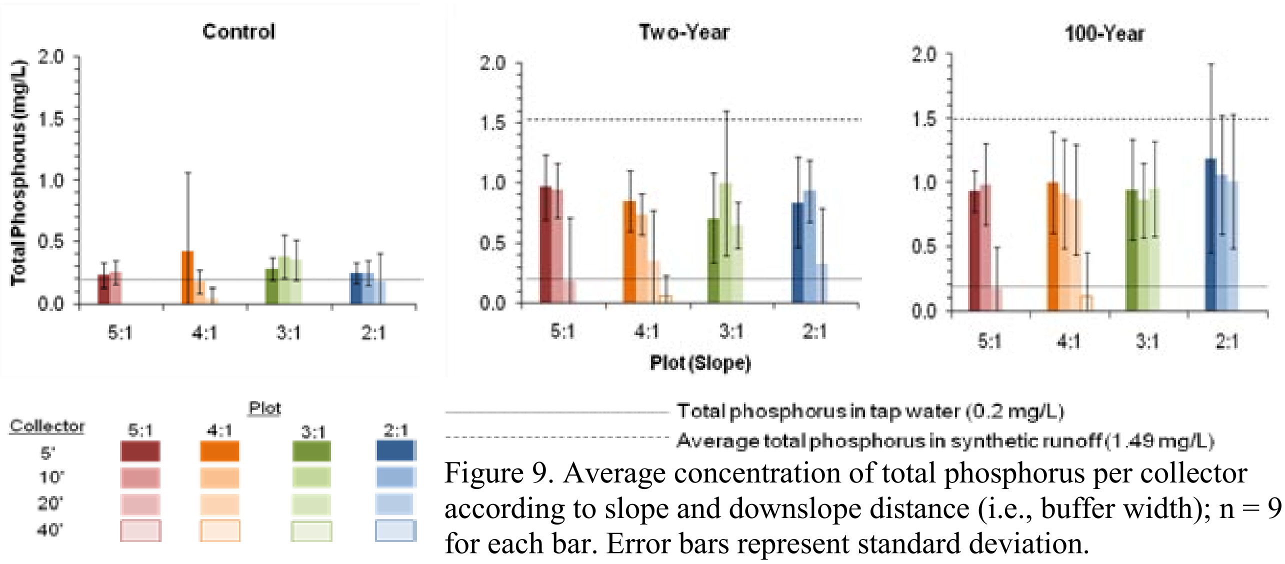


Figure 9. Average concentration of total phosphorus per collector according to slope and downslope distance (i.e., buffer width); n = 9 for each bar. Error bars represent standard deviation.

The overall effect of increasing buffer width on average total phosphorus removal efficiency appeared to be greater than the effect of width on total solids removal (Figure 10). In Control trials, the 5:1 plot was not informative because no runoff volume reached 20’, but the other plots experienced more pronounced increases in total phosphorus removal efficiency between 5’ and 20’ than they had for total solids (Figure 8). The 4:1 plot saw the largest increase between 5’ and 10’, while the 3:1 and 2:1 plots saw the largest increase between10’ and 20’. This result suggests that, as with width, slope may have had more of an effect on total phosphorus removal than on total solids removal.

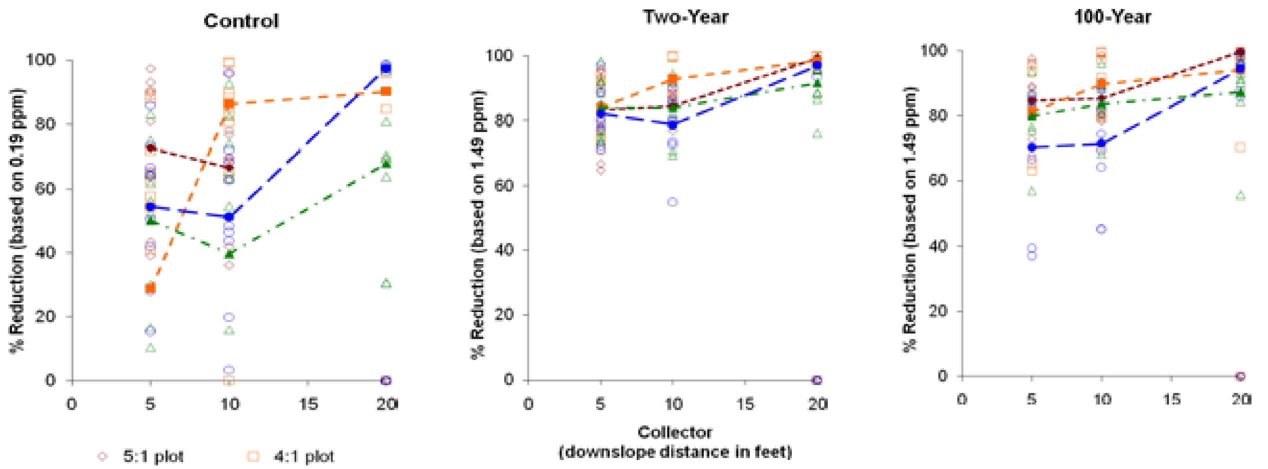


Figure 10. Removal efficiency of total phosphorus as a function of buffer width; n = 9 for each average marker. Hollow markers indicate individual values while solid markers represent averages.

Most total phosphorus removal appeared to occur within the first 5’. Average total phosphorus removal did not increase substantially between 5’ and 20’ for the 4:1 and 3:1 plots, but did increase somewhat between 10’ and 20’ for the 5:1 and 2:1 plots (Figure 10). As with total solids, the 5:1 and 2:1 plots appeared to be slightly more effective at removing total phosphorus compared to 4:1 and 3:1.

The observation that average total solids was more likely than average total phosphorus to approach background levels by 20’ may provide some clues to the mechanisms responsible for phosphorus removal in the buffer. Some phosphorus was likely being removed from the runoff as a function of volume infiltration and through the deposition of phosphorus-bearing sediment. The potential for phosphorus removal by plant adsorption may not have been fully realized due to the vegetative characteristics of the buffer and/or the width of buffer through which the runoff passed.

4. Conclusions and Recommendations

According to the results of this study, the relationship of buffer width to volume and to total solids and total phosphorus removal is asymptotic. Most reductions in volume, total solids, and total phosphorus occurred within the first 5’, and subsequent reductions were relatively gradual. All runoff volume was infiltrated or retained within 20’ in most cases, even on 50% slopes, and sometimes within 10’. Because runoff generally did not flow beyond 20’, examination of the effect of width on total solids and total phosphorus removal was limited to this same interval. There is evidence that buffer width is a more important determinant of total phosphorus removal than total solids removal.

The effect of width varied by slope. The 4:1 and 3:1 shared some similarities though the 3:1 appeared less effective overall; both plots showed a stepwise decrease in volume between 5’ and 20’, and a pattern of declining total solids and total phosphorus that reached a plateau at approximately 10’. The 5:1 and 2:1 plots behaved the most similarly; both showed a more pronounced decrease in volume between 10’ and 20’, and a more delayed decline in total solids and total phosphorus that approached a point of diminishing returns between 10’ and 20’.

The effect of slope was less clear than width and varied by both treatment and parameter. In general the effect of slope was more pronounced in 100-Year trials. Slope appeared to have a greater effect on volume reduction than on total solids or total phosphorus removal, and there was some indication that slope had more of an effect on total phosphorus removal than on total solids removal. Overall shallower slopes (5:1 and 4:1) did appear to be more effective at pollutant removal than steeper slopes (3:1 and 2:1). The 3:1 plot seemed more prone to erosion and this may have limited the buffer's ability to reduce pollutant levels at rates comparable to the other plots.

The high percentage of volume reduction and the high removal efficiency of total solids and total phosphorus within 20' were almost certainly a function of both the soil and vegetative characteristics of the site. The well-drained loam promoted high infiltration rates, while the dense, well-established vegetation further facilitated infiltration and retention of runoff. Consistency in behavior between the 5:1 and 2:1 plots, in spite of their extremely different slopes, was likely due to high similarity in composition and percent cover of their vegetation. The 4:1 and 3:1 plot may also have behaved similarly in part because of vegetation characteristics; these plots shared two of the same dominant plant species. The 4:1 plot was unique in some respects; it was characterized by a primarily grassy composition while the other plots were dominated by herbaceous plant species.

The results of this study suggest that buffer widths of 10-20' may be effective at reducing the runoff volume and the levels of total solids (especially suspended solids) and total phosphorus that characterize residential stormwater runoff in the TCMA. The effectiveness is largely related to certain circumstances, namely sheet flow occurring in unsaturated well-drained soil and well-established, primarily herbaceous vegetative cover. Relatively steep slopes offer some benefit though they appear not to be as effective as more shallowly sloped buffers, especially under extreme rainfall conditions.

Appendix A: Case Studies

7. Modeling to test the P8 model at Bass Creek Business Park

Provided by Brian Vlach (bvlach@threeriversparkdistrict.org) and John Barten (jbarten@threeriversparkdistrict.org) at Three Rivers Park District

CASE STUDY #7: MONITORING TO TEST THE P8 MODEL AT BASS CREEK BUSINESS PARK

Contributing Authors: Brian Vlach (bvlach@threeriversparkdistrict.org) and John Barten (jbarten@threeriversparkdistrict.org) at Three Rivers Park District

1. Introduction

The planning of a commercial development requires the implementation of best management practices to minimize runoff volume and nutrient loading. The particular management approach selected is often determined through modeling efforts. The proposed site plan is often modeled to determine the changes in runoff volume and nutrient loading. The model is re-run with different best management scenarios based on standard design criteria for the particular change in land use. However, the performance of best management practices implemented to correspond with a particular change in land use may not adequately reflect modeling efforts. Consequently, the preliminary modeling efforts may inaccurately predict the actual water volume and nutrient loading budgets for the proposed site development. In addition, monitoring efforts are rarely incorporated after completion of the development to determine whether best management practices were effective in reducing runoff volume and nutrient loading. There appears to be insufficient monitoring data to substantiate whether proposed best management practices are effective in reducing runoff volume and nutrient loading.

The Three Rivers Park District monitored the performance of a three-celled nutrient detention pond that was designed to reduce run-off volume and nutrient loading from a commercial development (Bass Creek Business Park) in the City of Plymouth. The water flows from the three-cell treatment pond to a wetland before discharging to Pike Lake. There have been numerous water quality models (e.g. P8, DETPOND) suggesting that multiple cell detention basins are more efficient at nutrient and sediment removal than single-cell ponds particularly when followed by wetland treatment. The Bass Creek Business Park was monitored to test the validity of the P8 model predictions.

2. Study Site

The Bass Creek Business Park is located west of Highway 169 on Bass Lake Road along the northern border of the City of Plymouth. The watershed is approximately 76 acres that were primarily developed as commercial/industrial land use from 1996 through 1998 (Table 1; Figure 1). The three-celled nutrient detention pond receives runoff from 42 acres of commercial/industrial land use. A monitoring station (TP1) was located at the discharge point of the commercial/industrial area prior to draining to the first cell of the three-cell treatment pond. The three-celled nutrient detention pond discharges into a 5-acre wetland. A second monitoring station (TP2) was located at the outlet of the three-cell treatment pond that drains to the wetland. The wetland was to provide additional treatment prior to flowing to Pike Lake. Consequently, a third monitoring station (TP3) was located down stream of the wetland outlet prior to draining to Pike Lake.

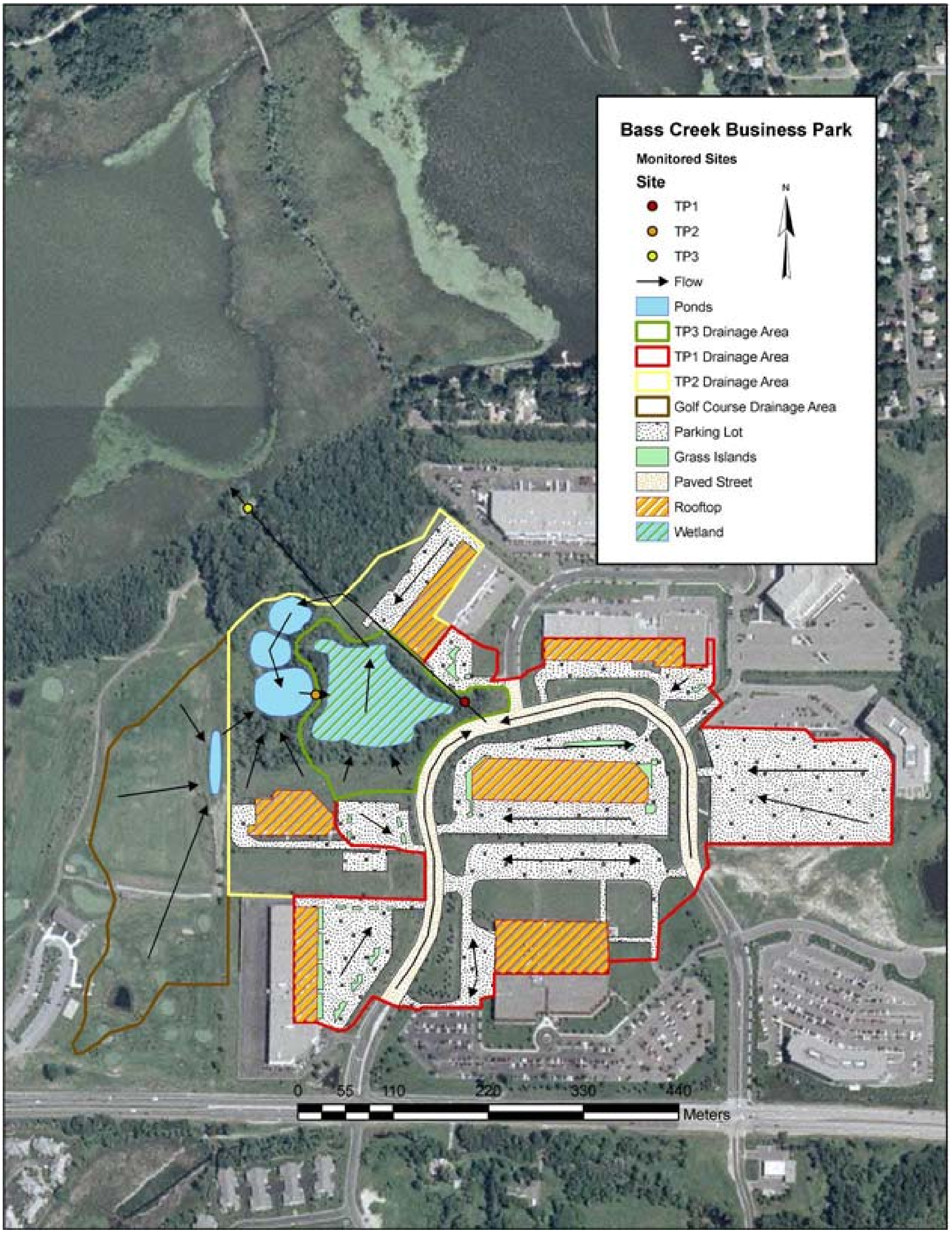


Figure 1: Bass Creek Business Park watershed.

3. Methods

Three Rivers Park District monitored each sampling site from 2004 through 2005. At each of the sampling sites, an automated sampler/flow data logger was installed to monitor continuous flow measurements from May through October. The data logger recorded changes in level, velocity, and flow at 1-minute intervals. The flow data loggers were programmed to initiate sample collection after a predetermined increase in water level was obtained. After sampling was initiated, flow-weighted composite water samples were sequentially collected to encompass the entire storm distribution. The anticipated storm events were based upon estimated precipitation volume. A tipping bucket rain gauge was installed at the TP2 sampling site to measure the actual amount of precipitation at 1-minute intervals. After each precipitation event, the water quality samples were collected within 24-hours. During extended periods without precipitation, grab samples were collected to determine nutrient concentrations during base flow conditions. All samples were labeled immediately after collection, stored in a cooler with ice, and delivered to the Three Rivers Park District for laboratory analysis. During each site visit, flow meter data was downloaded by a field laptop computer.

Three Rivers Park District analyzed each water quality sample for nutrient content. The water quality samples were analyzed for total phosphorus, soluble reactive phosphorus, total nitrogen, and total suspended solids. The Standard Methods for the Examination of Water and Wastewater (1995) was used to determine nutrient concentrations of the water samples. Sample analysis was prioritized by analyte holding time to ensure that analyses were completed within the recommended time interval. Samples were stored at 4° C in a refrigerator until all analysis was completed. A quality assurance and quality control protocol was followed to ensure the precision and accuracy of laboratory data analysis.

The flow meter data and water quality data were used to determine the nutrient loading for each monitoring site. The nutrient loading for each storm event was calculated by multiplying the flow volume and nutrient concentration. The monitoring data was used to calibrate a P8 model developed for the Bass Creek Business Park. The P8 model was calibrated to mimic similar flow and nutrient loading conditions that were observed during the sampling interval. The model was only calibrated with flow and nutrient concentration data that was considered reliable. There were time periods when flow or nutrient concentration information was missing for a particular storm event. The calibrated model was used to estimate the flow or nutrient concentration when data was missing. The nutrient loading was used to estimate the removal efficiency for the three-celled treatment pond and the wetland. The removal efficiency for the treatment devices were calculated using a mass balance equation. The nutrient loading and % removal efficiencies were compared to values estimated by the calibrated P8 model. The details pertaining to model calibration are further described in the following section.

4. Model Calibration

The P8 model was developed to assess nutrient removal efficiency of a three-cell NURP pond treatment device for the Bass Creek Business Park watershed. The same P8 model configuration was used to assess and compare performance of a single-cell NURP pond. The parameters entered into the model included the pervious and impervious sub-watershed characteristics (Table 1). The parameters corresponding to each treatment device included the morphological characteristics for each pond within the three-cell configuration as well as for the downstream wetland (Table 2). The rainfall data collected hourly at the monitoring site were used for model application, and a daily average temperature file was also developed from data collected at Crystal Airport in 2005. The flow network diagram further describes how the P8 model was set-up for the Bass Creek Business Park (Figure 2).

The model was initially calibrated using flow data collected at each monitoring site. The TP1 monitoring site received direct run-off from the Bass Creek Business Park watershed, and directly flowed into the first cell of three-cell NURP pond treatment device. The TP2 monitoring site received water from the third cell of the three-cell NURP treatment device, and outleted directly into the wetland treatment device. The TP3 monitoring site received water from the wetland treatment device, which ultimately drains to Pike Lake. Model adjustments were made so that the predicted total flow volume was similar to the observed total flow volume at each monitoring site. When there was reliable flow information at a particular monitoring site, the model was further calibrated so the time interval and peak flows for predicted and observed hydrographs were similar.

The model was further calibrated to simulate the nutrient loading at the monitoring sites. The water samples collected at each monitoring site were used for determination of nutrient concentration. The nutrient loading for each particular rain event was calculated by multiplying the nutrient concentration by the rain event flow volume. The model was calibrated for nutrient loading by adjusting the scale factor for each water quality parameter within the particle file (NURP50.PAR) until the model predicted nutrient loading estimates similar to observed conditions. In addition, the average nutrient concentration predicted by the model for each water quality parameter was compared to the observed concentrations for each monitoring site.

Table 1: Bass Creek Business Park sub-watershed characteristics.

Sub-Watershed Characteristics								
	Primary	Total	Impervious		Pervious		Treatment Device	
Sub-watershed	Land-Use	Acres	Acres	%	Acres	%	Type	Acres
TP1	Commercial	42.1	30.9	73.4	11.2	26.6	None	0
Eagle Lake Golf Course	Golf Course	13.2	0	0.0	13.2	100.0	Pond	0.2
TP2	Treatment	14.1	8.5	60.3	5.6	39.7	3-Cell Pond	1.6
TP3	Wetland	6.9	0	0.0	6.9	100.0	Wetland	3

Table 2: Bass Creek Business Park treatment device characteristics.

Treatment Device Characteristics										
		Bottom		Normal Water Level			OHW (100-Year)		
Device	Description/Type	Elevation (ft)	Area (Acres)	Elevation (ft)	Area (Acres)	Volume (Acre-ft)	Elevation (ft)	Area (Acres)	Volume (Acre-ft)
Pond 1	1st Pond of 3-Cell Stormwater Pond	886	0.34	892	0.76	3.2	894	0.9	4.9
Pond 2	2nd Pond of 3-Cell Stormwater Pond	886	0.32	892	0.68	2.9	892	0.68	2.9
Pond 3	3rd Pond of 3-Cell Stormwater Pond	886	0.51	892	0.97	4.3	892	0.97	4.3
EGC Pond	Eagle Golf Course Pond	890	0.01	896	0.27	0.9	900	0.54	2.2
Wetland	Wetland-Type 3-PEMF	890	3.1	892	3.8	6.9	892	3.8	6.9

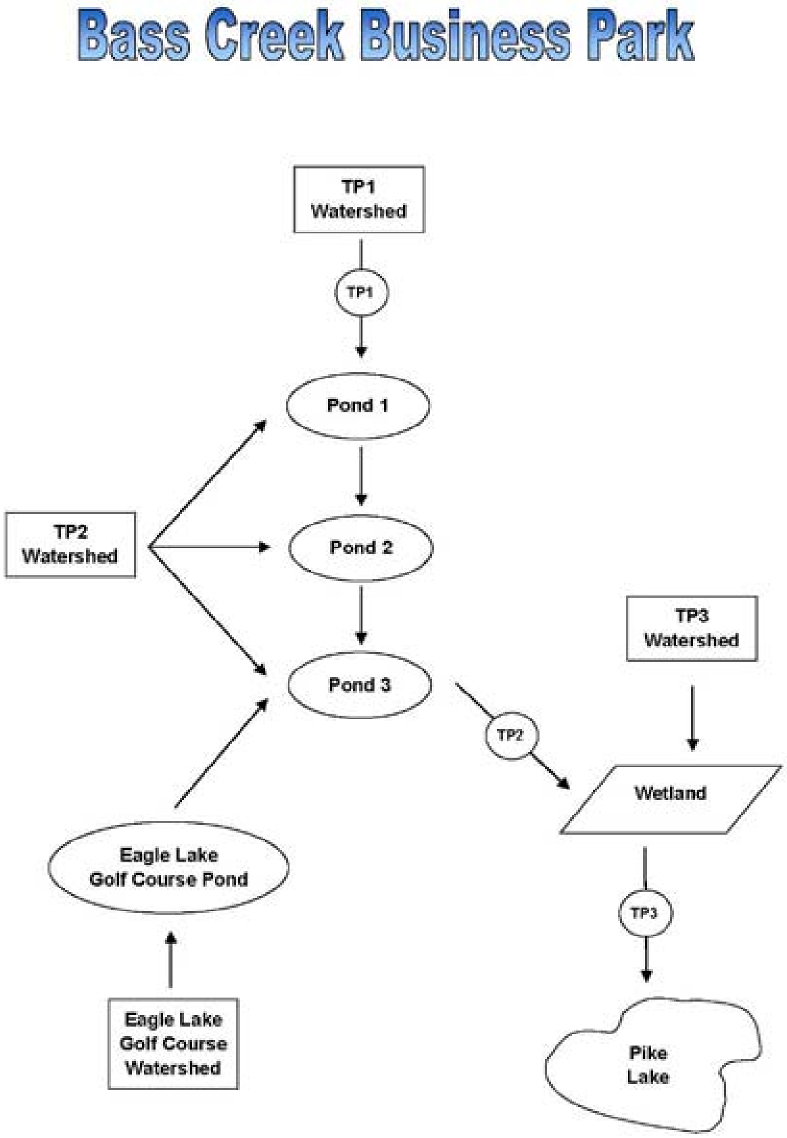


Figure 2: Bass Creek Business Park Flow Network.

After the model was calibrated to observed conditions, the model was used to determine the nutrient loading removal efficiency of the three-cell NURP pond and wetland treatment devices. The nutrient removal efficiency was calculated for each water quality parameter for precipitation condition in 2005. The nutrient removal efficiencies estimated by the model were compared to the observed nutrient removal efficiencies determined through monitoring efforts. The model was re-run with a rainfall file that represents average precipitation conditions for the Minneapolis, Minnesota area. The nutrient loading and removal efficiency of the three-cell NURP pond and wetland treatment device was estimated for these average precipitation conditions.

Modeling efforts were further used to determine whether a single-cell NURP pond would be more efficient at removing nutrients in comparison to the existing three-cell NURP pond configuration. The three-cell NURP pond was converted to a single-cell NURP pond with similar morphological characteristics (Table 3). The model was re-run using the precipitation conditions in 2005 and average precipitation conditions to predict the nutrient removal efficiency of the single-cell NURP pond. The nutrient removal efficiencies predicted from the model simulation was compared between the single-cell NURP pond and the three-cell NURP pond.

Table 3: Bass Creek Business Park Single-Cell Characteristics.

Device Description/Type	Treatment Device Characteristics							
	Bottom		Normal Water Level			OHW (100-Year)		
	Elevation (ft)	Area (Acres)	Elevation (ft)	Area (Acres)	Volume (Acre-ft)	Elevation (ft)	Area (Acres)	Volume (Acre-ft)
Single-Cell Pond	886	1.17	892	2.41	10.4	894	2.55	12.1
Wetland-Type 3-PEMF	890	3.1	892	3.8	6.9	892	3.8	6.9

5. Results and Discussion

The monitoring data collected at each of the sampling sites were critical for calibrating the P8 model. The model was calibrated using 2005 data collected from May through November because it provided the most complete data set of the study period. During the monitoring interval, the tipping bucket rain gauge recorded 21.8 inches of precipitation in 2005. There were 27 individual precipitation events that produced sufficient run-off volume for sample collection. A total of 67 water quality samples were collected from the three monitoring sites. Although water quality samples were not collected for each precipitation event, the samples were representative of the rainfall distribution with respect to the amount and intensity of precipitation observed in 2005. The total number of samples collected was similar for each monitoring site. There were 20 samples collected at the TP1 monitoring site, and there were 22 samples collected at the TP2 monitoring site. The TP3 monitoring site had more samples collected (25 samples) in comparison to the other sites monitored because of differences in the hydrologic flow regime. The flow and nutrient concentration data collected from these monitoring sites were used for calibration of the P8 model.

The model was initially calibrated to mimic the observed flow conditions during the sampling interval. Unfortunately, only two of the monitoring stations (TP1 & TP3) provided reliable flow information that could be used for model calibration. The TP2 monitoring site did not provide reliable flow measurements because the outlet weir structure was constantly obstructed with debris that inhibited drainage of the three-celled treatment pond into the wetland complex. The obstructions inhibiting flow at the TP2 sampling site did not appear to significantly affect upstream flow measurements due to the available storage capacity of the three-cell treatment pond. In addition, the TP1 sampling site was located far enough upstream of the three-cell treatment pond inlet to minimize any potential backwater effects. Consequently, the model was initially calibrated with flow data collected from the TP 1 monitoring site.

After calibration of the model with the TP1 flow data, the model was re-calibrated using the flow measurements from the TP3 monitoring site. The model was difficult to calibrate using the TP3 data because obstructions from the TP2 monitoring site delayed the drainage of run-off volume that flows downstream of the three-cell treatment pond into the wetland. In addition, there was additional groundwater inflow that occurred between the wetland and the TP 3 sampling site. These groundwater sources of inflow for the TP3 monitoring site were unexpected. Consequently, the monitored flow volume for TP3 included a significant amount of groundwater that needed to be accounted for in the total flow volume calculations. The groundwater flow volume was calculated for each event by identifying the portion of the hydrograph that contributed to groundwater flow volume. The portion of the hydrograph that represented groundwater volume was based on existing flow volumes prior to and after the storm event. In order to calibrate the model for the TP3 monitoring site, the ground water measurements had to be subtracted from the total flow volume during periods with reliable flow measurements. Unfortunately, the TP3 flow measurements were not considered reliable after June due to probe drift. Thus the model was calibrated for the TP3 sampling site using adjusted flow volumes from May through June in 2005.

Despite complications with calibrating the model for the observed flow conditions, the model appears to predict reasonable estimates of flow volume (Table 1). The model predicted that there was approximately 54.5 acre-ft of total flow volume for the TP1 monitoring site. The estimated flow volume was very similar to the measured flow volume of 58.5 acre-ft. In addition, the estimated flow volume for the TP3 monitoring site was also similar to observed monitoring conditions from May through June in 2005. The model predicted there was 12.5 acre-ft of total flow volume for the TP3 monitoring site. After groundwater was subtracted from the total flow volume, there was approximately 14.4 acre-ft of total flow volume measured for the TP3 monitoring site. Although these estimates are calculated from May through June, it appears that the model predicted a reasonable total flow volume for the entire sampling period. The model predicted that there was approximately 39.6 acre-ft of total flow volume for the TP3 monitoring site. Unfortunately, the TP2 monitoring site did not provide reliable flow data to compare to modeled flow volumes. Although there was insufficient flow data for model comparisons, the model appeared to provide a reasonable estimate of flow volume (63 acre-ft) for the TP2 monitoring site.

Table 1: Bass Creek Industrial Park observed versus predicted flow volumes.

Site	Observed Flow (Acre-ft)		Predicted Flow (Acre-ft)	
	May-June	May-Oct	May-June	May-Oct
TP1	13.4	58.5	19.7	54.5
TP2	--	--	22.6	63.0
TP3	14.4	42.9*	12.5	39.6

*** Flows estimated with model from July-Oct**

After the model was calibrated for flow volume, the model was further adjusted to mimic the observed nutrient loading conditions. Typically, the scale factors for each water quality parameter were adjusted accordingly until the model predicted nutrient loading and concentrations similar to observed conditions. The model provided reasonable estimates of nutrient loading and/or nutrient concentrations that were similar to measured conditions at the TP1 and TP2 monitoring sites (Tables 3-5). However, the model appeared to underestimate the amount of nutrient loading at the TP3 site. The disparity between observed and predicted nutrient loading estimates is due to differences in nutrient concentration. The observed nutrient concentrations are substantially higher than those estimated by the model (Figures 3-5). These discrepancies suggest that the wetland does not appear to be a treatment device, but appears to provide a source of nutrients downstream to Pike Lake. Consequently, it becomes difficult to calibrate the model for nutrient loading at the TP3 monitoring site because the model treats the wetland as a sedimentation device that removes nutrients.

Table 2: Total Phosphorus Nutrient Loading

TP	Observed		Predicted	
Site	Conc (µg/L)	Loading (lbs)	Conc (µg/L)	Loading (lbs)
TP1	173	31	210	31.0
TP2	108	--	72	12.4
TP3	240	29.8	64	6.9

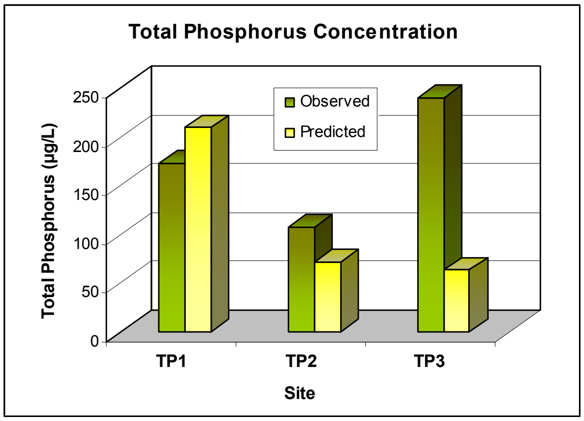


Figure 3: Total Phosphours Concentration

Table 3: Total Nitrogen Nutrient Loading

TN	Observed		Predicted	
Site	Conc (mg/L)	Loading (lbs)	Conc (mg/L)	Loading (lbs)
TP1	1.6	289	1.9	280
TP2	1.3	--	0.8	140.5
TP3	1.2	147	0.8	81.5

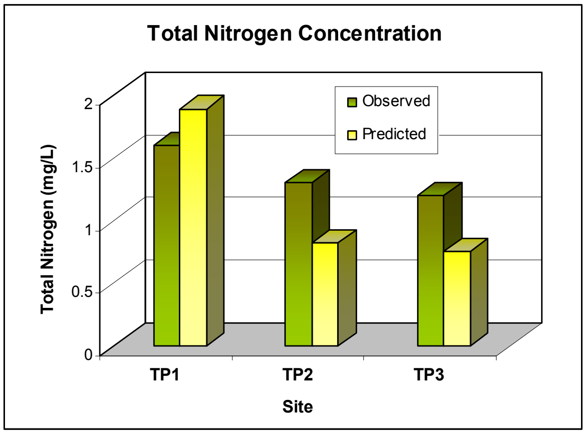


Figure 4: Total Nitrogen Concentration

Table 4: Total Suspended Solids nutrient loading

TSS	Observed		Predicted	
Site	Conc (mg/L)	Loading (lbs)	Conc (mg/L)	Loading (lbs)
TP1	72	12876	87	12846
TP2	10	--	5	774
TP3	8	993	2	162

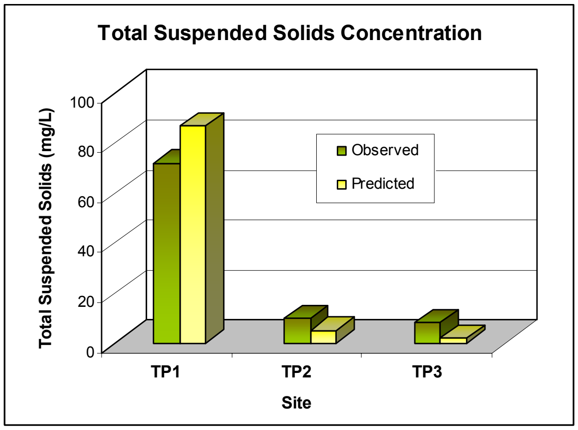


Figure 5: Total Suspended Solids Concentration

The estimates for total flow volume and nutrient loading were used to determine the removal efficiencies of the three-cell NURP pond treatment device. The model suggested that each cell of the three-cell NURP pond was effective at reducing nutrient loading (Table 5). The model estimated that the first cell (Pond 1) provided approximately 47% removal efficiency for total phosphorus, 40% removal efficiency for total nitrogen, and 77% removal efficiency for total suspended solids. The nutrient removal for the second cell (Pond 2) and third cell (Pond 3) was considerably less. The model estimated for Pond 2 that there was approximately 26% removal efficiency for total phosphorus, 20% removal efficiency for total nitrogen, and 59% removal efficiency for total suspended solids. The model estimated for Pond 3 that there was approximately 20% removal efficiency for total phosphorus, 15% removal efficiency for total nitrogen, and 66% removal efficiency for total suspended solids. Similar nutrient removal efficiencies were predicted when the model was re-run for average precipitation conditions (Table 6).

Table 5: Predicted nutrient loading and removal efficiencies for precipitation conditions in 2005.

Site	Predicted 2005 Conditions								
	TP Load (lbs)		TN Load (lbs)		TSS Load (lbs)		% Removal		
	In	Out	In	Out	In	Out	TP	TN	TSS
Pond 1	34	18	302	180	13852	3228	47	40	77
Pond 2	18	15	180	165	3228	2220	26	20	58
Pond 3	15	12	165	141	2220	774	20	14	64

Table 6: Predicted nutrient loading and removal efficiencies for average precipitation conditions.

Site	Predicted Average Conditions								
	TP Load (lbs)		TN Load (lbs)		TSS Load (lbs)		% Removal		
	In	Out	In	Out	In	Out	TP	TN	TSS
Pond 1	40	20	360	204	16870	3574	50	43	79
Pond 2	20	17	204	184	3574	2354	27	21	62
Pond 3	17	14	184	158	2354	731	20	14	68

The estimated removal efficiencies for each cell of the three-cell NURP pond appear to be reasonable. The model predicts removal efficiencies based upon the distribution of particle settling velocities in relation to the hydraulic characteristics of the treatment device. Typically, the highest removal efficiencies in a three-cell NURP pond occur within the first-cell because the majority of the sediment particles become filtered as settling velocities decreases. The second and third ponds provide additional treatment at a reduced efficiency since the ponds are considerably less effective at removing fine sediment particles. Despite the differences in removal efficiencies between ponds, the three-cell NURP pond design appears to provide adequate treatment for the Bass Creek Business Park.

It has been speculated that a three-cell NURP pond treatment system provides better nutrient removal than a single-cell NURP pond that has similar morphological characteristics. The model was applied to predict the differences in nutrient removal efficiencies for each best management scenario. Model simulations suggest that the single-cell NURP pond wasn't quite as effective at reducing nutrient loading in comparison to the three-cell NURP pond (Table 7). These differences did not appear to be very significant when comparing the total phosphorus and total nitrogen loading for each treatment device. However, these differences became more apparent when comparing total suspended solid loading. The model simulation suggests that the single-cell NURP pond was not quite as efficient at reducing total suspended solids in comparison to the three-cell NURP pond. The model produced similar results after re-running the simulation with average precipitation conditions (Table 8). Consequently, the model suggests that the three-cell NURP pond appears to provide somewhat better nutrient removal efficiency in comparison to the single-cell NURP pond.

Table 7: Comparison of nutrient removal efficiencies for single-cell versus three-cell NURP pond for 2005 precipitation conditions.

Site	Predicted May-Oct								
	TP Load (µg/L)		TN Load (mg/L)		TSS Load (lbs)		% Removal		
	In	Out	In	Out	In	Out	TP	TN	TSS
Three-Cell	34	12	302	141	13852	774	63	53	94
Single-Cell	36	14	323	156	14741	1509	59	51	89

Table 8: Comparison of nutrient removal efficiencies for single-cell versus three cell NURP pond for average precipitation conditions.

Site	Predicted Average Conditions								
	TP Load (µg/L)		TN Load (mg/L)		TSS Load (lbs)		% Removal		
	In	Out	In	Out	In	Out	TP	TN	TSS
Three-Cell	40	14	360	158	16870	731	66	56	96
Single-Cell	43	16	383	176	17894	1600	62	54	91

The P8 model indicates that the three-cell NURP pond treatment device substantially reduced the nutrient loading to the wetland. However, it appears that the wetland provides a primary source of nutrients to Pike Lake. The difficulty in calibrating the model to the observed conditions for the TP3 monitoring site indicates that the wetland does not conform to the anticipated standards that are necessary to classify the basin as a treatment device. The monitoring data indicate that the observed total phosphorus loading and concentrations draining out of the wetland are substantially higher than the observed loading and concentrations entering the wetland (Table 9). Unfortunately, the wetland potentially off-sets any nutrient removal benefits that the three-cell NURP pond may provide. Based on the morphological characteristics of the wetland, the model suggests that the wetland should provide an additional 40% removal efficiency for total phosphorus, 38% removal efficiency for total nitrogen, and 77% removal efficiency for total suspended solids (Table 10). Consequently, the model indicates that the wetland appears to have the potential to significantly reduce the amount of nutrient loading. This is contradictory to the observed monitoring data that was collected for the wetland. The disparity between observed and modeled conditions indicates that preliminary modeling effort may not be suitable to adequately determine the impacts alternative best management practices may have on the proposed change in land use. It might be necessary to monitor existing conditions prior to selecting best management practices to adequately reduce nutrient loading and run-off volume.

Table 9: Wetland observed and modeled nutrient concentrations and loading in 2005.

	Observed Conditions				Predicted 2005 Conditions			
	Concentration		Loading		Concentration		Loading	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
TP	108	240	---	30	72	64	13	7
TN	1.3	1.2	---	147	0.8	0.8	142	82
TSS	10	8	---	993	5	2	811	162

Table 10: Potential wetland nutrient loading and removal efficiency.

	Predicted 2005 Conditions			Predicted Average Conditions		
	Loading		% Removal	Loading		% Removal
	Inlet	Outlet		Inlet	Outlet	
TP	13	7	40	14	5	54
TN	142	82	38	159	63	52
TSS	811	162	77	747	113	85

6. Conclusions

A stormwater treatment train composed of a three-cell detention pond and a wetland at Bass Creek Business Park in City of Plymouth, Minnesota, was monitored during 2004-2005 season. The P8 model was calibrated using the flow volumes and nutrient loadings obtained from the monitoring program and used to simulate the performances of different pond configurations under the same condition of runoff. The runoff volume and nutrient removal efficiency of the three-cell pond simulated by the P8 model were well matched with measured data. The simulation results suggested that multiple-cell pond configuration can provide higher removal efficiency in nutrients and suspended solids than can single pond configuration with similar morphological conditions. The P8 model was a useful tool to determine the design configuration of a detention pond to maximize the pollutant removal efficiency for a given site and weather conditions.

The overall efficiency of the treatment train including the wetland was also simulated and compared to the measured data. The simulated nitrogen and phosphorous concentrations and loadings discharged from the wetland were significantly lower than the measured data, overestimating the performance of the wetland at removing nutrients. Monitoring data showed a negative pollutant removal efficiency of the wetland, suggesting that the wetland provides a primary source of nutrient to the receiving water body (i.e., Pike Lake). Because the pollutant removal mechanism in a wetland could not effectively be simulated simply using the sedimentation theory adapted by P8 model, it might be also necessary to monitor existing conditions prior to selecting best management practices to adequately reduce nutrient loading and run-off volume.

Appendix A: Case Studies

8. Monitoring and modeling to improve management at Eagle Creek Golf Course

Provided by Brian Vlach (bvlach@threeriversparkdistrict.org) and John Barten (jbarten@threeriversparkdistrict.org) at Three Rivers Park District

CASE STUDY #8: MONITORING AND MODELING TO IMPROVE THE MANAGEMENT OF EAGLE LAKE GOLF COURSE

Contributing Authors: Brian Vlach (bvlach@threeriversparkdistrict.org) and John Barten (jbarten@threeriversparkdistrict.org) at Three Rivers Park District

1. Introduction

The natural beauty and diversity of terrain in Minnesota has attracted top designers to build golf courses throughout the state. The abundance of water resources in Minnesota are aesthetic natural features that are often incorporated into specific site designs. Designing a golf course involves significant changes to the natural terrain and landscape that may potentially degrade these existing water resources. Consequently, it becomes important to incorporate practice and design standards that will ensure the preservation of environmental quality. Emphasis should be placed upon the design of irrigation, drainage, and retention systems that provide for efficient use of water and the protection of water quality. Drainage and stormwater retention systems are often incorporated into the design as features of the course to help provide for the short and long term irrigation needs that are required for maintenance. However, the actual performance of these stormwater retention systems relative to minimizing water quality impacts is unknown. There appears to be insufficient monitoring data to substantiate whether these stormwater retention systems designed for golf course irrigation purposes are effective in reducing runoff volume and nutrient loading.

The Three Rivers Park District designed a stormwater retention system that would be used for irrigation of Eagle Lake Golf Course. A major portion of the golf course watershed drains to the stormwater retention system that eventually flows to Pike Lake. A pond was constructed as part of the stormwater retention system and serves as a water reservoir for irrigation of the golf course. The irrigation pond also receives water from an adjacent augmentation well. The water volume in the pond is currently managed to ensure an adequate supply of water for turf needs. The pond also has the potential to manipulate the water volume storage to reduce potential run-off and nutrient loading. There is concern that the nutrient loading from the golf course may degrade Pike Lake water quality. The Minnesota Pollution Control Agency classified Pike Lake as an impaired water body for excessive nutrients in 2002. Consequently, Three Rivers Park District monitored the performance of the stormwater retention system to improve on the current management of Eagle Lake Golf Course. The monitoring data was further used to develop a P8 model to improve the operation of the irrigation pond to reduce run-off volume and nutrient loading to Pike Lake.

2. Study Site

The Eagle Lake Golf Course is located in the City of Plymouth, Hennepin County, north of the intersection of Zachary Lane and Bass Lake Road. The golf course has a network series of five inter-connected ponds that provide water quality treatment for runoff flowing to Pike Lake (Figure 1). The water quality ponds also provide flow-rate and volume control. The entrance road into Eagle Lake Golf Course separates nutrient detention Pond 1 and Pond 2. Pond 1 receives water run-off from the golf course maintenance facility building and parking lot. The water from Pond 1 discharges through a 12-inch pipe into Pond 2 when water levels exceed the culvert outlet elevation. Pond 2 also receives surface run-off from the Eagle Lake Golf Course Club House and main parking lot area. The discharge from Pond 2 flows north through a 12-inch pipe into a pond that is used as a water reservoir for irrigating the golf course. The irrigation pond also receives water from an adjacent augmentation well. The pond water volume is managed to ensure an adequate supply of water for turf needs. Because the irrigation system has a much higher pumping capacity than the augmentation well, the pond level is typically lowered during the nighttime irrigation activities, and then raised through use of the augmentation well during the day. The normal water level of the pond can be adjusted by controlling the volume of water pumped by the augmentation well.

During high intensity rainfall events, storm water flows over the embankment of the irrigation pond. The water continues to flow through a grassed buffer swale to Pond 3 (Figure 1). The discharge from Pond 3 drains through a 12-inch pipe into Pond 4 located at the northern edge of the golf course. The outlet for Pond 4 discharges through a 12-inch culvert into a drainage channel that conveys water to Pike Lake. Although these ponds receive some runoff from the adjacent golf course greens and fairways, the primary volume of stormwater and nutrients entering Ponds 3 and 4 is typically a function of the water level of the irrigation pond. Consequently, the water level elevation within the irrigation pond has the ability to influence the potential nutrient loading into Pike Lake.

Since the irrigation pond appears to be the control point for downstream nutrient loading, monitoring stations were located at the irrigation pond as well as downstream from the irrigation pond (Figure 1). The first monitoring station (EG1) was located at the irrigation pond to measure changes in water level elevation. There were three monitoring stations located down stream from the irrigation pond to measure flow volume and to collect water quality samples. The first sampling site (EG2) downstream of the irrigation pond monitored flow from the grassed buffer swale prior to draining into Pond 3. The second downstream station (EG3) monitored flow from a 12-inch culvert that drained from Pond 3 to Pond 4. The third downstream monitoring station (EG4) was located at the outlet of Pond 4 prior to draining into the channel that conveys water to Pike Lake.

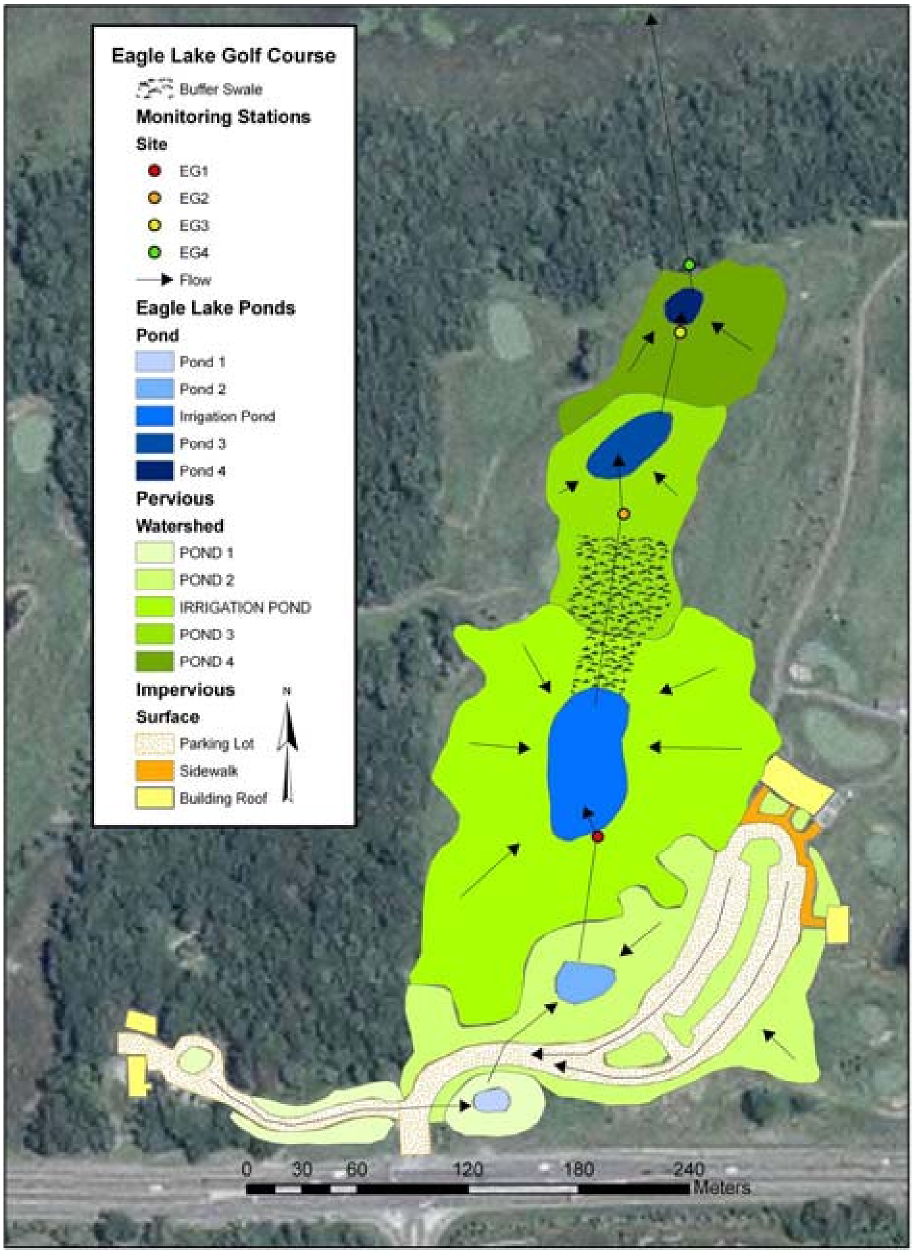


Figure 1: Eagle Lake Golf Course Watershed and Monitoring Sites.

3. Methods

Three Rivers Park District monitored each sampling site from May through November in 2005. At each of the monitoring stations, an automated sampler/data logger was installed. The monitoring station located at the irrigation pond (EG1) recorded the changes in water level elevation at 15 minute intervals. The monitoring stations located downstream (EG2, EG3, and EG4) of the irrigation pond measured water level, velocity, and flow at one-minute intervals. All of the data loggers were programmed to initiate sample collection after a predetermined increase in water level was obtained. After sampling was initiated, water samples were collected every 60 to 120 minutes for the EG1 sampling site; flow-weighted composite water samples were sequentially collected for the EG2, EG3, and EG4 sampling sites. Stormwater samples were collected to encompass the entire storm distribution. The anticipated storm events were based upon estimated precipitation volume. After each precipitation event, the water quality samples were collected within 24-hours. During extended periods without precipitation, grab samples were collected to determine nutrient concentrations during base flow conditions. All samples were labeled immediately after collection, stored in a cooler with ice, and delivered to the Three Rivers Park District for laboratory analysis. During each site visit, flow meter data was downloaded by a field laptop computer.

Three Rivers Park District analyzed each water quality sample for nutrient concentrations. The water quality samples were analyzed for total phosphorus, soluble reactive phosphorus, total nitrogen, and total suspended solids. The Standard Methods for the Examination of Water and Wastewater (1995) was used to determine nutrient concentrations of the water samples. Sample analysis was prioritized by analyte holding time to ensure that analyses are completed within the recommended time interval. Samples were stored at 4° C in a refrigerator until all analysis was completed. A quality assurance and quality control protocol was followed to ensure the precision and accuracy of laboratory data analysis.

The flow meter data and water quality data were used to determine the nutrient loading for each monitoring site. The nutrient loading for each storm event was calculated by multiplying the flow volume and nutrient concentration. The monitoring data were used to calibrate a P8 model developed for the Eagle Lake Golf Course. The P8 model was calibrated to mimic similar flow and nutrient loading conditions that were observed during the sampling interval. The model was only calibrated with flow and nutrient concentration data that were considered reliable. The differences in nutrient loading between monitoring sites provided estimates of nutrient removal efficiencies for each treatment device. The removal efficiency for the treatment devices were calculated using a mass balance equation. The nutrient loading and % removal efficiencies were compared to values estimated by the calibrated P8 model. The details pertaining to model calibration are further described in the following section.

4. Model Calibration

The P8 model was used to examine treatment efficiencies associated with golf course pond operation. The model was calibrated using monitoring data collected from the sampling sites. The parameters entered into the model included the pervious and impervious watershed characteristics (Table 1). The parameters corresponding to each treatment device included morphological characteristics of the irrigation pond, the buffer swale, and the downstream ponds (Table 2 & 3). The rainfall data collected hourly at the monitoring site was used for model application, and a daily average temperature file was also developed from data collected at Crystal Airport in 2005 (Appendix). The flow network diagram further describes how the P8 model was set up for the Eagle Lake Golf Course (Figure 2).

The Eagle Lake Golf Course modeling efforts needed to account for the volume of well water being pumped into and out of the irrigation pond. The augmentation well was metered to determine the volume of water entering and leaving the pond for irrigation. To simulate the amount of ground water pumped into the pond, an artificial watershed was created in the P8 model to capture rainfall that directly infiltrated into an aquifer device flowing directly to the irrigation pond. The watershed was sized appropriately to simulate the volume of water that was pumped into the irrigation pond from the well. The volume of water pumped out of the pond for irrigation of the golf course was incorporated into the P8 model rainfall file. Eagle Lake Golf Course irrigation records were used to determine the volume of water used per month. The monitored study area was approximately 25% of the total acreage for the Eagle Lake Golf Course (54.5 acres). Consequently, it was assumed that 25% of the total volume of water used for irrigation of the golf course was distributed throughout the study area and was incorporated into the rainfall file. Typically, irrigation of the golf course occurred during days without measurable precipitation between 12 to 6 A.M. The adjusted volume of water each day was incorporated into the P8 rainfall file to reflect the actual time period of irrigation.

The model was initially calibrated to mimic the 2005 observed flow conditions at each of the monitoring sites. The volume of water with the corresponding flow hydrographs that were predicted by the model was compared to observed flow conditions. The time of concentration within the model was adjusted accordingly to mimic the observed peaks in the hydrograph. After the model was calibrated to the observed flow conditions, the scale factor for each water quality parameter was adjusted in the particle file (NURP50.PAR) to estimate nutrient loading. The scale factor for each parameter was adjusted until the model accurately predicted nutrient loads similar to the observed conditions.

Table 1: Eagle Lake Golf Course Sub-watershed Characteristics.

Sub-Watershed Characteristics								
	Primary	Total	Impervious		Pervious		Treatment Device	
Sub-watershed	Land-Use	Acres	Acres	%	Acres	%	Type	Acres
Pond 1	Commercial/Golf Course	0.722	0.562	78	0.16	22	Pond	0.050
Pond 2	Commercial/Golf Course	3.146	2.208	70	0.938	30	Pond	0.136
Irrigation Pond	Commercial/Golf Course	6.044	0.167	3	5.877	97	Pond	0.737
Pond 3	Golf Course	1.987	0	0	1.987	100	Swale/Pond	0.993
Pond 4	Golf Course	1.394	0	0	1.394	100	Pond	0.080

Table 2: Eagle Lake Golf Course Treatment Pond Characteristics.

Treatment Pond Characteristics										
	Drainage Flow		Bottom		Normal Water Level			Ordinary High Water Level		
Device	Receives	Discharges	Elevation (ft)	Acres	Elevation (ft)	Acres	Volume (acre-ft)	Elevation	Acres	Volume (acre-ft)
Pond 1	Sub-watershed	Pond 2	922.6	0.005	928.6	0.110	0.43	929.6	0.226	0.67
Pond 2	Pond 1 & Sub-watershed	Irrigation Pond	920.9	0.045	927.9	0.275	1.00	931.5	0.471	2.04
Irrigation Pond	Pond 2 & Sub-watershed	Swale	912.0	0.045	924.5	0.761	4.70			
Pond 3	Swale & Sub-watershed	Pond 4	895.8	0.028	903.8	0.270	1.24	907.8	0.415	2.36
Pond 4	Pond 3 & Sub-watershed	Pike Lake	885.8	0.017	891.8	0.133	0.36	892.8	0.164	0.52

Table 3: Eagle Lake Golf Course Swale Characteristics.

Swale Characteristics									
		Drainage Flow		Bottom	Bottom	Flow Path	Maximum	Side Slope	Slope
Device	Description/Type	Receives	Discharges	Elevation (ft)	Width (ft)	Length (ft)	Depth (ft)	ft-h/ft/v	%
Swale	Wooded/Shrubs	Irrigation Pond	Pond 3	922	25	407	2	3	3

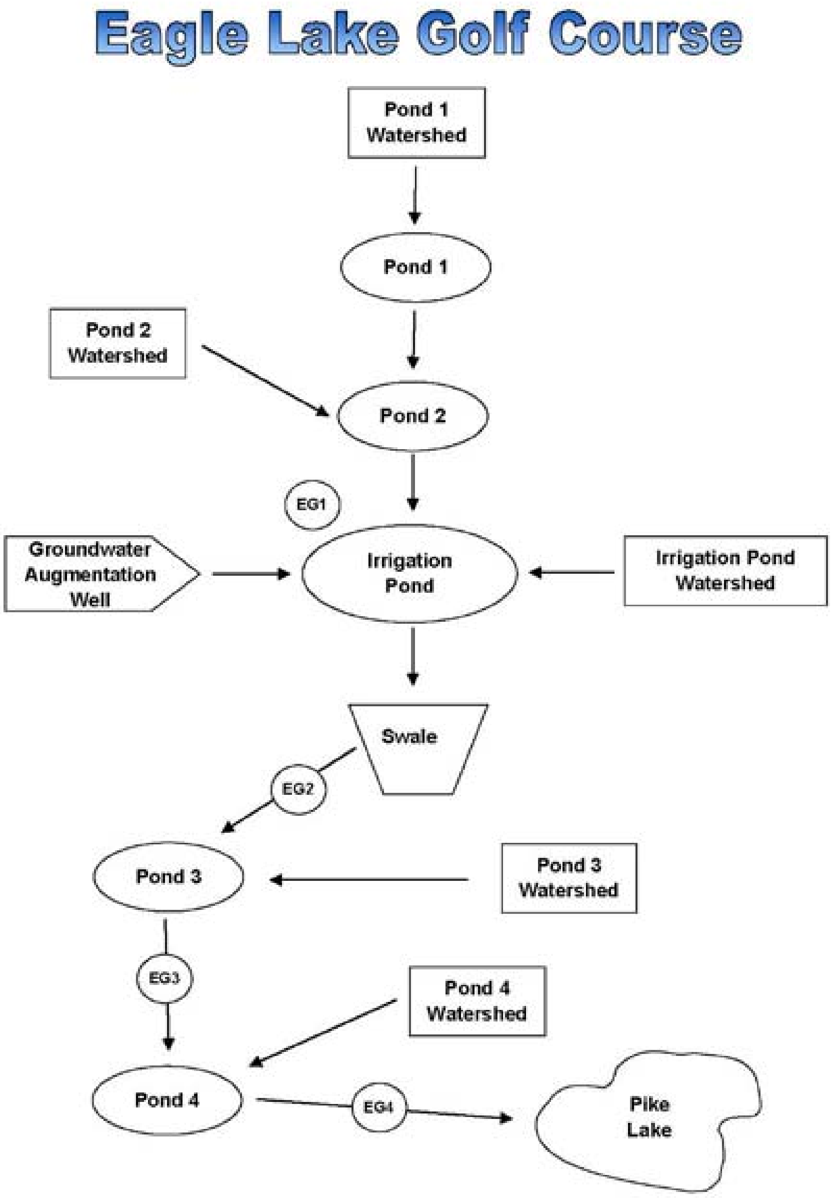


Figure 2: Eagle Lake Golf Course Flow Diagram.

After the model was calibrated to observed conditions, the model was used to determine the nutrient loading removal efficiency of the buffer swale and ponds downstream from the irrigation pond. The nutrient removal efficiency was calculated for each parameter for conditions observed in 2005. The model was re-run with a rainfall file that represents average precipitation conditions for the Minneapolis, Minnesota area. The nutrient loading and removal efficiency of the buffer swale and ponds downstream of the irrigation pond were compared to the observed conditions in 2005. To simulate nutrient loading conditions without the series of treatment devices, the model was re-run by removing the buffer swale and ponds from the model. This provided an estimate of the nutrient loading without the treatment devices downstream of the irrigation pond.

The P8 model was further used to improve the operation of the irrigation pond to reduce runoff volume and nutrient loading to Pike Lake. The water level within the irrigation pond can be adjusted to ensure that it receives the majority of the runoff without overflowing to the downstream treatment devices. The model was run with a 1-year storm event (2.5 inches in 24 hours) rainfall file to determine the volume of runoff from the irrigation pond watershed. The estimated volume of runoff (acre-ft) was the minimum storage capacity required to accommodate the runoff from a 1-year storm event so that there would be no overflow to the down stream treatment devices. The water level elevation on the irrigation pond was adjusted accordingly to accommodate the estimated runoff volume from the 1-year storm event. These model simulations should provide insight into the potential operation of the irrigation pond to further reduce potential downstream nutrient loading.

5. Results and Discussion

Three Rivers Park District monitored the performance of the stormwater retention system that was designed for the Eagle Lake Golf Course. The sampling sites were monitored from May 3 through November 14 in 2005. During the monitoring interval, the rain gauge recorded 21.8 inches of precipitation. There were 15 precipitation events that produced sufficient runoff volume for sample collection. Water quality samples were collected throughout the flow hydrograph for each precipitation event. A total of 53 water quality samples were collected from all of the sample sites. The data collected from the monitoring sites suggest that the stormwater retention system downstream from the irrigation pond appears to reduce runoff volume and nutrient loading prior to draining to Pike Lake (Table 4). The annual runoff volume for the series of treatment devices decreased from 31 acre-ft to 8 acre-ft, and the total phosphorus concentration decreased from 288 µg/L to 177 µg/L. Consequently, the stormwater retention system provides storage capacity for runoff volume as well as nutrient removal. Although water quality samples were not collected for each precipitation event, the samples were representative of the rainfall distribution with respect to the amount and intensity of precipitation observed in 2005. The flow and nutrient concentration data collected from these monitoring sites were used for calibration of the P8 model.

Table 4: Eagle Lake Golf Course Monitoring Data Summary in 2005.

Site	Samples (n)	Observed Volume (acre-ft)	Average Concentrations TP (µg/L)	SRP (µg/L)	TN (mg/L)	TSS (mg/L)
EG1	15	-	197.4	114.9	1.3	10.7
EG2	15	31.2	288.3	237.2	1.4	14.2
EG3	12	17.9	190.4	91.4	1.2	27.1
EG4	11	8	176.7	102.9	1.3	21.5

The model was initially calibrated for flow conditions that were observed in 2005. To simulate the observed flow conditions, modeling efforts needed to account for the volume of well water pumped into and out of the irrigation pond. The augmentation well pump operation records indicated that there were 32.9 acre-ft of water used for irrigation of the Eagle Lake Golf Course in 2005 (Table 5). Based on the study area acreage, approximately 25% of the volume of water was used for irrigation of the monitored portion of the watershed study area. It was estimated that there were approximately 8 acre-ft used for irrigation of the study area (Table 5). The adjusted irrigation volume for the study area provided approximately 7.4 inches of water that was incorporated into the model rainfall file for each month (Table 5). The adjusted rainfall file was used for modeling the ground water pumped into the irrigation pond. To simulate ground water pumped into the irrigation pond, an artificial watershed was developed in the model to receive rainfall that infiltrated into an aquifer device flowing directly to the irrigation pond. The size of the watershed was adjusted until the modeled flow volume was similar to observed conditions. Modeling with a 25-acre watershed was required to simulate the

52 acre-ft of water pumped into the irrigation pond. The volume adjustments pumped into the irrigation pond were necessary to mimic the downstream observed hydrologic flow conditions.

Table 5: Eagle Lake Golf Course irrigation volume in 2005.

Month	Total Irrigation Volume (acre-ft)	Study Area Irrigation Adjusted Volume (acre-ft)	Irrigation Depth (inches)
April	0.85	0.21	0.19
May	2.03	0.51	0.46
June	4.61	1.15	1.04
July	12.86	3.21	2.90
August	9.71	2.43	2.19
September	2.52	0.63	0.57
October	0.28	0.07	0.06
Total	32.86	8.22	7.41

The model appears to adequately simulate the observed hydrologic flow conditions. The model provided reliable estimates of total flow volumes that were similar to the observed conditions (Table 6). The only discrepancy between the modeled and observed flow conditions is that the model appears to slightly over predict the total flow volume for the sampling sites. Variations in predicted versus observed total flow volumes may be related to the time of concentration applied for the treatment devices network. The time of concentration for each treatment device was adjusted accordingly in the model so that predicted hydrographs were similar to the observed flow conditions. The adjustments pertaining to the time of concentration was difficult due to the inputs and outputs of the irrigation pond. Despite the difficulty with flow calibration efforts, the model appears to provide estimates that are reasonably similar to the observed flow conditions.

Table 6: Eagle Lake Golf Course observed and modeled flow volumes.

Site	Observed Flow Volume (Acre-ft)	Modeled Flow Volume (Acre-ft)
EG2	31.2	34.0
EG3	17.9	19.4
EG4	8.0	11.1

After the model was calibrated for flow volume, the model was further adjusted to mimic the observed nutrient loading conditions. Typically, the scale factors for each water quality parameter are adjusted accordingly until the model predicts nutrient loading and concentrations similar to observed conditions. Unfortunately, scale factors for each water quality parameter in the model can-not be adjusted for each treatment device. The limitations in adjusting scale factors led to difficulties in model calibration for nutrient concentrations. The model appears to substantially over predict the concentrations for total phosphorus and total nitrogen for the EG3 and EG4 sampling sites (Table 7). Scale factors for these water quality parameters could not be adjusted appropriately to compensate for the differences in predicted and observed concentrations. Despite these differences in nutrient concentrations, the modeled estimates for nutrient loading were similar to observed conditions (Table 8). The only substantial difference in modeling estimates in comparison to observed conditions occurred for total nitrogen loading at the EG4 sampling site (Table 8). The model estimation of nutrient loading does not appear to be sensitive to the predicted increase in nutrient concentrations when flow volumes are relatively low. The predicted flow-weighted mean concentrations may have more influence on nutrient loading estimates during periods of increased flow volume. The majority of the storm events in 2005 produced low amounts of runoff volume. Consequently, the model appears to provide estimates of nutrient loading that are reasonably comparable to observed conditions.

Table 7: Eagle Lake Golf Course observed and modeled nutrient concentrations.

Site	Observed			Modeled		
	TP (µg/L)	TN (mg/L)	TSS (mg/L)	TP (µg/L)	TN (mg/L)	TSS (mg/L)
EG2	288	1.4	14.2	257	1.3	11.8
EG3	190	1.2	18.9	294	1.5	21.8
EG4	177	1.3	21.5	294	1.5	12.5

Table 8: Eagle Lake Golf Course observed and modeled nutrient loadings.

Site	Observed			Modeled		
	TP (lbs)	TN (lbs)	TSS (lbs)	TP (lbs)	TN (lbs)	TSS (lbs)
EG2	25.4	120.0	1060.4	23.8	119.6	1087.4
EG3	13.5	79.0	1170.7	15.5	76.7	1148.2
EG4	4.7	26.6	378.6	8.9	44.6	378.0

The calibrated P8 model was used to determine the removal efficiencies for the network of treatment devices. The model suggests that the series of treatment devices were efficient at reducing nutrient loading downstream of the irrigation pond (Tables 9-11). The buffer swale immediately downstream of the irrigation pond provided approximately 18% removal of total phosphorus and total nitrogen loading and provided approximately 42% removal of total suspended solids. The buffer swale flows directly into the Pond 3 treatment device. Pond 3 reduced total phosphorus and total nitrogen loading by approximately 38%; and reduced the total suspended solid loading by approximately 56%. The furthest downstream pond provided additional treatment for water flowing out of Pond 3. The model estimated that Pond 4 had a nutrient removal efficiency of approximately 40% for total phosphorus and total nitrogen, and a nutrient removal efficiency of 69% for total suspended solids. Consequently, it appears that the series of treatment devices were extremely effective at reducing the nutrient loading.

Table 9: Total Phosphorus Nutrient Removal Efficiency.

Site	Volume (Acre-ft)		Total Phosphorus (pounds)		% Removal
	In	Out	In	Out	
Buffer-Swale	41.9	34.0	29.9	23.8	18.6
Pond 3	34.3	19.4	26.6	15.5	37.9
Pond 4	19.4	11.1	15.8	8.9	40.3

Table 10: Total Nitrogen Nutrient Removal Efficiency.

Site	Volume (Acre-ft)		Total Nitrogen (pounds)		% Removal
	In	Out	In	Out	
Buffer-Swale	41.9	34.0	149.0	119.6	17.9
Pond 3	34.3	19.4	131.1	76.7	37.7
Pond 4	19.4	11.1	78.1	44.6	39.1

Table 11: Total Suspended Solids Removal Efficiency.

Site	Volume (Acre-ft)		Total Suspended Solids (pounds)		% Removal
	In	Out	In	Out	
Buffer-Swale	41.9	34.0	1869.3	1087.4	41.8
Pond 3	34.3	19.4	2610.1	1148.2	56.0
Pond 4	19.4	11.1	1221.6	378.0	69.1

These estimates could not sufficiently be compared to the measured conditions. The nutrient loading inputs to the buffer-swale were not monitored to determine nutrient removal efficiency. In addition, the monitored conditions did not take into account nutrient loading to treatment devices that was attributed to direct run-off. The model incorporates direct watershed loading that was not captured from the monitoring sites. The model was calibrated to the observed nutrient loading conditions for each respective monitoring site, so the estimates for nutrient removal efficiency should corroborate with the measured conditions. The modeled nutrient removal efficiencies should provide a conservative estimate that is more accurate than the measured conditions because direct watershed nutrient loading is accounted for in the model.

After removal efficiencies were calculated for each treatment device, the model was re-run by removing the series of connected treatment devices to further assess the potential impact on nutrient loading. There was a significant increase in the amount of nutrient loading when the treatment devices were removed from the model (Figure 2). The model estimated that the total phosphorus loading increased from 8.9 to 35 pounds, and total nitrogen loading increased from 44.6 to 168.5 pounds. In addition, the model predicted that the total suspended solids would increase from 378 to 4460 pounds. The Eagle Lake Golf Course flows directly to Pike Lake. Consequently, the potential increases in nutrient loading without the series of treatment devices would have had a significant impact on Pike Lake water quality. The modeling scenario suggests that the development of a series of connected treatment devices significantly reduced the nutrient loading as well as potential impacts on Pike Lake water quality.

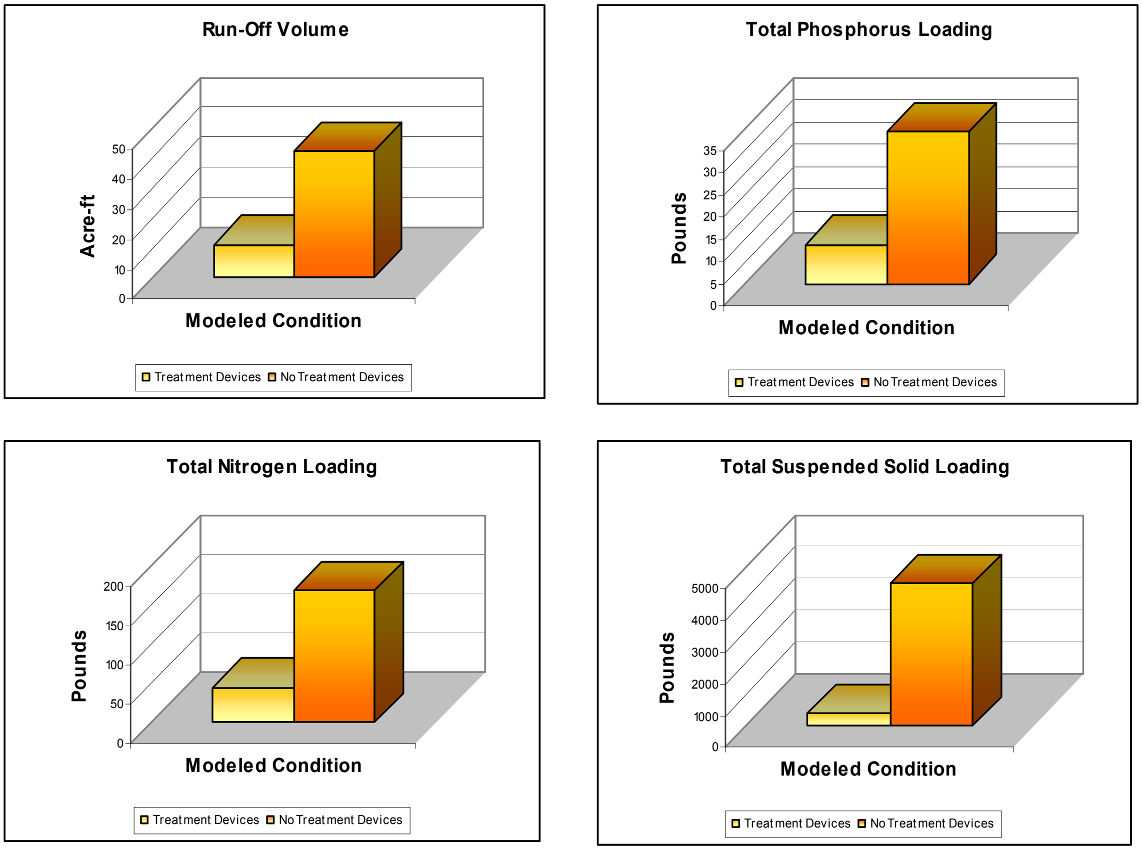


Figure 3: Modeled changes in nutrient loading after removing treatment devices.

Although the series of connected treatment devices are effective at reducing nutrient loading, there are potential opportunities to improve the treatment network by managing the water level of the irrigation pond. A significant portion of the Eagle Lake Golf Course watershed flows into the irrigation pond. The watershed primarily consists of impervious acreage that drains to the irrigation pond. Based on modeling estimates in 2005, the irrigation pond received approximately 16 pounds of phosphorus loading, 64 pounds of total nitrogen loading, and 10,021 pounds of total suspended solids. The available storage volume within the irrigation pond has the potential to contain the majority of the nutrient loading from the upper portion of the watershed. Consequently, the potential exists to contain the majority of the nutrient loading within the irrigation pond through water level management.

The model was re-run to determine the operational water level elevation of the irrigation pond that would adequately provide enough storage volume for a 2.5-inch precipitation event in a 24-hour period. Modeling for the 2.5-inch precipitation event results in approximately 1.29 acre-ft of runoff draining to the irrigation pond. The modeling scenario indicates that the 2.5-inch precipitation event potentially can provide 32 pounds of total phosphorus loading, 120 pounds of total nitrogen loading, and 26,000 pounds of total suspended solids. The spillway elevation of the pond is at 924.5 feet, in which the pond overflows to the buffer swale. Based on the modeling scenario, the irrigation pond should be maintained at a maximum water level elevation of 923 feet to ensure adequate storage volume necessary to accommodate the runoff from the 2.5-inch rainfall event. Maintaining the pond at a water level elevation of 923 feet would allow approximately 9.44 acre-ft of water to be available for irrigation of the golf course. The modeling scenario suggests that adjusting the water level elevation of the irrigation pond potentially could provide adequate storage volume to capture runoff from majority of the precipitation events. Consequently, adjusting the water level within the irrigation pond could reduce nutrient loading as well as provide enough water available to accommodate the irrigation of the golf course.

6. Conclusions

A network treatment system of five inter-connected ponds at Eagle Lake golf course was monitored in 2005. Four monitoring stations were used at the inlets of the last three detention ponds connected in series (one irrigation pond followed by two detention ponds) and the final outlet to Pike Lake. The first two detention ponds were not monitored because they receive relatively insignificant storm runoff volume. A total of 53 water quality samples were collected from 15 storm events, and nitrogen, phosphorous and suspended solids concentrations were analyzed.

The monitoring results reveal the effectiveness of the series of the three detention pond system, reducing annual runoff volume from 31 acre-ft to 8 acre-ft and average effluent phosphorous concentration from 288 µg/L to 177 µg/L. The P8 model was calibrated using the monitored flow and water quality data and simulated different scenarios of pond operation. Simulation with and without the pond system showed that a serial pond system can provide significant reduction in runoff volume as well as nutrient and suspend solids loadings to Pike Lake. The P8 model was also useful to determine the operational condition of the irrigation pond such as water level control to store water volume for irrigation, volume reduction of runoff discharge, and pollutant removal.

Appendix A: Case Studies

9. Assessment of source reduction due to phosphorus-free fertilizers

Provided by Brian Vlach (bvlach@threeriversparkdistrict.org), John Barten, James Johnson, and Monica Zachay at Three Rivers Park District

CASE STUDY #9: ASSESSMENT OF SOURCE REDUCTION DUE TO PHOSPHORUS-FREE FERTILIZERS

Contributing Authors: Brian Vlach (bvlach@threeriversparkdistrict.org), John Barten, James Johnson, and Monica Zachay at Three Rivers Park District

1. Objectives:

The objective of this project was to evaluate the effectiveness of select alternative urban best management practices (BMPs) including infiltration areas called rain gardens, the effects of adoption of a municipal phosphorus-free fertilizer ordinance on phosphorus loss from lawns to surface waters, a stormwater treatment train on golf course runoff quantity and quality, and a three-cell nutrient detention basin.

2. Methods

Lawn Fertilizer Runoff Monitoring – Paired Watershed Study

Six small residential sub-watersheds were monitored from 2001 to 2006 to characterize residential runoff and track changes in phosphorus concentration and export associated with the use of phosphorus-free fertilizer. The study design utilized a paired-watershed approach where three of the sub-watersheds were located in the city of Plymouth, Minnesota, where the use of lawn fertilizer containing phosphorus was restricted in 1999, (treatment watersheds). The remaining three sub-watersheds were located in Maple Grove, Minnesota where phosphorus fertilizer restrictions were not initiated until 2004 (control watersheds). These sub-watersheds were carefully selected to include one newly developed area less than 5-years old (P1 and MG1), one development between 5 and 15-years old (P2 and MG2), and one neighborhood older than 15-years (P3 and MG3), within each of the municipalities (Figures 1 and 2). The sub-watershed areas were located within 10 kilometers of each other to minimize differences in precipitation patterns, soil types, and aerial phosphorus loading.

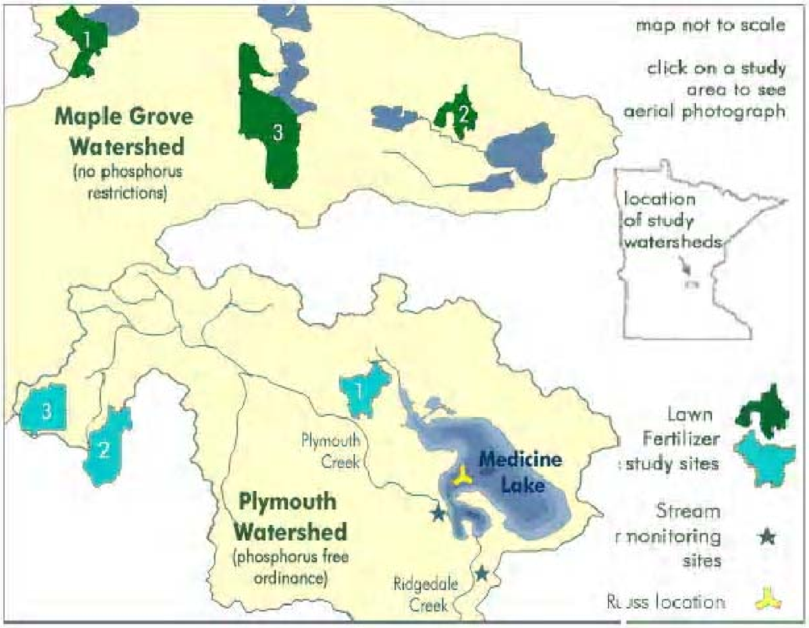


Figure 1: Map showing the relative location of the study sub-watersheds in Plymouth (south) and Maple Grove (north), MN.

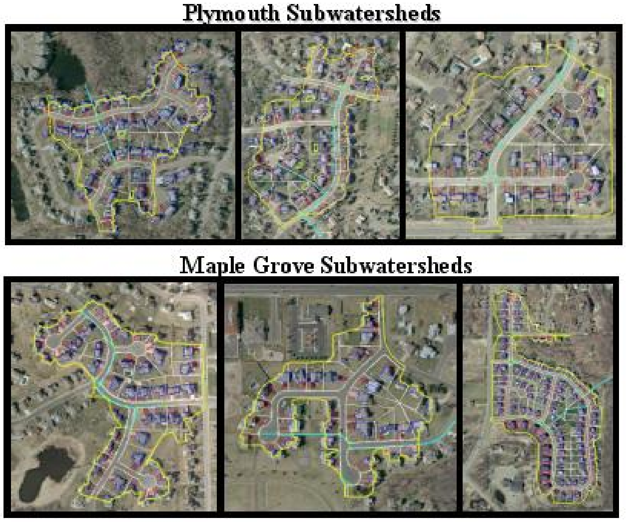


Figure 2: Maps of the six sub-watersheds (P1-MG1, P2-MG2, and P3-MG3 sequentially), monitored from 2001 to 2006.

To ensure similarity in physical characteristics of the sub-watersheds, the amount of impervious and connected impervious surface area in each sub-watershed was measured (Table 1), the soil phosphorus fertility concentration was measured, and lawn-care practices including fertilizer use were determined, (Table 2). Impervious area was measured with aerial photography, desktop geographic information system software, and field verification. Public surveys were administered to a portion of the homeowners by local high school students to characterize lawn-care practices including fertilizer application, watering, mowing, and soil aeration. Soil fertility characteristics were determined through soil sample collection at 10% of lawns within the sub-watersheds. These samples were analyzed for nutrient levels, organic matter, particle size, pH, and soil compaction.

Table 1. Selected physical characteristics of Plymouth and Maple Grove sub-watersheds.

Sample site	Size (Ha)	Number of homes	Impervious area (%)	Connected Impervious (%)
P1	5.1	43	38	23.9
P2	6.8	47	35.1	22.9
P3	5.6	37	27.3	17.8
MG1	5.5	49	40.5	26.2
MG2	3.5	36	38.8	25.9
MG3	16	108	34.8	21.1

Stormwater runoff from each of these residential areas drained into catch basins and was transported off site by underground storm sewer pipes. Automated monitoring equipment (computer data logger with associated velocity/level sensor slaved to an automatic sampling unit) was installed in each storm sewer system at the outlet point of each sub-watershed. The data logger recorded water level and water velocity in the storm sewer at 15 minute intervals from approximately April 15 to November 1 each year during the study period.

A stage-discharge relationship for each site was developed from the Mannings equation for each storm sewer. Discharge estimated from the Mannings equation was verified by periodically measuring the velocity of storm water flow utilizing a pulse Doppler velocity sensor. Calibration of the velocity probes was completed utilizing a portable velocity meter calibrated in the laboratory. Level readings for each probe were verified by staff gauge readings taken weekly during the monitoring period.

Stormwater samples were collected during rainfall runoff events and baseflow conditions at discrete flow volume intervals. The discrete samples collected during a specific rainfall event were discharged into a single container to produce a flow weighted sample for the event. Samples were removed from the monitoring devices at each site within 12 hours following the end of the runoff event. The samples were placed on ice in the dark and transported to the laboratory. Analysis of samples was completed within 48 hours of receipt by the laboratory. Laboratory analytical protocol and chain of custody protocol follow requirements of the Minnesota Department of Health Laboratory Certification requirements.

For each sampled flow event, the load of total phosphorus, dissolved phosphorus, total nitrogen, and suspended solids from each watershed were calculated using the observed flow-weighted event mean concentration and the total event flow volume.

Table 2. Soil phosphorus concentrations and fertilizer use in six residential sub-watersheds in Plymouth and Maple Grove, MN, in 2001.

Sample site	Soil phosphorus concentration (% of lawns)			Fertilizer applied	Phosphorus fertilizer applied
	>50 ppm	**25 – 50 ppm**	**<25 ppm**	**%**	**%**
P1	**36**	**57**	**7**	**100**	**44.4**
P2	**90**	**10**	**0**	**72**	**20**
P3	**89**	**11**	**0**	**76**	**21**
MG1	**92**	**8**	**0**	**100**	**64**
MG2	**78**	**22**	**0**	**89**	**83**
MG3	**43**	**26**	**30**	**92**	**74**

3. Results

Runoff samples and flow data were collected from approximately 570 rain events during the monitoring period, equally distributed among the six sites. The data showed that areal runoff volume increased substantially for rainfall events greater than 2 cm (Figure 3). For rainfall events less than 2 cm, the runoff volume could be accounted for by estimating the rainfall volume falling on impervious surfaces such as streets, driveways and rooftops. For events greater than 2 cm, however, runoff from impervious surfaces alone could not account for the total runoff volume, indicating that runoff from pervious surfaces (lawns) was occurring. All six sub-watershed sites showed a similar pattern.

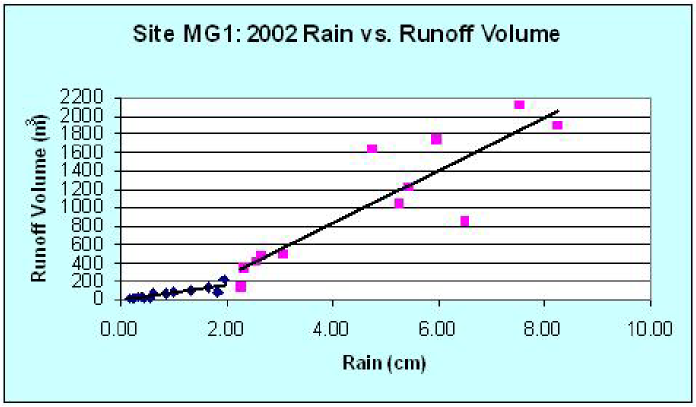


Figure 3: Relationship between rain event total (cm) and runoff volume total (cubic meters) for site MG1 in 2002.

As noted in Table 1, the three Maple Grove sub-watersheds had a larger percentage of both total and connected impervious surface area than the three Plymouth sub-watersheds. Consequently, the average unit runoff volume was higher for the Maple Grove sites (27.8 m3/ha/cm rainfall) than for the Plymouth sites (20.1 m3/ha/cm rainfall). In addition, the total annual runoff volume (m3/ha)at the MG3 site (Maple Grove sub-watershed #3) was substantially greater than for any of the other five sites. The high runoff volume was a result of the high baseflow recorded at the monitoring station, typically greater than 3000 cubic meters/day, caused by basement sump pumps discharging into the storm sewer system.

There were significant differences in the total phosphorus (TP), soluble reactive phosphorus (SRP) and total nitrogen (TN) event mean concentrations in runoff from rainfall events greater and less than 2 cm (Table 3, below). The total phosphorus and total nitrogen concentrations were higher in rainfall runoff from events less than 2 cm, but the SRP concentration was higher in events greater than 2 cm. The TSS concentration was higher for rainfall events greater than 2cm, but the difference was not significant.

Table 3: Mean Concentrations of selected parameters in runoff from small (<2 cm) and large (> 2 cm) rainfall events in six sub-watersheds in Plymouth and Maple Grove from 2001 to 2006.

Parameter	Rainfall < 2 cm	Rainfall >2 cm	Significance
Mean TP (µg/L)	310	240	0.000
Mean SRP (µg/L)	111	142	0.014
Mean TN (mg/L)	3.02	2.23	0.000
Mean TSS (mg/L)	109	81	0.045

There was no significant difference in the event mean total phosphorus or total nitrogen concentration between the two municipalities over the six year monitoring period (Table 4, below). However, the event mean soluble reactive phosphorus concentration in runoff from the three Plymouth sites (phosphorus-free fertilizer used) was significantly lower than the concentration in the three Maple Grove sites. Conversely, the total suspended solids concentration was significantly higher in the Plymouth sites, 110 mg/L, than the Maple Grove sites, 70 mg/L.

Table 4: Mean concentration (with standard errors) of selected parameters in runoff from six sub-watersheds in Plymouth and Maple Grove, MN, from 2001 to 2006.

Parameter	Plymouth P-free fertilizer	Maple Grove P -fertilizer	Significance
Mean TP (µg/L)	262 ± 14.0	278 ± 11.6	0.865
Mean SRP (µg/L)	112 ± 6.5	135 ± 8.6	0.007
Mean TN (mg/L)	2.69 ± 0.10	2.61 ± 0.12	0.631
Mean TSS (mg/L)	111 ± 10.9	64 ± 5.8	0.004

There was a large amount of variability in the event mean concentrations for all parameters during the study period. Total phosphorus concentrations ranged from 56 to 1516 µg/L, and total nitrogen concentrations ranged from 0.20 to 13.60 mg/L. The high variability made detection of real differences in the EMC between the two treatments difficult. Consequently, the constituent export/unit areas were calculated for the two treatments and compared to detect differences between the two municipalities. As shown in Table 5, phosphorus export from Maple Grove sites (where phosphorus fertilizer was used) was significantly greater than phosphorus export from Plymouth sites (where phosphorus-free fertilizer was used). However, as noted in Table 3, it was observed that Maple Grove sites tended to have greater runoff volume per unit area than the Plymouth sites, probably a result of the slighter higher impervious surface area. To normalize the data, therefore, the unit area export per unit runoff was calculated (g/ha/cm).

As indicated previously, the City of Plymouth initiated phosphorus fertilizer use restrictions beginning in 1999, but Maple Grove did not implement restrictions until adoption of the Minnesota Phosphorus Lawn Fertilizer Law in 2004. Therefore, data collected from 2001 to 2003 were examined to detect differences in nutrient export that could have resulted from the use of phosphorus-free fertilizer in Plymouth. There was no difference in the area-weighted total or soluble phosphorus loading between the two municipalities for rain events less than 2cm (Table 5). A comparison of the area-weighted phosphorus loading from each city during large rain events (>2cm) showed significantly lower area-weighted total and soluble phosphorus loading in Plymouth (Table 5). Differences in the area-weighted soluble phosphorus loading between the two municipalities were larger than the total phosphorus differences.

Table 5: Phosphorus Export (g/ha/cm rainfall) from Plymouth, MN (phosphorus-free fertilizer used), and Maple Grove, MN (phosphorus fertilizer used), from 2001 to 2003.

	TP		SRP	
	0-2cm	>2cm	0-2cm	>2cm
Mean Event Export (P-used)	**N=34**	**N=31**	**N=31**	**N=31**
(g/ha)	3.9 ± **1.7**	23.5 ± **6.7**	2.0 ± **1.3**	16.0 ± **4.9**
(g/ha/cm runoff)	33.2 ± **15.9**	23.1 ± **3.2**	11.3 ± **7.4**	15.2 ± **2.8**
Mean Event Export (P-free)	**N=41**	**N=28**	**N=34**	**N=24**
(g/ha)	3.4 ± **0.08**	12.6 ± **4.1**	1.4 ± **0.5**	5.9 ± **1.9**
(g/ha/cm runoff)	35.9 ± **7.9**	18.7 ± **2.3**	12.5 ± **3.8**	7.9 ± **1.9**
Mean Paired Event Difference	**N=35**	**N=25**	**N=30**	**N=25**
(g/ha)	0	12.6 ± **8.7**	0	12.4 ± **5.7**
(g/ha/cm runoff)	0	5.2 ± **3.8** ***(P-free sites lower)***	0	8.1 ± **3.5** ***(P-free sites lower)***
% Annual Reduction*	**12-16%**		**24-34%**	

***Based upon 2001-2003 daily rainfall record for St. Louis Park, MN, and observed rainfall vs. export relationship from monitored watersheds with and without phosphorus fertilizer use.**

The mean phosphorus export for all monitored rainfall events from 2001 to 2003 was 30.5 g/ha/cm from the Maple Grove (phosphorus fertilizer used) sites and 25.5 g/ha/cm from the Plymouth sites (phosphorus-free fertilizer used). As stated earlier, the Minnesota Phosphorus Lawn Fertilizer Law was adopted in 2004 and restricted the use of phosphorus fertilizer in Maple Grove as well as Plymouth. The mean phosphorus export from Maple Grove sites decreased from 30.5 g/ha/cm to 24.9 g/ha/cm (p=0.172) in 2005 and 2006 following adoption of the statewide phosphorus fertilizer restriction. Phosphorus export from the Plymouth sites remained relatively constant between the two periods: 25.5 and 26.4 g/ha/cm in 2001 to 2003 and 2005 to 2006, respectively.

4. Discussion

The data collected from the paired-watershed study showed a significant reduction in the phosphorus export resulting from implementation of a phosphorus lawn fertilizer restriction in the city of Plymouth, MN. Determination of the magnitude of the difference was complicated by a number of factors. Initial calculations showed that the Plymouth sub-watersheds (treatment sites) exported approximately 25 to 30 percent less phosphorus compared to the Maple Grove sub-watersheds (control sites). However, some of that difference resulted from the higher areal runoff volume at the Maple Grove sites, presumably because of the greater percent impervious surface area in the sub-watersheds. Both the SLAMM and P8 Models estimated a higher rainfall runoff volume for the Maple Grove sites because of the impervious surface area difference. To determine the portion of the phosphorus export difference that could be attributed to the phosphorus fertilizer restriction, the export per unit area per rainfall volume was calculated. This calculation showed a reduction of 12 to 15 percent from the Plymouth (phosphorus-free fertilizer) sites compared to the Maple Grove sites and is believed to more accurately reflect the effectiveness of the phosphorus fertilizer restriction.

The second complicating factor was the similarity in the mean phosphorus concentration between the treatment and control sites utilizing pooled data for all rainfall events. The difference in the calculated phosphorus export rates (g/ha/cm) between the treatment sites (Plymouth) and the control sites (Maple Grove) were minimal using the pooled data. However, it was recognized that phosphorus concentrations in runoff from impervious surfaces would not be affected by the phosphorus lawn fertilizer restriction, and phosphorus export from impervious surfaces would be similar between the treatment and control sites. The data shown in Table 5 confirmed this assumption. Determination of differences in phosphorus export attributable to the phosphorus lawn fertilizer restriction required estimating runoff from turf areas.

Because the runoff volume (m3/ha) increased substantially for rainfall events >2cm at all six sites, it was assumed that runoff from pervious surfaces (lawns) occurred at 2cm of rainfall. Therefore, phosphorus export rates were calculated for rainfall events greater and less than 2cm. As shown in Table 5, there was no difference between the control and treatment sites for events <2cm, but a significant difference in the phosphorus export rate for events >2cm. To estimate the effect of the lawn fertilizer restriction on annual phosphorus export, the reported difference shown in Table 5 was multiplied by the annual runoff volume from rain events >2m.

The final factor affecting the magnitude of the difference in phosphorus export rates between the two municipalities was the excessive runoff volume measured at the MG3 sub-watershed. As noted earlier, baseflow from this sub-watershed averaged approximately 3000 m3/day during the study period, presumably as a result of basement sump pumps and groundwater seepage discharging into the storm sewer system. When the flow data from this sub-watershed were included in the calculations, a difference of over 50% in the phosphorus export rate between Plymouth and Maple Grove was determined. Since this difference was believed to be a function of groundwater flow not affected by fertilizer use, data from the MG3 site was excluded from the final phosphorus export calculations.

It should also be noted that the long term effectiveness of a phosphorus lawn fertilizer restriction may be greater than the 12 to 15 percent shown in Table 5. As indicated by the homeowner survey, approximately 25% of Plymouth (treatment sites) continued to use fertilizer containing phosphorus after implementation of the restriction in 1999, and approximately 25% of Maple Grove homeowners used phosphorus-free fertilizer. By 2001, phosphorus-free fertilizer was available in a few of the retail outlets in Maple Grove, and some homeowners were obviously purchasing it. The study results, therefore, represent phosphorus export reductions from a 50% reduction in the use of phosphorus containing fertilizer. Presumably, the reduction would be greater if 100% compliance with the restriction could be achieved.

The data showed a significantly higher mean TSS concentration in runoff from the Plymouth sites than the Maple Grove sites. This was unexpected since the SRP concentration in Plymouth samples was significantly higher than in the Maple Grove sites, and high phosphorus concentrations in runoff water are typically correlated with high suspended solids concentrations. For this study, there was actually an inverse relationship between soluble reactive phosphorus and suspended solids concentrations. A similar relationship was observed in a previous study (Barten and Jahnke, 1997). Some horticulturists have expressed concerns that phosphorus fertilizer restrictions could result in reduced turf vigor and increased soil wash-off from lawns. This could ultimately increase the phosphorus export from turf areas. However, data collected in this and the referenced previous study found that increased suspended solids loss did not increase the phosphorus loss from residential area.

It should also be noted that a portion of observed difference in the TSS load between Plymouth and Maple Grove could be a result of street sweeping practices in the respective communities in 2001 to 2003. According to information provided by the Public Works Departments in the two communities, street sweeping in Maple Grove occurred three to four times each year, including during fall leaf drop. Street sweeping in Plymouth occurred only in early spring to remove sand spread for snow and ice control. No sweeping during fall leaf drop occurred.

5. Conclusions

The data collected by this study strongly suggest that restricting the use of phosphorus lawn fertilizer reduces the export of phosphorus from urban residential developments by 12 to 15 percent. The reduction in phosphorus export appears to be mainly attributable to reductions in the concentration of soluble phosphorus. Typical stormwater BMPs do not tend to reduce SRP concentrations. Thus, this BMP appears to be a new tool for municipalities and watershed management organizations to help achieve SWPP and non-degradation objectives. The observed phosphorus export reduction is financially significant because typical storm water BMP construction costs approach $500/pound of phosphorus removed. The cost of implementing fertilizer restrictions in Plymouth was negligible. The study results show that restricting the use of phosphorus lawn fertilizers can be an effective and financially sound best management practice for areas with substantial residential development.

Appendix A: Case Studies

10. Lawn care impacts on phosphorus loading

Provided by Brian Vlach (bvlach@threeriversparkdistrict.org) and John Barten (jbarten@threeriversparkdistrict.org) at Three Rivers Park District

CASE STUDY #10: LAWN CARE IMPACTS ON PHOSPHORUS LOAD

Contributing Authors: Brian Vlach (bvlach@threeriversparkdistrict.org) and John Barten (jbarten@threeriversparkdistrict.org) at Three Rivers Park District

1. Introduction

Grass clippings from residential lawns have frequently been cited as a significant source of nutrients and organic matter that are transported to receiving waters from residential developments. Anecdotal evidence suggests that many residential homeowners blow grass clippings into city streets during normal lawn mowing operations. However, data showing the magnitude of this source of loading to receiving waters is lacking. From 2002 to 2006, the frequency, quantity and nutrient content of grass clippings blown into streets during mowing operations in six typical residential neighborhoods in Plymouth and Maple Grove, Minnesota, was measured.

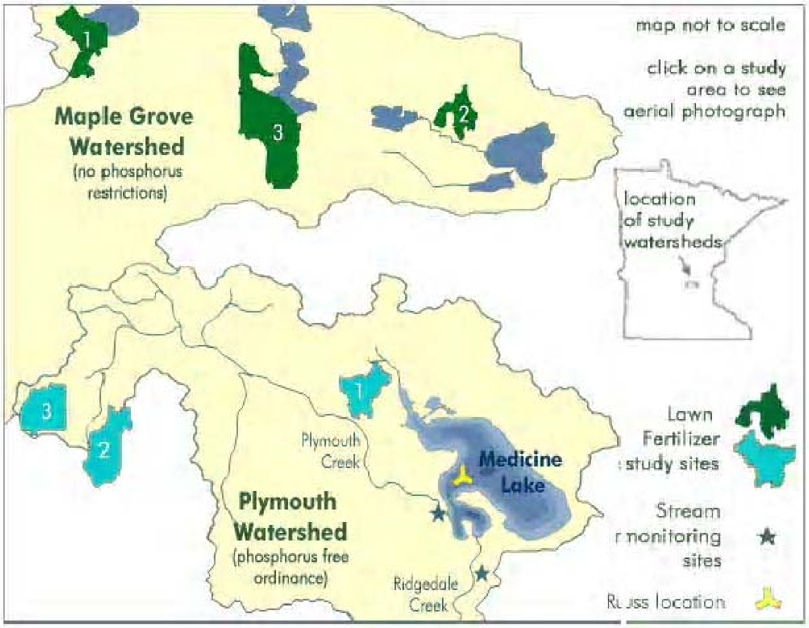


Figure 1: Map showing the relative location of the study sub-watersheds in Plymouth (south) and Maple Grove (north), MN.

2. Methods

Six residential neighborhoods comprising 327 residential lots with houses were selected for the grass clipping monitoring study (Figure 1). The neighborhood size and number of housing units in each study area are shown on Table 1. The curb length along each lot was determined from the legal property description. The presence or absence of grass clippings in the street adjacent to each residential lot was recorded during each site inspection. The location of each lot with grass clippings blown into the street was recorded with a Global Positioning System (GPS) unit. The majority of site visits were scheduled randomly among the five days of the week. However, because mowing operations frequently occurred on weekends, Monday site visits were scheduled periodically throughout the mowing seasons to ensure adequate observations following known mowing events. Periodically, three site inspections were scheduled during a one week period when frequent mowing was observed due to rainy weather and rapid turf growth.

Table 1. Selected parameters of residential neighborhoods in Plymouth and Maple Grove, MN.

Sample Site	Size (Ha)	Number of Lots	Curb Length (m)
P1	5.1	46	1231.2
P2	6.8	47	1818.9
P3	5.6	40	1148.3
MG1	5.5	50	1666.5
MG2	3.5	36	1095.3
MG3	16	108	4106.7

Observed grass clippings were given a density rating from 1 to 3 based on the following criteria:

1. Only a few grass clippings visible on the street
2. Clippings covering approximately 50% of street surface along curb.
3. Clippings very dense, covering nearly 100 % of street along curb.

Grass clippings were collected from the street along ten percent of residential lots with visible clippings present. Clippings from a one square meter area were collected by sweeping all material into a sample container. The curb length associated with the sampled area was measured and recorded. The clippings were washed in the laboratory to remove street dirt, leaves, and other debris. The cleaned grass clippings were oven dried to 105° C and weighed to determine grass clipping mass. Samples were then digested and the phosphorus concentration per unit mass determined. The grass clipping mass and associated phosphorus mass per curb mile was then determined by multiplying the measured mass by the associated rating factor for each site with clippings present. .

3. Results

During the course of the study, each of the 327 lots was inspected on 32 occasions from June through September, for a total of 10,464 site observations. Multiple site visits during a given week were completed on five occasions during the study, and on three occasions, three site visits were completed in a seven day period.

Grass clippings were present in the street adjacent to some lots during every site visit. A total of 978 positive observations (9.4%) were recorded during the study period. The number of sites (residential lots) with grass clippings present during each site visit averaged 30.6 (9.4 %), and ranged from a low of 9 (2.8 %) on 24 August 2005 to a high of 92 (28.1%) on 23 June 2006. The lowest number of positive observations occurred during the second of two visits in a single week. When multiple site visits occurred during a week, only fresh clippings were recorded. Old clippings that had been observed at the previous site visit were not recorded. No sites had two instances of positive observations during any of the five or seven day multiple site visit periods. Although the timing of mowing operations relative to each site visit was not determined, visual observations of turf condition indicated that mowing operations typically occurred weekly. Because over 50% of homeowners in the study areas irrigated their turf, mowing operations occurred regularly throughout the May to September period.

The curb length along each site (residential lot) averaged 24.2 m (79.4) feet, with a range of 16.2 to 67.1 meters (53 to 220 feet). The longest curb length/lot occurred along corner lots, of which there were 35 in the study neighborhoods. During site inspections, each side of a corner lot was considered a separate curb section. The curb length of each side of corner lots averaged 25.1 m (82.4 feet). The shortest curb lengths were on the inside of cul-de-sac curves.

Of the 327 residential lots inspected during the study, 36.2% (119) had no instances where clippings were present along the curb (Table 2). An additional 14.3% (47 lots) had only one instance when clippings were present during 32 site visits. Conversely, 15.9% (52 lots), had clippings present on five or more occasions, and were responsible for 47.5% of positive observations. The maximum number of positive observations at any given lot was nine,

Table 2. Number and percent of lots where grass clippings were present in the street in Maple Grove and Plymouth, MN in 2002, 2003, 2005 and 2006 during 32 site visits.

Frequency Clippings Observed	Number of Lots	Percent of Lots
0	119	36.2
1	47	14.3
2	41	12.5
3	36	10.9
4	33	10
5	19	5.8
6	16	4.9
7	8	2.4
8	3	0.9
9	7	2.1

There was no significant difference in the percent of lots in Plymouth (39%) and Maple Grove (34%) where clippings were never observed. Approximately half of all lots in the two communities, 49.9 % and 51.2% in Maple Grove and Plymouth respectively, had one or no recorded instances of clippings present in the street. Residential lots where clippings were absent during all 32 site visits were relatively equally distributed among the six neighborhoods (Table 3). Plymouth neighborhoods P2 and P3 included six of the seven lots where grass clippings were observed on 9 occasions.

Table 3. Observed grass clippings frequency in six neighborhoods in Plymouth and Maple Grove, MN 2003 to 2006.

Frequency	Percent of Lots					
Clippings Observed/Lot	MG1	MG2	MG3	P1	P2	P3
0	49	28	30	53	36	35
1	16	28	12	14	13	11
2	2	11	13	19	19	14
3	10	6	16	7	6	16
4	4	11	15	7	11	8
5	10	8	2	0	9	5
6	6	3	10	0	0	3
7	4	5	2	7	2	8
8	0	0	0	0	2	3
9	0	0	1	0	6	5

Of the 978 positive observations recorded during the study, 351 (36%) had a density rating of 1; 418 (43%) had a density rating of 2; and 209 (21%) had a density rating of 3 (Table 4). The frequency with which clippings were observed on a given lot did not affect the rating category. Thirty percent of lots with only one positive observation had a density rating of 1, and 34% of observations at lots with 6 or more positive observations had a density rating of 1. There was no discernable relationship between the mass of grass clippings on the streets, as estimated by the assigned density ranking, and the time of year, weather patterns, day of the week, or timing of site visit (Table 5). None of these factors had a statistical effect on the ratio of density rankings.

As indicated above, grass clippings were collected from a square meter area and weighed to determine the mass of clippings in the street. The curb length associated with a square meter sample area varied widely, ranging from one meter to 15 cm, with an average of 49 cm, depending on how far clippings were blown into the street. As indicated by the curb length associated with collected samples, clippings at most sites were blown more than a meter into the street. Typically, sites with a Density Rating of 3 had clippings blown farther into the street than sites with a Density Rating of 1.

The average weight of 79 grass clipping samples collected during the study was 7.37 g/m of curb. Twice as many clippings in Density Rating Category 2 and 3 were collected than in Category 1. The average weight of clippings in each rating category is shown in Table 4. There was a significant difference between the weight of clippings assigned a density rating of 3 and the weight of density rating 1 and 2. Differentiation between Density Rating Category 1 and 2, however, was less clear, and some overlap in the weights occurred. This may have been a result of the limited number of Category 1 samples collected.

Table 4. Number of observations and weight of grass clippings for each density rating category (g/m of curb) measured in Plymouth and Maple Grove samples in 2002, 2003 and 2005.

Density Rating	# of observations	Clippings weight (g/m)	# of Samples
1	351	1.95 ± 0.396	15
2	418	3.56 ± 0.44	31
3	209	13.42 ± 1.27	33

The total grass clipping mass accumulation on streets for each site visit was estimated with the following equation:

Total Clippings (g) = ∑(# positive observation/rating factor × weight/rating factor (g/m) × average curb length/lot (m)).

The estimated mass of grass clippings in the street observed during individual site visits averaged 1.2 kg, and ranged from a low of 0.4 kg to a maximum of 4.3 kg (Table 5). Weekly grass clipping mass accumulation was estimated from the intervals when three site visits occurred in a seven day time period: 6 July to 11 July 2005, 29 July to 4 August 2005, and 10 August to 15 August 2005. The grass clipping mass during these three weeks totaled 4.1 kg, 3.2 kg and 3.7 kg respectively.

The weight of phosphorus per kilogram of grass clippings in 36 samples averaged 2.85 g (0.29%), and ranged from 1.57 g to 5.65g or 0.16% to 0.57% respectively (Table 6). Grass clippings samples were collected from all six study neighborhoods, and tended to have a similar percent of phosphorus in the grass tissue. Replication of results for Density Rating Category #1 was difficult because of the lack of adequate sample mass. The high and low values for the percent phosphorus in the grass tissue were both derived from Density Rating Category 1 samples. Results from Rating Category 2 and 3 samples tended to be more consistent because of the greater sample mass available for analysis.

Table 5. Grass clippings frequency of observations/Rating Category, total mass (kg), and phosphorus mass (g) for 32 site inspections at 327 residential lots in Plymouth and Maple Grove, MN.

Date	Rating 1	Rating 2	Rating 3	Clippings Mass (kg)	TP Mass (g)
7/19/2002	16	2	0	0.8	2.5
7/22/2002	17	9	2	1.3	3.8
8/2/2002	6	8	3	0.8	2.3
8/14/2002	15	18	2	1.7	4.8
8/26/2002	18	38	11	3.2	9.2
6/18/2003	0	10	7	0.8	2.3
7/1/2003	9	14	7	1.4	4.1
7/9/2003	10	22	20	2.5	7.1
8/15/2003	27	41	22	4.2	12.3
6/18/2003	9	5	2	0.8	2.2
6/17/2005	2	4	4	0.5	1.4
6/23/2005	4	4	1	0.4	1.2
6/30/2005	5	12	5	1.0	3.0
7/6/2005	17	13	10	1.9	5.5
7/8/2005	9	10	11	1.4	4.1
7/11/2005	6	8	3	0.8	2.3
7/21/2005	2	6	4	0.6	1.6
7/29/2005	10	14	16	1.9	5.5
8/1/2005	4	8	5	0.8	2.3
8/4/2005	1	5	4	0.5	1.4
8/10/2005	2	5	7	0.7	1.9
8/12/2005	10	9	7	1.2	3.6
8/15/2005	15	12	12	1.8	5.3
8/22/2005	11	11	4	1.2	3.6
8/24/2005	4	2	3	0.4	1.2
9/2/2005	4	6	6	0.8	2.2
9/14/2005	9	8	12	1.4	4.0
9/16/2004	3	13	6	1.0	3.0
9/23/2005	1	6	3	0.5	1.4
6/23/2006	52	36	4	4.3	12.6
6/30/2006	38	48	5	4.3	12.5
7/7/2006	15	11	1	1.3	3.7

Table 6. Mass (g) of phosphorus per mass of grass clippings (kg) collected from residential streets in Plymouth and Maple Grove, MN in 2005.

	g TP/kg (dry weight) clippings					
Date	**P1**	**P2**	**P3**	**MG1**	**MG2**	**MG3**
6/17/2005	2.78	2.48	3.22			
6/17/2005	2.49	3.38	3.42			
6/17/2005	5.65	2.99	3.48			
6/17/2005	2.81	2.45				
6/23/2005			3.61	2.37		2.91
6/23/2005			3.98	2.4		2.93
6/23/2005				2.56		3.17
7/8/2005					1.57	
7/8/2005					1.75	
7/8/2005					1.94	
7/23/2005		1.97				
7/23/2005		2.37				
7/29/2005			2.5	2.81	4.41	2.46
7/29/2005			2.47	2.99	4.08	2.44
8/10/2005						2.88
8/10/2005						2.56
8/12/2005	2.24					
8/12/2005	2.25					

Total phosphorus mass accumulation on the streets during each site visit was estimated as the product of the grass clipping mass multiplied by the average percent total phosphorus in the clippings (0.29%). The phosphorus mass averaged 4.2 g per site visit with a minimum of 1.2 g and a maximum of 12.6 g. On an aerial loading basis, this amounted to an average of 0.1 g/ha of phosphorus per site visit, assuming that all clippings wash off of the street during rainfall events.

4. Discussion

The study results indicate that a minority of property owners (16%) were responsible for approximately half (48%) of the grass clippings observed on municipal streets in residential areas of Minnesota. These property owners showed a persistent propensity to blow grass clippings onto the street during mowing operations. Conversely, over half of homeowners had one or no instances when clippings were observed on the street. It appears that these infrequent incidents of improper mowing operations were isolated events, and these homeowners typically do not blow clippings onto streets.

Careless mowing patterns tended to occur along individual blocks of the study neighborhoods. For instance, in the Maple Grove 1 (MG1) neighborhood, lots 1 through

5, which are directly adjacent to each other, all had multiple instances of observed clippings while lots 17 to 23 had either one or no positive observations. It appears that neighbor expectations may guide behavior to some degree. Targeted education campaigns in these areas could reduce the incidence of improper mowing.

Lawns in Minnesota are typically dominated by cool season grass species. It was anticipated, therefore, that the frequency of grass clippings observed on streets, and the density of clippings would decrease during the hot, dry late July and August time period when turf growth slowed. However, neither the frequency of positive observations nor the clippings density appeared to decrease during July and August. The majority of homeowners water their turf routinely, and grass growth appeared to be relatively uniform throughout the growing season. A previous study completed by Three Rivers Park District staff documented lawn watering by over half of homeowners in the Maple Grove and Plymouth area.

One objective of the study was to estimate the annual phosphorus loading from grass clippings blown onto municipal streets and potentially carried into receiving waters with rainfall runoff water. The phosphorus loading associated with improper mowing operations was estimated in two ways:

- The total mass of grass clippings estimated from the instances when three site inspections were performed in a seven day time period was used as the weekly average for the growing season. The phosphorus associated with the weekly average clippings mass (3.67 kg grass clipping/week from Table 5) was multiplied by the weeks of the mowing season (25 weeks) to estimate the annual phosphorus load.

- The average phosphorus loading for each site visit from Table 5 was assumed to be the daily average during the mowing season. This quantity was multiplied by the number of days (175) in the average turf mowing season.

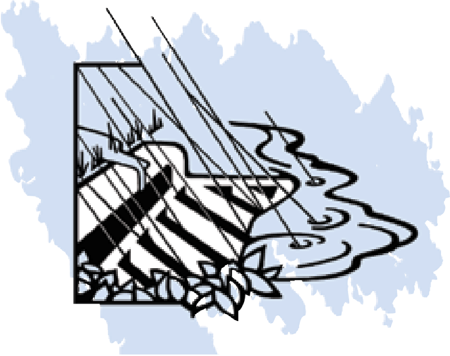
For both estimates, it was assumed that all clippings blown onto streets were washed off into the stormwater system. Using the weekly grass clippings mass, the estimated annual phosphorus loading was calculated to be 0.26 kg, or 0.006 kg/ha. Assuming that the average site visit grass clippings mass was deposited on the streets daily throughout the mowing season, the calculated annual phosphorus load from grass clippings was 0.73 kg or 0.017 kg/ha. These estimates likely represent the minimum and maximum loading rates from grass clippings.

Typical phosphorus exports rates from urban residential areas range from 0.56 to 0.9 kg/ha annually (Brach, *Protecting Water Quality in Urban Area*; Corsi, Graczyk, Ownes and Bannerman, *Unit-Area Loads of Suspended Sediment, Suspended Solids, and Total Phosphorus From Small Watersheds in Wisconsin*). The loading associated with grass clippings therefore represents between 1 and 3 percent of the estimated annual load.

Although the phosphorus export from grass clippings blown into residential streets from improper turf mowing practices appears to be minimal, it is nevertheless a source easily addressed. Educational programs targeting neighborhood areas where grass clippings are frequently observed on streets could reduce phosphorus export for minimal cost.

5. Conclusions

A four year study of two suburban municipalities in Minnesota found that approximately half of 327 homeowners routinely blow grass clippings into residential streets during mowing operations. The mass of clippings measured on the streets averaged 1.2 kg during 32 site visits. The grass clipping mass had an average of 4.2 g of associated phosphorus mass. This amounted to approximately 1 to 3 percent of the estimated annual phosphorus export from typical urban residential areas. Educational programs targeted at neighborhoods where clippings are frequently observed could reduce loading from this source.



B1.

Appendix B part one: filtration practices

Procedures for the Visual Inspection of Stormwater Best Management Practices

Visual inspection is a rapid assessment procedure for qualitatively evaluating the functionality of a stormwater best management practice (BMP). Visual inspections use a set of criteria that, under certain circumstances (described in chapter 3), determine if the stormwater BMP is malfunctioning. Procedures and checklists for visual inspection are provided at the end of chapters 8–11 and are reproduced here.

Gulliver, J.S. and J.L. Anderson, ed. 2007. *Assessment of Stormwater Best Management Practices.* St Paul, MN: University of Minnesota.

UNIVERSITY OF MINNESOTA
Stormwater Management Practice Assessment Project

Standard Procedure for Level 1 Assessment: Visual Inspection

Filtration Practices (including soil and sand media filters)

1. Certified Reference:

1.1. None.

2. Application:

2.1. This method is applicable to sand and soil filters as defined in Chapter 8, Filtration Practices.

3. Summary of Method:

3.1. This standard protocol is used as a basis for the visual inspection of sand and soil filters. The questions in section 8.4 below are answered from visual observations of the site and documented with a photographic or video-graphic camera.

4. Interferences:

4.1. Visual inspection requires adequate weather conditions. Fog or other visually limiting weather condition can result in an inaccurate or incomplete visual inspection. Such weather conditions should be avoided whenever possible.

5. Apparatus:

5.1. Camera (digital or film, video or photographic)

6. Materials:

6.1. Field Data Sheet (i.e., this document).

7. Safety:

7.1. This procedure requires field inspection of the site and photographic or video graphic documentation. Caution and appropriate use of safety equipment and traffic controls should be used when walking around and in stormwater BMPs to avoid personal injury.

8. Procedure:

8.1. Print out this Standard Protocol for the visual inspection of sand and soil filters.
8.2. Obtain apparatuses and materials as outlined in sections 5 and 6 above.
8.3. Travel to the sand or soil filter that will be assessed by visual inspection.
8.4. Fill out the attached Field Data Sheet (see below).

9. Calculations:

9.1. None required. See Chapter 12.

10. Quality Control:

10.1. Photographic documentation for the questions answered above (section 8.4) must be provided with this protocol.

11. Additional References:

11.1. None

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Field Data Sheet for Level 1 Assessment: Visual Inspection

Filtration Practices

Inspector's Name (s): ______________________________________
Date of Inspection: ____
Location of the filtration practice
Address or Intersection: ___________________________________
Latitude, Longitude: _______________________________________
Date the filtration practice began operation: _______________________
Filter size (ft x ft):____
Time since last rainfall (hr): __________________________________
Quantity of last rainfall (in): __________________________________
Rainfall Measurement Location: ______________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ____

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Does this filtration practice utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don't know

3.a) If yes, please describe: ____

____

____

____

4) Are there multiple inlet structures?

☐ Yes ☐ No

4.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

4.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

4.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

5) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

5.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don't know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

6) Is there standing water in the filtration practice?

☐ Yes ☐ No

6.a) If yes, does the water have:

☐ Surface sheen (from oils/gasoline)
☐ Murky color (from suspended solids)
☐ Green color (from algae or other biological activity)
☐ Other: ____

7) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

7.a) If yes, please describe: ____

____
____
____

8) Is there vegetation in the bottom of the filtration practice?

☐ Yes ☐ No

8.a) What is the approximate vegetation cover?

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

9) Are there indications of any of the following in the bottom of the filtration practice?

☐ Sediment deposition
☐ Erosion or channelization
☐ Excessive vegetation (that needs mowing or removal)
☐ Litter, large debris, solid waste
☐ Other: ____
☐ No

9.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

10) Are there indications of any of the following on the banks of the filtration practice?

☐ Erosion or channelization

☐ Other: ____

☐ No

11) Is the bottom of the filtration practice covered with a layer of silts, clays, or both?

☐ Yes ☐ No

12) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

12.a) If yes, what with?

☐ Debris

☐ Sediment

☐ Vegetation

☐ Other: ____

13) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

13.a) If yes, why?

☐ I don't know

☐ Ice/Frost heave

☐ Other: ____

14) Is there evidence of any of the following downstream of the outlet structure?

☐ Sediment deposition

☐ Erosion, Channelization

☐ Other: ____

☐ No

14.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

Other observations:

____
____
____
____
____

Inspector's Recommendations:

15) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

____
____
____
____
____

Maintenance Recommendations:

____
____
____
____
____

Troubleshooting Failure: Visual Inspection

Filtration Practices

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many filtration practices are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessing a filtration practice within 48 hours of a rainfall event may provide additional assessment clues than assessment during a long dry period. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Does this filtration practice utilize any pretreatment practices upstream?

If any pretreatment practices exist they should also be inspected and maintained on a regular basis.

4) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the filtration practice. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the filtration practice.

5) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a filtration practice by means other than those intended by design or prevent stormwater runoff from entering the filtration practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

6) Is there standing water in the filtration practice?

Standing water in a filtration practice is the result of one of three possibilities: (1) rainfall has occurred recently such that stormwater runoff has not had 48 hours to pass through the filter, (2) the filtration rate of the practice is slow such that stormwater runoff does not pass through the filter within 48 hours, but does pass through the filter given enough time, or (3) the filter is clogged and does not filter any stormwater runoff. If it has rained in the last 48 hours (question 2), then the filtration practice may be functioning properly and requires additional assessment (level 2 or higher). If, however, it has not rained in the last 48 hours, it is likely that the filtration practice is either option (2) or (3).

Question 3a provides clues that may determine whether the filtration practice is clogged. Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven not to be illegally discharged into the filtration practice, then a surface sheen may indicate that stormwater runoff is stored in the filtration practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. If this is happening, then the filtration practice is failing. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a high suspended solids concentration that is most likely made up of fine particle sizes such as clays and silts because sand particles settle out of standing water rapidly (as discussed in Chapter 10, Sedimentation). Stormwater runoff with a murky color further indicates that the watershed may be a significant source of fine particle suspended solids, which can clog a filtration practice.

Stormwater runoff with a green color from algae has been stored in the filtration practice for a long period of time such that microorganisms have developed. The filtration practice is not filtering stormwater runoff and is therefore failing.

7) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

8) Is there vegetation in the bottom of the filtration practice?

Vegetation in the bottom of filtration practice can reduce its effectiveness. Plants lose approximately 30% of their root structures annually, which produces macropores. Macropores in a filtration practice often result in short circuiting of stormwater runoff and low sediment removal efficiency. Vegetation does, however, reduce overland flow velocities and can therefore reduce erosion and resuspension of captured solids. It can also maintain or increase filtration rates, because of the macropores, while reducing the effectiveness of filtration. There are both positives and negatives to deep-rooted vegetation in the bottom of the filtration practice. The positives, in general, outweigh the negatives because it is important to maintain filtration capacity.

9) Are there indications of any of the following in the bottom of the filtration practice?

Sediment deposition may indicate that pretreatment devices have reached sediment storage capacity, are not efficiently removing settable solids, or are not present. Sediment deposition may also indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution. Sediment deposition limits the filtration practice surface area available for filtration and therefore can reduce the rate at which stormwater runoff volume is treated.

Erosion or channelization indicates that flow velocities entering, or in, the filtration practice are large or that stormwater runoff is entering the filtration practice by means other than those intended by design. Erosion and channelization can reduce filtration media depth and therefore reduce the practice's effectiveness.

Excessive vegetation, especially with deep roots, can cause short circuiting or damage the subsurface collection system in a filtration practice. If the surface of the filtration practice becomes clogged or sealed, shallow root vegetation can provide pathways for stormwater runoff to reach the filter media below the surface for treatment. Vegetation in filtration practices should be controlled such that deep root vegetation does not damage the collection system or allow stormwater to short-circuit through the practice.

Litter, large debris, and solid waste in a filtration practice are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of filtration practices by reducing the surface available for filtering stormwater runoff.

10) Are there indications of any of the following on the banks of the filtration practice?

Erosion or channelization on the banks of a filtration practice indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the filtration practice with sediment from the bank and subsequently reduce the practice's effectiveness by clogging the media and reducing the volume available for stormwater storage.

11) Is the bottom of the filtration practice covered with a layer of silts, clays, or both?

A visible layer of silts, clays, or both is an indication that the filter media may be clogged. Filtration practices collect particles in the pore spaces of the media. If silts, clays, or both are present on the surface of the filter, the pore spaces within the filter media may be full. Additionally, silts, clays, or both present on the surface of the filter indicates that stormwater runoff is stored in the filtration practice long enough for these fine particles to settle out or for the stored stormwater runoff to evaporate and infiltrate into the surrounding soils.

12) Is the outlet structure clogged?

Like an inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the filtration practice. If the outlet structure is partially or completely clogged, the filtration rate may be limited and stormwater runoff may not pass through the filtration practice in less than 48 hours, as recommended by design (Minnesota Stormwater Steering Committee 2005). Any obstructions should be removed immediately to ensure proper operation of the filtration practice.

13) Is the outlet structure askew or misaligned?

Misaligned outlet structures often allow stormwater runoff to enter or exit a filtration practice by means other than those intended by design or prevent stormwater runoff from entering the filtration practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Outlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact.

14) Is there evidence of any of the following downstream of the outlet structure?

Conditions downstream of a filtration practice can provide evidence of the function of the practice itself. Properly designed and functioning filtration practices remove a large percentage of suspended solids from stormwater runoff. Sediment deposition downstream of a filtration practice indicates that erosion is occurring between the filtration practice and the sediment deposition or that sediments are present in the filtration practice effluent. If sediments are present in the effluent such that downstream deposition is occurring, the geotextile fabric or the subsurface collection system is likely failing. The filtration practice could require complete replacement to repair this problem.

Erosion downstream of a filtration practice indicates that flow velocities are larger than the conveyance channel can withstand. Stormwater runoff filters slowly through filtration practices and therefore downstream erosion is usually only a problem for large filtration practices that treat large volumes of stormwater runoff. Downstream erosion can be mitigated by reconstructing the conveyance such that erosion does not occur (i.e., riprap, concrete), or energy dissipaters should be installed to reduce the flow velocities (i.e., check dams).

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

B2.

Appendix B part two: infiltration practices

Procedures for the Visual Inspection of Stormwater Best Management Practices

Visual inspection is a rapid assessment procedure for qualitatively evaluating the functionality of a stormwater best management practice (BMP). Visual inspections use a set of criteria that, under certain circumstances (described in chapter 3), determine if the stormwater BMP is malfunctioning. Procedures and checklists for visual inspection are provided at the end of chapters 8–11 and are reproduced here.

Gulliver, J.S. and J.L. Anderson, ed. 2007. *Assessment of Stormwater Best Management Practices.* St Paul, MN: University of Minnesota.

University of Minnesota
Stormwater Management Practice Assessment Project

Standard Procedure for Level 1 Assessment: Visual Inspection

Infiltration Practices (including infiltration basins, infiltration trenches, and porous pavements)

1. Certified Reference:

1.1. None.

2. Application:

2.1. This method is applicable to infiltration practices as defined in Chapter 9.

3. Summary of Method:

3.1. This standard protocol is used as a basis for the visual inspection of an infiltration practice. The questions in section 8.4 below are answered from visual observations of the site and documented with a photographic or video-graphic camera.

4. Interferences:

4.1. Visual inspection requires adequate weather conditions. Fog or other visually limiting weather condition can result in an inaccurate or incomplete visual inspection. Such weather conditions should be avoided whenever possible.

5. Apparatus:

5.1. Camera (digital or film, video or photographic)

6. Materials:

6.1. Field Data Sheet (see attached).

7. Safety:

7.1. This procedure requires field inspection of the site and photographic or video graphic documentation. Caution and appropriate use of safety equipment and traffic controls should be used when walking around and in stormwater BMPs to avoid personal injury.

8. Procedure:

8.1. Print out this Standard Protocol for the visual inspection of infiltration practices.
8.2. Obtain apparatuses and materials as outlined in sections 5 and 6 above.
8.3. Travel to the infiltration practices that will be assessed by visual inspection.
8.4. Fill out the attached Field Data Sheet (see below).

9. Calculations:

9.1. None required. See Chapter 12.

10. Quality Control:

10.1. Photographic documentation for the questions answered above (section 8.4) must be provided with this protocol.

11. Additional References:

11.1. None

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Field Data Sheet for Level 1 Assessment: Visual Inspection

Infiltration Basins and Trenches

Inspector's Name (s): ____

Date of Inspection: ____

Location of the infiltration practice

Address or Intersection: ____________________________________

Latitude, Longitude: _______________________________________

Date the infiltration practice began operation: _____________________

Size of the infiltration practice (ft x ft):____________________________

Time since last rainfall (hr): ____________________________________

Quantity of last rainfall (in): ________________________________

Rainfall Measurement Location: ________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ___________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Does this infiltration basin or trench utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don't know

3.a) If yes, please describe: ____

____

____

____

4) Are there multiple inlet structures?

☐ Yes ☐ No

4.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

4.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

4.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

5) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

5.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don’t know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

6) Is there standing water in the infiltration basin or trench?

☐ Yes ☐ No

6.a) If yes, does the water have:

☐ Surface sheen (from oils/gasoline)

☐ Murky color (from suspended solids)

☐ Green color from (algae or other biological activity)

☐ Other: ____

☐ No

7) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

7.a) If yes, please describe: ____

____

____

____

8) Does the infiltration basin or trench smell like gasoline or oil?

☐ Yes ☐ No

9) Is there vegetation in the bottom of the infiltration basin or trench?

☐ Yes ☐ No

9.a) What is the approximate vegetation cover?

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

10) Are there indications of any of the following in the bottom of the infiltration basin or trench?

☐ Sediment deposition

☐ Erosion or channelization

☐ Excessive vegetation (that needs mowing or removal)

☐ Litter, large debris, solid waste

☐ Other: ____

☐ No

10.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

11) Are there indications of any of the following on the banks of the infiltration basin?

☐ Erosion or channelization

☐ Other: ____

☐ No

12) Is the bottom of the infiltration basin or trench covered with a layer of silts, clays, or both?

☐ Yes ☐ No

13) Is the overflow structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

13.a) If yes, what with?

☐ Debris

☐ Sediment

☐ Vegetation

☐ Other: ____

14) Is the overflow structure askew or misaligned?

☐ Yes ☐ No

14.a) If yes, why?

☐ I don't know

☐ Ice/Frost heave

☐ Other: ____

Other observations:

____

____

____

____

____

Inspector's Recommendations:

15) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

____

____

____

____

____

Maintenance Recommendations:

____

____

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____

____

Troubleshooting Failure: Visual Inspection

Infiltration Basins and Trenches

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many infiltration practices are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessing a infiltration practice within 48 hours of a rainfall event may provide additional assessment clues than assessment during a long dry period. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Does this infiltration basin or trench utilize any pretreatment practices upstream?

If any pretreatment practices exist they should also be inspected and maintained on a regular basis.

4) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the infiltration practice. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system, or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

5) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit an infiltration practice by means other than those intended by design or prevent stormwater runoff from entering the infiltration practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

6) Is there standing water in the infiltration basin or trench?

Standing water in an infiltration practice is the result of one of three possibilities: (1) rainfall has occurred recently such that stormwater runoff has not had 48 hours to infiltrate, (2) the infiltration rate of the practice is slow such that stormwater runoff does not infiltrate within 48 hours, but does infiltrate given enough time, or (3) the infiltration practice is clogged and does not infiltrate any stormwater runoff. If it has rained in the last 48 hours (question 2), then the infiltration practice may be functioning properly and requires additional assessment (level 2 or higher). If, however, it has not rained in the last 48 hours, it is likely that the infiltration practice is either option (2) or (3).

Question 3a provides clues that may determine whether the infiltration practice is clogged. Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven not to be illegally discharged into the infiltration practice, then a surface sheen may indicate that stormwater runoff is stored in the infiltration practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. If this is happening, then the infiltration practice is failing. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a high suspended solids concentration that is most likely made up of fine particle sizes, such as clays and silts, because sand particles settle out of standing water very rapidly (as discussed in Chapter 10: Sedimentation). Stormwater runoff with a murky color further indicates that the watershed may be a significant source of fine particle suspended solids, which can quickly clog an infiltration practice.

Stormwater runoff with a green color from algae or biological activity has been stored in the infiltration practice for a long period of time such that microorganisms have developed. The infiltration practice is not infiltrating stormwater runoff and is therefore failing.

7) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

8) Does the infiltration basin or trench smell like gasoline or oil?

If an infiltration practice smells like gasoline or oil it is possible that hydrocarbon substances such as automotive oil or gasoline are being illicitly discharged into the practice or upstream in the watershed. If hydrocarbons are proven not to be illegally discharged into the infiltration practice, then an oil/gasoline smell may indicate that stormwater runoff is stored in the infiltration practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. For more information on identifying, locating, and eliminating illicit discharges, refer to a manual such as Brown *et al.* (2004).

9) Is there vegetation in the bottom of the infiltration basin or trench?

Vegetation in the bottom of an infiltration basin can increase the infiltration effectiveness. Plants can lose 30% of their root structures annually, which produces macropores. Macropores in a infiltration practice can increase the infiltration rate of the basin or trench so that more stormwater runoff is infiltrated. Additionally, vegetation can reduce overland flow velocities and can therefore reduce erosion and resuspension of captured solids. Infiltration trenches typically have a larger grain size so that vegetation cannot grow without clogging of the pores.

Vegetation can also be an indication of the drain time of an infiltration basin. Terrestrial vegetation often cannot withstand long periods of inundation, and some cannot withstand short periods of inundation. If an infiltration practice has an abundance of terrestrial vegetation, it is likely that the practice infiltrates stormwater runoff quickly (< 48 hours) and is therefore operating properly. If, however, the infiltration practice has signs of aquatic vegetation, the practice may not be infiltrating stormwater runoff and is therefore failing.

10) Are there indications of any of the following in the bottom of the infiltration basin or trench?

Sediment deposition may indicate that pretreatment devices have reached sediment storage capacity, are not efficiency removing settable solids, or are not present. Sediment deposition may also indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution. Sediment deposition reduces the surface area available for infiltration and therefore can reduce the stormwater runoff volume that is infiltrated.

Erosion or channelization indicates that the velocity of flow entering, or in, the infiltration practice is large or that stormwater runoff is entering the infiltration practice by means other than those intended by design. Erosion or channelization indicates that the velocity of flow entering, or in, the infiltration practice is large or that stormwater runoff is entering the infiltration practice by means other than those intended by design. In either case, stormwater runoff is not stored such that significant infiltration is occurring in the areas where erosion and channelization are present.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in infiltration basins and trenches. If the surface of the infiltration practice becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils. Vegetation in infiltration practices is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in an infiltration practice are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of infiltration practices by reducing the surface available for infiltrating stormwater runoff.

11) Are there indications of any of the following on the banks of the infiltration basin or trench?

Erosion or channelization on the banks of an infiltration practice indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the practice with sediments from the bank and subsequently reduce effectiveness by clogging the soil or sealing the surface and reducing the volume available for stormwater storage.

12) Is the bottom of the infiltration basin or trench covered with a layer of silts, clays, or both?

A visible layer of silts, clays, or both is a likely indication that the infiltration practice is clogged. Infiltration basins collect particles on the surface and in the pore spaces of the soil. Silts, clays, or both present on the surface of the basin or trench indicates that the pore spaces within the soil are likely filled or that stormwater runoff is stored in the basin or trench long enough for these fine particles to settle out or for the stored stormwater runoff to evaporate. The infiltration practice is not likely infiltrating stormwater runoff in less than 48 hours as recommended by design guidelines (Minnesota Stormwater Steering Committee 2005).

13) Is the overflow structure clogged?

Infiltration basins and trenches typically have overflow structures instead of outlet structures. Outflow for an infiltration practice is intended to go into the soil such that deep percolation or evaporation occurs. The overflow structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the infiltration practice in the event of a large storm event. If the overflow structure is partially or completely clogged, surrounding areas may be flooded by stored stormwater runoff. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

14) Is the overflow structure askew or misaligned?

Misaligned overflow structures often allow stormwater runoff to enter or exit an infiltration practice by means other than those intended by design or prevent stormwater runoff from entering the infiltration practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Overflow structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned overflow structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

UNIVERSITY OF MINNESOTA
Stormwater Management Practice Assessment Project

Field Data Sheet for Level 1 Assessment: Visual Inspection

Porous Pavements

Inspector's Name (s): ____________________________________
Date of Inspection: ______________________________________
Location of the porous pavement
  Address or Intersection: _________________________________
  Latitude, Longitude: ____________________________________
Date the porous pavement began operation: _____________________
Size of the porous pavement (ft x ft):___________________________
Time since last rainfall (hr): _________________________________
Quantity of last rainfall (in): ________________________________
Rainfall Measurement Location: _________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ____

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Is there standing water on top of the porous pavement?

☐ Yes ☐ No

4) Are there indications of any of the following on top of the porous pavement?

☐ Sediment deposition

☐ Erosion or channelization

☐ Litter, large debris, solid waste

☐ Other: ____

☐ No

4.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

Inspector's Recommendations:

5) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

Maintenance Recommendations:

Troubleshooting Failure: Visual Inspection

Porous Pavements

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Porous pavement is designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) immediately (Minnesota Stormwater Steering Committee 2005). Assessing a porous pavement within 48 hours of a rainfall event may provide additional assessment clues than assessment during a long dry period. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Is there standing water on top of the porous pavement?

For any runoff volume that does not exceed the design storm, porous pavement should not have any standing water. Standing water on top of porous pavement is the result of two possibilities: (1) substantial rainfall above design has occurred recently such that the stormwater has not been able to infiltrate, (2) the porous pavement is clogged and does not infiltrate sufficient stormwater.

4) Are there indications of any of the following on top of the porous pavement?

Sediment deposition may indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution. Sediment deposition limits the porous pavement surface area available for infiltration and therefore can reduce the stormwater runoff volume that is infiltrated.

References

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

B3.

Appendix B part three: sedimentation practices

Procedures for the Visual Inspection of Stormwater Best Management Practices

Visual inspection is a rapid assessment procedure for qualitatively evaluating the functionality of a stormwater best management practice (BMP). Visual inspections use a set of criteria that, under certain circumstances (described in chapter 3), determine if the stormwater BMP is malfunctioning. Procedures and checklists for visual inspection are provided at the end of chapters 8–11 and are reproduced here.

Gulliver, J.S. and J.L. Anderson, ed. 2007. *Assessment of Stormwater Best Management Practices.* St Paul, MN: University of Minnesota.

University of Minnesota
Stormwater Management Practice Assessment Project

Standard Procedure for Level 1 Assessment: Visual Inspection

Sedimentation Practices (including Dry Ponds, Wet Ponds, Wet Vaults, and Proprietary Devices)

1. Certified Reference:

1.1. None.

2. Application:

2.1. This method is applicable to sedimentation practices as defined in Chapter 10, Sedimentation Practices.

3. Summary of Method:

3.1. This standard protocol is used as a basis for the visual inspection of sedimentation practices. The questions in section 8.4 below are answered from visual observations of the site and documented with a photographic or video-graphic camera.

4. Interferences:

4.1. Visual inspection requires adequate weather conditions. Fog or other visually limiting weather condition can result in an inaccurate or incomplete visual inspection. Such weather conditions should be avoided whenever possible.

5. Apparatus:

5.1. Camera (digital or film, video or photographic)

6. Materials:

6.1. Field Data Sheet (see attached).

7. Safety:

7.1. This procedure requires field inspection of the site and photographic or video graphic documentation. Caution and appropriate use of safety equipment and traffic controls should be used when walking around and in stormwater BMPs to avoid personal injury.

8. Procedure:

8.1. Print out this Standard Protocol for the visual inspection of sedimentation practices.
8.2. Obtain apparatuses and materials as outlined in sections 5 and 6 above.
8.3. Travel to the sedimentation practice that will be assessed by visual inspection.
8.4. Fill out the attached Field Data Sheet (see below).

9. Calculations:

9.1. None required. See Chapter 12.

10. Quality Control:

10.1. Photographic documentation for the questions answered above (section 8.4) must be provided with this protocol.

11. Additional References:

11.1. None

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Stormwater Management Practice Assessment Project

Field Data Sheet for Level 1 Assessment: Visual Inspection

Dry Ponds

Inspector's Name (s): ____
Date of Inspection: ____
Location of the Pond
    Address or Intersection: ____________________________________
    Latitude, Longitude: _______________________________________
Date the dry pond began operation: ____________________________
Size of the dry pond (ft x ft):____________________________________
Time since last rainfall (hr): ____________________________________
Quantity of last rainfall (in): ___________________________________
Rainfall Measurement Location: ________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ____

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Are there multiple inlet structures?

☐ Yes ☐ No

3.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

3.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

3.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

4) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

4.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don’t know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

5) Is there standing water in the dry pond?

☐ Yes ☐ No

5.a) If yes, does the water have:

☐ Surface sheen (from oils/gasoline)

☐ Murky color (from suspended solids)

☐ Green color (from algae or other biological activity)

☐ Other: ____

☐ No

6) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

6.a) If yes, please describe: ____
____
____
____

7) Are there indications of any of the following in the bottom of the dry pond?

☐ Sediment deposition

☐ Erosion or channelization

☐ Excessive vegetation (that needs mowing or removal)

☐ Litter, large debris, solid waste

☐ Other: ____

☐ No

7.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

8) Are there indications of any of the following on the banks of the dry pond?

☐ Erosion or channelization
☐ Other: ____
☐ No

9) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

9.a) If yes, what with?

☐ Debris
☐ Sediment
☐ Vegetation
☐ Other: ____

10) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

10.a) If yes, why?

☐ I don’t know
☐ Ice/Frost heave
☐ Other: ____

11) Is there evidence of any of the following downstream of the outlet structure:

☐ Sediment deposition

☐ Erosion or channelization

☐ Other: ____

☐ No

11.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

Other observations:

____

____

____

____

____

Inspector's Recommendations:

12) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

____

____

____

____

____

Maintenance Recommendations:

____

____

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____

____

Troubleshooting Failure: Visual Inspection

Dry Ponds

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many dry ponds are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessing a dry pond within 48 hours of a rainfall event may provide additional assessment clues than assessment during a long dry period. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the dry pond. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system, or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the dry pond.

4) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a dry pond by means other than those intended by design or prevent stormwater runoff from entering the dry pond at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the dry pond.

5) Is there standing water in the dry pond?

Standing water in a dry pond is the result of one of three possibilities: (1) rainfall has occurred recently such that stormwater runoff has not had 48 hours to pass through the dry pond, (2) the treatment rate of the dry pond is slow such that stormwater runoff does not pass through the dry pond within 48 hours, but does pass through the dry pond given enough time, or (3) the outlet structure is clogged and does not allow any stormwater runoff to exit the dry pond. If it has rained in the last 48 hours (question 2), then the dry pond may be functioning properly and requires additional assessment (level 2 or higher). If, however, it has not rained in the last 48 hours, it is likely that the dry pond is either option (2) or (3).

Question 3a provides clues that may determine whether the outlet structure of the dry pond is clogged. Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven not to be illegally discharged into the dry pond, then a surface sheen may indicate that stormwater runoff is stored in the dry pond such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. If this is happening, then the dry pond is failing. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a large suspended solids concentration that is most likely made up of fine particle sizes, such as clays and silts, because sand particles settle out of standing water very rapidly (as discussed in Chapter 10, Sedimentation). Stormwater runoff with a murky color can indicate that the watershed is a significant source of fine particle suspended solids, which can quickly clog a dry pond. Murky stormwater runoff in a dry pond may indicate that stormwater runoff has recently entered the dry pond such that fine particles have not had time to settle out.

Stormwater runoff with a green color from algae or biological activity has been stored in the dry pond for a long period of time such that microorganisms have developed. Stormwater runoff is not passing though the dry pond properly and therefore the practice is failing.

6) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

7) Are there indications of any of the following in the bottom of the dry pond?

Sediment deposition may indicate either a significant source of sediment in the watershed that may require remediation to prevent downstream pollution or that the dry pond has not been recently maintained. Sediment deposition reduces the stormwater storage volume of a dry pond and can allow sediments to become resuspended during subsequent storm events.

Erosion or channelization indicates that flow velocities entering, or in, the dry pond are large or that stormwater runoff is entering the dry pond by means other than those intended by design. Erosion and channelization can reduce treatment by sedimentation within a dry pond by reducing the retention time within the pond. Additionally, previously captured sediments can become entrained by poorly or untreated stormwater and pass through the dry pond with the effluent.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in dry ponds that do not have impermeable surfaces (e.g., concrete). If the surface of the dry pond becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the dry pond. Vegetation in dry ponds is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in a dry pond are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of a dry pond by reducing the stormwater storage volume and therefore the retention time.

8) Are there indications of any of the following on the banks of the dry pond?

Erosion or channelization on the banks of a dry pond indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the dry pond with sediments from the bank and subsequently reduce the dry pond's effectiveness by reducing the volume available for stormwater storage and treatment.

9) Is the outlet structure clogged?

Like an inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the dry pond. If the outlet structure is partially or completely clogged, the treatment rate may be limited and stormwater runoff may not pass through the dry pond in less than 48 hours, as recommended by design (Minnesota Stormwater Steering Committee 2005). Any obstructions should be removed immediately to ensure proper operation of the dry pond.

10) Is the outlet structure askew or misaligned?

Misaligned outlet structures often allow stormwater runoff to enter or exit a dry pond by means other than those intended by design or prevent stormwater runoff from entering the dry pond at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Outlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the dry pond.

11) Is there evidence of any of the following downstream of the outlet structure?

Conditions downstream of a dry pond can provide evidence of the function of the pond itself. Properly designed and functioning dry ponds should remove most sand-sized particles (0.125 to 2 mm) from stormwater runoff. Sediment deposition downstream of a dry pond indicates that erosion is occurring between the dry pond and the sediment deposition or that sediments are present in the dry pond effluent. If sediments are present in the effluent such that downstream deposition is occurring, the dry pond is likely failing.

Erosion downstream of a dry pond indicates that flow velocities are larger than the conveyance channel can withstand. The conveyance channel should be resized to accommodate the amount of flow exiting the dry pond, or the channel should be augmented with energy dissipaters or riprap to reduce or eliminate the impact of erosion.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

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Stormwater Management Practice
Assessment Project

Field Data Sheet for Level 1 Assessment: Visual Inspection

Wet Ponds

Inspector's Name (s): ______________________________________
Date of Inspection: ____
Location of the Pond
    Address or Intersection: __________________________________
    Latitude, Longitude: _____________________________________
Date the wet pond began operation: ____________________________
Size of the wet pond (ft x ft x ft): ______________________________
Time since last rainfall (hr): __________________________________
Quantity of last rainfall (in): ______________________________
Rainfall Measurement Location: ______________________________
Water Surface Elevation: _____________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ____

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Are there multiple inlet structures?

☐ Yes ☐ No

3.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

3.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

3.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

4) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

4.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don’t know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

5) Is the wet pond a multi-cell system?

☐ Yes ☐ No

5.a) If yes, how many cells are present?

☐ 2 cells ☐ 3 cells ☐ 4 or more

6) Does the water in the pond have:

☐ Surface sheen (from oils/gasoline)

☐ Murky color (from suspended solids)

☐ Green color (from algae or other biological activity)

☐ Invasive, tolerant fish species such as carp or shiners

☐ Other: ____

☐ No

7) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

7.a) If yes, please describe: ______________________________________

____

____

____

8) Does the wet pond smell like gasoline or oil?

☐ Yes ☐ No

9) Are there indications of any of the following in the bottom of the wet pond?

☐ Sediment deposition

☐ Excessive vegetation (that needs mowing or removal)

☐ Litter, large debris, solid waste

☐ Other: ____

☐ No

9.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

10) Are there indications of any of the following on the banks of the wet pond?

☐ Erosion or channelization

☐ Other: ____

☐ No

11) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

11.a) If yes, what with?

☐ Debris

☐ Sediment

☐ Vegetation

☐ Other: ____

12) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

12.a) If yes, why?

☐ I don't know

☐ Ice/Frost heave

☐ Other: ____

13) Is there evidence of any of the following downstream of the outlet structure?

☐ Sediment deposition

☐ Erosion or channelization

☐ Other: ____

☐ No

13.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

Other observations:

____

____

____

____

____

Inspector's Recommendations:

14) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

____

____

____

____

____

Maintenance Recommendations:

____

____

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____

____

Troubleshooting Failure: Visual Inspection

Wet Ponds

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many wet ponds are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) and return to normal water surface level within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessing a wet pond within 48 hours of a rainfall event may provide additional assessment clues than assessment during a long dry period. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the wet pond. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system, or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the wet pond.

4) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a wet pond by means other than those intended by design or prevent stormwater runoff from entering the wet pond at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment, or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the wet pond.

5) Is the wet pond a multi-cell system?

Wet ponds are often designed as multi-cell systems to increase treatment and retention time. It is important to recognize multi-cell systems and perform this visual inspection on *each* of the cells in the system to ensure the entire practice is functioning properly.

6) Does the water in the pond have:

Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven to not be illegally discharged into the wet pond, then small amounts of hydrocarbons typically found in stormwater runoff are accumulating and remediation may be necessary to maintain the water quality of the stored runoff and prevent downstream pollution. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a high suspended solids concentration that is most likely made up of fine particle sizes, such as clays and silts, because sand particles settle out of standing water very rapidly (as discussed in Chapter 10, Sedimentation). Stormwater runoff with a murky color also indicates that the watershed may be a significant source of fine particle suspended solids or that erosion is suspending fine sediments from within the wet pond. Murky color in a wet pond further indicates that significant turbulence may be preventing suspended particles from settling. If a rainfall event has occurred in the last 48 hours, this may not be a problem. If rainfall has not occurred in the last 48 hours, murky color may be an indication of illicit discharge.

Stormwater runoff with a green color from algae or biological activity is not uncommon in a wet pond. Wet ponds with excessive algal or biologically activity may require maintenance to prevent pollution of downstream receiving waters.

Invasive, tolerant fish species like carp (*Cyprinus carpio*) or shiner minnows (*Notropis cornutus*) are indications of poor water quality in the wet pond (low dissolved oxygen, turbid, limited habitat) such that tolerant and invasive species are present. More information should be gathered to determine the cause of the poor water quality, and remediation should be performed.

7) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

8) Does the wet pond smell like gasoline or oil?

If a wet pond smells like gasoline or oil it is possible that hydrocarbon substances such as automotive oil or gasoline are being illicitly discharged into the practice or upstream in the watershed. If hydrocarbons are proven not to be illegally discharged into the wet pond, then an oil/gasoline smell may indicate that small amounts of hydrocarbons typically found in stormwater runoff are accumulating in the wet pond. For more information on identifying, locating, and eliminating illicit discharges refer to a manual such as Brown *et al.* (2004).

9) Are there indications of any of the following in the bottom of the wet pond?

Sediment deposition may indicate either a significant source of sediment in the watershed that may require remediation to prevent downstream pollution or that the wet pond has not been recently maintained. Sediment deposition reduces the stormwater storage volume of a wet pond and can allow sediments to become resuspended during subsequent storm events.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in wet ponds that do not have impermeable surfaces (e.g., concrete). If the surface of the wet pond becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the wet pond. Vegetation in wet ponds is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in a wet pond are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of wet pond by reducing the stormwater storage volume and therefore the retention time.

10) Are there indications of any of the following on the banks of the wet pond?

Erosion or channelization on the banks of a wet pond indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the wet pond with sediments from the bank and subsequently reduce the volume available for stormwater storage and treatment.

11) Is the outlet structure clogged?

Like an inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the wet pond. If the outlet structure is partially or completely clogged, the treatment rate may be limited and stormwater runoff may not pass through the wet pond in less than 48 hours, which can result in flooding or untreated stormwater runoff passing as overflow. Any obstructions should be removed immediately to ensure proper operation of the wet pond.

12) Is the outlet structure askew or misaligned?

Misaligned outlet structures often allow stormwater runoff to enter or exit a wet pond by means other than those intended by design or prevent stormwater runoff from entering the wet pond at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Outlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the wet pond.

13) Is there evidence of any of the following downstream of the outlet structure:

Conditions downstream of a wet pond can provide evidence of the function of the pond itself. Properly designed and functioning wet ponds should remove most sand-sized particles (0.125 to 2 mm) from stormwater runoff. Sediment deposition downstream of a dry pond indicates that erosion is occurring between the wet pond and the sediment deposition or that sediments are present in the wet pond effluent. If sediments are present in the effluent such that downstream deposition is occurring, the wet pond is likely failing.

Erosion downstream of a wet pond indicates that flow velocities are larger than the conveyance channel can withstand. The conveyance channel should be resized to accommodate the amount of flow exiting the wet pond, or the channel should be augmented with energy dissipaters or riprap to reduce or eliminate the impact of erosion.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

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Field Data Sheet for Level 1 Assessment: Visual Inspection

Wet Vaults and Proprietary Devices

Inspector's Name (s): ____
Date of Inspection: ____
Location of the Pond
    Address or Intersection: ____________________________________
    Latitude, Longitude: _______________________________________
Date the device began operation: ______________________________
Size of the device (ft x ft x ft): ___________________________________
Time since last rainfall (hr): ____________________________________
Quantity of last rainfall (in): ____________________________________
Rainfall Measurement Location: ________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ____

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Are there multiple inlet structures?

☐ Yes ☐ No

2.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

2.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

2.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

3) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

3.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don't know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

4) Is a significant amount of water entering the wet vault or proprietary device?

☐ Yes ☐ No

5) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

5.a) If yes, please describe: ____
____
____
____

6) Are there excessive amounts of solids, debris, vegetation, or other objects that could be hindering performance or be re-suspended and exit the system during subsequent runoff events?

☐ Yes ☐ No

7) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

7.a) If yes, what with?

☐ Debris
☐ Sediment
☐ Vegetation
☐ Other: ____

8) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

8.a) If yes, why?

☐ I don't know
☐ Ice/Frost heave
☐ Other: ____

9) Is there evidence of any of the following downstream of the outlet structure:

☐ Sediment deposition
☐ Erosion or channelization
☐ Other: ____
☐ No

9.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice
☐ Erosion or channelization outside the practice
☐ Construction site erosion
☐ Other: ____
☐ I don't know

Other observations:

____
____
____
____
____

Inspector's Recommendations:

10) When is maintenance needed?

☐ 5 – Before the next rainfall
☐ 4 – Before the next rainy season
☐ 3 – Possibly after the next season
☐ 2 – Within a year or two
☐ 1 – No sign that any will be required

Additional Comments:

____
____
____
____
____

Maintenance Recommendations:

____
____
____
____
____

Troubleshooting Failure: Visual Inspection

Wet Vaults and Proprietary Devices

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the wet vault or proprietary device. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the wet vault or proprietary device.

3) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a wet vault or proprietary device by means other than those intended by design or prevent stormwater runoff from entering the wet vault or proprietary device at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact.

4) Is a significant amount of water entering the wet vault or proprietary device?

Water entering a wet vault of proprietary device can be an indication that either (1) rainfall has occurred recently and the device is treating stormwater runoff or (2) water is entering the stormwater conveyance system from a leak, spill, or surface application (e.g., lawn watering, etc.).

5) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

6) Are there excessive amounts of solids, non-floating debris, vegetation, or other objects that could be hindering performance or be re-suspended and exit the system during subsequent runoff events?

Excessive amounts of solids, debris, vegetation, or other objects in a wet vault or proprietary device can reduce storage volume and subsequently treatment efficiency. Maintenance should be preformed to remove these obstructions.

7) Is the outlet structure clogged?

Like an inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the wet vault or proprietary device. If the outlet structure is partially or completely clogged, the treatment rate may be limited and stormwater runoff may not pass through the wet vault or proprietary device quickly, resulting in potential flooding of surrounding areas or conveyance systems, or untreated stormwater runoff bypassing the wet vault or proprietary device. Any obstructions should be removed immediately to ensure proper operation of the wet vault or proprietary device.

8) Is the outlet structure askew or misaligned?

Misaligned outlet structures often allow stormwater runoff to enter or exit a wet vault or proprietary device by means other than those intended by design or prevent stormwater runoff from entering the wet vault or proprietary device at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Outlet structures can become misaligned for several reasons, including frost heave of the soil and geotechnical failure. Misaligned outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact.

9) Is there evidence of any of the following downstream of the outlet structure:

Conditions downstream of a wet vault or proprietary device can provide evidence of the function of the practice itself. Properly sized and functioning wet vaults or proprietary devices should remove most sand-sized particles (0.125 to 2 mm) from stormwater runoff. Sediment deposition downstream of a wet vault or proprietary device indicates that erosion is occurring between the wet vault or proprietary device and the sediment deposition or that sediments are present in the wet vault or proprietary device effluent. The sediment storage capacity of the wet vault or proprietary device may have been reached and maintenance may be required to remove captured sediments.

Erosion downstream of a wet vault or proprietary device indicates that flow velocities are larger than the conveyance channel can withstand. The conveyance channel should be resized to accommodate the amount of flow exiting the wet vault or proprietary device, or the channel should be augmented with energy dissipaters or riprap to reduce or eliminate the impact of erosion.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

B4.

Appendix B part four: biologically enhanced practices

Procedures for the Visual Inspection of Stormwater Best Management Practices

Visual inspection is a rapid assessment procedure for qualitatively evaluating the functionality of a stormwater best management practice (BMP). Visual inspections use a set of criteria that, under certain circumstances (described in chapter 3), determine if the stormwater BMP is malfunctioning. Procedures and checklists for visual inspection are provided at the end of chapters 8–11 and are reproduced here.

Gulliver, J.S. and J.L. Anderson, ed. 2007. *Assessment of Stormwater Best Management Practices.* St Paul, MN: University of Minnesota.

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Standard Procedure for Level 1 Assessment: Visual Inspection

Biologically Enhanced Practices (including Bioretention, Constructed Wetlands, Swales, and Filter Strips)

1. Certified Reference:

1.1. None.

2. Application:

2.1. This method is applicable to biologically enhanced practices as defined in Chapter 11, Biologically Enhanced Systems.

3. Summary of Method:

3.1. This standard protocol is used as a basis for the visual inspection of biologically enhanced practices. The questions in section 8.4 below are answered from visual observations of the site and documented with a photographic or video-graphic camera.

4. Interferences:

4.1. Visual inspection requires adequate weather conditions. Fog or other visually limiting weather condition can result in an inaccurate or incomplete visual inspection. Such weather conditions should be avoided whenever possible.

5. Apparatus:

5.1. Camera (digital or film, video or photographic)

6. Materials:

6.1. Field Data Sheet (see attached).

7. Safety:

7.1. This procedure requires field inspection of the site and photographic or video graphic documentation. Caution and appropriate use of safety equipment and traffic controls should be used when walking around and in stormwater BMPs to avoid personal injury.

8. Procedure:

8.1. Print out this Standard Protocol for the visual inspection of biologically enhanced practices.
8.2. Obtain apparatuses and materials as outlined in sections 5 and 6 above.
8.3. Travel to the biologically enhanced practice that will be assessed by visual inspection.
8.4. Fill out the attached Field Data Sheet (see below).

9. Calculations:

9.1. None required. See Chapter 12.

10. Quality Control:

10.1. Photographic documentation for the questions answered above (section 8.4) must be provided with this protocol.

11. Additional References:

11.1. None

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Field Data Sheet for Level 1 Assessment: Visual Inspection

Bioretention Practices (including Rain Gardens)

Inspector's Name (s): ______________________________________
Date of Inspection: ____
Location of the Pond
  Address or Intersection: ___________________________________
  Latitude, Longitude: ______________________________________
Date the bioretention practice began operation: ____________________
Size of the practice (ft x ft):_______________________________________
Time since last rainfall (hr): ______________________________________
Quantity of last rainfall (in): ______________________________
Rainfall Measurement Location: ______________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ____________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____
____
____
____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Does this bioretention practice utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don't know

3.a) If yes, please describe: ____
____
____
____

4) Are there multiple inlet structures?

☐ Yes ☐ No

4.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

4.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

4.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ____
If Other: ____
If Other: ____
If Other: ____
If Other: ____

5) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

5.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don’t know					
Other					

If Other: ____
If Other: ____
If Other: ____
If Other: ____
If Other: ____

6) Is there standing water in the bioretention practice?

☐ Yes ☐ No

6.a) If yes, does the water have:

☐ Surface sheen (from oils/gasoline)

☐ Murky color (from suspended solids)

☐ Green color (from algae or other biological activity)

☐ Other: ____

☐ No

7) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

7.a) If yes, please describe: ____

____

____

____

8) Does the bioretention practice smell like gasoline or oil?

☐ Yes ☐ No

9) Is there vegetation in the bottom of the bioretention practice?

☐ Yes ☐ No

9.a) What is the approximate vegetation cover?

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

10) Are there indications of any of the following in the bottom of the bioretention practice?

☐ Sediment deposition

☐ Erosion or channelization

☐ Excessive vegetation (that needs mowing or removal)

☐ Litter, large debris, solid waste

☐ Other: ____

☐ No

10.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

11) Are there indications of any of the following on the banks of the bioretention practice?

☐ Erosion or channelization

☐ Other: ____

☐ No

12) Is the bottom of the bioretention practice covered with a layer of silts and/or clays?

☐ Yes ☐ No

13) Is the overflow or bypass structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

13.a) If yes, what with?

☐ Debris

☐ Sediment

☐ Vegetation

☐ Other: ____

14) Is the overflow or bypass structure askew or misaligned?

☐ Yes ☐ No

14.a) If yes, why?

☐ I don't know

☐ Ice/Frost heave

☐ Other: ____

Other observations: ____
____
____

Inspector's Recommendations:

15) When is maintenance needed?

☐ 5 – Before the next rainfall
☐ 4 – Before the next rainy season
☐ 3 – Possibly after the next season
☐ 2 – Within a year or two
☐ 1 – No sign that any will be required

Additional Comments: ____
____
____
____
____

Maintenance Recommendations: ____
____
____
____
____

Troubleshooting Failure: Visual Inspection

Bioretention Practices

The following sections provide discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many bioretention practices are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessment within 48 hours of a rainfall event may provide performance clues. Additionally, rainfall within the last 48 hours at a location will alter the interpretation of answers to other questions.

3) Does this bioretention practice utilize any pretreatment practices upstream?

If any pretreatment practices exist they should also be inspected and maintained on a regular basis. Pretreatment practices are required by the MPCA in some MS4 construction permits for bioretention practices. If this practice does not have any pretreatment upstream, it may be in violation of this code.

4) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the bioretention practice. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the bioretention practice.

5) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a bioretention practice by means other than those intended by design or prevent stormwater runoff from entering the practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

6) Is there standing water in the bioretention practice?

Standing water in a bioretention practice is the result of one of three possibilities: (1) rainfall has occurred recently such that stormwater runoff has not had 48 hours to pass infiltrate, (2) the infiltration rate of the bioretention practice is slow such that stormwater runoff does not pass through the bioretention practice within 48 hours, but does pass through the bioretention practice given enough time, or (3) the soil media is clogged and does not allow any stormwater runoff to infiltrate. If it has rained in the last 48 hours (question 2), then the bioretention practice may be functioning properly and requires additional assessment (level 2 or higher) to determine whether the soil media is clogged. If, however, it has not rained in the last 48 hours, it is likely that the bioretention practice is either option (2) or (3).

Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven not to be illegally discharged into the bioretention practice, then a surface sheen may indicate that stormwater runoff is stored in the bioretention practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. If this is happening, then the bioretention practice is failing. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a high suspended solids concentration that is most likely made up of fine particle sizes, such as clays and silts, because sand particles settle out of standing water very rapidly (as discussed in Chapter 10, Sedimentation). Stormwater runoff with a murky color also indicates that the watershed may be a significant source of fine particle suspended solids, which can quickly clog a bioretention practice. Murky stormwater runoff in a bioretention practice further indicates that stormwater runoff may have recently entered the bioretention practice such that fine particles have not had time to settle out.

Stormwater runoff with a green color from algae has been stored in the bioretention practice for a long period of time such that microorganisms have developed. Stormwater runoff is not passing though the bioretention practice properly and therefore the practice is failing.

7) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

8) Does the bioretention practice smell like gasoline or oil?

If a bioretention practice smells like gasoline or oil it is possible that hydrocarbon substances such as automotive oil or gasoline are being illicitly discharged into the practice or upstream in the watershed. If hydrocarbons are proven not to be illegally discharged into the bioretention practice, then an oil/gasoline smell may indicate that stormwater runoff is stored in the bioretention practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. For more information on identifying, locating, and eliminating illicit discharges, refer to a manual such as Brown *et al.* (2004).

9) Is there vegetation in the bottom of the bioretention practice?

Vegetation in the bottom of a bioretention practice is designed to dry out the soil in between storms and to maintain the infiltration effectiveness. Plants can lose 30% of their root structures annually, which produces macropores. Macropores in a bioretention practice can increase the infiltration rate of the practice so that more stormwater runoff is infiltrated. Additionally, vegetation can reduce overland flow velocities and can therefore reduce erosion and resuspension of captured solids.

Vegetation can also be an indication of the drain time of a bioretention practice. Terrestrial vegetation often cannot withstand long periods of inundation, and some cannot withstand short periods of inundation. If a bioretention practice has an abundance of terrestrial vegetation, it is likely that the practice infiltrates stormwater runoff quickly (< 48 hrs) and is therefore operating properly. If, however, the bioretention practice has signs of aquatic vegetation or has little vegetation, it is likely the practice is not infiltrating stormwater runoff at all and is therefore failing.

10) Are there indications of any of the following in the bottom of the bioretention practice?

Sediment deposition may indicate that pretreatment devices have reached sediment storage capacity, are not efficiently removing settable solids, or are not present. Sediment deposition may also indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution. Sediment deposition reduces the bioretention practice surface area available for infiltration and therefore can reduce the stormwater runoff volume that is infiltrated.

Erosion or channelization indicates that flow velocities entering, or in, the bioretention practice are large or that stormwater runoff is entering the practice by means other than those intended by design. In either case, stormwater runoff is not stored in the bioretention practice such that significant infiltration in the areas where erosion and channelization are occurring.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in bioretention practices that do not have impermeable surfaces (e.g., concrete). If the surface of the bioretention practices becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the bioretention practices. Vegetation in bioretention practices is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in a bioretention practice are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of bioretention practice by reducing the surface available for infiltrating stormwater runoff.

11) Are there indications of any of the following on the banks of the bioretention practice?

Erosion or channelization on the banks of a bioretention practice indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the bioretention practice with sediments from the bank and subsequently reduce the practice’s effectiveness by clogging the soil or sealing the surface and reducing the volume available for stormwater storage.

12) Is the bottom of the bioretention practice covered with a layer of silts and/or clays?

A visible layer of silts, clays, or both is a likely indication that the bioretention practice is clogged. Bioretention practices collect particles on the surface and in the pore spaces of the soil. Silts, clays, or both present on the surface of the bioretention practice indicates that the pore spaces within the soil are likely filled, or that stormwater runoff is stored in the basin or trench long enough for these fine particles to settle out or for the stored stormwater runoff to evaporate. The bioretention practice is not likely infiltrating stormwater runoff in less than 48 hours as recommended by design guidelines (Minnesota Stormwater Steering Committee 2005).

13) Is the overflow or bypass structure clogged?

Bioretention practices typically have overflow structures instead of outlet structures. Outflow for a bioretention practice is intended to go into the soil such that deep percolation or evaporation occurs. The overflow structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the bioretention practice in the event of a large storm event. If the overflow structure is partially or completely clogged, surrounding areas may be flooded by stored stormwater runoff. Any obstructions should be removed immediately to ensure proper operation of the bioretention practice.

14) Is the overflow structure askew or misaligned?

Misaligned inlet or overflow structures often allow stormwater runoff to enter or exit a bioretention practice by means other than those intended by design or prevent stormwater runoff from entering the practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet and overflow structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet or overflow structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

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Field Data Sheet for Level 1 Assessment: Visual Inspection

Constructed Wetlands

Inspector's Name (s): ____
Date of Inspection: ____
Location of the Pond
    Address or Intersection: ____________________________________
    Latitude, Longitude: ____
Date the constructed wetland began operation: ____________________
Size of the wetland (ft x ft x ft): _________________________________
Time since last rainfall (hr): ____________________________________
Quantity of last rainfall (in): ________________________________
Rainfall Measurement Location: ________________________________
Water Surface Elevation____

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ________________________________

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Does this constructed wetland utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don't know

3.a) If yes, please describe: ________________________________

____

____

____

4) Are there multiple inlet structures?

☐ Yes ☐ No

4.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

4.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

4.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________

5) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

5.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don't know					
Other					

If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________
If Other: ____________________________________

6) Is the constructed wetland a multi-cell system?

☐ Yes ☐ No

6.a) If yes, how many cells are present?

☐ 2 cells ☐ 3 cells ☐ 4 or more

7) Is there standing water in the constructed wetland?

☐ Yes ☐ No

7.a) If yes, does the water have:

☐ Surface sheen (from oils/gasoline)

☐ Murky color from suspended solids

☐ Green color from algae or other biological activity

☐ Invasive, tolerant fish species such as carp or shiners

☐ Other: ____

☐ No

8) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

8.a) If yes, please describe: ______________________________________

____

____

____

9) Does the constructed wetland smell like gasoline or oil?

☐ Yes ☐ No

10) Is there vegetation in the constructed wetland?

☐ Yes ☐ No

10.a) What is the approximate vegetation cover?

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

11) Are there indications of any of the following in the constructed wetland?

☐ Sediment deposition

☐ Erosion or channelization

☐ Excessive vegetation (that needs mowing or removal)

☐ Litter, large debris, solid waste

☐ Other: ____

☐ No

11.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don’t know

12) Are there indications of any of the following on the banks of the constructed wetland?

☐ Erosion or channelization

☐ Other: ____

☐ No

13) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

13.a) If yes, what with?

☐ Debris

☐ Sediment

☐ Vegetation

☐ Other: ____

14) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

14.a) If yes, why?

☐ I don’t know

☐ Ice/Frost heave

☐ Other: ____

15) Is there evidence of any of the following downstream of the outlet structure:

☐ Sediment deposition

☐ Erosion or Channelization

☐ Other: ____

☐ No

15.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don’t know

Other observations:

____

____

____

____

____

Inspector's Recommendations:

16) When is maintenance needed?

- ☐ 5 – Before the next rainfall
- ☐ 4 – Before the next rainy season
- ☐ 3 – Possibly after the next season
- ☐ 2 – Within a year or two
- ☐ 1 – No sign that any will be required

Additional Comments:

____
____
____
____
____

Maintenance Recommendations:

____
____
____
____
____

Troubleshooting Failure: Visual Inspection

Constructed Wetlands

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Many constructed wetlands are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) and return to previous water level within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessing a wetland within 48 hours of a rainfall event may provide performance clues. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Does this constructed wetland utilize any pretreatment practices upstream?

If any pretreatment practices exist they should also be inspected and maintained on a regular basis.

4) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the constructed wetlands. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the constructed wetlands.

5) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit constructed wetlands by means other than those intended by design or prevent stormwater runoff from entering the constructed wetlands at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the constructed wetlands.

6) Is the constructed wetland a multi-cell system?

Constructed wetlands may be designed as multi-cell systems to increase treatment and retention time. It is important to recognize multi-cell systems and perform this visual inspection on *each* of the cells in the system to ensure the entire practice if functioning properly.

7) Is there standing water in the constructed wetland?

Constructed wetlands are designed to have a permanent pool of water. The absence of standing water in constructed wetlands is the result of one of three possibilities: (1) rainfall has not occurred in a length of time such that all stored stormwater runoff has evaporated (i.e., drought conditions), infiltrated, or both, (2) the outlet structure is damaged or malfunctioning such that stormwater runoff is allowed to drain out of the constructed wetlands, or (3) the inlet structure is clogged or misaligned such that stormwater runoff is not entering the constructed wetlands. If it has rained in the last 48 hours (question 2), then the constructed wetlands should have received or will soon receive stormwater runoff and therefore drought conditions are not occurring. If approximately 48 hours has passed since the last rainfall event and standing water is not present in the constructed wetlands, it is likely that possibility (2) or (3) is occurring.

Surface sheen is often caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. Natural and constructed wetlands, however, can produce hydrocarbons through the chemical and biological processes that occur within the wetland. If hydrocarbons are proven not to be illegally discharged into the constructed wetlands, then remediation may be necessary to maintain the water quality of the stored runoff and prevent downstream pollution. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown *et al.* 2004).

Stormwater runoff with a murky color is evidence of a high suspended solids concentration that is most likely made up of fine particle sizes, such as clays and silts, because sand particles settle out of standing water very rapidly (as discussed in Chapter 10, Sedimentation). Stormwater runoff with a murky color also indicates that the watershed may be a significant source of fine particle suspended solids or that erosion is suspending fine sediments from within the constructed wetlands. Murky color in constructed wetlands further indicates that significant turbulence may be preventing suspended particles from settling. If a rainfall event has occurred in the last 48 hours, this may not be a problem. If rainfall has not occurred in the last 48 hours, murky color may be an indication of illicit discharge.

Stormwater runoff with a green color from algae or biological activity is not uncommon in constructed wetlands. Constructed wetlands with excessive algal or biologically activity may require maintenance to prevent pollution of downstream receiving waters.

Invasive, tolerant fish species like carp (*Cyprinus carpio*) or shiner minnows (*Notropis cornutus*) are indications of poor water quality in the constructed wetlands (low dissolved oxygen, turbid, limited habitat) such that tolerant and invasive species are present. More information should be gathered to determine the cause of the poor water quality, and remediation should be performed.

8) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

9) Does the constructed wetland smell like gasoline or oil?

If constructed wetlands smell like gasoline or oil, it is possible that hydrocarbon substances such as automotive oil or gasoline are being illicitly discharged into the practice or upstream in the watershed. If hydrocarbons are proven not to be illegally discharged into the constructed wetlands, then an oil/gasoline smell may indicate that small amounts of hydrocarbons typically found in stormwater runoff are accumulating in the constructed wetlands. For more information on identifying, locating, and eliminating illicit discharges, refer to a manual such as Brown *et al.* (2004).

10) Is there vegetation in the constructed wetland?

Vegetation in constructed wetlands should be consistent with native or design-specified wetland vegetation. The absence of vegetation anywhere in or around constructed wetlands may be an indication of poor water quality or excessive infiltration that will dry the wetland.

11) Are there indications of any of the following in the constructed wetland?

Sediment deposition may indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution, or that the constructed wetlands have not been recently maintained. Sediment deposition reduces the stormwater storage volume of constructed wetlands and can allow sediments to become resuspended during subsequent storm events.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in constructed wetlands that do not have impermeable surfaces (e.g., concrete). If the surface of the constructed wetlands becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the constructed wetlands. Vegetation in constructed wetlands is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in constructed wetlands are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may reduce the stormwater storage volume and therefore the retention time.

12) Are there indications of any of the following on the banks of the constructed wetland?

Erosion or channelization on the banks of constructed wetlands indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the constructed wetlands with sediments from the bank and subsequently reduce the volume available for stormwater storage and treatment.

13) Is the outlet structure clogged?

Like an inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the constructed wetlands. If the outlet structure is partially or completely clogged, the treatment rate may be limited and stormwater runoff may not pass through the constructed wetlands in less than 48 hours, which can result in flooding or untreated stormwater runoff passing as overflow. Any obstructions should be removed immediately to ensure proper operation of the constructed wetlands.

14) Is the outlet structure askew or misaligned?

Misaligned outlet structures often allow stormwater runoff to enter or exit constructed wetlands by means other than those intended by design or prevent stormwater runoff from entering the constructed wetlands at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Outlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the constructed wetlands.

15) Is there evidence of any of the following downstream of the outlet structure:

Conditions downstream of a constructed wetland can provide evidence of the function of the pond itself. Properly designed and functioning constructed wetlands should remove most sand-size particles (0.125 to 2 mm) from stormwater runoff. Sediment deposition downstream of a constructed wetland indicates that erosion is occurring between the wetland and the sediment deposition or that sediments are present in the wetland effluent. If sediments are present in the effluent such that downstream deposition is occurring, the wetland is likely failing.

Erosion downstream of a filtration practice indicates that flow velocities are larger than the conveyance channel can withstand. The conveyance channel should be resized to accommodate the amount of flow exiting the wet pond, or the channel should be augmented with energy dissipaters or riprap to reduce or eliminate the impact of erosion.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

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Field Data Sheet for Level 1 Assessment: Visual Inspection

Swales and Filter Strips

Inspector's Name (s): ____
Date of Inspection: ____
Location of the Pond
    Address or Intersection: ___________________________________
    Latitude, Longitude: ______________________________________
Date the stormwater BMP began operation: _______________________
Size of the practice (ft x ft):_____________________________________
Time since last rainfall (hr): ____________________________________
Quantity of last rainfall (in): ________________________________
Rainfall Measurement Location: ________________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ____

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action(s) taken and date(s):

____

____

____

____

2) Has it rained within the last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Does this swale or filter strip utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don't know

3.a) If yes, please describe: ____

____

____

____

4) Are there inlet structures associated with this practice?

☐ Yes ☐ No

4.a) If no, proceed to question 7.

5) Are there multiple inlet structures?

☐ Yes ☐ No

5.a) If yes, how many inlets are present?

☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 or more

5.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

5.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

6) Are any of the inlet structures askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

6.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don’t know					
Other					

If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________
If Other: ______________________________

7) Is there standing water in the swale or filter strip?

☐ Yes ☐ No

8) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No ☐ I don't know

8.a) If yes, please describe: ______________________________________

____

____

____

9) Is there vegetation in the swale or filter strip?

☐ Yes ☐ No

9.a) What is the approximate vegetation cover?

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

10) Are there indications of any of the following in the bottom of the swale or filter strip?

☐ Sediment deposition

☐ Erosion or channelization

☐ Excessive vegetation (that needs mowing or removal)

☐ Litter, large debris, solid waste

☐ Other: ______________________________________

☐ No

10.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ______________________________________

☐ I don't know

11) Are there indications of any of the following on the banks of the swale?

☐ Erosion or channelization

☐ Other: ____

☐ No

12) Are there outlet structures associated with this practice?

☐ Yes ☐ No

12.a) If no, proceed to question 15.

13) Is the outlet structure clogged?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

13.a) If yes, what with?

☐ Debris

☐ Sediment

☐ Vegetation

☐ Other: ____

14) Is the outlet structure askew or misaligned?

☐ Yes ☐ No

14.a) If yes, why?

☐ I don't know

☐ Ice/Frost heave

☐ Other: ____

15) Is there evidence of any of the following downstream of the outlet structure:

☐ Sediment deposition

☐ Erosion

☐ Channelization

☐ Other: ____

☐ No

15.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

Other observations:

____

____

____

____

____

Inspector's Recommendations:

16) When is maintenance needed?

☐ 5 – Before the next rainfall

☐ 4 – Before the next rainy season

☐ 3 – Possibly after the next season

☐ 2 – Within a year or two

☐ 1 – No sign that any will be required

Additional Comments:

____

____

____

____

____

Maintenance Recommendations:

____

____

____

____

____

Troubleshooting Failure: Visual Inspection

Filter Strips and Swales

The following section provides discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within the last 48 hours at this location?

Assessing a filter strip or swale within 48 hours of a rainfall event may provide additional performance clues. Additionally, rainfall within the last 48 hours at a location will alter how answers to other questions in this assessment are interpreted.

3) Does this swale or filter strip utilize any pretreatment practices upstream?

If any pretreatment practices exist they should also be inspected and maintained on a regular basis.

4) Are there inlet structures associated with this practice?

5) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the swale or filter strip. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system, or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the swale or filter strip.

6) Are any of the inlet structures askew or misaligned?

Misaligned inlet or outlet structures often allow stormwater runoff to enter or exit a swale or filter strip by means other than those intended by design or prevent stormwater runoff from entering the swale or filter strip at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet and outlet structures can become misaligned for several reasons including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet or outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the swale or filter strip.

7) Is there standing water in the swale or filter strip?

Filter strips and swales are designed for stormwater conveyance and not stormwater storage. Standing water in a filter strip or swale is an indication of failure by (1) downstream flooding, or (2) blockage that is preventing stormwater runoff from being conveyed downstream. Areas downstream of the filter strip or swale should be inspected for signs of flooding, and the filter strip or swales should inspected for any obstructions.

8) Is there evidence of illicit storm sewer discharges?

An illicit discharge manual (e.g., Brown *et al.* 2004) should be consulted for identifying and locating illicit stormwater discharges.

9) Is there vegetation in the swale or filter strip?

Vegetation in the bottom of a filter strip or swale can increase the infiltration rate and remove particulates from stormwater runoff. Plants can lose 30% of their root structures annually, which produces macropores. Macropores in a filter strip or swale can increase the infiltration rate of the practice so that more stormwater runoff is infiltrated. Additionally, vegetation reduces overland flow velocities, which reduces erosion, resuspension of captured solids, and increases suspended solids removal.

10) Are there indications of any of the following in the bottom of the swale or filter strip?

Sediment deposition can indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution or that the swale or filter strip has not been recently maintained. Sediment deposition reduces the stormwater storage volume of a swale or filter strip and can allow sediments to become resuspended during subsequent storm events.

Erosion or channelization indicates that flow velocities entering, or in, the swale or filter strip are large or that stormwater runoff is entering the swale or filter strip by means other than those intended by design. Erosion and channelization can reduce treatment by sedimentation within a swale or filter strip by reducing the retention time and treatment area. Additionally, previously captured sediments can become entrained by poorly or untreated stormwater and pass through the swale or filter strip with the effluent.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in swales and filter strips. If the surface of the swales and filter strips becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the swales and filter strips. Vegetation in swales and filter strips is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in a swale or filter strip are indications that pretreatment practices are failing or not present. Litter, large debris and solid waste may limit the effectiveness of swale or filter strip by altering flow paths which may create channelization, erosion, or both.

11) Are there indications of any of the following on the banks of the swale or filter strip?

Erosion or channelization on the banks of a swale indicates that stormwater runoff is entering at a large velocity by means other than those intended by design. Erosion and channelization on the banks can fill the swale with sediments from the bank and subsequently reduce the swale's effectiveness by reducing the volume available for stormwater conveyance and treatment.

12) Are there outlet structures associated with this practice?

13) Is the outlet structure clogged?

Like the inlet structure, the outlet structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the swale or filter strip. If the outlet structure is partially or completely clogged, the treatment rate may be limited, and stormwater runoff may not pass through the swale or filter strip untreated or flood surrounding areas. Any obstructions should be removed immediately to ensure proper operation of the swale or filter strip.

14) Is the outlet structure askew or misaligned?

Misaligned inlet or outlet structures often allow stormwater runoff to enter or exit a swale or filter strip by means other than those intended by design or prevent stormwater runoff from entering the swale or filter strip at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet and outlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet or outlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the swale or filter strip.

15) Is there evidence of any of the following downstream of the outlet structure:

Conditions downstream of a swale or filter strip can provide evidence of the function of the practice itself. Properly designed and functioning swale or filter strip should remove most sand-size particles (0.125 to 2 mm) from stormwater runoff. Sediment deposition downstream of a swale or filter strip indicates that erosion is occurring between the practice and the sediment deposition or that sediments are present in the swale or filter strip effluent. If sediments are present in the effluent such that downstream deposition is occurring, the swale or filter strip is likely failing.

Erosion downstream of a swale or filter strip indicates that flow velocities are larger than the conveyance channel can withstand. The conveyance channel should be resized to accommodate the amount of flow exiting the swale or filter strip, or the channel should be augmented with energy dissipaters or riprap to reduce or eliminate the impact of erosion.

References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

C.

Appendix C

Capacity Tests for Infiltration Practices

B.C. Asleson, R.S. Nestingen, J.S. Gulliver (gulli003@umn.edu)

This appendix discusses the procedures for estimating saturated hydraulic conductivity in the field using the Modified Philip-Dunne permeameter.

Gulliver, J.S. and J.L. Anderson, ed. 2007. *Assessment of Stormwater Best Management Practices.* St Paul, MN: University of Minnesota.

1. Selection of field permeameters and infiltrometers

There are several devices that can be used to make measurements of the soil's saturated hydraulic conductivity in the field. Some of the devices available include the air-entry permeameter, Guelph permeameter, tension infiltrometer, double and single ring infiltrometers, disk infiltrometer, and the Modified Philip-Dunne permeameter. Table C.1 shows a summary of an evaluation of several of these devices. The evaluations were based on specific criteria. The data in the table demonstrate that the Modified Philip-Dunne permeameter has an advantage over the other devices in several of the criteria, making it one of the simplest and most efficient devices for use in the field. Based on the evaluation of the devices, the Modified Philip-Dunne permeameter is recommended for estimating saturated hydraulic conductivity in the field.

Table C.1: Comparison of Infiltrometers and Permeameters

CRITERIA	Double Ring Infiltrometer	Modified Philip-Dunne Permeameter	Minidisk Infiltrometer	Guelph Permeameter	Tension Infiltrometer
Transportability of equipment	2	1	1	2	3
Volume of water Needed	3	1	1	2	3
Experiment Duration	3	2	1	3	2
Simplicity of operation	2	1	2	3	3
Cost	2	1	1	3	3
Personnel requirements	1	1	1	2	2
Accuracy	?	?	?	?	?

Criteria evaluation: 1 = most desired, 2 = second-most desired, 3 = least desired

2. Constructing a Modified Philip-Dunne Permeameter

The Modified Philip-Dunne permeameter is an open-ended cylinder which should have a minimum height of 12 inches and a maximum height of approximately 24 inches with a diameter of 4 inches or greater. Any rigid material can be used to construct the cylinder; however, thin-walled aluminum pipe works well because the permeameter is both light-weight and durable. Bevelling the bottom of the cylinder, to ease insertion into the soil, is helpful if a thicker-walled material is being used. The next step is to connect a transparent piezometer tube from which to make visual readings to the cylinder with a small elbow joint approximately 2 inches from the bottom and on the outside of the device . Measuring tape for making height measurements of water inside the piezometer tube should be positioned parallel and next to the tube with zero starting at the piezometer elbow joint. To ease identification, mark the height at which the water level will be at the maximum height (h_0) on the permeameter. Finally, mark around the outside of the cylinder at the base of the piezometer elbow to indicate the depth that the cylinder should be inserted into the soil. Figure C.1 is an example of a Modified Philip-Dunne permeameter.

Figure C.1: Modified Philip-Dunne permeameter

3. Field procedure for Modified Philip-Dunne permeameter

1. Determine the number of testing locations required by using the estimated variance of the saturated hydraulic conductivity of the soil within the specific stormwater BMP. Several bioretention practices (rain gardens) have been evaluated for variance of saturated hydraulic conductivity to approximate the number of locations necessary to obtain an accurate representation of the entire rain garden. For a site-specific estimate, the variance and mean of the saturated hydraulic conductivity must first be estimated by making several measurements. Once an estimate of the mean and variance are obtained, equation C.1 can be used to calculate the appropriate number of locations required for a representative saturated hydraulic conductivity value.

$$n = \frac{\sigma^2 (z_u - z_{1-\alpha/2})^2}{\mu_0 - \mu} \qquad \text{(Equation C.1)}$$

   Where n is the number of tests, σ^2 is the variance, z_u and $z_{1-\alpha/2}$ are the standard normal probability upper and lower limits, and μ is the mean.

   To obtain a general estimate for the number of measurements required that is not based on a site specific mean and variance, figure C.2 may be used. The figure is based on data compiled from several different rain garden sites. Select the range about the mean value and confidence interval based on the level of accuracy desired, and then refer to figure C.2 to determine an estimate for the number of tests required.

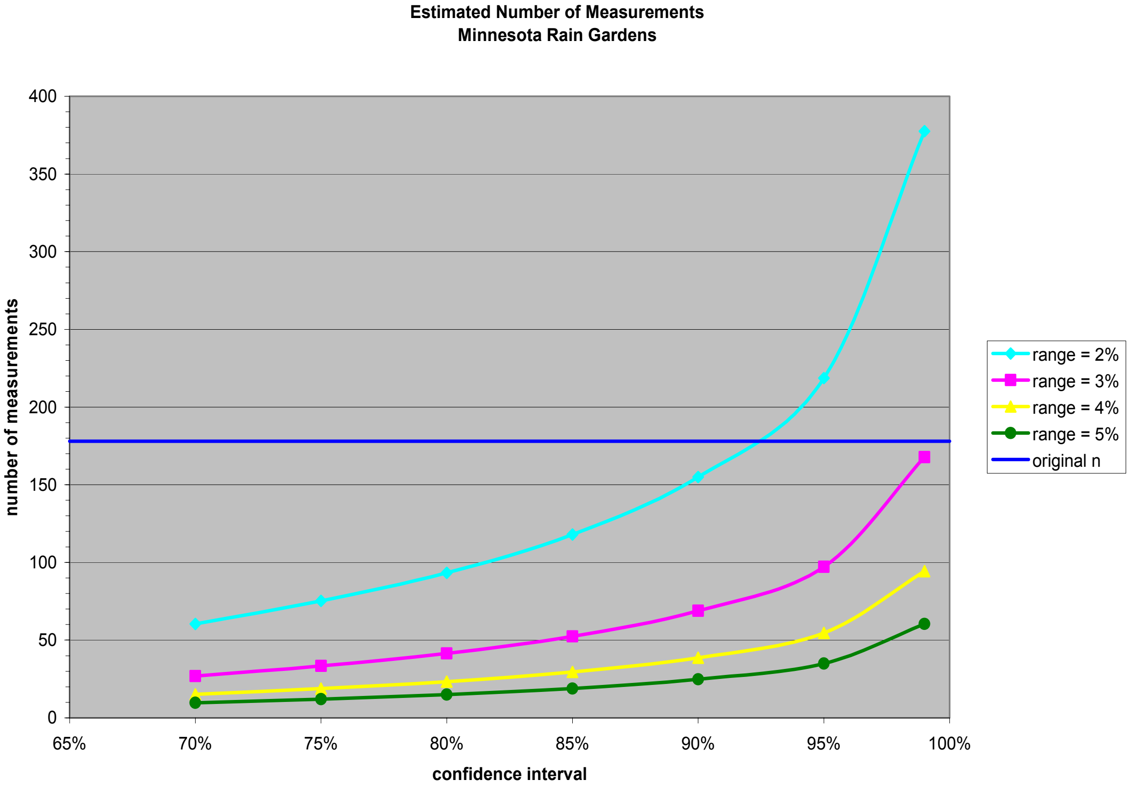

Figure C.2: Estimated Number of Measurements for Rain Garden Infiltration Assessment

Randomly select the locations throughout the stormwater BMP where the point measurements are to be performed. Ideally, point measurements should be evenly distributed throughout the site. It may also be advantageous to record the location of each point measurement with a hand-drawn map or GPS if additional assessments will be performed at the site in the future.

2. At a point measurement location, pound the device uniformly into the ground to a depth of approximately 2 inches, making sure not to pound the piezometer tube opening below the surface. Ensure that the soil around the base of the Modified Philip-Dunne permeameter is pressed firmly against the device to prevent seepage.

3. Record an initial volumetric soil moisture measurement directly around the base of the Modified Philip-Dunne permeameter. Suggested moisture measurement techniques include the gravimetric method (and using dry bulk density to convert it to volumetric moisture) or using a portable soil moisture sensor such as a ThetaProbe®. Refer to Methods of Soil Analysis, Part 1 (Klute 1986) or ASTM Test Methods D2216/D4643 for a more detailed procedure on measuring soil moisture using the gravimetric method.

4. Once the initial soil moisture measurement has been made, the Modified Philip-Dunne permeameter can be filled with water. To prevent scouring of the soil surface, a porous material such as hay may be placed at the bottom of the device. When the water level reaches the marked initial height (h_0), stop filling the device and begin the timer.

5. Once the test has begun, record either periodically or at a regular time intervals the time since the test began and corresponding height of water in the device until the device empties. The test is complete once all the water has drained from the device.

6. After all the time vs. height measurements have been recorded and the device is empty, remove the Modified Philip-Dunne permeameter and take the final soil moisture measurement as soon as possible from where the device was positioned.

7. Repeat steps 3 through 7 at all of the pre-determined test locations within the stormwater BMP.

4. Data Analysis for Modified Philip-Dunne Permeameter

The original Philip-Dunne permeameter technique involved placing the device in a borehole. This permeameter was modified to incorporate surface infiltration and capture any effects of sediment accumulation in the stormwater BMP. Due to these modifications in the technique, methods for determining saturated hydraulic conductivity needed to be altered accordingly. This alteration included changing the geometry of the source from a sphere to a hemisphere and accounting for one-dimensional flow through the soil contained within the bottom of the device. The radius of the hemispherical source, r_0, is then given by equation C.2 where r_1 is the radius of the device.

$$r_0 = \frac{r_1}{\sqrt{2}} \qquad \text{(Equation C.2)}$$

Applying these alterations to the original analysis completed by J.R. Philip (1993) yields equations C.3 and C.4.

$$\Delta P = \frac{r_0^{\;2}}{R} + \frac{r_0^{\;2}}{L_{\max}} - \frac{(\theta_f - \theta_i)R}{\overline{K}} \left(\frac{R}{L_{\max}} + 1 \right) \frac{dR}{dt} \qquad \text{(Equation C.3)}$$

$$\Delta P = C - h(t) \qquad \text{(Equation C.4)}$$

Where ΔP is the change in pressure from the source to the wetting front, r_0 is the radius of the hemispherical source, L_{max} is the distance the device is inserted into the ground, θ_f and θ_i are the final and initial moisture contents, respectively, $h(t)$ is the height of water at time t, K is the mean saturated hydraulic conductivity, and C is the capillary pressure. The radial distance to the sharp wetting front, R, can be found using equation C.5.

$$R(t)=\sqrt[3]{\frac{3r_1^{\ 2}}{2(\theta_f-\theta_i)}[H_0-h(t)-L_{\max}(\theta_f-\theta_i)]+r_0^{\ 3}} \qquad \text{(Equation C.5)}$$

The derivative of *R* with respect to time, *dR/dt*, may be estimated by taking a finite difference of *R* versus time. Lastly, the remaining unknown variables are *K* and *C*, which can be found by setting the right sides of equations C.3 and C.4 equal to one another and finding the best fitting solution by varying *K* and *C*. To aid in this analysis, a Microsoft Excel® spreadsheet with instructions for use is provided via the Internet for download at the following link: http://wrc.umn.edu/outreach/stormwater/bmpassessment/linksandresources.html.

Once the saturated hydraulic conductivity has been calculated for all the locations within the stormwater BMP, the arithmetic mean should be considered as the overall value. As a conservative estimate, saturated hydraulic conductivity can be considered equal to the infiltration rate.

To determine if the stormwater BMP is able to infiltrate a certain runoff volume within the required 48-hour time period, use the following calculations:

1. Saturated hydraulic conductivity multiplied by the surface area to obtain a conservative estimate of the infiltration rate (volume per time), and
2. Runoff volume divided by the infiltration rate to estimate the time required to infiltrate the selected runoff volume. Example C.1 illustrates this procedure.

Example C.1

A rain garden with a surface area of 3000 ft^2 (279 m^2), a ponding depth of 0.667 ft (0.20 m), and an estimated conservative infiltration rate of 1.6 in/hr (0.041 m/hr) is to be assessed for total time to infiltrate water at its storage capacity. Determine the storage capacity and the time required to infiltrate water.

Solution

- Determine the storage capacity.
    - $\text{Storage capacity} = 0.667 \text{ ft x } 3000 \text{ ft}^2 = 2000 \text{ ft}^3$
- Determine the overall infiltration rate of the rain garden.
    - $\text{Overall Infiltration Rate} = 0.133 \text{ ft/hr x } 3000 \text{ ft}^2 = 400 \text{ ft}^3\text{/hr}$
- Determine the total time required to infiltrate the water in the rain garden at capacity.
    - $\text{Storage capacity/Infiltration rate} = \text{total time}$

$\text{Total time to empty} = 2000 \text{ ft}^3/400 \text{ ft}^3\text{/hr} = 5 \text{ hr}$

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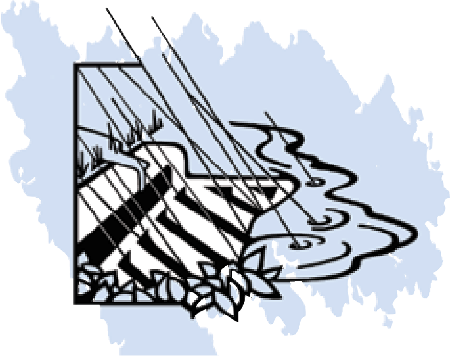

D.

Appendix D

Automatic Sampling of Water Containing Suspended Solids

O. Mohseni (omohseni@umn.edu), T. R. Riter, and J.S. Gulliver.

This appendix discusses how to accurately sample suspended solids using an automated sampler.

Gulliver, J.S. and J.L. Anderson, ed. 2007. *Assessment of Stormwater Best Management Practices.* St Paul, MN: University of Minnesota.

Research conducted on an ISCO 2700 automatic sampler at the St. Anthony Falls Laboratory has shown that samples collected by automatic samplers do not accurately represent the suspended solids concentration in stormwater runoff. A sediment feeder was installed at the upstream end of a 20-ft long, 24-inch wide pipe where sediment and water were fed into the pipe. Discharge through the pipe was measured using a v-notch weir downstream of the pipe. Sediment was fed into the pipe at 100 and 300 mg/L concentrations. The tests were conducted using three sediment size distributions: (1) medium to coarse sand (Lakeland), (2) fine sand (F110), and (3) silt (SCS250). The results of the tests showed that the automatic sampler over-estimated the concentration of the coarse sand by a factor of three to four (figure 1). Fine sand concentrations were either over-estimated or under-estimated by 30 to 40%. Silt concentrations were measured more accurately than the other two size distributions. Two possible causes for this include (1) the location of the sampler intake and (2) the velocity with which the sample is drawn.

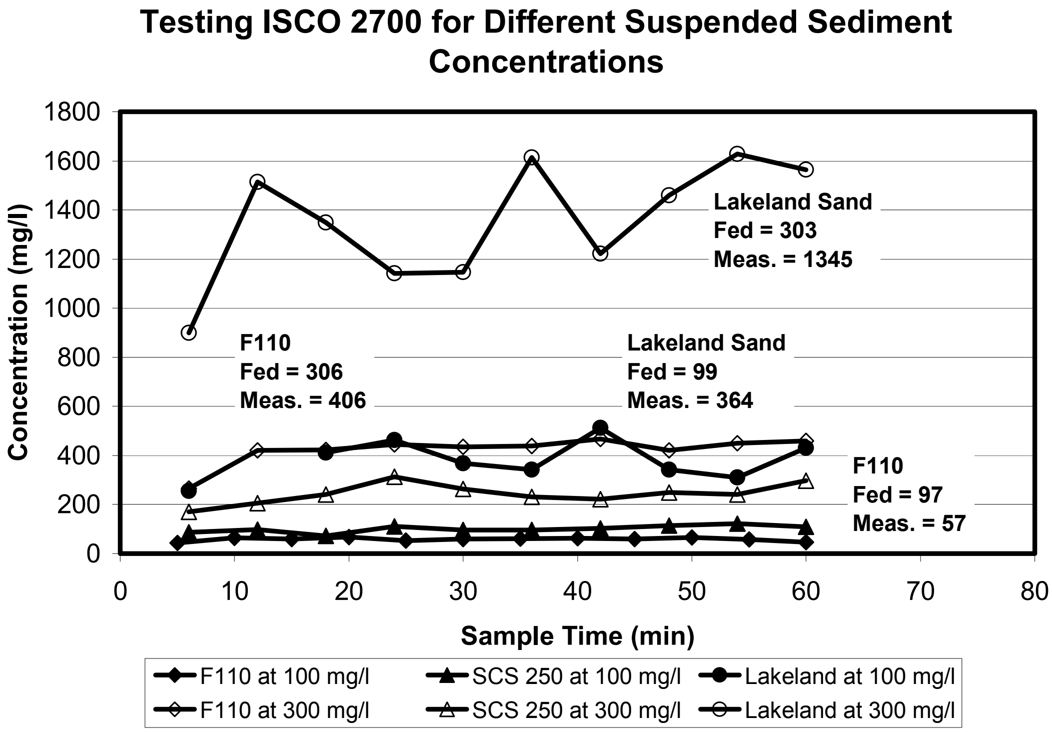

Figure 1: Suspended sediment concentrations measured downstream of pipe using an automatic sampler. Two different suspended sediments concentration were used.

Solids suspension is a function of flow characteristics, particle size, and depth. Sampling suspended solids concentration is strongly influenced by the location of the intake within the depth of the flow. For a typical stormwater conduit, concentrations larger than the mean concentration are found at lower relative depths for most particle sizes (>10 µm = micrometers or microns). Intakes of automatic samplers are typically placed at the base of conduits, which can result in suspended solids concentrations containing larger particles being over-estimated.

As depicted by the dotted line in figure 2, if a sampler intake is located at 10% of the total depth (y/d = 0.1), the resulting sampled concentration for 250 µm sand particles will be approximately 2.1 times the mean concentration for the given flow condition. Similarly, at that same relative depth and flow condition, 100 µm fine sand-silt and 11 µm clay particles are sampled at approximate concentrations of 1.3 and 1.0 times the mean concentration, respectively. For this conduit, only clay particles can be sampled accurately. Suggestions have been made to place the sampler intakes at a depth above the bed, but the automatic sampler is unable to capture any events below the intake depth.

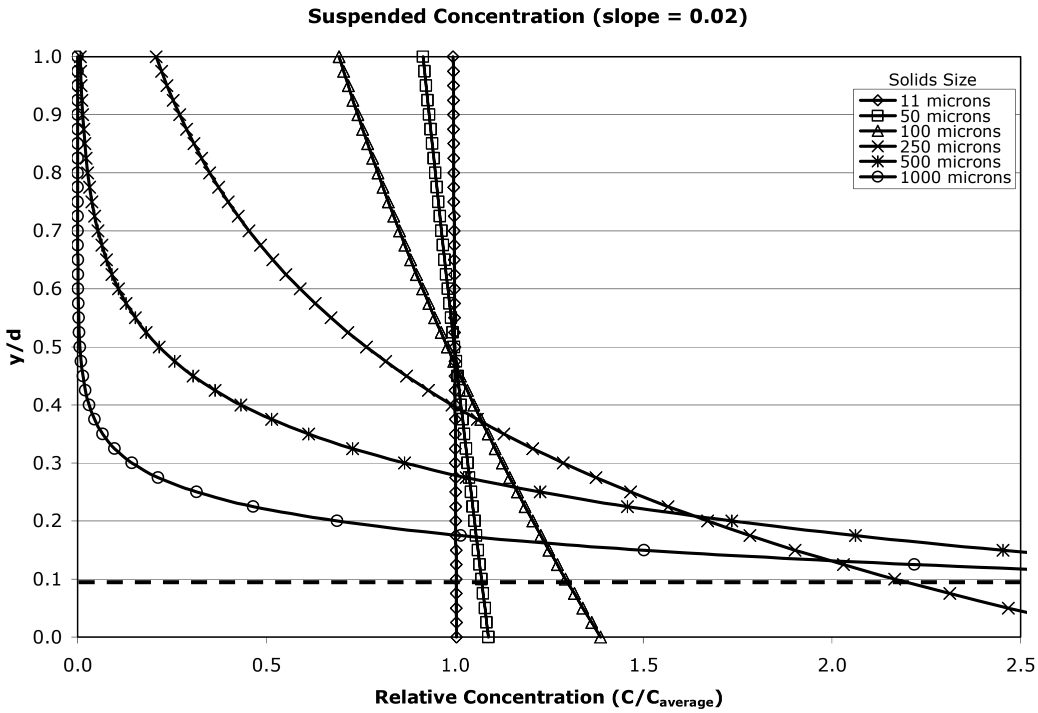

Figure 2: Suspended solids concentrations in a given flow condition as a function of depth (Rouse 1937). Where *C* = actual concentration, $\overline{C}$ = mean concentration, *y* = distance up from the bed, and *d* = depth of flow. Uniform flow in a wide open-channel with particle density of sand is assumed.

Developed from equations given in Rouse (1937), figure 3 represents a limiting particle size for a measured flow condition to ensure a sample concentration within 20% of the mean. Figure 3 assumes that the flow is fully developed, i.e., does not depend upon upstream entrance conditions. When sampling solids concentrations with automatic samplers, the sample is within 20% of the mean when the maximum particle size is at or below the limiting line depicted in figure 3.

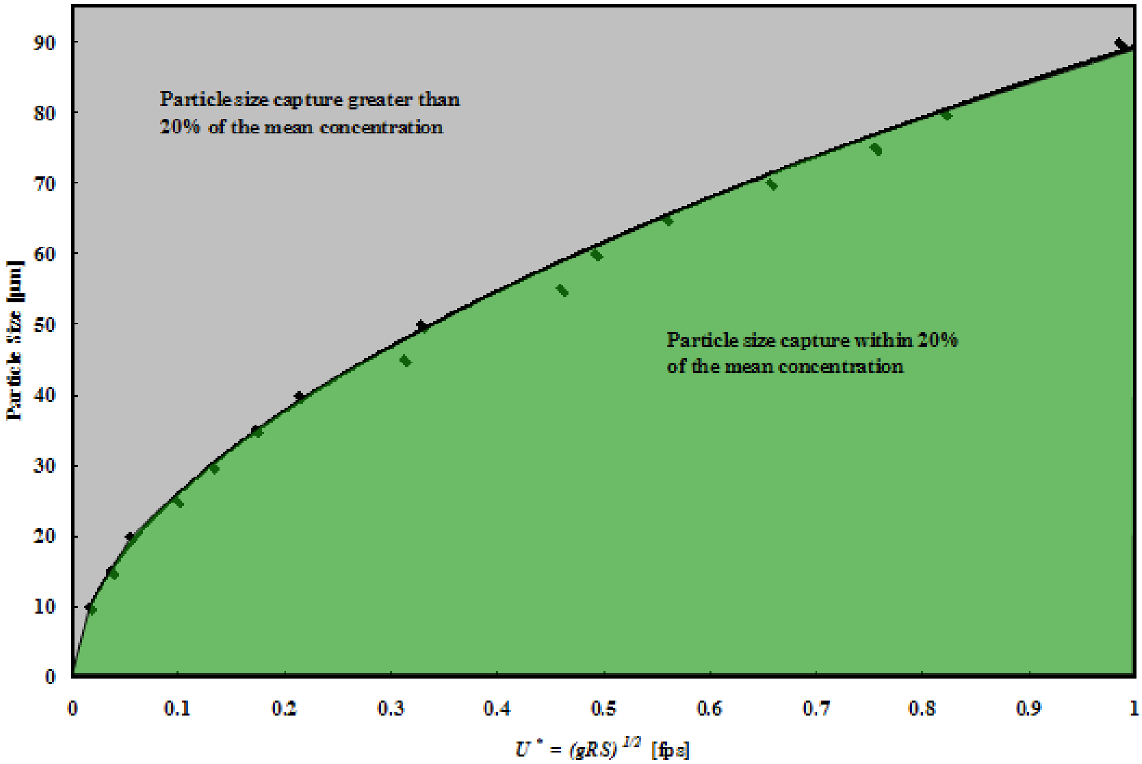

Figure 3: Particle size capture (density of sand) within 20% of the mean concentration under a measured flow condition typical of stormwater culverts. U^* = shear velocity (the square root of wall shear divided by liquid density), g = gravitational acceleration, R = hydraulic radius (A/P, where A = cross sectional area and P = wetted perimeter) and S = water surface slope, assumed equal to the culvert slope.

Example 1: Accuracy of automatic sampling of water containing suspended solids.
An 18 inch inside diameter culvert is oriented at a 2% slope and flowing at 6 inches of depth. Determine the solid size of sand density particles that will be captured within 20% of the mean concentration of that particle size.

> To use figure **3**, we need to calculate the shear velocity of the flow, which is the shear stress on the culvert wall divided by the density of stormwater. The hydraulic radius can be found in books on fluid mechanics or calculated at a Web site, such as http://www.ajdesigner.com/phphydraulicradius/hydraulic_radius_equation_pipe.php. In this case R = 0.31 ft. Then,
>
> $$U^* = \sqrt{gRS} = \sqrt{32.2\,ft/s^2 \times 0.31\,ft \times 0.02\,ft/ft} = 0.45\,ft/s$$
>
> Then, using figure **3**, we can determine that the particles less than or equal to 60 µm, i.e., silts and clays, will be measured within 20% of their true mean concentration. Sand-like particles greater than 60 µm, such as fine sand and above, will not be measured within 20% because of their vertical distribution in the flowing stormwater.

A second challenge is the velocity with which the sample is drawn. Automatic samplers are equipped with pumps to draw samples, which create velocities different from localized streamflow velocities at the intake. When the intake velocity is equal to the streamline velocity (i.e., localized streamflow velocity), the sampled suspended solids concentration equals the mean suspended solids concentration and is referred to as isokinetic sampling. With varying flow velocities and fixed intake velocities, automatic samplers rarely sample isokinetically. Research on non-isokinetic samplers (Federal Interagency Sedimentation Project 1941) found significant errors for particle sizes greater than 60 μm silt. Errors associated with non-isokinetic sampling are due to inertial effects of the particles. The larger particles have a significant mass, which corresponds to inertial forces that can result in particles not following curved flow streamlines coming into a non-isokinetic sampling port.

Dividing flow streamlines are indicated in figures 4a and 4b as illustrations of non-isokinetic sampling. Figure 4a is an example of when the intake velocity is greater than the flow velocity. Figure 4b is an example of when the intake velocity is less than the flow velocity. The green dashed line is an initial capture control volume upstream of the intake, and the blue dashed line is the corresponding capture control volume of the intake. Both figures contain two particles sizes, one significantly larger than the other.

The small particles have low inertial forces and have less of a tendency to cross streamlines. The larger particles have enough inertia to move in a horizontal direction and can cross the streamlines. For the case in figure 4a, a portion of the larger particles crosses out of the streamlines and is not captured by the intake, resulting in a measured concentration smaller than the true mean. When the flow velocity is greater than the intake velocity, as in figure 4b, the larger particles cross into the streamlines, resulting in a larger measured concentration than the true mean.

Figures 4a and 4b: Examples of non-isokinetic sampling. (Arrows indicate larger particles crossing streamlines.)

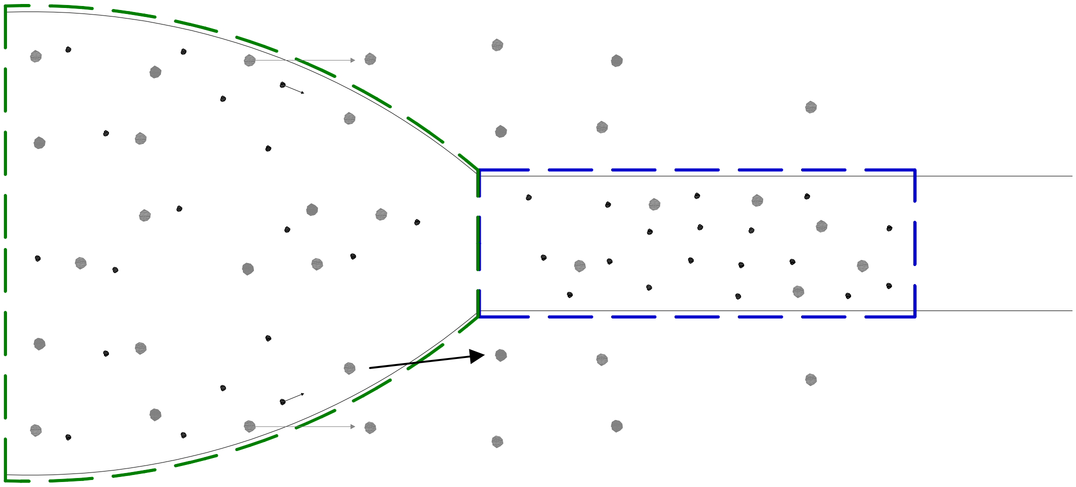

Figure 4a: The intake velocity is greater than the flow velocity.

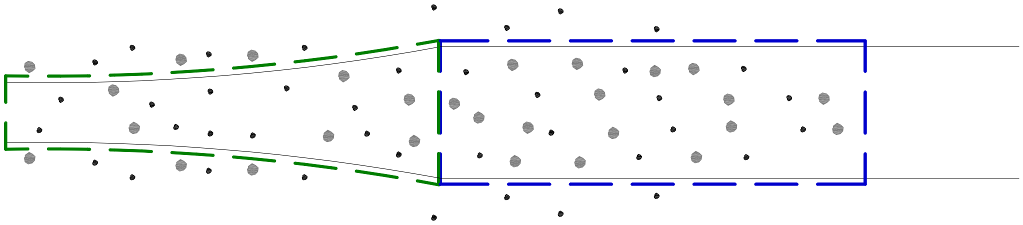

Figure 4b: The intake velocity is less than the flow velocity.

For most stormwater conditions, the sampling of fine sand and sand will not be sufficiently accurate. This does create additional challenges in sampling chemicals that are attached to particles, such as particulate phosphorus and many metals and organic chemicals. Currently, the only means of ensuring accurate solids sampling is to capture all of the solids over a known length of time and discharge. Then, suspended solids concentration may be computed from equation D.1. The units should be equivalent on each side of equation D.D.1.

$$C = M \times {}^{t}\!/_{Q} \qquad \text{(Equation D.1)}$$

where:
C = solids concentration (e.g., mg/L)
M = mass of solids collected (e.g., mg)
t = time of collection (e.g., seconds)
Q = stormwater discharge (e.g., liters per second)

Research is being conducted at the University of Minnesota's St. Anthony Falls Laboratory to investigate the limits of sampling suspended solids and particulates and to improve sampling methods for automatic samplers.

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E.

Appendix E

Assessing Thermal Impacts of Stormwater BMPs

O. Mohseni (omohseni@umn.edu) and W.R. Herb

This appendix provides instruction on how to assess thermal impacts of stormwater BMPs via monitoring influent and effluent flow temperatures.

Gulliver, J.S. and J.L. Anderson, ed. 2007. *Assessment of Stormwater Best Management Practices.* St Paul, MN: University of Minnesota.

While stormwater BMPs are designed to remove pollutants from stormwater runoff, they may increase the runoff temperature and adversely affect receiving cold water streams and the habitats of cold water fish species, such as brook or rainbow trout. Wet ponds, infiltration ponds, constructed wetlands, and underground vaults are examples of stormwater BMPs with the potential to thermally impact nearby trout streams. To assess the thermal impact of stormwater BMPs on stormwater runoff, the temperature of influent into and effluent from the stormwater BMP should be monitored.

Prior to monitoring, the temperature probes need to be calibrated against a NIST (National Institute of Standards and Technology) traceable thermometer, or against 32°F temperature by placing the probe in a mix of ice and water.

To measure the effluent and influent temperatures, the probe should be placed in a shaded area of the sewer pipe to avoid solar heating of the probe. It is recommended the probe be placed inside a PVC pipe anchored to the sewer to protect it from debris, as shown in figure 1. By using a pressure transducer or a probe equipped with a pressure transducer (as discussed in Chapter 4), the time at which stormwater runoff commences can be detected and recorded. When there is no runoff, the temperature probe records air temperature inside the storm sewer.

Figure 1: Installation of a temperature probe in a sewer pipe.

For wet ponds, constructed wetlands, and underground vaults, two probes are required to determine the thermal impact of the stormwater BMP on stormwater runoff. One probe should be installed upstream and one probe downstream of the stormwater BMP (T_u and T_d in figure 2). The difference between the temperatures recorded by these two probes can be used to determine the impact of the stormwater BMP on stormwater runoff.

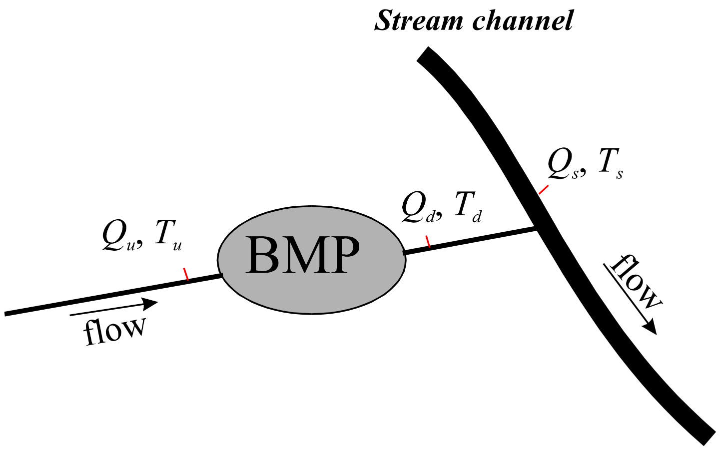

Figure 2: Schematic of locations where temperatures and flows should be measured to assess the thermal impacts of a stormwater BMP on a receiving stream.

To assess the thermal impact of the stormwater BMP on a receiving stream, a third probe in the stream located upstream of the stormwater BMP outfall (location of Q_s and T_s in figure 2) is required. To measure the water temperature in a stream or creek, the probe should be installed at least a few inches above the streambed and attached to stakes that are inserted securely into the streambed. It is not recommended to install the probe directly on, or buried in, the sediment bed because cold water streams are most often fed by groundwater. If the stream is groundwater fed, the water in and near the stream bed sediments is typically cooler than the water near the water surface. Most streams are well-mixed water bodies, and the temperature at or above the sediment surface is representative of the entire water column temperature. For shallow streams (less than 8 inches deep), it is recommended that the temperature probe be installed in a shaded area of the stream channel to avoid direct solar radiation affecting the temperature measurement of the probe.

The thermal impact of the stormwater BMP on the receiving stream at each time interval will then be estimated using the following equations:

Flow-weighted temperature of a stream without a stormwater BMP:

$$T_0 = \frac{Q_s\ T_s + Q_u\ T_u}{Q_s + Q_u} \qquad \text{(Equation E.1)}$$

where:

T_0 = Temperature in the stream without a stormwater BMP

Q_s = stream discharge upstream of stormwater BMP outfall

T_s = stream temperature upstream of stormwater BMP outfall

Q_u = runoff discharge entering stormwater BMP

T_u = temperature of runoff entering stormwater BMP

Flow-weighted temperature of a stream with a stormwater BMP:

$$T_1 = \frac{Q_s\ T_s + Q_d\ T_d}{Q_s + Q_d} \qquad \text{(Equation E.2)}$$

where:

T_1 = Temperature in the stream with a stormwater BMP

Q_s = stream discharge upstream of stormwater BMP outfall

T_s = stream temperature upstream of stormwater BMP outfall

Q_d = runoff discharge exiting stormwater BMP

T_d = temperature of runoff exiting stormwater BMP

Temperature change in a stream due to stormwater runoff.

$$\Delta T_{BMP} = T_1 - T_0 \qquad \text{(Equation E.3)}$$

where:

ΔT_{BMP} = Change in stream temperature due to the stormwater BMP

T_0 = Temperature in the stream without a stormwater BMP

T_1 = Temperature in the stream with a stormwater BMP

In equations E.1, E.2, and E.3, Q is discharge, T is water temperature, and the subscripts s, u and d refer to the receiving stream, upstream and downstream of the stormwater BMP, respectively, as shown in figure 2. T_1 and T_0 are temperatures of the receiving stream downstream of the outfall with and without the stormwater BMP in place, respectively. When stormwater runoff ceases (i.e., $Q_u = 0$), ΔT_{BMP} becomes the difference between T_1 and T_s.

Alternatively, the thermal impact of the stormwater BMP on the receiving stream can also be assessed by measuring water temperature at points upstream and downstream of the stormwater BMP outfall. The probe downstream of the outfall should be placed downstream of the mixing zone. The length of the mixing zone depends upon the base flow and width of the stream, as well as the stormwater BMP effluent discharge (Gulliver 2007). Assessing thermal impacts of a stormwater BMP in this way is only recommended for creeks and small streams because estimating the mixing zone length for large streams during all flow conditions may be challenging. For large streams and rivers, the stream discharge can be estimated using discharge monitoring stations on the stream. The stormwater BMP influent and effluent discharge can be measured using the techniques described in Chapter 4.

Assessing the impacts of an infiltration pond constructed near a cold water stream can be a challenging task, and in many cases, inconclusive. The thermal impact is via warmed groundwater and therefore the impact may be a relatively small change in temperature over a relatively long time period compared to surface water impacts. For assessing infiltration ponds, water temperature of the receiving stream should be measured at a minimum of two locations in addition to the stormwater BMP influent temperature and discharge. Temperature probes should be carefully calibrated and placed in the stream upstream and downstream of the infiltration pond, as shown in Figure 3. Water level and temperature of stormwater within the infiltration pond may be used to estimate infiltration rate (Q_u) and temperature of the infiltrating runoff (T_u), respectively.

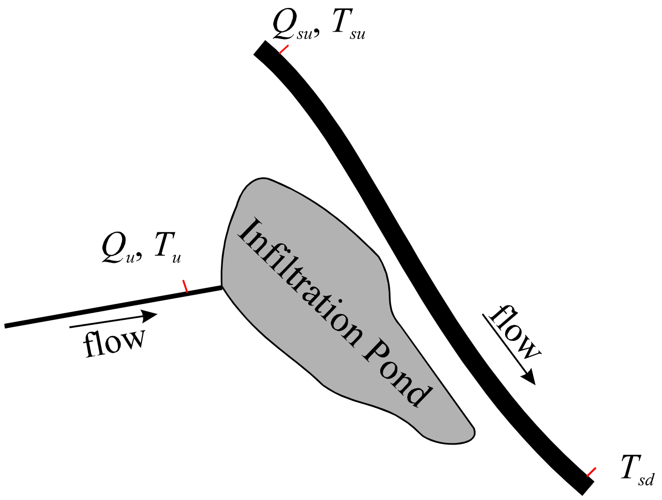

Figure 3: Schematic of locations where temperatures and flows should be measured to assess the thermal impacts of an infiltration pond on a receiving stream.

A measured difference in stream temperature (T_{sd} - T_{su}) may be due to atmospheric heating, surface inflow, or warmed groundwater feeding the stream from the infiltration BMP. During hot summer days, solar radiation can heat the stream such that the water temperature at the downstream point (T_{sd}) becomes warmer than at the upstream point (T_{su}). The temperature difference varies diurnally and depends upon the solar radiation received, the distance between the upstream and downstream measurement locations, stream discharge, and stream geometry (see figure 4). During storm events and for several hours after, inflow of surface runoff directly into the stream may have a significant impact on the temperature difference (T_{sd} - T_{su}). The thermal impact of surface inflow may be identified as transient change in the temperature difference (see figure 4). The thermal impacts due to an infiltration basin may be identified as a relatively constant temperature difference during periods of infiltration after storms (see figure 4). If both atmospheric heating and surface inflows are negligible, the thermal impact of the stormwater BMP on the receiving stream can be estimated using equations E.4 and E.5.

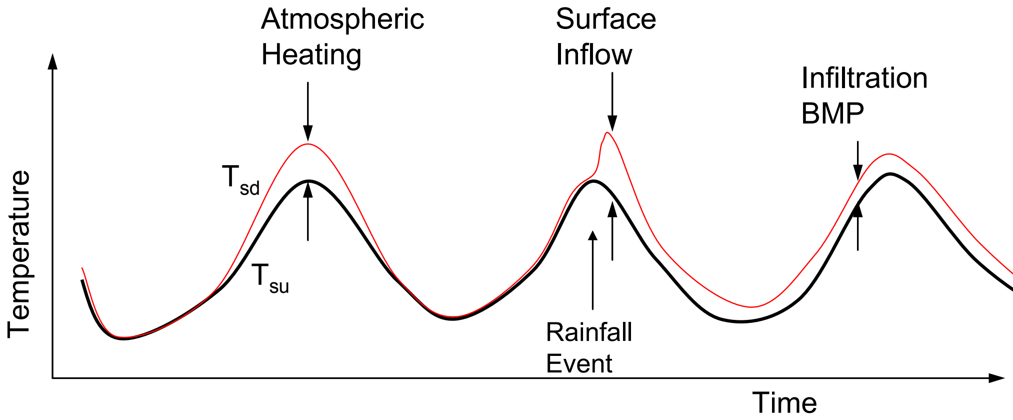

Figure 4: Typical characteristics of thermal impacts due to atmospheric heating, surface inflows, and warmed groundwater from an infiltration stormwater BMP.

Flow-weighted temperature of a stream without an infiltration BMP:

$$T_0 = \frac{Q_{su}\ T_{su} + Q_u\ T_u}{Q_{su} + Q_u} \qquad \text{(Equation E.4)}$$

where:

T_0 = Temperature in the stream without an infiltration BMP

Q_{su} = stream discharge upstream of infiltration BMP

T_{su} = stream temperature upstream of infiltration BMP

Q_u = runoff discharge entering infiltration BMP

T_u = temperature of runoff entering infiltration BMP

Temperature change in a stream due to infiltrated stormwater runoff:

$$\Delta T_{BMP} = T_{sd} - T_0 \qquad \text{(Equation E.5)}$$

where:

ΔT_{BMP} = Change in stream temperature due to the infiltration BMP

T_0 = Temperature in the stream without an infiltration BMP

T_{sd} = Temperature in the stream with an infiltration BMP

The temperature and runoff data collection should be conducted near-continuously during the warmer months of the year; e.g., from the end of May until the end of August in the northern USA. The recording time steps should be selected based on the capacity of the data storage system and the frequency of data retrieval. It is recommended that a small time step (e.g., one measurement per 5 or 10 minutes) is used to measure stormwater BMP influent. A longer time step (e.g., one measurement per 30 minutes) can be used for measuring temperature and discharge downstream of the stormwater BMP because discharge from wet ponds, infiltration ponds, and constructed wetlands often occurs over longer time periods. One measurement per 30 minutes can also be used for stream temperature measurement because changes in stream temperature often occur over longer time periods.

Thermal impact of stormwater BMPs is not necessarily detectable during every storm event. Small storms often do not result in measurable thermal impact of stormwater BMPs on nearby streams. Large storms, however, with warm weather patterns before and after the storm can result in a measurable thermal impact of stormwater BMPs on stormwater runoff and subsequently, receiving waters.

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