CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No. 17-015
UILU-ENG-2017-2015
ISSN: 0197-9191

EFFECTIVE POST-CONSTRUCTION BEST MANAGEMENT PRACTICES (BMPs) TO INFILTRATE AND RETAIN STORMWATER RUN-OFF

Prepared By

Abdolreza Osouli
Assistant Professor
Department of Civil Engineering
Southern Illinois University Edwardsville

Mark Grinter
Associate Professor
Department of Construction
Southern Illinois University Edwardsville

Jianpeng Zhou
Professor
Department of Civil Engineering
Southern Illinois University Edwardsville

Laurent Ahiablame
Department of Agriculture and Biosystems Engineering
South Dakota State University

Timothy Stark
Professor
Department of Civil and Environmental Engineering
University of Illinois at Urbana Champaign

Research Report No. FHWA-ICT-17-011
A report of the findings of
ICT PROJECT R27-141
Effective Post-Construction Best Management Practices (BMPs) to Infiltrate and Retain Stormwater Run-Off

---

Illinois Center for Transportation
June 2017

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-ICT-17-011	N/A	N/A

4. Title and Subtitle Effective Post-Construction Best Management Practices (BMPs) to Infiltrate and Retain Stormwater Runoff	**5. Report Date** June 2017 **6. Performing Organization Code** N/A
7. Author(s) Abdolreza Osouli, Mark Grinter, Jianpeng Zhou, Laurent Ahiablame, Timothy Stark	**8. Performing Organization Report No.** ICT-17-015 UILU-ENG-2017-2015
9. Performing Organization Name and Address Department of Civil Engineering SIEU School of Engineering Campus Box 1804 Engineering Bldg., Room 3057 Southern Illinois University Edwardsville Edwardsville, IL 62026	**10. Work Unit No.** N/A **11. Contract or Grant No.** R27-141
12. Sponsoring Agency Name and Address Illinois Department of Transportation (SPR) Bureau of Material and Physical Research 126 East Ash Street Springfield, IL 62704	**13. Type of Report and Period Covered** Final Report: 2/1/14 – 6/30/17 **14. Sponsoring Agency Code** FHWA

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

Performance analyses of newly constructed linear BMPs in retaining stormwater run-off from 1 in. precipitation in post-construction highway applications and urban areas were conducted using numerical simulations and field observation. A series of simulations were conducted using an idealized catchment on a four-lane highway located on sites with soil types ranging from clayey to sandy material across state of Illinois. The use of turfgrasses and prairie grass vegetative surface covers in pre-BMP scenarios in promoting infiltration and reducing stormwater run-off were investigated. Three types of BMPs—bioswale, infiltration trench, and vegetated filter strips—as well as combinations thereof, were studied for determining their ability to control stormwater run-off in an idealized catchment. This report also documents the maintenance cost, construction cost, and life-cycle analyses of those BMPs to identify cost-effective solutions. The effects of erosion and a sediment accumulation rate of 1 t/ac/y on BMPs during the 2-year and 10-year lifespans of bioswales and infiltration trenches were studied using full-scale field tests. The simulation and field test results provide insight for developing guidelines for cost-effective BMPs to control stormwater run-off in linear projects.

17. Key Words	18. Distribution Statement
Stormwater volume reduction, bioswale, infiltration trench, vegetated filter strip, BMP performance, BMP cost, maintenance, construction, field performance, linear BMPs	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	114 pp + appendices	N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This publication is based on the results of **ICT-R27-141: Effective Post-Construction Best Management Practices (BMPs) to Infiltrate and Retain Stormwater Runoff**. ICT-R27-141 was conducted in cooperation with the Illinois Center for Transportation, the Illinois Department of Transportation, and the U.S. Department of Transportation, Federal Highway Administration.

Members of the Technical Review panel were the following:

- Scott Marlow (TRP Chair), Illinois Department of Transportation
- Tom Brooks, Illinois Department of Transportation
- Mike Copp, Illinois Department of Transportation
- Jeff Harpring, Illinois Department of Transportation
- Matt Sunderland, Illinois Department of Transportation
- Rick Warner, Illinois Department of Transportation
- John Szabo, Illinois State Toll Highway Authority
- Joseph Vespa, Illinois Department of Transportation
- David Broviak, Illinois Department of Transportation
- Stephanie Dobbs, Illinois Department of Transportation

The authors would like to acknowledge the Technical Review Panel in this project and especially the chair, Scott Marlow, for their support, comments, and guidelines. The authors would like to thank the Illinois Department of Transportation and Illinois Center for Transpiration for facilitating this study. The authors would like to thank many individuals who helped as consultants or provided data to make this study possible. Special thanks go to many students who participated in various aspects of this project. The authors would sincerely thank Azadeh Akhavan Bloorchain for modeling scenarios, Seyed Sina Nasiri for helping with the design, construction and running the field tests, Sudesh Thapa for helping with construction and field tests, Srood Omer for helping with the literature review of the first phase of the project, and Aneseh Alborzi for helping with the cost analyses.

EXECUTIVE SUMMARY

To comply with the Clean Water Act, the Illinois Environmental Agency (IEPA) plans to mandate retaining the first 1 in. of stormwater run-off as part of the requirements for National Pollution Discharge Elimination System (NPDES) permits (ILR10 and ILR40).

The R27-141 IDOT/ICT project focuses on performance and cost effectiveness of post-constriction best management practices (BMPs) to infiltrate and retain the first 1 in. of stormwater run-off. Implementing run-off volume reduction strategies in a transportation right-of-way environment presents a number of challenges and restrictions caused by the limited space available in the right-of-way for on-site use of infiltration, evapotranspiration, or flow control measures. Because greater challenges are expected in urban areas, highways in an urban setting were the focus of this study.

An extensive literature search was conducted to identify the reported efficiency of BMPs in controlling stormwater run-off. The review of national and Illinois BMP resources revealed that infiltration practices such as bioswales, infiltration trenches, and vegetated filter strips are best suited for this objective. The review of literature showed that the performance of BMPs depends on site and watershed characteristics. To consider these variables, a numerical approach was selected. The simulations of the performances of these BMPs were conducted using the Personal Computer Storm Water Management Model (PCSWMM). The simulation methodology was examined with the reported performance of sites in South Carolina and Virginia to make sure that results are in general agreement with observed performances.

A series of simulation analyses were performed using an idealized catchment, which included a four-lane highway, foreslope, BMP area, and backslope as part of the right-of-way. These analyses considered (1) sites with no BMP to sites with single or combined BMPs, (2) BMP size effect on stormwater run-off control, (3) soil vegetative covers varying from no vegetation to deep-rooted vegetation, and (4) soil types ranging from sandy material to clayey material.

It was concluded that prairie grass cover provided up to 40% more run-off volume reduction for a 1-in./24-hour event than the site without vegetative cover. The inclusion of turfgrass cover marginally improves the infiltration capacity of the system. The simulation results also showed that the newly constructed BMPs with typical dimensions are effective in controlling 80% to 100% of the run-off from a 1-in. rainfall in the catchment area.

It should be noted that the results obtained for newly constructed or well-maintained BMPs may overestimate the performance of the BMPs when compared to field observations owing to factors such as aging, clogging, and poor maintenance. The limited field test results conducted in this study show that for bioswales, the run-off volume reduction of an idealized catchment with a 10-year-old bioswale may be half of the reduction resulting from a new bioswale.

Construction cost, maintenance cost, and the expected life of three BMPs (infiltration trench, bioswale, and vegetated filter strip) were also evaluated. Construction costs were determined based on the price that a qualified subcontractor would submit to a general contractor for a project of at least two weeks' duration. The cost estimates are exclusive of general conditions, inspections, design, sales tax,

mobilization, and traffic control. The estimated costs are for the BMP only and are based on June 2015 Illinois prevailing wage rates and equipment cost. Because the costs were itemized based on unit costs, the developed methodology can be used for any other state or year. BMP costs should be weighed against the benefits they offer.

Regarding run-off reduction factors, a simulated model revealed that the averages of percentage stormwater run-off reduction from a 1-in. rainfall event were 80% for bioswales, 100% for infiltration trenches, and 76% for vegetated filter strips, implying that vegetative filter strip performance is the lowest among the BMPs analyzed. However, filter strip construction and maintenance costs are substantially lower than costs for bioswales or infiltration trenches, indicating that, in cases where capital is limited, vegetative filter strips may be a superior choice.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

Term	Abbreviation
Best management practice	BMP
BMP runoff volume reduction	BMP_{RVR}
Department of Transportation	DOT
Hydrological Simulation Program—Fortran	HSPF
Idealized catchment performance efficiency	ICPE
Illinois Environmental Protection Agency	IEPA
Low-impact development	LID
National Pollutant Discharge Elimination System	NPDES
PC Storm Water Management Model	PCSWMM
Soil and Water Assessment Tool	SWAT
Storm Water Management Model	SWMM
U.S. Environmental Protection Agency	USEPA
Vegetated filter strip	VFS

TERMS AND DEFINITIONS

Bare soil: The condition when there is no surface cover on the soil.

BMP run-off volume reduction (BMP_{RVR}): The percentage of run-off that is reduced by the BMP subcatchment. It is calculated by comparing the run-off from the BMP and the sum of run-on and precipitation to the BMP.

Catchment area: The total area including the highway and the right-of-way that contributes stormwater run-off to BMP.

Conductivity: Hydraulic conductivity of saturated soils (in./hr or mm/hr).

Initial deficit: Fraction of soil volume that is initially dry.

Prairie grass: Native prairie vegetation is a dense root structure capable of growing to substantial depths below the ground surface.

Subcatchment: Portions of the catchment area. In this report, subcatchments are highway, foreslope, level ground, backslope, and BMP.

Suction head: Average value of soil capillary suction along the wetting front (in. or mm).

Turfgrass: Turf or dense grass, which includes species such as weeping lovegrass, bluegrass, buffalograss, blue grama grass, and fescue.

CHAPTER 1: INTRODUCTION

Stormwater run-off from roads such as highways may negatively affect the environment. Suspended solids, deicing chemicals, salt, and antiskid materials may have impacts on vegetation, soil, and water quality (DEP 2006). National Pollutant Discharge Elimination System (NPDES) permits for construction sites in the state of Illinois (NPDES Permit No. ILR10 and ILR40) were designed to regulate stormwater management strategies. Expected new permit revisions require land developers to retain or control the first 1 in. of precipitation on-site. The underlying idea is that if the quantity of the stormwater run-off is controlled on-site, the quality of the water is automatically preserved, per the Association of Illinois Soil and Water Conservation Districts (IEPA 2013). The focus of this project is to identify appropriate post-construction practices for linear projects that can cost effectively control 1 in. of precipitation.

USEPA Fact Sheet 2.7 outlines the guidelines for post-construction run-off control measures. Per Phase II of the regulated small (MS4) stormwater program, post-construction run-off control is one of the six components in stormwater management programs required to meet the conditions of NPDES permits. Control of post-construction run-off is necessary, especially for areas experiencing new development or redevelopment. The rule requires developing, implementing, and enforcing practices to reduce run-off in newly developed and redeveloped projects. The specific requirements are the following:

- Develop and implement planning strategies, including both structural and non-structural best management practices (BMPs).
- Establish a regulatory mechanism requiring control of post-construction run-off.
- Develop a long-term operation and maintenance guide.
- Identify appropriate BMPs and measurable goals for their performance (Illinois Urban Manual 2002).

Best management practices are the primary approach to control stormwater discharges on-site. The USEPA defines a BMP as an engineered and constructed system designed to control water quantity and quality (USEPA 1999b). Most often, the purpose of a BMP is to restore the site's pre-development hydrologic condition (USEPA 2000; PGC 1999). Structural BMPs include storage, infiltration, and vegetatative practices.

- Storage Practices: These practices store run-off in wet/dry ponds or basins and then release water in a controlled manner to receiving water bodies. Storage basins typically have a minimum depth of 3 ft and side slopes no steeper than 5 horizontal to 1 vertical.
- Infiltration Practices: The design objective of these practices is to facilitate the infiltration of run-off to the soil. These practices are effective in reducing run-off quantities. Several examples include infiltration basins, infiltration trenches, and porous pavements. Per NCHRP 2006, the following are recommended:
    - These practices be established on areas with hydrologic soil groups A or B.

- Run-off from impervious areas may discharge to filter strips and bioswales before being directed to infiltration practices or detention basins or storm sewer drainage system. Pollutants and sediments should be removed by a settling basin before reaching infiltration basins or trenches.
    - Infiltration practices designed to recharge groundwater should not be constructed in close proximity (i.e., 75 ft) of a water supply well.
    - Infiltration BMPs should have a bottom elevation at least 4 ft above groundwater or bedrock level.
- Vegetative Practices: These BMPs perform a number of duties, including increasing aesthetic features, improving pollutant removal, and enhancing natural hydrology. Examples of these practices can be grass swales, filter strips, and wetland basins. These practices remove coarse sediments and enhance run-off infiltration. Run-off should be directed to filter strips and bioswales before reaching drainage systems or detention basins (Illinois Urban Manual 2002).

The goal of this research is to identify the BMPs and strategies that can help the Illinois Department of Transportation (IDOT) capture stormwater run-off induced by 1 in. of precipitation along highways in urban areas. To compare BMP performances, a survey of the reported performances of different BMPs was conducted. The survey results are presented in Chapter 2. Owing to limited monitoring data, a numerical approach had to be taken to analyze the performance of BMPs. The simulation methodology, assumptions, considered scenarios, performance metrics, and verification methodology are discussed in Chapter 3. The effect of surface cover vegetation, individual and combined BMPs, and BMP scale on stormwater reduction in an idealized catchment is discussed in Chapter 4. Chapter 4 also includes the performance results for BMP subcatchment sizing required to capture all run-off produced by 0.25-, 0.5-, and 1-in. rainfall events during a 24-hour period. Chapter 5 presents the construction, maintenance, and life-cycle cost analysis. Chapter 6 includes the field test results on new and aged bioswale and infiltration trenches. Chapter 7 compares the simulation and field tests results. Chapter 8 includes recommendations for selecting and installing, as well as cost and maintenance of BMPs.

CHAPTER 2: MONITORED PERFORMANCE OF POST-CONSTRUCTION BMPs

The hydrologic performance of stormwater BMPs is an important factor in the overall effectiveness of BMPs in reducing potential adverse impacts of urbanization on receiving waters (Poresky et al. 2011). Various studies, which focused on the performance of different BMPs at different scales via field measurement or numerical modeling indicated that site characteristics influence the effectiveness of run-off volume reduction. Site characteristics include local climate, soil types, geologic conditions, groundwater conditions, site topography, project location in the watershed, and adjacent land uses. Project characteristics influencing run-off volume reduction include project type, highway type, amount of open space in medians and shoulders, shoulder width and use, highway landscaping and vegetation, and maintenance access (Strecker et al. 2015).

Implementing run-off volume reduction approaches (VRAs) along urban highways presents a number of challenges and restrictions because of the limited space available in the right-of-way for on-site use of infiltration, evapotranspiration, or flow control measures (Strecker et al. 2015). NCHRP 25-41 (2014) provides information to DOTs for developing guidelines on implementing effective measures for urban highway areas. The NCHRP report provides guidelines for several VRAs that primarily promote infiltration practices. The report also provides a volume performance tool allowing users to estimate approximate volume reduction of a VRA or a series of VRAs. This tool is an Excel spreadsheet application in which the user selects project location, precipitation data, and general project information. The tool calculates an estimate of long-term volume reduction for that VRA. These tools are useful for planning stages and for ranking VRAs. However, for more site-specific estimates of volume reduction performance, a more detailed approach is needed.

The NCHRP 728 (2012) and NCHRP 792 (2014) reports, which both refer to Poresky et al. (2011) study, summarized BMP monitoring data reported in the International BMP Database. Table 1 shows the reported volume reductions for various BMPs (Poresky et al. 2011; Clary et al. 2012; NCHRP 2012, 2014). The report database shows a range of volume reduction of 34% to 57 % for biofilter or bioretention with underdrain practices and less than 11% for wet practices such as wet ponds or wetland basins/channels. One of the limitations of these data is that the watershed to BMP area is not known.

Vegetated filter strips, vegetated swales, bioretention, and grass-lined detention basins are described in the international BMP database as normally dry vegetated BMPs. Normally dry vegetated BMPs provide high-volume reduction for smaller events, which occur more frequently than large storm events. On average, filter strips and grass-lined detention basins have been reported to have 30% to 40% volume reduction while grass swales have more than 40% volume reduction, and bioretention with underdrains has 50% volume reduction (Poresky et al. 2011). Other studies show that the percentage run-off volume reduction for vegetated filter strips ranges from 40% to 85%; for vegetated swales, the reduction is 50% to 94% (Hunt et al. 2010; Xiao and McPherson 2009). The difference in performances may be related to the sizes of the studied BMP, sizes of storm events, site conditions, and BMP conditions at the time of monitoring. It should also be noted that the majority of the grass swales in the BMP database (approximately 70%) were designed in the 1990s and 1980s or earlier, suggesting that they may not have performed at their original full capacity at the time of monitoring (Clary et al. 2012).

Studies demonstrated almost 100% mitigation capacity for infiltration trenches (Geosyntec 2008; Caltrans 2004). The NCHRP 565 (2006) study shows that biofilters would result in an average 38% volume reduction, while wet practices typically have less than 7% volume reduction capacity (NCHRP 2006). Retention ponds, wetland basins, and channels have been reported to provide insignificant volume reduction and should not be considered for volume reduction purposes (Poresky et al. 2011). For linear projects in urban areas, volume reduction may best be achieved using infiltration practices, vegetated filter strips, and grass swales (NCHRP 2012).

Table 1. Summary of BMP Performance Reported by the International BMP Database (Clary et al. 2012)

BMP Category	Number of Monitoring Studies	25th Percentile	Median	75th Percentile
Vegetated Filter Strips	16	18%	34%	54%
Bioswales	13	35%	42%	65%
Bioretention (with underdrains)	7	45%	57%	74%
Detention Basins, Grass Lined	11	26%	33%	43%
Retention (Wet) Ponds	20	2%	11%	18%
Wetland Basins/Channels	11	3%	4%	5%

Relative volume reduction = (total inflow volume – total outflow volume) / (total inflow volume).

The summary does not reflect performance categorized according to storm size.

Although the literature offers extensive information regarding BMP performance, monitoring efforts have been limited to short-term and localized evaluations. There are additional study limitations that make it difficult to derive comprehensive conclusions regarding BMP performance:

- The reported sites might have significant differences in site conditions, including geometry, soil conditions, vegetated surface covers, and topography.
- Theoretically, all BMPs can be designed in a way that all stormwater is captured by the BMP. Therefore, the sizing of the BMP relative to the contributing watershed is important when the comparisons are made.
- The intensity and duration of the storm event are critically important. A BMP may have enough capacity to capture all storm run-off from 1-in. rainfall during a 24-hour event. However, it may not capture all run-off if that 1-in. rainfall is precipitated in an hour.
- The age and conditions of the BMPs at the time of monitoring are also important. BMPs that are poorly maintained or covered with sediment and debris will not perform as well as BMPs that are new or well maintained.

- The maintenance practice itself is a contributing key factor. Sites that are covered with vegetation and are frequently mown by heavy machinery will be compacted over time and may lose their infiltration capacity.

To compensate for site variability, some studies used numerical simulations to evaluate the effect of each parameter on BMP system performance. For example, Zimmerman et al. (2010) used Hydrological Simulation Program–Fortran (HSPF) to calibrate and validate a hydrologic model for a river basin in Massachusetts (Zimmerman et al. 2010) and model the grass swale (Ackerman et al. 2008). Other tools, such as the Soil and Water Assessment Tool (SWAT) (White et al. 2009) and the Long-Term Hydrologic Impact Assessment Low-Impact Development (L-THIA-LID) models (Ahiablame et al. 2012; Liu et al. 2015) have also been used to analyze vegetated filter strip at the watershed scale. Some studies used the Storm Water Management Model (SWMM), which is a dynamic rainfall-run-off-routing simulation model. These modeling studies indicated that the algorithms used in LID control parameters provide satisfactory results for the event and continuous simulations (Abi Aad et al. 2010; McCutcheon et al. 2013; Sun et al. 2014).

This study employed a numerical modeling approach for considering site variabilities. Following IEPA requirements, this study sought to explore how effectively the first 1 in. of precipitation can be retained on-site either by linear BMPs or soil surface vegetative cover in the right-of-way using the PC Storm Water Management Model (PCSWMM). The PCSWMM has an SWMM engine and employs a numerical modeling approach to evaluate the impact of many factors on BMP performance. More information about PCSWMM is provided in Section 3.1.

CHAPTER 3: BMP PERFORMANCE SIMULATION

An idealized catchment was used in this study to represent subcatchment variables associated with different types of soil and site conditions in Illinois. The idealized catchment area includes half of an eight-lane interstate highway and its right-of-way in an urban area. An eight-lane highway (four lanes in each direction) was selected as a representative highway in an urban area (AASHTO 2005). Assuming a symmetric condition, simulating one side of the highway was deemed sufficient. BMPs located within the right-of-way were modeled to identify their performance efficiency in capturing a 1-in. rainfall.

The idealized subcatchment consists of four 12-ft-wide lanes of pavement, a 10-ft paved shoulder, and 60 ft of additional right-of-way (AASHTO 2005; Harwood et al. 2014). The 60-ft right-of-way includes a foreslope, level ground, and backslope that may be covered by vegetation, have a BMP, or be bare soil (Figure 1). The total idealized catchment width is 118 ft, as shown in Figure 1.

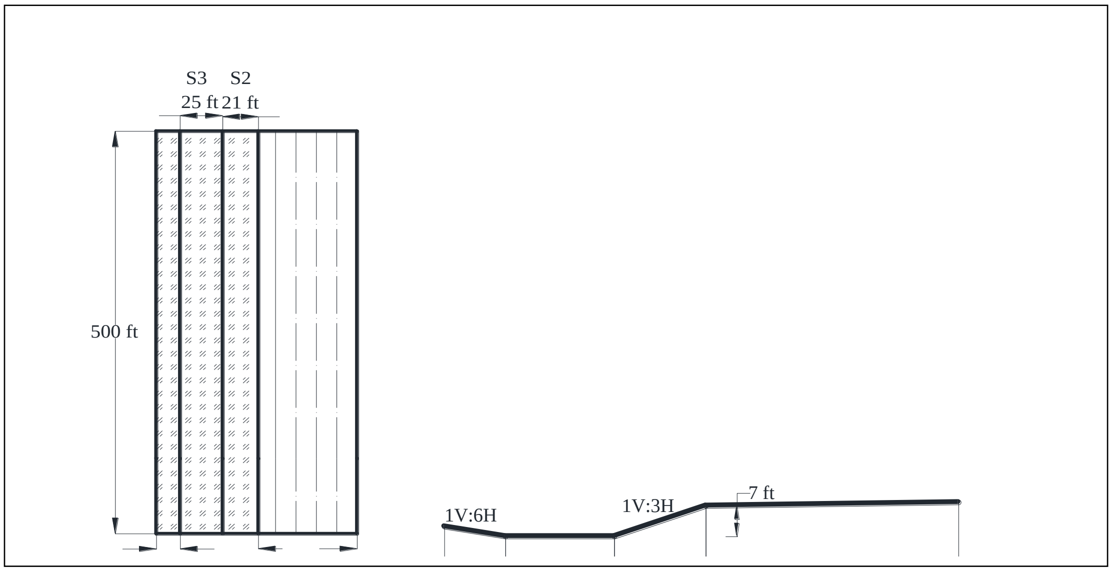


Figure 1. Idealized catchment for highway run-off modeling; subcatchments from right to left are S1 (highway), S2 (foreslope), S3 (level ground), and S4 (backslope).

The normal cross-slope for interstate highways varies between 1.5% to 2% and is typically for drainage purposes (AASHTO 2005; Harwood et al. 2014; Roess et al. 2011). A cross-slope of 1.5% was used for the highway (paved area) in this study.

The assumed length of the highway in the idealized catchment for this study is 500 ft (Table 2). The right-of-way area on the sides of the idealized highway is divided into three subcatchments: foreslope, level ground, and backslope. A slope of 3H:1V (33%) was used for the foreslope, 0% for level ground, and 6H:1V (17%) for the backslope. It should be noted that the 3H:1V slope for the foreslope is the maximum allowable slope for safe operations of maintenance and mowing equipment, and the 6H:1V slope for the backslope is the recommended maximum slope for stability in locations where sandy soils are predominant (Roess et al. 2011).

Based on typical Illinois highway design guides (2IM group 2009; Christian-Roge & Associates 2011), a 7-ft-high road embankment was chosen as the idealized catchment. A summary of dimensions for each subcatchment shown in Figure 1 is provided in Table 2. The input parameters used for characterizing each subcatchment are shown in Table A1-1 in the appendix to this report.

Table 2. Subcatchment's Geometric Characteristics in the Idealized Catchment Area for Highway Run-Off Modeling

Subcatchment	Area (ac)	Length (ft)	Width (ft)	Slope (%)
S1	0.67	500	58	1.5
S2	0.24	500	21	33
S3	0.28	500	25	0
S4	0.16	500	14	17

3.1 PCSWMM

PCSWMM is the proprietary software that was used in this study. It was developed based on USEPA SWMM. PCSWMM combines the SWMM computational engine with a geographic information system (GIS). The Storm Water Management Model (SWMM) is a dynamic rainfall-run-off simulation model widely used for single events or long-term (continuous) simulation of run-off quantity and quality from urban areas (James et al. 2010). PCSWMM includes the full USEPA SWMM engine with additional features to account for various hydrologic processes that influence run-off from rural and urban areas. The model can represent a watershed with pervious and impervious areas, a stream network, and sewers, and it can accommodate various time steps ranging from seconds to hours. Some of the key features of PCSWMM are as follows (CHIWATER 2011):

- Scalability—PCSWMM provides support for a range of watershed scales.
- Integrated GIS—PCSWMM has a high-performance GIS engine that is optimized for many common data processing and topological operations relating to stormwater and watershed modeling.
- Flexible choice of hydrology/hydraulics engine—PCSWMM supports all versions of the official USEPA SWMM engine.
- User-friendliness—PCSWMM is designed to be efficient to use.

Although PCSWMM has hydrological modeling capability and can incorporate dynamic analysis with nonlinear reservoir model, it has—like any other modeling software—some limitations. For example, the watershed size limit is 10 mi^2 (Borah and Weist 2008). Additional limitations experienced during this research include a restriction on defining a detailed soil profile within 60 in. from the ground surface and not accepting slopes less than 0.5%. PCSWMM has no module available for vegetated filter strip analyses. Therefore, the bioretention model was adapted to represent vegetated filter strips.

Three infiltration simulation method options are available in PCSWMM: curve number, Horton, and Green-Ampt. The curve number method is a simple, widely used, and efficient method for determining the approximate amount of run-off from a rainfall event in a particular area for a single storm event.

The Horton method is an empirical method. It assumes that if the amount of rainfall exceeds the infiltration capacity, infiltration tends to decrease exponentially over time. The Horton equation captures the basic behavior of infiltration, but the physical interpretation of the exponential constant requires lab or field tests.

Green-Ampt, one of the most widely used infiltration models, is an approach based on Darcy's Law. This model has provided results that match empirical observations. The simplicity and accuracy of this model facilitate its use in many field problems, such as infiltration computation in rainfall run-off modeling (Kale and Sahoo 2011). The Green-Ampt method was selected for run-off and BMP simulations in this study because of its superior representation of infiltration events (Lee 2011).

3.2 SIMULATED SITE CONDITIONS

3.2.1 Precipitation

Design guidelines in Illinois recommend that green infrastructure design be based on the 95th percentile storm (IEPA 2013). In 2013, an IEPA workgroup recommended that new development sites should either demonstrate no net increase in run-off resulting from the development or retain run-off from a 1-in./24-hour storm event, which is approximately equivalent to a 90th percentile storm in Illinois (IEPA 2013). This recommendation provides significant protections for Illinois water resources. For example, if a site has 50% impervious area and is located in an area with Category B soils, capturing the run-off from a 1-in. rain event will typically keep 95% of phosphorus pollutants out of the downstream waters and will keep 98% of the total suspended solids out of the discharges (IEPA 2013)

PCSWMM is not limited to a defined storm type or the built-in hydrographs. PVSWMM can work with any hydrograph based on detailed precipitation data. This project modeled BMP performances under an Illinois Type II storm of 1 in. of rainfall in 24 hours (McCuen 2005). The simulation results presented in Chapter 4 are based on a 24-hour, 1-in. precipitation event. It was conservatively assumed that evaporation during the precipitation is negligible. Also, it was assumed the site did not have rainfall before this precipitation event; therefore, antecedent moisture conditions were not taken into consideration. Figure 2 shows the 1-in. precipitation intensity distribution of the 24-hour rainfall event used for the simulations.

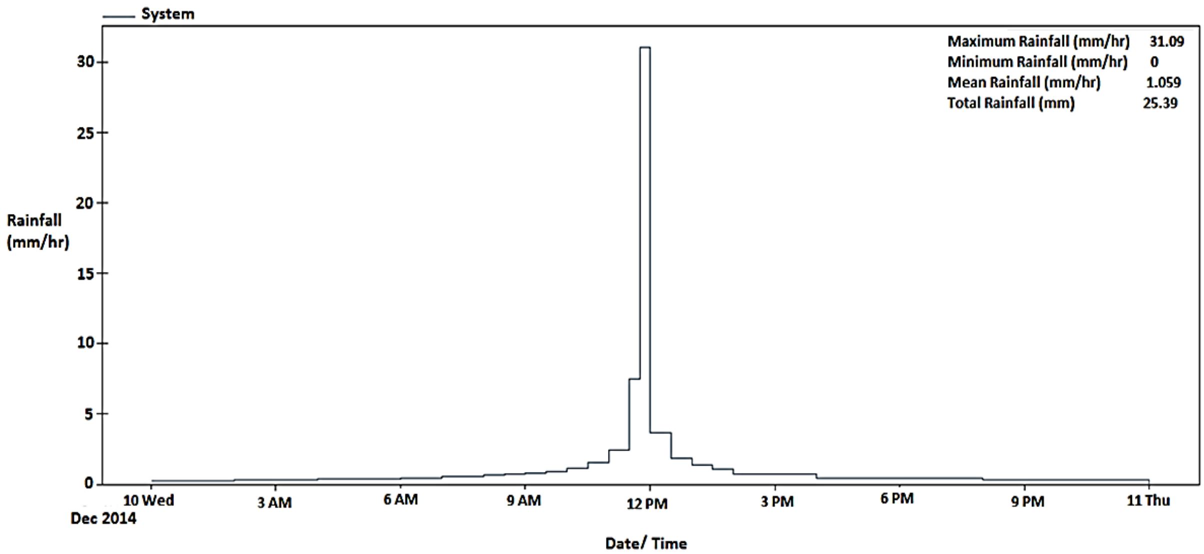


Figure 2. Storm Type II 24-hour rainfall intensity distribution based on Soil Conservation Service (SCS) method developed by the USDA Natural Resources Conservation Service.

3.2.2 Soil Surface Cover for Non-BMP Areas

Infiltration depends on the soil hydrologic conditions and vegetation characteristics of the site. Vegetation root system characteristics are an important infiltration factor. Vegetation distribution, quantity, and type have been found to be significant factors for controlling spatial and temporal variations in infiltration in Nevada, Idaho, and Texas (Pellant et al. 2005). Changes in plant composition and the distribution of species can influence the ability of a site to capture and store precipitation. Plant rooting patterns, litter production, and associated decomposition processes can all affect infiltration and/or run-off. Research showed that the shifts in plant composition between bunchgrass (i.e., grass the grows in clumps) and shortgrass over time have the greatest potential to influence infiltration (Pellant et al. 2005).

Another important factor is the amount of litter. For example, bunchgrasses and shrubs tend to produce greater amounts of foliage than annuals and short grasses. The fallen foliage accumulates as litter, which in turn leads to an increase in soil organic matter. Litter also creates a more consistent temperature and moisture microenvironment that favors microorganism activity. These factors enhance the surface soil structure, which aids infiltration (Arnalds and Archer 2013). Certain plants (e.g., *Phragmites australis*) may influence infiltration via penetration by plant roots and rhizomes that loosen the soil and increase hydraulic conductivity (Cooper et al. 2005). Dead roots and rhizomes may create large pores or channels for water movement (Brix 1997).

Vegetation adjacent to highways is common in Illinois. Bare soil is subject to rapid erosion and moisture loss. A surface cover with drought and heat tolerance and salt resistance is desirable. Turfgrass and prairie grass species are the most common vegetative covers in Illinois. Prairie grass has a dense root structure capable of growing to substantial depths below level ground (as shown in Figure 3). This type of vegetation is assumed to promote run-off interception and infiltration. Turfgrass seed germinates and produces cover quickly to keep soil in place and retain moisture. Turfgrasses also filter total suspended (TSS) and salt (Vettel 1986). Turfgrass is easy to mow and maintain, and it is very commonly used on foreslopes. Therefore, in this study, the foreslopes—even on the simulated sites with prairie grass surface cover—were still covered with turfgrass to represent common practice. Previous studies determined the infiltration rate for turf on clay soil is 0.28 in. per hour; for prairie on clay soil, it is 0.88 in. per hour. However, for turfgrasses and prairie grasses on sandy soil, the infiltration rates were 2.5 and 4.2 in. per hour, respectively (Selbig and Balster 2010).

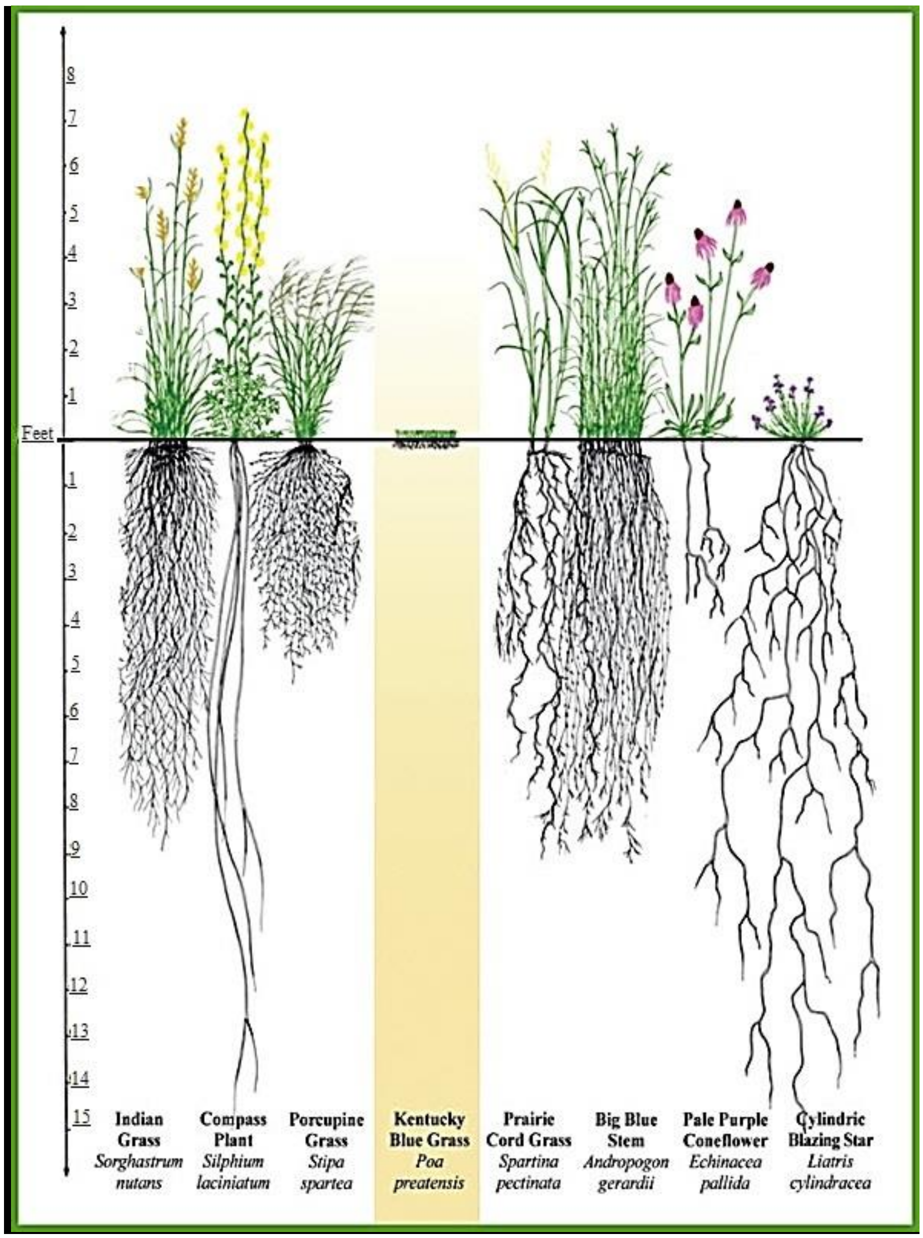


Figure 3. Comparing the root systems of turfgrass (Kentucky bluegrass) and prairie plants (others) (Natura 1995).

In this study, two types of vegetated surface covers were considered: turfgrasses and prairie grasses. Models simulating turfgrass cover of the foreslope, level ground, or backslope were considered. Prairie grass was modeled for level ground and back slope.

3.2.3 Soil Types

The U.S. Department of Agriculture (USDA) soil type classifications of sand, sandy loam, loamy sand, sandy clay loam, sandy clay, loam, silt loam, clay loam, silty clay loam, silty clay, and clay (see Figure A1-1 in the appendix) were considered in this study. Table 3 shows the inventory of soil types in Illinois based on the USDA soil survey (USDA 2016).

Table 3. Soil Types Found in Illinois

Surface Soil	Soil Types	Note
✓	Sand	
✓	Loamy Sand	
✓	Sandy Loam	
✓	Loam	
✓	Silt Loam	
—	Sandy Clay Loam	Not as surface soil but in shallow depths
✓	Clay Loam	
✓	Silty Clay Loam	
—	Sandy Clay	Not as surface soil but in shallow depths
✓	Silty Clay	
✓	Clay	

3.2.4 Soil Parameters

Soil parameter values for conductivity, suction head, and initial deficit were based on PCSWMM user manual guidelines (James et al. 2010). These parameters are shown in Tables A1-1 and A1-2 in the appendix.

3.2.5 Soil Imperviousness Percentage

Imperviousness plays a key role in run-off estimates. Therefore, for each USDA soil type, there would be three imperviousness percentages associated with soil surface cover (bare soil, turfgrass, or prairie grass). To characterize the proper imperviousness for each soil type, the Natural Resources Conservation Service (NRCS) curve number (CN) values were used as a guide. As the first step, the CN numbers of each soil type with turfgrass conditions were determined. Curve number values for “lawn, open space, fair condition” were used for turfgrass condition as the surface cover. Then the CN numbers of various soils with no vegetative and prairie grass surface cover were determined.

For each soil type, a curve number was interpolated from the curve numbers associated with sand, clay, and silt. Curve numbers for hydrologic soil group (HSG) A and HSG D (shown in Table A1-6 of Appendix 1) were assumed for sand and clay soils, respectively. The CN numbers of Groups B and C were averaged to obtain the CN number for silt. Based on the percentages of silt, clay, and sand, the CN number for each type of soil was calculated and assigned to each soil type. The imperviousness percentage for each soil type with turfgrass cover was interpolated based on CN numbers, using 0% imperviousness for sand and 100% imperviousness for clay.

3.2.6 Field Infiltration Tests

To obtain infiltration rates for all three surface covers (bare soil, turfgrass and prairie grass), several 8-in. diameter soil sample cores were collected from sites within 50 mi of Edwardsville, Illinois (Figure 4). The selected sites had three soil types: silt loam, silty clay loam, and clay. At each site, cores were collected from areas that had no vegetative surface cover as well as those that had turfgrass and prairie grass cover.

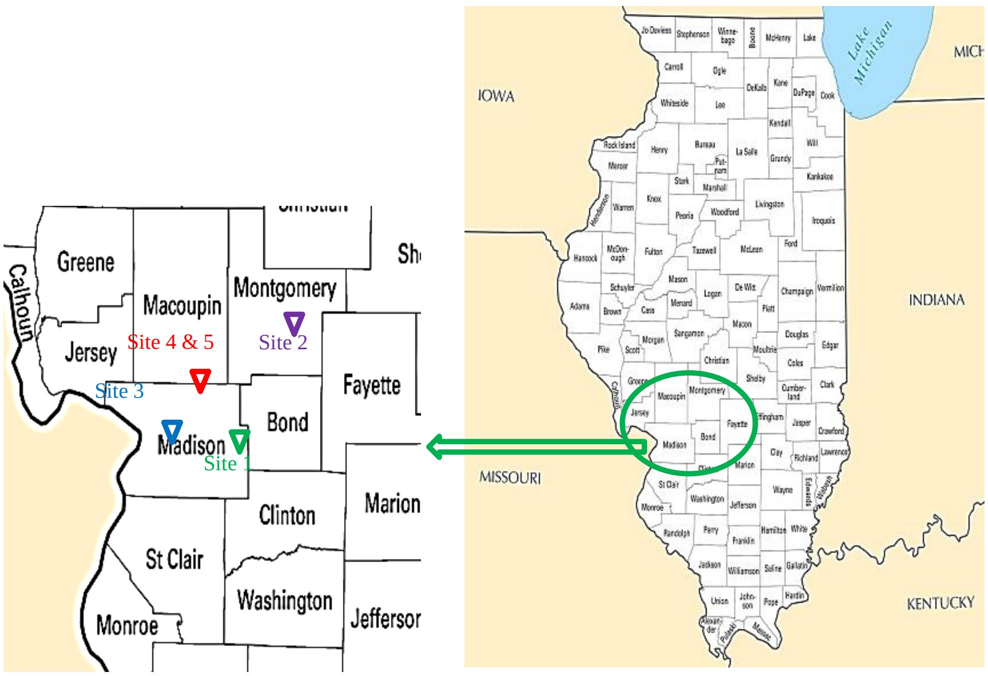


Figure 4. Site locations for soil infiltration test.

Infiltration tests were performed on core samples in accordance with the ASTM D5856 standard (ASTM 2015). Table 4 shows that the ratio of infiltration rate of soils covered with prairie to the one covered with turfgrass was 2.1 at a minimum, and the ratio of the infiltration rate of soils covered with turf to the one without any vegetative surface cover was 1.3.

Table 4. Field Test Results for Soil Infiltration Rate (K)

	Infiltration rate based on the test on samples from field					Remolded Samples	Infiltration Rate from Other References (mm/hr)				
	Surface Cover (mm/hr)			Infiltration Ratio							
Site No.	Prairie	Turf	Bare	Prairie / Turf	Turf / Bare	ASTM Lab. Rate (mm/hr)	USDA	Saxton and Rawls (2005)	Rawls (1998)	Clapp 1978	PCSWMM Manual
1	1846	656	499	2.8	1.3	283	33.012	64.8	3.23	2.53	6.6
2	1462	678	—	2.2	—	—					
3	2026	824	—	2.5	—	—					
4	1809	875	—	2.1	—	—	7.2	7.68	5.03	0.73	1.02
5	594	201	—	3	—	10	1.51	1.7	1.82	2.13	0.25

Soil type for site Nos. 1, 2, 3: Silt loam.

Soil type for site No. 4: Silty clay loam.

Soil type for site No. 5: Clay.

Remolded samples made from field material at in situ void ratio.

A series of infiltration simulations with various imperviousness ratios ranging from 0% to 100% for prairie and bare soil conditions were conducted. The ratio of infiltration rates obtained from simulated results was compared to the ones measured in the field. The imperviousness ratio, which resulted in the same ratio of infiltration rates observed in the field, was selected for this study. The updated imperviousness percentages are shown in Table 5 for USDA soil types and various soil surface covers.

Table 5. Percent Imperviousness for Each Soil Type and Ground Cover

USDA Soil Type	Bare Soil Imperviousness (%)	Turfgrass Imperviousness (%)	Prairie grass Imperviousness (%)
Sand	11	0	0
Loamy Sand	26	15	0
Sandy Loam	39	28	0
Sandy Clay Loam	42	31	0
Sandy Clay	58	47	0
Loam	60	49	2
Silt Loam	65	54	7
Clay loam	74	63	16
Silty Clay Loam	89	78	31
Silty Clay	94	83	36
Clay	100	100	53

3.2.7 Field Infiltration and Effect of Mowing

Cool-season grasses produce seed before early summer. They are well adapted to Illinois's cold freezing winters and hot summers. Common species include smooth brome, orchardgrass, tall fescue, perennial rye, and bluegrass. To evaluate the effects of mowing on soil infiltration rate, field soil tests were performed on three sites that had both frequently mown and unmown cool-season grass areas. The site locations are shown in Figure 5, and the results are shown in Table 6.

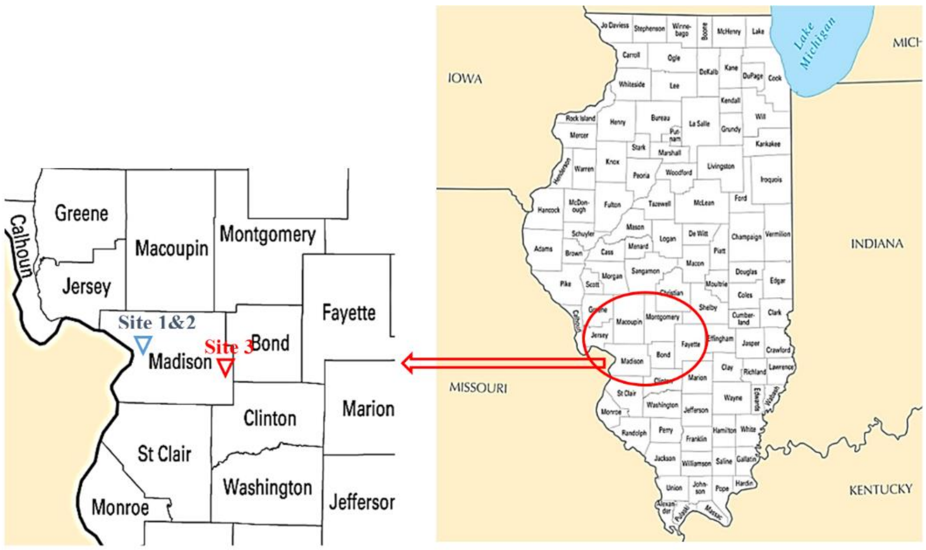


Figure 5. Site location for infiltration rate of mown and unmown cool-season grasses.

The tests indicated that there are differences between infiltration rates for the soils with frequently mown and with unmown surface cover. The higher infiltration rate ratio of unmown to frequently mown grass for Site 3, compared with Site 1 and 2, might be due to the higher frequency of mowing at Site 3.

Table 6. Infiltration Rate of Mown Versus Unmown Cool-Season Grasses

Site No.	Mown / Unmown	Soil Type	Infiltration Rate (mm/hr)	Infiltration Rate Ratio of Unmown to Mown grass
1	Mown	Silt Loam	22.23	4.07
	Unmown	Silt Loam	90.42	
2	Mown	Silt Loam	32.24	4.79
	Unmown	Silt Loam	154.55	
3	Mown	Silt Loam	10	10
	Unmown	Silt Loam	100	

3.3 BMPs SIMULATED

In this project, four major groups of scenarios were simulated to examine the performance of BMPs for infiltrating and retaining post-construction stormwater run-off. The four groups of simulations are as follows:

- ***Pre-BMP Condition:*** In these scenarios, highways without any structural BMPs are simulated. Although some engineers may consider surface vegetative cover a BMP, this report does not.
- ***Post-Highway + Individual BMPs:*** These scenarios refer to the cases where one type of BMP was implemented as part of the idealized catchment area.
- ***Post-Highway + BMP Combination:*** These scenarios include cases where a combination of two BMPs was implemented in the idealized catchment area.
- ***Post-Highway + BMP Scaling:*** These scenarios include one type of BMP of varying sizes.

Table 7 displays the BMP dimensions that were used for the Group B and C simulations. These dimensions were selected based on the typical dimensions reported in the literature and design guides. To analyze BMP scale effects, a range of dimensions was considered for each BMP (see Section 3.3.4). All scenarios simulated in this study are shown in Figure 6. Run-off was either infiltrated, stored on the surface, or flowed overland. PCSWMM BMP design parameters and subcatchment parameter values are shown in Table A1-4 (see appendix).

Table 7. BMP Physical Characteristics in the Idealized Catchment Area for Highway Run-Off Modeling

BMP Subcatchment	Area (ac)	Length (ft)	Width (ft)	Lateral Slope* (%)
Bioswale	0.1608	500	14	0.5
Infiltration Trench	0.0338	500	3	0.5
Vegetated Filter Strip	0.2868	500	25	0.5

*Lateral slope means the longitudinal slope along the highway; in PCSWMM, the minimum accepted slope is 0.5.

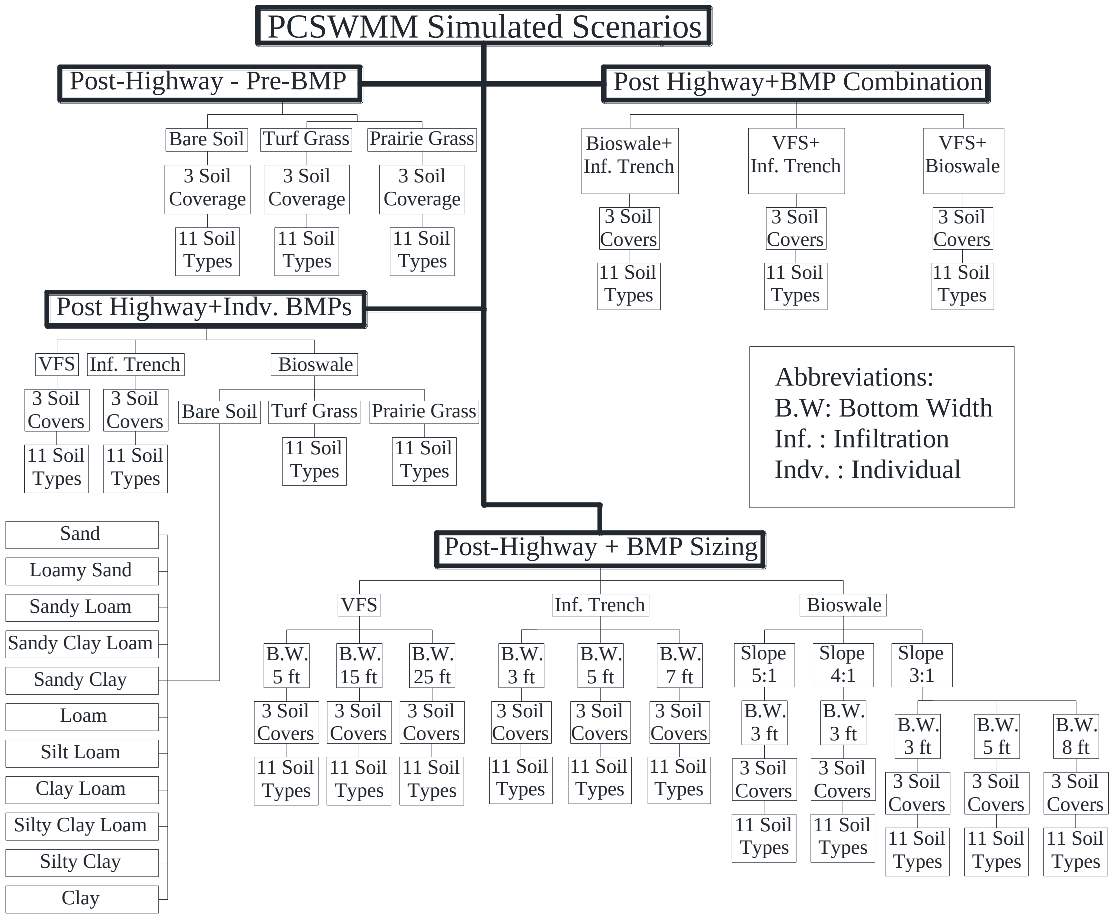


Figure 6. BMP simulation scenarios.

3.3.1 Structural BMPs

Controlling stormwater run-off from linear projects in rural areas is much more feasible than in urban areas because of the availability of space to place BMPs. In urban areas, which have restricted rights-of-way and larger paved areas per linear foot of roads or highways, stormwater run-off control is more challenging. For linear projects in urban areas, bioswales, vegetated filter strips, and infiltration trenches are the most effective structural BMPs for control and retention of stormwater run-off on-site. Wetland channels and basins are not typically feasible in urban areas because of limited space, and they are typically less effective in run-off volume reduction. Permeable pavement is also not a suitable BMP because its use is not recommended on highways with high traffic loads.

The BMPs discussed in Chapters 4 and 5 simulated newly constructed BMPs or well-maintained BMPs without any defects or clogging. The volume reduction efficiency of BMPs will decline over time.

3.3.2 BMP Simulation Scenarios

3.3.2.1 Baseline Pre-BMP Scenario

The baseline scenario for this research is the pre-BMP installation scenario illustrated in Figure 1. Run-off from the highway flows to the foreslope then to the level-ground subcatchment. Run-off from the backslope also flows to the level-ground subcatchment. Water received by the BMP in excess of its storage capacity and infiltration rate flows to the outfall point of the BMP.

3.3.2.2 Post-Highway + Bioswale

A bioswale was implemented as a part of the idealized catchment area as shown in Figure 7. The bioswale was installed in the middle of the level-ground subcatchment (see S3 in Figure 1). The bioswale bottom width is 5 ft, with 3:1 side slopes. The top width of the bioswale is 14 ft. The order of subcatchments and routing of run-off from foreslope to level ground and backslope is the same as that of the pre-BMP highway scenarios.

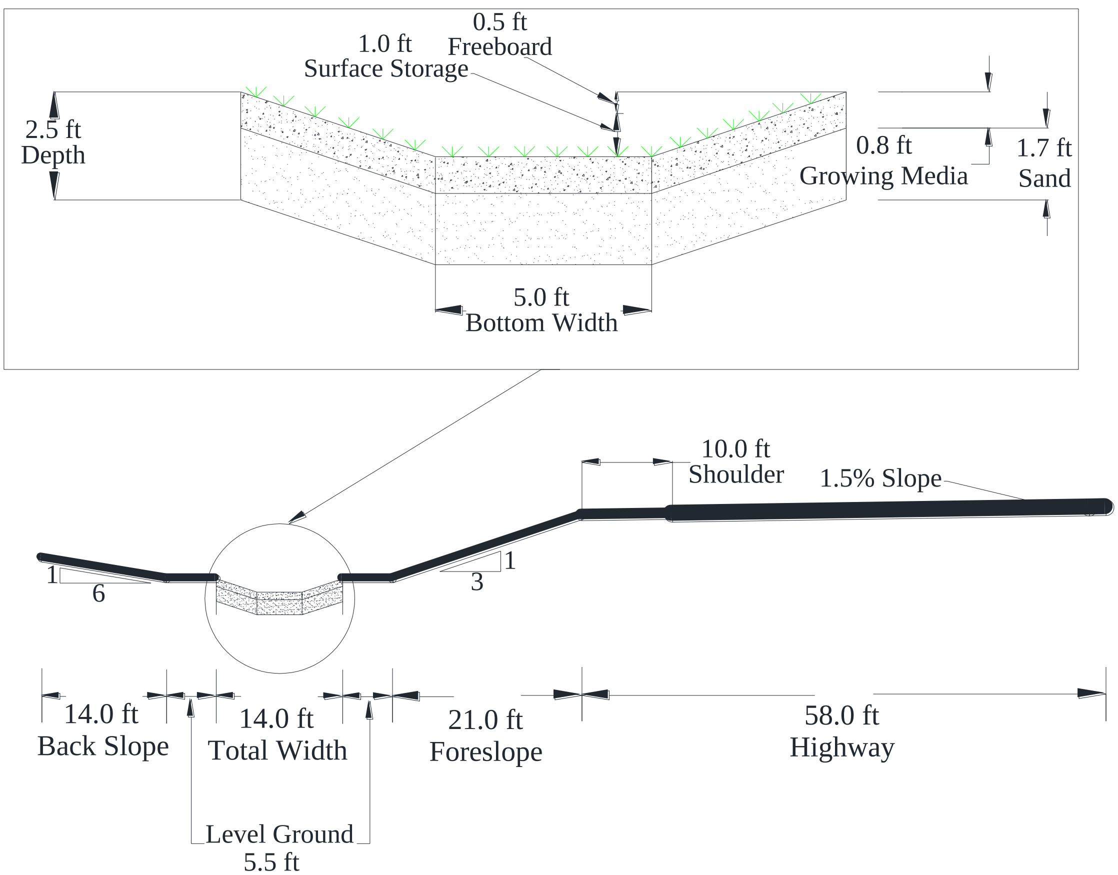


Figure 7. Schematic cross-section of idealized catchment area with bioswale as BMP.

3.3.2.3 Post-Highway + Infiltration Trench

Figure 8 illustrates how modeled infiltration trench BMPs were incorporated into the idealized catchment cross-section. The modeled infiltration trench width is 3 ft. Run-off routing from foreslope to BMP and backslope to BMP remains constant in all modeled scenarios.

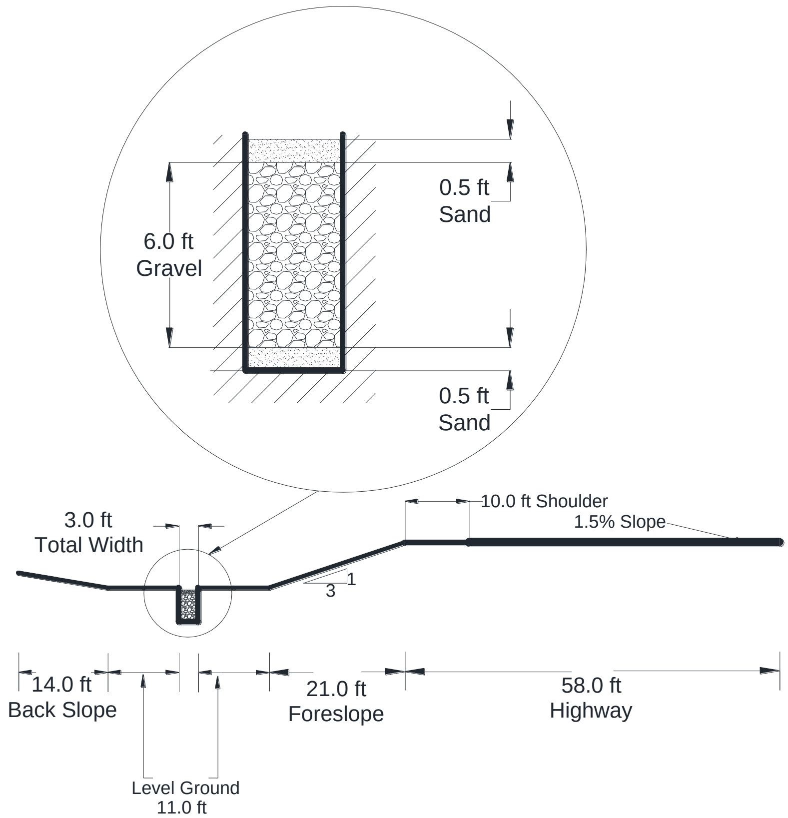


Figure 8. Schematic cross-section of idealized catchment area with infiltration trench as BMP.

3.3.2.4 Post-Highway+ Vegetated Filter Strip

Figure 9 illustrates how the modeled vegetated filter strip (VFS) BMPs were incorporated into the idealized subcatchment. The modeled vegetated filter strip width is 25 ft. Run-off from foreslope to BMP and backslope to BMP remains constant in all modeled scenarios.

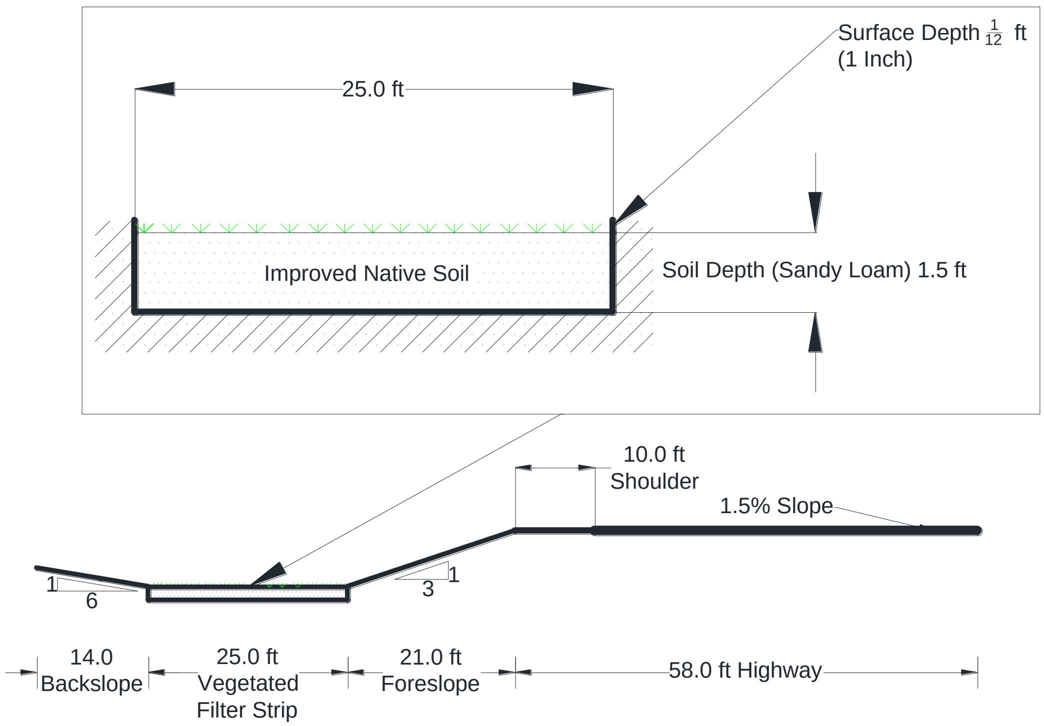


Figure 9. Schematic cross-section of idealized catchment area with a VFS as the BMP.

3.3.3 Combination of BMPs

Combined BMPs are used to provide a combination of run-off treatment and flow control at the same time. The construction and maintenance costs of a combined BMP are more cost effective than a series of individual BMPs (WisDOT 2008). This project analyzed a combination of two BMPs and considered factors such as the right-of-way space, operation and maintenance costs, and BMP efficiency. The combinations included a vegetated filter strip and a bioswale, a vegetated filter strip and an infiltration trench, and a bioswale and an infiltration trench.

The runoff routing through combined BMPs is important. Previous studies determined that suspended solids (SS) are the most common contaminant of highway run-off, especially in first-flush run-off (Aryal et al. 2009; Herrera Environmental Consultants 2007). Removing SS not only improves the quality of run-off stormwater but also decreases BMP clogging. These studies showed that a vegetated filter strip can effectively remove SS (Han et al. 2005). A vegetated filter strip often is installed as a pre-treatment practice for other BMPs (Barrett et al. 1998).

When combined with other BMPs, a vegetated filter strip is placed between the highway and bioswale or infiltration trench.

Bioswales are designed to reduce flow velocity and to allow limited infiltration. Bioswales also filter run-off and reduce clogging of downstream BMPs (Simon et al. 2004; Grenz 2007). When combined with infiltration trenches, bioswales are placed between the highway and the infiltration trench.

BMPs discussed in this section simulated newly constructed BMPs without a reduction in performance caused by age or poor maintenance. BMPs that are not well maintained will have reduced run-off reduction efficiency.

3.3.3.1 Vegetated Filter Strip and Bioswale Combination

The modeled combined vegetated filter strip and bioswale were placed between the foreslope and the edge of the right-of-way. The width of the vegetated filter strip is 25 ft, and the top of the bioswale is 14 ft, with a 5-ft bottom width and a 3:1 side slope (see Figure 10). This configuration was simulated for all 11 natural soil types considered in this study. The modeled foreslope surface cover had no vegetation or turfgrass cover.

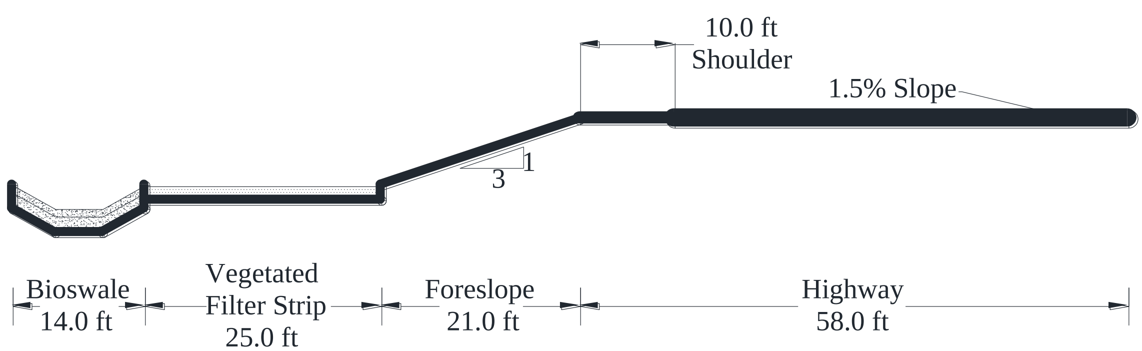


Figure 10. Schematic cross-section of idealized catchment area with combined VFS and bioswale.

3.3.3.2 Vegetated Filter Strip and Infiltration Trench

Figure 11 illustrates the modeled configuration of a combined VFS and infiltration trench. This configuration was simulated for all 11 soil types as well as all surface covers of bare soil, turfgrass, and prairie grass.

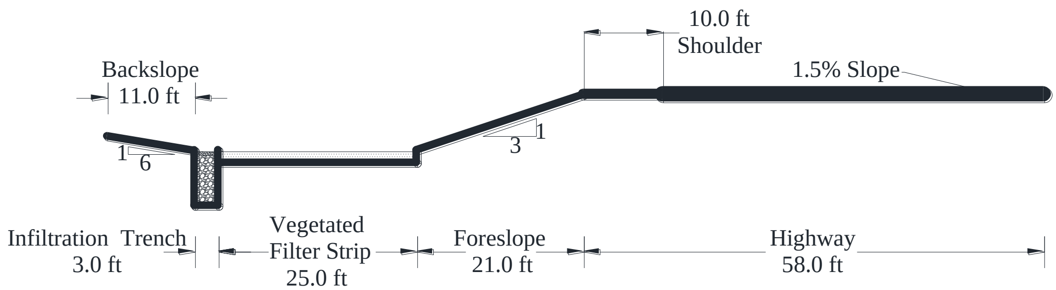


Figure 11. Schematic cross-section of idealized catchment area with a VFS and an infiltration trench.

3.3.3.3 Bioswale and Infiltration Trench

Figure 12 illustrates the modeled condition of a combined bioswale with a 5-ft bottom width and a 3:1 side slope covering 14 ft of the level ground (S3) subcatchment, and an infiltration trench. This configuration was simulated for the 11 soil types in the study, as well as all three surface covers.

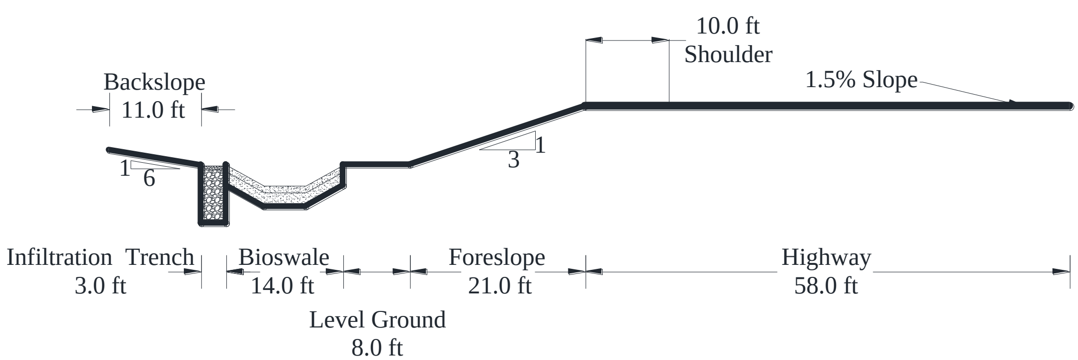


Figure 12. Schematic cross-section of idealized catchment area with a bioswale and an infiltration trench.

3.3.4 BMP Scaling

To understand the impact of different sizes of each BMP type on stormwater run-off volume reduction, a range of BMP sizes were considered. Differing bioswale side slopes and bottom width variables were considered. Three side slopes (3:1, 4:1, and 5:1) and bottom widths (3, 5, and 8 ft) were considered for bioswale scaling. Infiltration trench bottom widths of 3, 5, and 7 ft were considered, and vegetated filter strips of 5, 15, and 25 ft were considered. The matrix shown in Table 8 provides a summary of scaled BMPs.

Table 8. Scaled BMP Matrix

	Bioswale Slope			**Infiltration Trench**	**Vegetated Filter Strip**
	3:1	**4:1**	**5:1**		
Width (ft)	*3	3	3	3	5
	*5	5	5	5	15
	*8	8	8	7	25

*Width for bioswale refers to the bottom width.

3.4 EVALUATION OF THE BMP EFFECTIVENESS

3.4.1 Effectiveness of the System

In this report, the effectiveness of the system (i.e., an idealized catchment) is determined as the percent run-off volume reduction for the total catchment area. To determine the effectiveness of the studied BMPs, the volume run-off at the outfall point of the idealized catchment (including BMP) was compared with the total input to the idealized catchment, which is storm volume resulting from a 1-in. rainfall. The difference between the total input run-on and what is running off at the outfall is the amount that is controlled by the system. The effectiveness of the system in controlling rainfall-produced run-off is determined by Equation 1:

$$\text{Idealized catchment performance efficiency} = \text{ICPE} = ((P - \text{R}))/\text{P} * 100 \quad (1)$$

where P is the input precipitation (1-in. rainfall) to the idealized catchment area, and R is the discharge at the outfall point of the catchment area expressed as depth in inches.

It is worth noting that all the models simulated a 500-ft-long section of a highway; therefore, all volumes were normalized by length to obtain the values per linear foot. The percent efficiency of the system, ICPE, is an appropriate index to compare the performance of various scenarios.

3.4.2 BMP Performance

The performance of a BMP is the percentage run-off volume reduction by the applied single BMP. To estimate BMP percentage run-off volume reduction, the water budget was considered. A water budget, as shown in Figure 13, considers all the water that flows into and out of the BMP subcatchment. Evaporation and evapotranspiration were conservatively assumed negligible in the 24-hour time period under consideration. Inflow to the BMP subcatchment includes precipitation and run-on (i.e., run-off from the upstream subcatchments), and outflow is run-off at the outfall point.

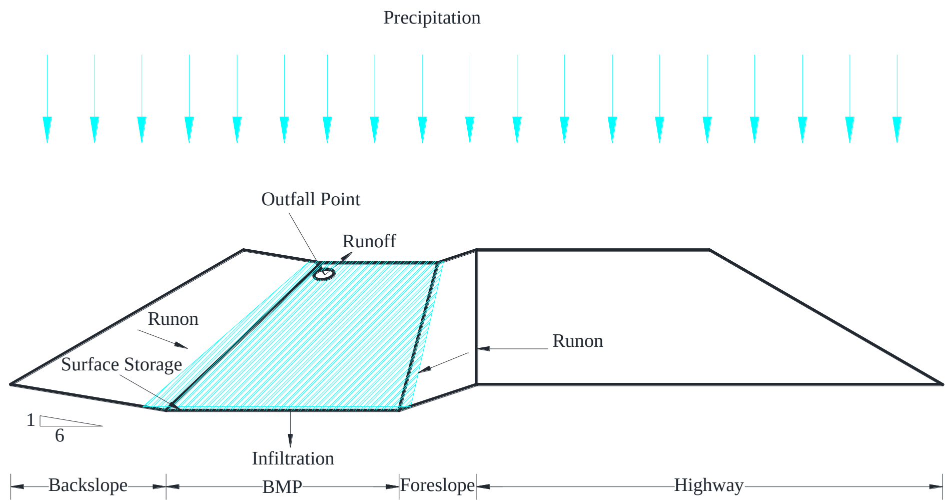


Figure 13. Schematic water budget components for the BMP subcatchment area.

In this study, BMP performance is associated with run-off volume reduction computed for the BMP subcatchment only and is calculated as shown in Equation 2:

$$\text{BMP run} - \text{off volume reduction} = \text{BMP}_{RVR} = \frac{(\text{I} - \text{O})}{\text{I}} * 100 \qquad (2)$$

where I is the inflow to the BMP, including precipitation (P) and the run-on from the upstream subcatchments to the BMP; and O is the outflow at the outfall point from the BMP. It is worth noting that because of differences in BMP area for each scenario, the service area of that scenario for the BMP is different. Therefore, the BMP_{RVR} values of the various considered scenarios are not comparable to each other.

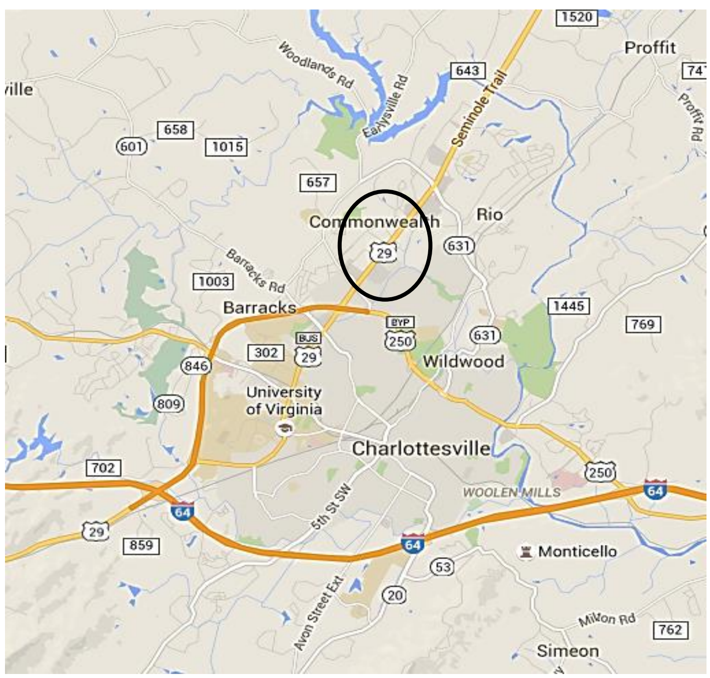
3.5 VERIFICATION OF MODELING RESULTS

Model results should be verified via field-collected data. For this purpose, the literature was surveyed to identify BMP sites that had monitoring data. Most of the monitored data were reported in the international BMP database. That database provided average observed run-off volume reductions (BMP_{RVR}) for bioswales and vegetated filter strips of 42% based on 13 monitored sites and 34% based on 16 monitored sites (see Table 1). No monitored infiltration trench sites were reported in the database. The reported BMP performances in the database were based on the measured inflow and outflow of the BMPs as shown in Eq. 2.

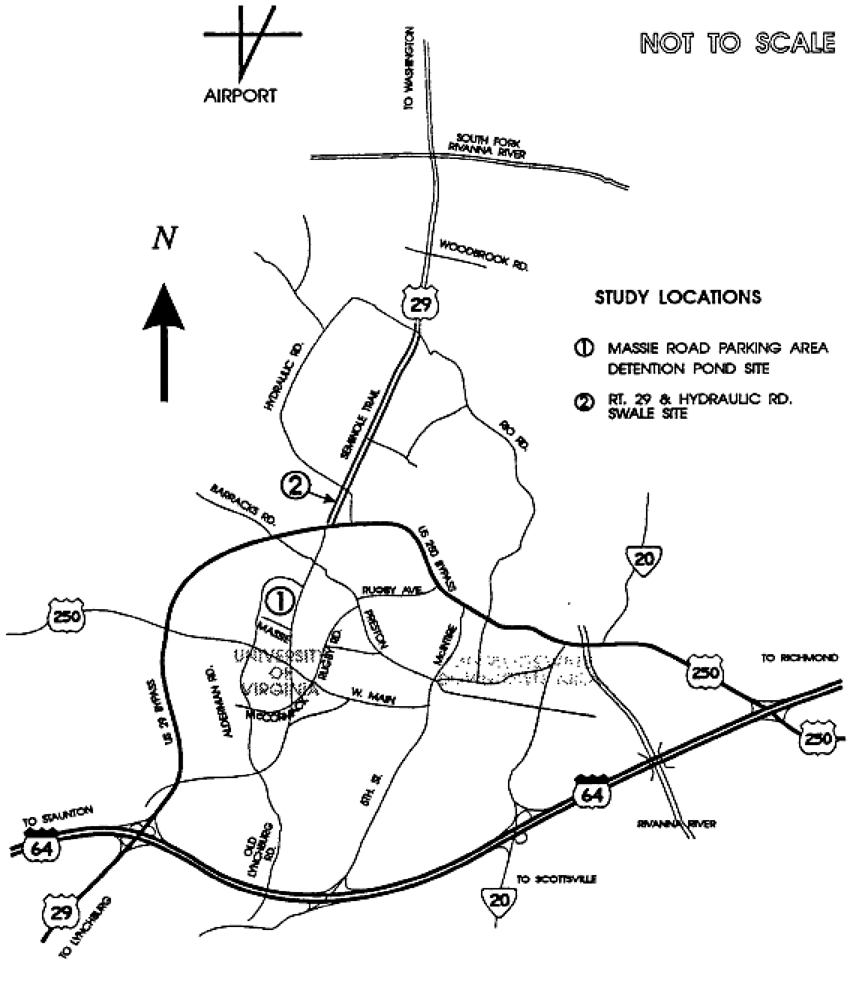
Two sites with a bioswale and a vegetative filter strip that had field measurements were identified in the international BMP database and are analyzed herein.

3.5.1 Monitored Site—Bioswale

Based on the information provided in the international BMP database, the majority (about 70%) of the monitored and reported bioswales in the database were designed and implemented in the 1990s (Clary et al. 2012). The remaining 30% of the studies were conducted in the 1980s or earlier. These bioswales may be subject to maintenance issues such as clogging; however, maintenance information was not reported in the database (Clary et al. 2012). The bioswale site selected for this study is located on I-29 South near Charlottesville, Virginia (Figure 14). BMP installation or monitoring dates were not available. However, because the database reporting this BMP's performance was published in 2010, it had to be monitored before 2010. This BMP is 98 ft long and has a longitudinal slope of 2%. The contributing area is 0.81 ac, with 57% imperviousness and soil type C. Because there was no information about the bioswale width, a 5-ft bottom width and a side slope of 3:1 was assumed for PCSWMM simulation. The ratio of the I-29 South swale area to its contributing area is about 3.8%, which is much smaller than the one for the idealized catchment (13%, described in this study).



(a)



(b)

Figure 14. International BMP database bioswale study site, Charlottesville, Virginia.

Because the soil type in the area was not reported, the USDA soil survey map was used to identify the soil type as loam (USDA 2016). The performance of this BMP under more than two 1-in. rainfall events (2.14 and 1.42 in. of rainfall) were reported for the I-29 South swale, and the average relative BMP_{RVR} measured for these events is 41%. In this study, the site was modeled using PCSWMM, and the performance of the BMP was analyzed under both rainfall events.

The simulations do not consider any maintenance issues with BMP or clogging of BMP. Therefore, the BMP_{RVR} obtained from simulations are more representative of new or well-maintained BMPs. The simulated bioswale indicates an average BMP_{RVR} of 62%, which is about 20% more than the observed data reported in the international BMP database (Table 9). The surface cover for this simulation was turfgrass. There are many assumptions about the boundary of contributing areas for this BMP case study, the details of soils, the layout of BMP, and the surface cover. Therefore, the simulation results may not reflect the actual site conditions because detailed information was not available.

Table 9. Comparison of Modeled and Monitored BMP_{RVR} for the I-29 South Bioswale

Monitored Bioswale			Modeled Bioswale		
Storm No.	**Precipitation (in.)**	**BMP Run-Off Volume Reduction (%)**	**Inflow to BMP Subcatchment (in.)**	**Outflow of BMP Subcatchment (in.)**	**BMP Run-Off Volume Reduction (%)**
1	2.14	64	38.6	17.1	56
2	1.42	18	23.3	7.3	69
Avg.		***41***			***62***

The poor maintenance or deterioration of a BMP also affects the infiltration rate of BMPs. Therefore, the BMP aging was represented in simulations by reducing the hydraulic conductivity of the bioswale's sandy soil at the bottom of bioswale by 25%, 50%, and 75% of the selected conductivity (see Table 10) for modeling purposes. As the sandy soil's hydraulic conductivity is reduced, the infiltration amount will reduce. The simulation results are shown in in Table 11. With a 50% reduction in hydraulic conductivity, the model showed a 47% reduction in run-off, which matches the reported monitored values from the international BMP database for this particular site.

Table 10. Soil Conductivity Reduction for the Sandy Soil at I-29 South Bioswale

Percentage Reduction in Soil Conductivity for BMP Subcatchment	Hydraulic Conductivity (mm/hr)
0	120.4
25	90.3
50	60.2
75	30.1

Table 11. Comparison of Modeled and Monitored BMP_{RVR} for Different Soil Conductivity for the I-29 South Bioswale

BMP Run-Off Volume Reduction %					
		Considered Conductivity for PCSWMM (mm/hr)			
Precipitation (cm)	**Measured**	**120.4**	**90.3**	**60.2**	**30.1**
5.46	64	56	49	42	25
3.63	18	69	62	52	34
Avg.	***41***	***63***	***56***	***47***	***30***

3.5.2 Monitored Site—Vegetated Filter Strip

Over 80% of the monitored vegetated filter strips reported in the international BMP database were designed and implemented prior to 2000 (Clary et al. 2012). The majority of these vegetated filter strips are located in highway settings (Clary et al. 2012).

The vegetated filter strip site selected for this study is located near I-40 and adjacent to NC Highway 42 in Clayton, North Carolina (see Figure 15), installed by NCDOT. The date of construction was not available. Based on NCDOT's BMP evaluation record, the monitoring was done during 2004 (Wu and Allen 2006). This BMP is 55 ft long and has a longitudinal slope of 0.06. The contributing area is 12.35 ac, with 49% imperviousness and soil type C (Clary et al. 2012). Using the USDA soil survey map, the soil type was determined to be sandy clay loam (USDA 2016). Based on the BMP evaluation by NCDOT, the vegetated filter strip is 24 ft wide. Therefore, the ratio of the observed VFS area to its contributing area is about 3.4% (Wu and Allen 2006). It is worth noting the ratio for the idealized catchment area discussed in the results chapter of this report is about 27%.

The simulated results of this site with all rainfall events are shown in Table 12 and represent the performance of a new VFS. The average simulated BMP_{RVR} for different rainfall events is 51%. This is about 22% more than the average measured BMP_{RVR} reported for these events in the international BMP database. Moreover, if only the events with more than 1 in. of rainfall are considered, the average simulated BMP_{RVR} shows a 27% run-off reduction, while the average BMP_{RVR} of observed data for more than 1 in. of rainfall shows a 16% run-off reduction.

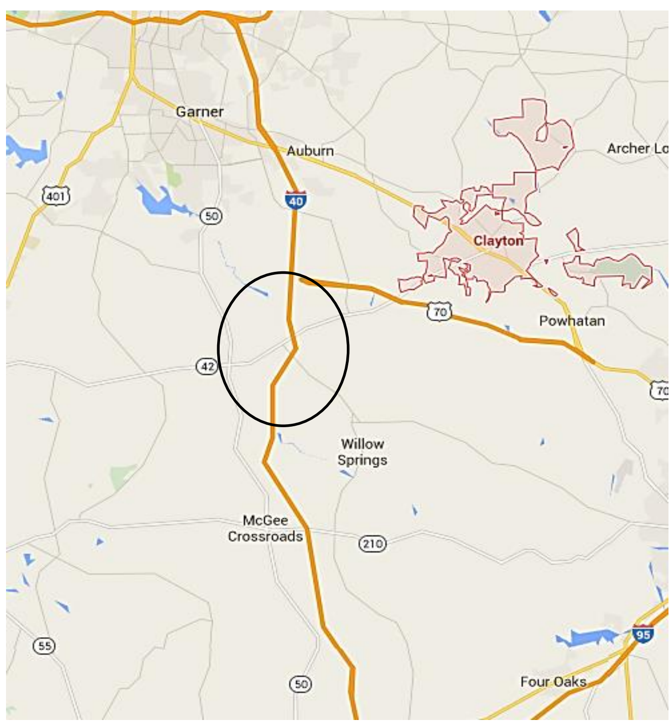


Figure 15. NCDOT vegetated filter strip map, the study site international BMP database in Clayton, North Carolina.

Table 12. Comparison of Modeled and Monitored BMP_{RVR} for the Highway 42 VFS

Monitored VFS			Modeled VFS		
Storm #	Precipitation (in.)	BMP Run-Off Reduction (%)	Inflow to BMP Subcatchment (mm)	Outflow of BMP Subcatchment (mm)	BMP Run-Off Reduction %
1	0.45	50	139.22	47.95	66
2	1.04	10	338.18	207.19	39
3	0.34	37	100.12	22.62	77
4	2.24	***15***	893.89	746.57	***16***
5	1.07	***26***	348.77	216.64	***38***
6	1.46	***13***	501.62	361.89	***28***
7	0.25	48	70.05	4.67	93
8	0.69	32	219.08	106.45	51
9	0.65	33	207.02	97.1	53
Avg.		**29**			**51**
Avg. BMP_{RVR} for events > 1 in. precipitation		***16***			***27***
Underlined numbers are the BMP_{RVR} for events more than 1 in**.**					

To represent BMP aging, the vegetated filter strip loamy soil conductivity was reduced by 25%, 50%, and 75% of the original selected, as indicated in Table 13.

Table 13. Soil Conductivity Reductions for Loamy Soil at NCDOT VFS

Percentage Reduction in Soil Conductivity for BMP Subcatchment	Conductivity (mm/hr)
0	3.3
25	2.5
50	1.7
75	0.8

In the case of reduction of loam conductivity by 75%, the modeling results match reasonably with the measured values as shown in Table 14 (or Figure 16). With a 75% change in hydraulic conductivity, the model showed 33% average reduction in run-off, which is close to the observed data from the international BMP database. Also, if the events with more than 1 in. of rainfall are considered, with a 50% reduction in hydraulic conductivity, the model showed a 19% average BMP_{RVR}, which is close to the average measured BMP_{RVR} of 16% for events having more than 1 in. of rainfall.

Table 14. Comparison of Modeled and Monitored BMP_{RVR} for Different Soil Conductivity for the Highway 42 VFS

	BMP Run-Off Volume Reduction %				
		Considered Conductivity for PCSWMM (mm/hr)			
Precipitation (in.)	**Measured**	**3.3**	**2.5**	**1.7**	**0.8**
0.45	50	66	62	56	44
1.04	10	39	34	28	20
0.34	37	77	74	68	57
2.24	***15***	***16***	***14***	***11***	***8***
1.07	***26***	***38***	***33***	***27***	***19***
1.46	***13***	***28***	***24***	***20***	***14***
0.25	48	93	90	84	75
0.69	32	51	47	40	29
0.65	33	53	49	42	31
Avg.	**29**	**51**	**47**	**42**	**33**
Avg. BMP_{RVR} for events > 1 in. precipitation	***16***	***27***	***24***	***19***	***14***
Underlined numbers are the BMP_{RVR} for events more than 1 in.					

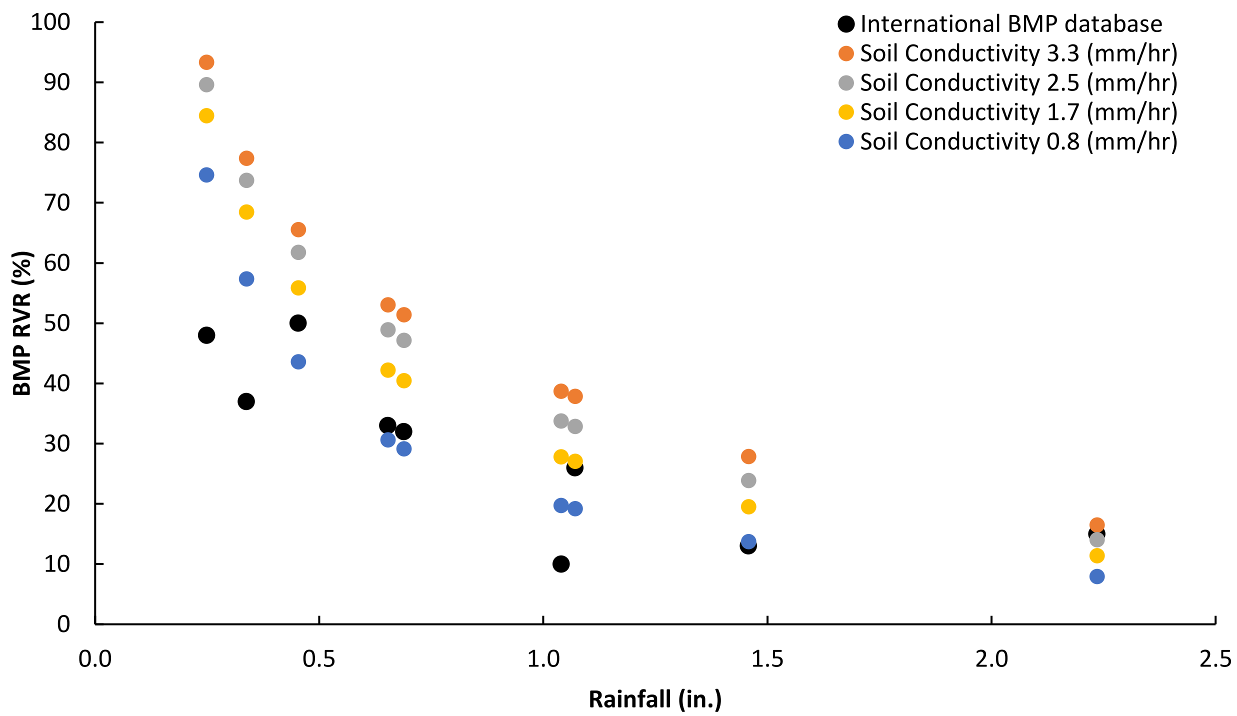


Figure 16. BMP_{RVR} (%) in different soil conductivity of the VFS.

Because the specific details of the two sites were not available, it was not possible to accurately verify the simulations. However, the presented case studies show that the simulated results can be in reasonable agreement with the observed values. In fact, with only changes of hydraulic conductivity in the order of two to three times, the simulated results matched the observed values. Furthermore, it is very common to observe that the hydraulic conductivity of the soils increase or decrease ten to a hundred times the original value during the life of the BMPs. The best way of verifying the simulations is to have controlled sites to monitor the BMP performances and compare them.

CHAPTER 4: PERFORMANCE SIMULATION RESULTS

The simulation results of the idealized catchments scenarios (see Figure 6) are presented in this chapter.

4.1 BASELINE PRE-BMP

The simulation results for pre-BMP conditions can produce different amount of run-off for various in-place soil types. As Figure 17 shows the soil type with higher conductivity such as sandy soil type can promote infiltration and retain more stormwater. On the other hand, if the dominant soil type is clay in the entire catchment area, about 0.96 in. (24.4 mm) run-off was produced out of 1 in. (25.4 mm) precipitation.

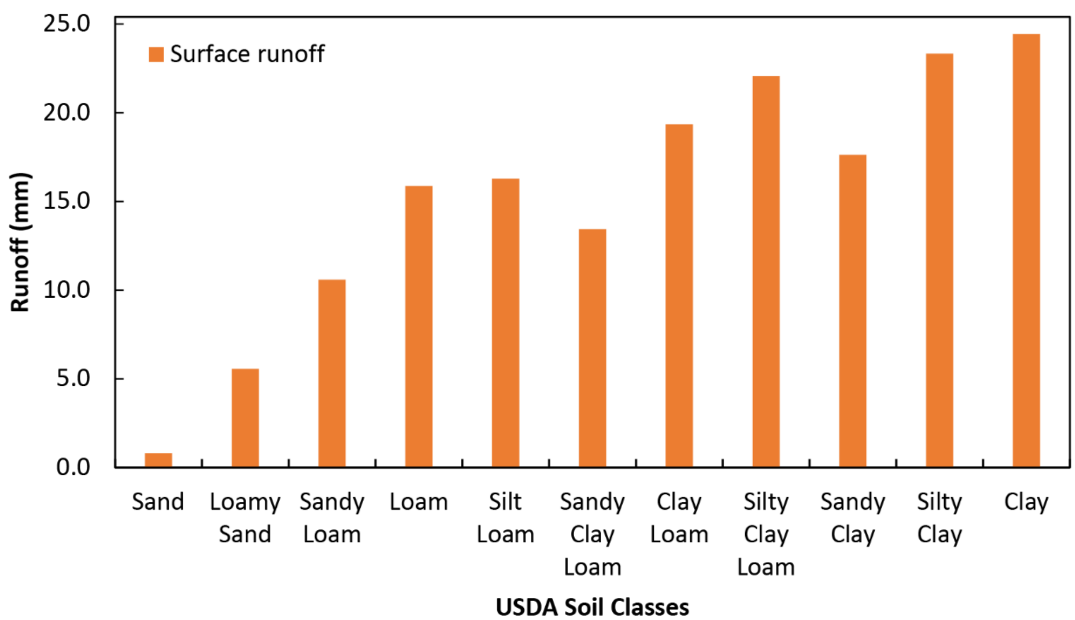


Figure 17. Run-off for baseline Pre-BMP catchment area.

Table 15 shows the run-off volume reduction (ICPE) (see Section 3.4.1 for definition) results in pre-BMP condition with no vegetative soil surface cover. As shown in the table, the ICPE of a site with loam is only 38%, which means 0.62 in. (15.7 mm) of 1 in. (25.4 mm) of precipitation at the idealized catchment will be run-off.

Table 15. Run-Off Volume Reduction (ICPE) in Pre-BMP, No Vegetative Surface Cover Condition

Soil Type	Bare Soil (%)
Sand	97
Loamy Sand	78
Sandy Loam	58
Loam	38
Silt Loam	36
Sandy Clay Loam	47
Clay Loam	24
Silty Clay Loam	13
Sandy Clay	31
Silty Clay	8
Clay	4

4.2 EFFECT OF SURFACE VEGETATIVE COVER (TURFGRASSES AND PRAIRIE GRASSES)

Simulation results for sites without BMPs showed that the sites with prairie grass had higher ICPE than the sites covered by turfgrass. However, ICPE—depending on in-place soil types in the catchment area—may vary. As shown in Table 16 and Figure 18, the ICPE for turfgrass ranges from 4% in clayey soil to 100% in sandy soil, and for prairie grass it ranges from 25% in clayey soil to 100% in sandy soil. The table shows that use of prairie grass will result in two to seven times more ICPE than turfgrass for soil types changing from loam to clay. Therefore, even without implementing a BMP and by just using more grass cover in the right-of-way, a reasonable run-off reduction can be achieved.

Table 16. Effectiveness of Turfgrasses and Prairie Grasses for Run-Off Volume Reduction (ICPE)

Soil Type	Turfgrass (%)	Prairie Grass (%)
Sand	100	100
Loamy Sand	91	100
Sandy Loam	71	87
Loam	49	76
Silt Loam	47	74
Sandy Clay Loam	59	74
Clay Loam	34	59
Silty Clay Loam	24	51
Sandy Clay	41	64
Silty Clay	17	42
Clay	4	25

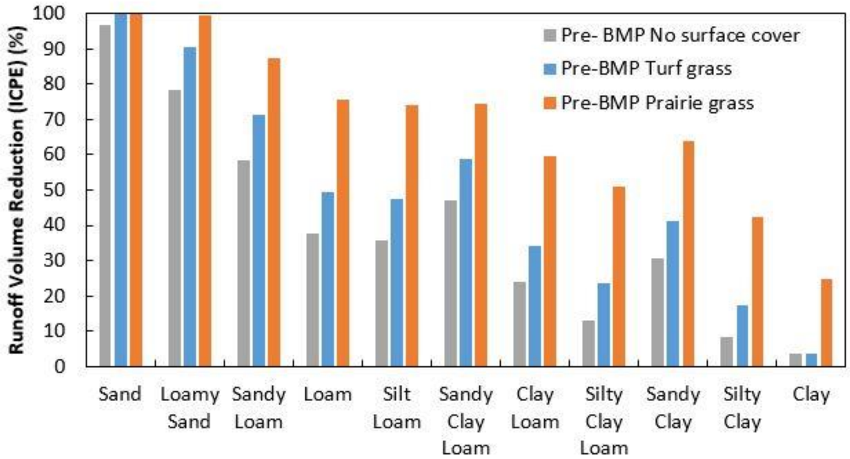


Figure 18. Effectiveness of turfgrasses and prairie grasses on the system run-off volume reduction (ICPE).

4.3 EFFECTIVENESS OF THE SYSTEM WITH INDIVIDUAL BMP

As explained in Section 3.4.1, the efficiency of a BMP was evaluated using Equation 1 by comparing run-off from an idealized catchment area at the outfall point for each scenario to the input stormwater volume resulting from a 1-in. rainfall as inflow to the catchment.

4.3.1 Single BMP with No Vegetative Surface Cover in the Catchment Area

As shown in Table 17, post-BMP construction at sites with no vegetative surface cover in the right-of-way resulted in average run-off volume reduction (ICPE) of 89%, 100%, and 86%, for bioswale, infiltration trench, and vegetated filter strip, respectively. Results showed that for an idealized catchment using a single new bioswale or vegetated filter strip with the dimensions shown in Figure 7 and Figure 9, almost 80% of the run-off produced by a 1-in. rainfall is captured, whereas an infiltration trench with the dimensions shown in Figure 8 captures 100% of run-off volume.

Table 17. ICPE Value for Idealized Catchment with No Vegetative Surface Cover and Single BMPs

Soil Type	Bioswale	Infiltration Trench	Vegetated Filter Strip
Sand	100	100	100
Loamy Sand	96	100	96
Sandy Loam	91	100	88
Loam	88	100	83
Silt Loam	88	100	84
Sandy Clay Loam	88	100	84
Clay Loam	86	100	82
Silty Clay Loam	86	100	81
Sandy Clay	86	100	82
Silty Clay	85	100	80
Clay	85	100	80
Average Reduction Percentage	**89**	**100**	**86**

4.3.2 Single BMP with Vegetated Cover (Turfgrasses and Prairie Grasses)

Table 18 displays the effectiveness of post-BMP condition for sites with turfgrass in the right-of-way. For sites with turfgrass surface cover in the right-of-way, use of bioswale, infiltration trench, and vegetated filter strip will result in average run-off volume reduction (ICPE) of 90%, 100%, and 88%, respectively. Depending on the soil type, the ICPE varies—for example, at the sites with bioswale and silt loam in-place soil, which is covered by turfgrass, the captured run-off in the idealized catchment was 83% of the 1-in. precipitation. The implementation of a vegetated filter strip led to 86% effectiveness in the system. Similar to the sites without any vegetative surface cover, under any types of soil, implementation of an infiltration trench resulted in 100% ICPE at the outfall point of the idealized catchment. A comparison of Table 17 and Table 18 shows that the inclusion of turfgrass did not have any major influence on ICPE. This is in agreement with the field infiltration tests that were performed and were discussed in Section 3.2.6.

Table 18. ICPE Value for Idealized Catchment with Turfgrass Surface Cover and Single BMP

Soil Type	**Bioswale**	**Infiltration Trench**	**Vegetated Filter Strip**
Sand	100	100	100
Loamy Sand	97	100	99
Sandy Loam	94	100	93
Loam	90	100	87
Silt Loam	83	100	86
Sandy Clay Loam	90	100	87
Clay Loam	88	100	84
Silty Clay Loam	87	100	83
Sandy Clay	88	100	84
Silty Clay	86	100	82
Clay	85	100	80
Average Reduction Percentage	**90**	**100**	**88**

Table 19 demonstrates the effectiveness of post-BMP condition for sites with prairie grass in the right-of-way. For sites with prairie grass surface cover, use of bioswale, infiltration trench, and vegetated filter strip will result in average run-off volume reduction (ICPE) of 92%, 100%, and 90%, respectively. For example, at the sites with a bioswale and silt loam soil that is covered by prairie grass, the captured run-off in the area was 92% of the 1-in. precipitation. The implementation of a vegetated filter strip led to 89% effectiveness in capturing run-off in the idealized catchment. Similar to the sites without any surface cover, under any types of soil, implementation of infiltration trench resulted in 100% ICPE.

The comparison of the results of scenarios where prairie grass was used with scenarios that did not have any vegetation surface cover shows that a slight advantage to using prairie grass. However, because the majority of run-off is captured by the BMP structure, the pronounced benefit of using prairie grass rather than turfgrass was not clearly observed as with the scenarios for which a BMP was not implemented at the site (see Section 4.2). The presence of a grass surface cover offer the benefit of improving the quality of run-off and may help with longer performance of the BMP.

Table 19. ICPE Value for Idealized Catchment with Prairie Grass Surface Cover and Single BMPs

Soil Type	Bioswale	Infiltration Trench	Vegetated Filter Strip
Sand	100	100	100
Loamy Sand	98	100	100
Sandy Loam	95	100	94
Loam	92	100	89
Silt Loam	92	100	89
Sandy Clay Loam	92	100	89
Clay Loam	90	100	86
Silty Clay Loam	89	100	85
Sandy Clay	90	100	87
Silty Clay	88	100	84
Clay	87	100	83
Average Reduction Percentage	**92**	**100**	**90**

It should also be mentioned that the simulated BMPs in this study are assumed as newly installed BMPs. Depending on the maintenance practice and frequency, these BMPs deteriorate with time because of clogging or lost storage capacity.

4.4 EFFECTIVENESS OF THE SYSTEM WITH COMBINED BMPS

The efficiency of using combined BMPs at idealized catchments was assessed using Equation 1. The effects of combined BMPs were evaluated by comparing the run-off from the idealized catchment area at the outfall point for each scenario to the 1-in. rainfall as inflow to the catchment area.

4.4.1 Combined BMPs with No Vegetated Surface Cover

In this section, the scenarios in which the idealized catchments had no vegetative surface cover were considered. The effectiveness of the idealized catchment (ICPE) by simulating the combined BMPs is shown in **Table 20**. Like previous sections, the effectiveness of the system shows how much of the 1-in. precipitation into the idealized catchment area was captured. The combination of bioswale and infiltration trench retained 100% of the run-off (**Table 20**). While the average ICPE out of 1-in. precipitation for all types of soil by a combination of vegetated filter strip (VFS) and bioswale is about 98%. This value for the combination of VFS and infiltration trench is around 94%. Overall, the combination of two BMPs will capture essentially all run-off from the idealized catchment.

Table 20. ICPE Value for Idealized Catchment with No Surface Cover and Combined BMPs

Soil Type	VFS + Bioswale Run-Off	VFS + Infiltration Trench	Bioswale + Infiltration Trench
Sand	100	100	100
Loamy Sand	100	100	100
Sandy Loam	99	97	100
Loam	98	93	100
Silt Loam	98	93	100
Sandy Clay Loam	98	94	100
Clay Loam	98	92	100
Silty Clay Loam	98	91	100
Sandy Clay	98	92	100
Silty Clay	97	91	100
Clay	97	91	100
Average	**98**	**94**	**100**

4.4.2 Performance of Combined BMPs With Turfgrasses and Prairie Grasses in Catchment Area

The idealized catchments that had turf or prairie grass vegetative surface cover were considered. This means that all areas are covered by grass except the BMP area and highway subcatchments. The effectiveness of the idealized catchment (ICPE) for combined BMP simulations that had turf or prairie surface cover is shown in Table 21. The percent reductions were calculated by comparing the run-off at the outfall point of the catchment area and the 1-in. precipitation. A comparison of **Table 20** and Table 21 demonstrates that run-off volume can be completely captured if two BMPs are installed in the idealized catchment, regardless of the surface vegetative cover type.

Table 21. ICPE Value for Idealized Catchment with Turf and Prairie Grass Surface Cover and Combined BMPs

Soil Type	VFS + Bioswale	VFS + Infiltration Trench		Bioswale + Infiltration Trench	
	Turf	Turf	Prairie	Turf	Prairie
Sand	100	100.0	100.0	100.0	100.0
Loamy Sand	100	100.0	100.0	100.0	100.0
Sandy Loam	99	100.0	100.0	100.0	100.0
Loam	98	100.0	100.0	100.0	100.0
Silt Loam	98	100.0	100.0	100.0	100.0
Sandy Clay Loam	98	100.0	100.0	100.0	100.0
Clay Loam	98	100.0	100.0	100.0	100.0
Silty Clay Loam	98	100.0	100.0	100.0	100.0
Sandy Clay	98	100.0	100.0	100.0	100.0
Silty Clay	98	100.0	100.0	100.0	100.0
Clay	97	100.0	100.0	100.0	100.0
Average	**98**	**100.0**	**100.0**	**100.0**	**100.0**

4.5 EFFECTIVENESS OF BMP SCALING ON RUN-OFF VOLUME REDUCTION IN THE SYSTEM

The efficiency of using various sizes of each BMP at idealized catchments was also assessed using Equation 1.

4.5.1 Bioswale

The simulation results for a bioswale with different dimensions at an idealized catchment without any surface vegetation cover are shown in Figure 19. A higher run-off volume reduction was obtained using bioswales with milder slopes and wider bottom widths. For sites that have soils more permeable than loam-type soils, the side slopes and bottom width of the bioswale do not noticeably affect the efficiency of the system in controlling runoff. However, for sites with soils less permeable than loams, the milder slopes or wider bioswales will result in up to about 10% more efficiency in capturing run-off volume resulting from a 1-in. rainfall. Overall, it seems that the minimal increase in efficiency with milder slopes or wider bioswales for the considered idealized catchment is not worth the additional construction costs and maintenance costs in the long term.

Figure 20 shows run-off reduction for sites with a bioswale in an idealized catchment and turfgrass surface cover. The results are very similar to those shown in Figure 19. The runoff reduction has a range of 82% for a 3:1 side slope and 3-ft bottom width to 100% for a side slope of 5:1 and bottom width of 8 ft. Similar to scenarios with no vegetative surface cover, the side slopes and bottom width of the bioswale dos not noticeably affect the efficiency of the system in controlling runoff for the sites that have soils more permeable than loam-type soils. However, for sites with soils less permeable than loams, the milder slopes or wider bioswales will result in up to about 7% more efficiency in capturing run-off volume from a 1-in. rainfall.

Figure 21 shows run-off volume reduction for sites with a bioswale in an idealized catchment and prairie grass surface cover. The efficiency of these simulated scenarios is up to about 5% more than what is shown in Figure 19. Overall, it seems that the change in side slopes or bottom widths of bioswales does not significantly influence their run-off reduction capacity in the idealized catchment. The reason is that the total right-of-way is constant; therefore, the increase in the footprint area of the bioswale will decrease the grass-covered areas—and those effects counterbalance each other.

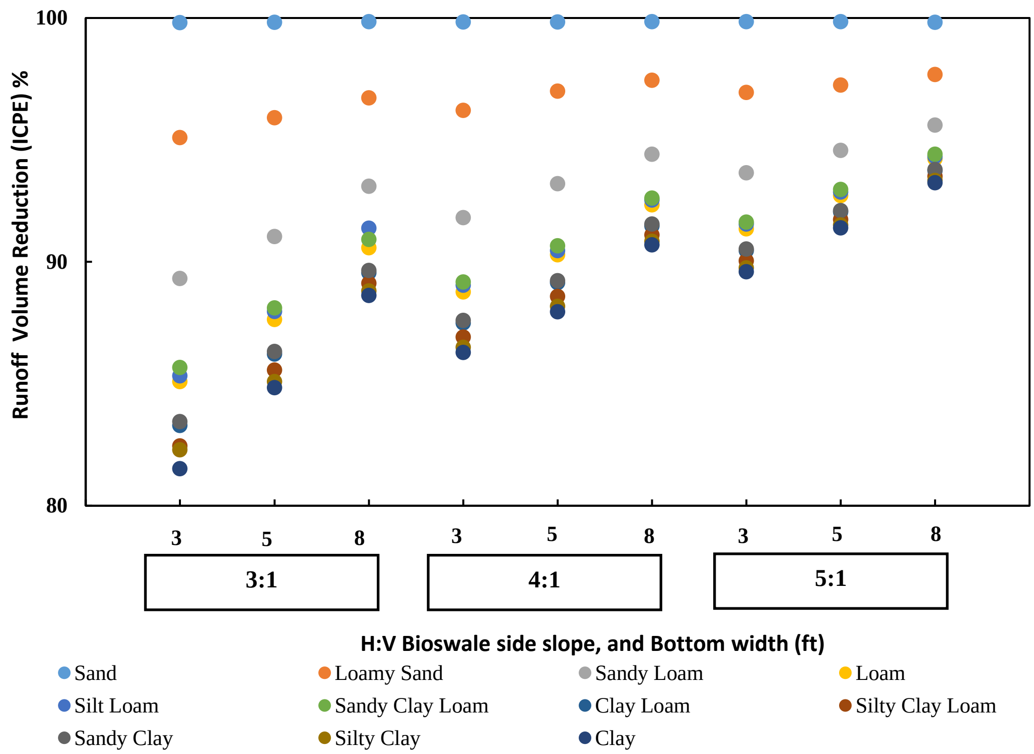


Figure 19. Effects of bioswale scaling on run-off volume reduction (ICPE) for all soil types for sites with no vegetative surface cover.

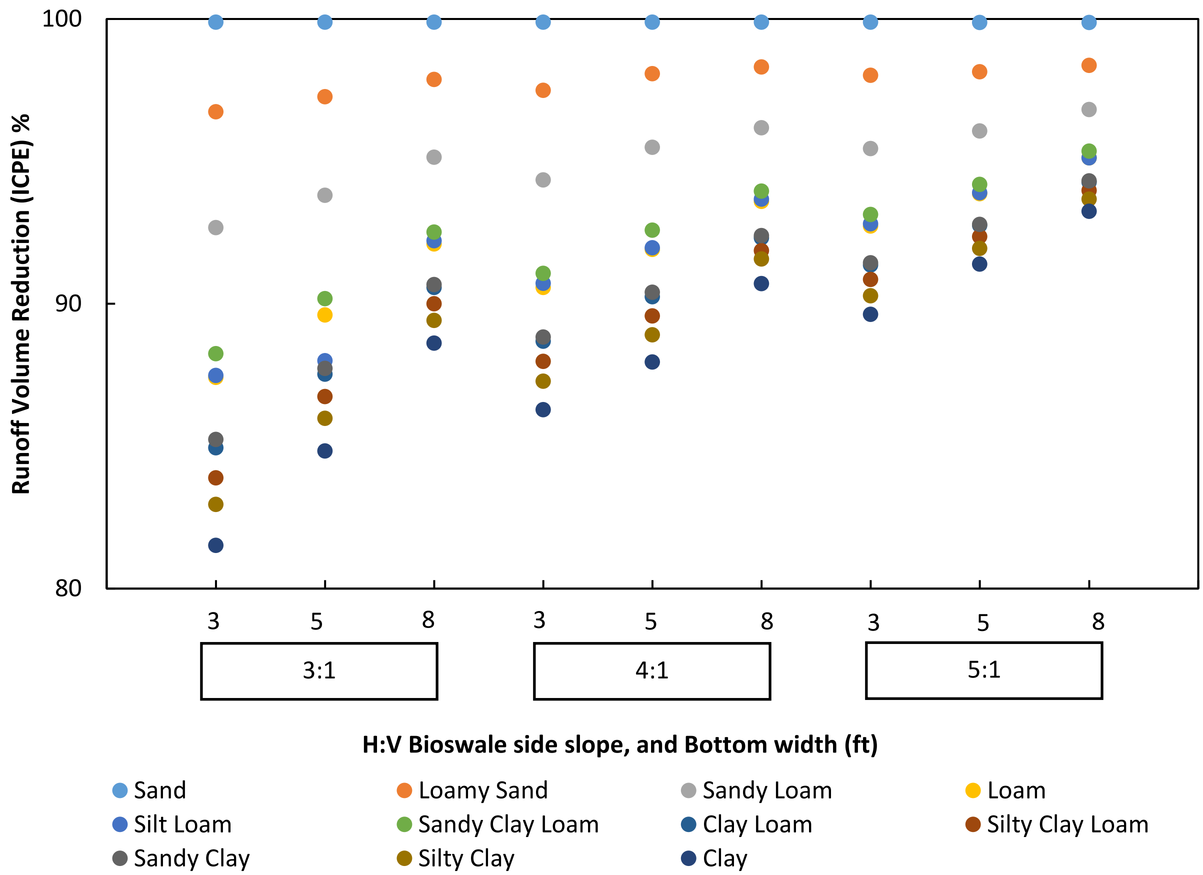


Figure 20. Effects of bioswale scaling on run-off volume reduction (ICPE) for all soil types for sites with turfgrass condition.

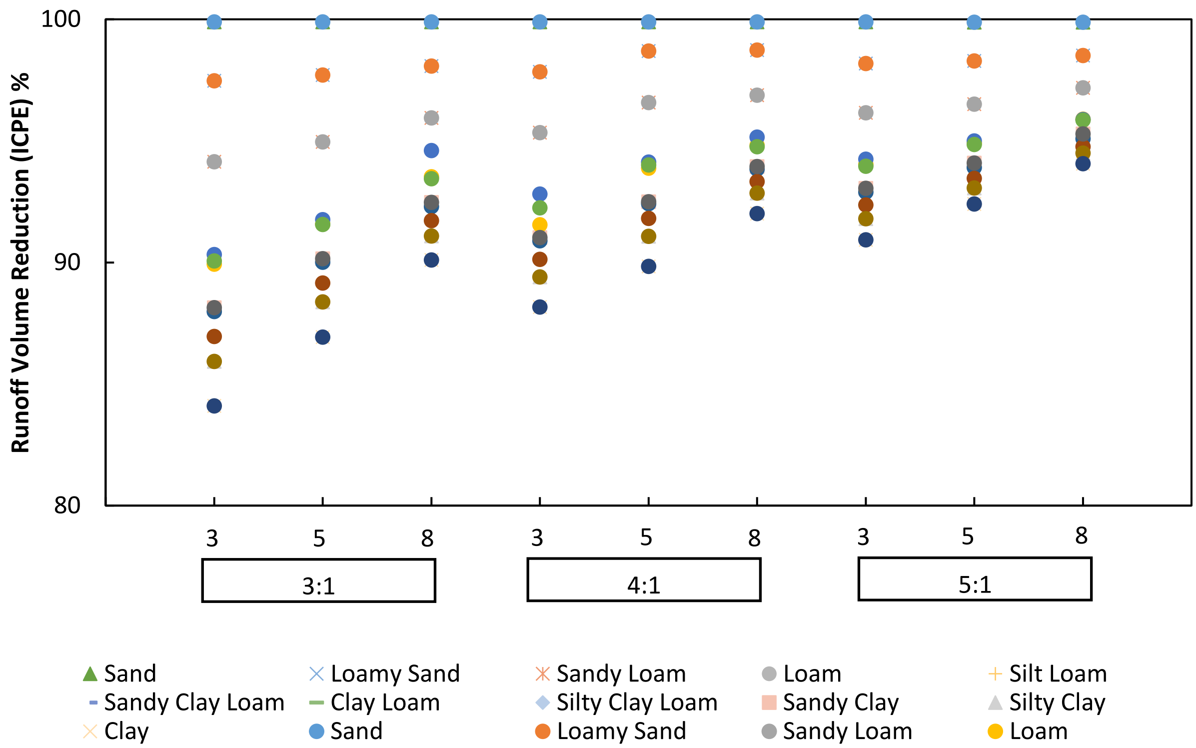


Figure 21. Effects of bioswale scaling on run-off volume reduction (ICPE) for all soil types for sites with prairie grass condition.

4.5.2 Infiltration Trench

One hundred percent run-off volume reduction was achieved with the minimum bottom width of 3 ft, as suggested by USEPA (1999a) for an infiltration trench for 1-in. rainfall events. Therefore, no further analysis was conducted to assess the effects of larger widths on run-off volume reduction. The challenge with infiltration trenches is the proper maintenance to keep them fully operational in the long term.

4.5.3 Vegetated Filter Strip

Figure 22 shows run-off volume reduction for sites with a vegetated filter strip (VFS) in an idealized catchment that does not have any vegetative surface cover. The run-off volume reduction has a range of about 36% for 5-ft-wide BMPs to 96% for 25-foot-wide BMPs. At sites with native sandy soil, 100% runoff reduction is expected. The width of the VFS has an important effect on the efficiency of the system in capturing the run-off. For sites with loamy and clayey soils, an increase in VFS width from 5 to 25 ft can result in 40% and 120% less run-off volume, respectively. The results indicate that the width of a VFS should be more than 15 ft in order to capture at least 50% of the run-off produced at the site.

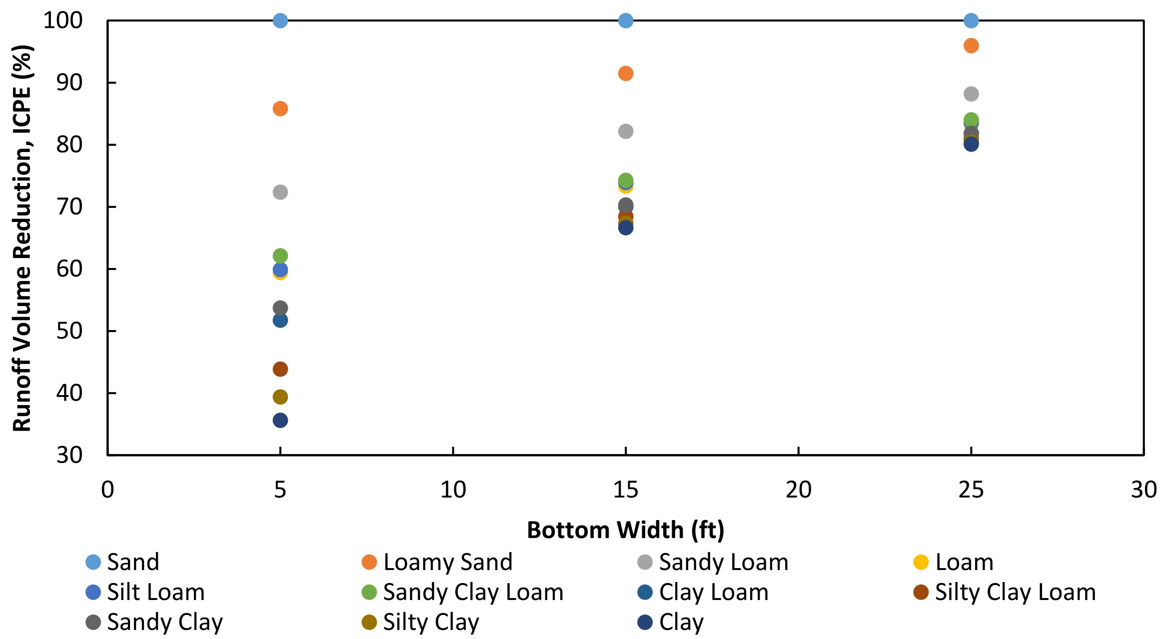


Figure 22. Effect of VFS scaling on run-off volume reduction (ICPE) in the system for all soil types, no vegetative surface cover condition.

Figure 23 shows run-off volume reduction for sites with a VFS in an idealized catchment that is covered with turfgrass as surface cover. A comparison of Figure 22 and Figure 23 shows that inclusion of turfgrass cover can improve the efficiency of the system by capturing up to 20% and 7% more run-off for the 5- and 25-ft-wide VFS practices, respectively. A comparison of the results shows that the main increase in efficiency occurs when VFS width changes within 5 to 15 ft.

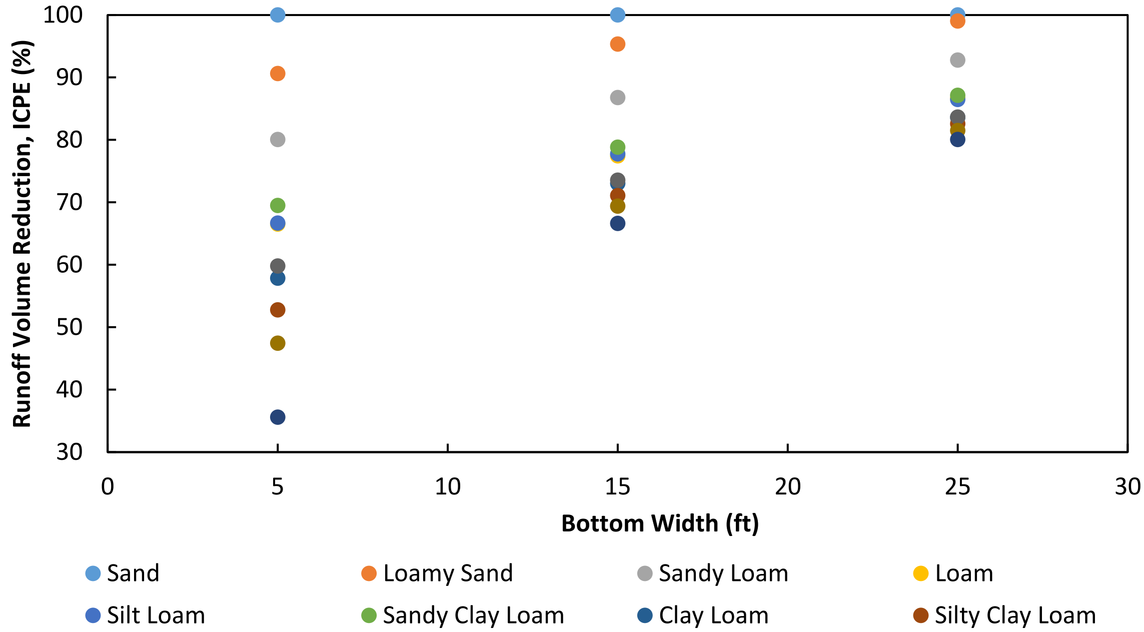


Figure 23. Effects of VFS scaling on run-off volume reduction (ICPE) for all soil types, turfgrass condition.

Figure 24 shows run-off volume reduction for sites with a VFS in an idealized catchment that is covered with prairie grass as surface cover. A comparison of Figure 22 and Figure 24 shows that inclusion of prairie grass cover can improve the efficiency of the system by capturing up to 45%, 12%, and 7% more run-off for 5-, 15-, and 25-ft wide VFS practices, respectively. The use of prairie grass in areas not covered by a BMP footprint can substantially improve the run-off-capturing efficiency compared to the use of turfgrass for scenarios that have VFS widths of 5 or 15 ft.

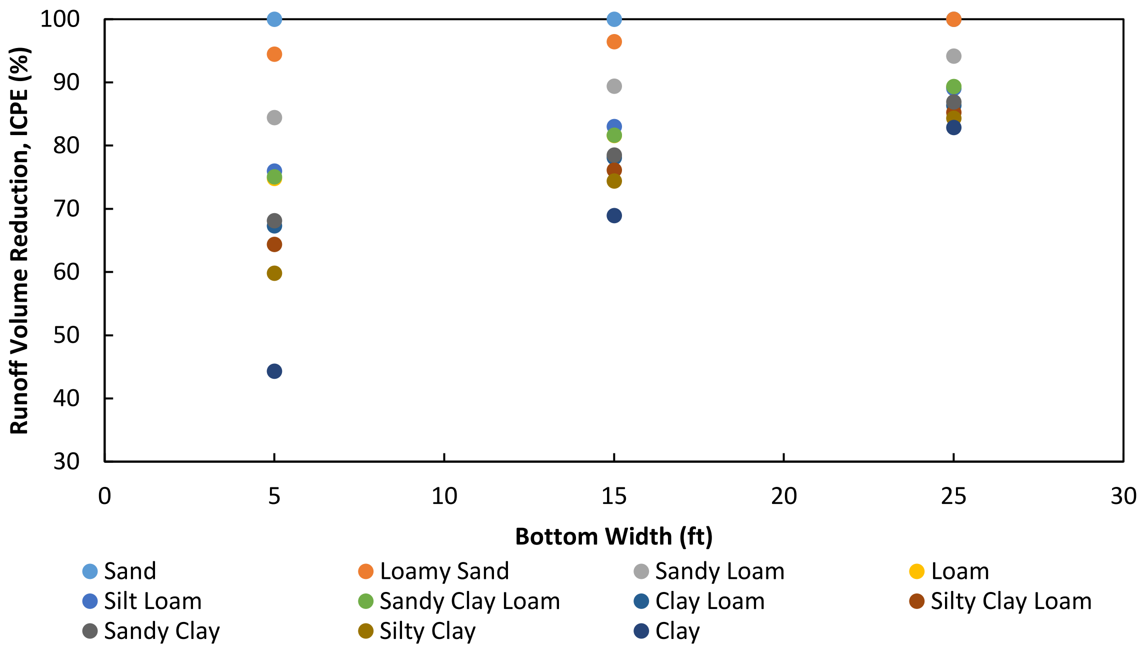


Figure 24. Effects of VFS scaling on run-off volume reduction (ICPE) for all soil types, prairie grass condition.

4.6 PERFORMANCE OF BMP SUBCATCHMENTS

As explained in the methodology section (Section 3.4.2), comparing the inflow to and outflow from the BMP subcatchment can be used to determine the run-off volume reduction (BMP_{RVR}) of the installed BMP. Most of the measured BMP_{RVR} reported in the literature are calculated based on this method because it is easier to measure the input flow to the BMP and output flow from the BMP. However, those studies are often focused on the performance of BMP itself. The application of this concept for the linear projects, where the objective is to maintain or control all the run-off produced by a 1-in. rainfall within a catchment area is not appropriate. Nevertheless, for completeness, these values are presented for the studied scenarios.

The inflow to the subcatchment included the precipitation and the run-on from the other subcatchments, such as ground level and backslope. Table 22 shows BMP_{RVR} values for all the considered scenarios. It is worth mentioning that, owing to different dimensions of BMPs, the input run-on to the BMP is different for each of the scenarios mentioned in the table. Therefore, the BMP_{RVR} values can be compared only within different soil types and surface covers for each BMP scenario and not within various dimensions or types of BMPs.

The comparison of calculated BMP_{RVR} values shown in Table 22 with the reported values from the literature (see Table 1) shows that higher BMP_{RVR} values are obtained in this study, which is attributable to two main reasons. The first is that the ratio of BMP covered area to contributing watershed area in this study is different from the ratios most often reported in the literature. In this study, the ratios of BMP area to contributing watershed area are 13% and 26% for bioswale and VFS, respectively. However, in the reported BMPs in the literature, particularly in the international BMP database, the BMP area to contributing watershed area ratios are significantly smaller. For example, the bioswale and VFS sites that were discussed in Section 3.5 had ratios of 3.5% and 3.8% of BMP area to contributing watershed area. Therefore, expectedly, the run-off reduction in the BMP is greater in this study than what is reported in those cases.

The second reason is related to the deterioration of BMPs with time, which was discussed in Section 3.5. Because the infiltration capacity of BMPs can be significantly reduced as a result of poor maintenance or frequent mowing, it is very common that the field measurements done several years post-construction show lower BMP_{RVR} values.

Table 22. Run-Off Volume Reduction: BMP_{RVR} for All Scenarios (Performance of the BMP Subcatchment)

Soil Type	Post Highway	Bioswale									Infiltration Trench		Vegetated Filter Strip		
		3H:1V			4H:1V			5H:1V							
		3ft BW	5ft BW	8ft BW	3ft BW	5ft BW	8ft BW	3ft BW	5ft BW	8ft BW	3ft BW	5ft BW	5 ft BW	15 ft BW	25 ft BW
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Sand	97	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Loamy Sand	78	95	96	97	96	97	97	97	97	98	100	100	86	91	96
	91	97	97	98	98	98	98	98	98	98	100	100	91	95	99
	100	97	98	98	98	99	99	98	98	99	100	100	94	96	100
Sandy Loam	58	89	91	93	92	93	94	94	95	96	100	100	72	82	88
	71	93	94	95	94	95	96	95	96	97	100	100	80	87	93
	87	94	95	96	95	97	97	96	97	97	100	100	84	89	94
Loam	38	85	88	91	89	90	92	91	93	94	100	100	59	73	83
	49	87	90	92	91	92	94	93	94	95	100	100	67	77	87
	76	90	92	94	92	94	95	94	95	96	100	100	75	82	89
Silt Loam	36	85	88	91	89	90	93	92	93	94	100	100	60	74	84
	47	87	83	92	91	92	94	93	94	95	100	100	67	78	86
	74	90	92	95	93	94	95	94	95	96	100	100	76	83	89
Sandy Clay Loam	47	86	88	91	89	91	93	92	93	94	100	100	62	74	84
	59	88	90	93	91	93	94	93	94	95	100	100	70	79	87
	74	90	92	93	92	94	95	94	95	96	100	100	75	82	89
Clay Loam	24	83	86	90	87	89	91	90	92	94	100	100	52	70	82
	34	85	88	91	89	90	92	91	93	94	100	100	58	73	84
	59	88	90	92	91	92	94	93	94	95	100	100	67	78	86
Silty Clay Loam	13	82	86	89	87	89	91	90	92	94	100	100	44	68	81
	24	84	87	90	88	90	92	91	92	94	100	100	53	71	83
	51	87	89	92	90	92	93	92	93	95	100	100	64	76	85
Sandy Clay	31	83	86	90	88	89	92	91	92	94	100	100	54	70	82
	41	85	88	91	89	90	92	91	93	94	100	100	60	74	84
	64	88	90	92	91	93	94	93	94	95	100	100	68	78	87
Silty Clay	8	82	85	89	87	88	91	90	92	93	100	100	39	67	80
	17	83	86	89	87	89	92	90	92	94	100	100	47	69	82
	42	86	88	91	89	91	93	92	93	94	100	100	60	74	84
Clay	4	82	85	89	86	88	91	90	91	93	100	100	36	67	80
	4	82	85	89	86	88	91	90	91	93	100	100	36	67	80
	25	84	87	90	88	90	92	91	92	94	100	100	44	69	83

4.7 SCALING PARAMETER EFFECTS ON BMP UNIT PERFORMANCE

Based on the cost of BMP construction and capacity in run-off volume reduction (BMP_{RVR}) and the goal of the design, engineers or decision makers can choose the type and size of the BMP. In this section, the appropriate size of bioswale and VFS for capturing run-off produced by 0.25, 0.5, 0.75, and 1 in. of rainfall is investigated. In these analyses, the idealized catchment area with silt loam as the soil type and turfgrass as the surface cover and a single BMP unit was modeled. The results in this section are obtained using Equation 2 in Section 3.4.2.

In scaling of the bioswale, the bottom width is a significant factor in BMP performance. It can be observed in Table 23 that the bioswale can be practically designed to capture almost all run-off from 0.25 and 0.5 in. rainfalls. However, if it is intended to capture all 0.75- and 1-in. amounts of rain, it should have a bottom width of more than 12 and 20 ft, respectively.

Table 23. Bioswale Unit Performance (BMP_{RVR}) with Change in Bottom Width)

		Rainfall (in.)			
Bottom Width (ft)	**Total width (ft)**	**1**	**0.75**	**0.5**	**0.25**
20	29	100	100	100	100
16	25	94	96	98	100
12	21	91	94	97	100
8	17	87	91	95	99
5	14	83	87	93	99
3	12	79	84	91	99

According to Table 24, for the 3-ft-wide infiltration trench, the required storage thickness for capturing all of the run-off produced by 0.25, 0.5, 0.75, and 1 in. of rainfall are 0.2, 0.2, 0.7, and 2 ft, respectively. According to Table 25, for the VFS, the required widths for capturing all of the run-off produced by 0.25-, 0.5-, 0.75-, and 1-in. rainfall events are 5, 20, 30, and 39 ft, respectively.

Table 24. Infiltration Trench Unit Performance (BMP_{RVR}) with Change in Storage Thickness

	Rainfall (in.)			
Storage Thickness (ft)	**1**	**0.75**	**0.5**	**0.25**
7	100	100	100	100
3	100	100	100	100
2	100	100	100	100
1	99	100	100	100
0.7	89	100	100	100
0.5	83	97	100	100
0.35	76	90	100	100
0.2	67	80	100	100
0.1	59	71	94	100

Table 25. VFS BMP Unit Performance (BMP_{RVR}) and Change in Bottom Width

Bottom Width (ft)	Rainfall (in.)			
	1	**0.75**	**0.5**	**0.25**
39	98	100	100	100
30	88	100	100	100
25	83	97	100	100
20	72	86	100	100
15	63	74	98	100
14	61	72	95	100
7	46	54	71	100
5	40	48	61	100
2	23	32	42	71

CHAPTER 5: COST OF POST-CONSTRUCTION BMPs

5.1 COST DATA

Permanent BMP construction and maintenance historical cost data are available from a variety of sources. Government agencies, professional organizations, and academic investigations contribute to publicly available historical cost data. However, several issues must be overcome to reliably use historical cost data. Project age, units of measure (or lack thereof), ranked rather than explicit cost, project size, and urban/rural application variables all affect cost data.

For comparative purposes, costs must be adjusted to a common time period. For instance, historical cost data from the 1970s must be adjusted for 30+ years of inflation and material price variation to compare with current costs. While simple, inflationary adjustment calculations can be applied and approximate time-adjusted costs calculated, the results will not accurately reflect time variable costs associated with every component of a particular BMP's construction. Some materials may actually become less expensive over time; other commodities—fuel, for example—experience wide fluctuations in price both up and down over time, requiring very specific analysis to correct for current price comparison.

Many sources of historical BMP cost data do not explicitly or precisely define costs in terms of a definable unit; providing cost per linear measure without defining width or depth, or cost per area of catchment without defining expected precipitation or level of run-off capture, or just cost per BMP with no dimensional information at all. This type of data should not be used for any purpose other than very general comparison.

Cost data for BMP construction associated with a single building and cost data for the same BMP constructed along many thousands of feet of right-of-way are not readily comparable because of widely different mobilization, working room, scheduling, productivity, and labor factors. Many cost data sources are associated with small, one-of-a-kind demonstration projects and are not readily comparable with large-scale BMP construction associated with transportation infrastructure.

Some BMPs have been strongly associated with agriculture for many decades. Vegetated swales, wet and dry retention structures, subdrain systems, and vegetative filter strips all originated as agricultural practices in the early 20th century. Government subsidies to construct permanent BMPs have been available to farmers for many decades, usually on a cost-share basis, with farmers paying some fraction of the cost and the government providing the remaining funds. These agricultural BMPs were usually installed with on-farm labor and farmer-owned equipment. As a result, the cost of these practices for agricultural applications is markedly lower than for commercial projects. For example, a recent Natural Resource and Conservation Service (NRCS formerly Soil Conservation Service, SCS) brochure for vegetative filter strips estimated construction cost at less than \$400 per ac, while commercial landscapers routinely charge over \$2,000 per ac.

Cost estimators must adjust historical data for time, project size, project location, units of measurement, and commercial versus agricultural application. As a result of the uncertainty inherent with these multiple adjustments, a professional estimator would not rely on publicly available data to price a BMP project. Instead, estimators rely on privately held productivity, unit cost, and subcontractor provided itemized cost data from similar, recent projects. Maintaining an up-to-date cost history dataset is a crucial component of successful contracting. Contracting firms closely guard cost history information in an attempt to maintain a competitive advantage. Publicly available cost data use would be limited to verifying order-of-magnitude price ranges and making initial decisions to pursue a project.

Construction costs for the BMPs identified in this report as most suitable for additional study (infiltration trench, bioswale, and vegetated filter strip) are based on current, privately held cost data provided by our consultant. However, for completeness of this report, individual BMP construction and maintenance costs provided in the available literature is also provided. For example, Table 26 presents the associated cost and maintenance requirement of BMPs according to the Arizona DOT post-construction best management practices manual. The Federal Highway Administration (FHWA) has proposed similar tables. Table 27 shows another BMP cost comparison prepared by USEPA (USEPA 1999b).

Table 26. Management Considerations (ADOT 2009)

BMP	Costs		Maintenance	Effective Life (years)	References
	Capital	O&M			
Manufactured Treatment Devices	Low to Moderate	Moderate to High	High; frequent cleanouts	10 –50	FHWA 2000 CDOT 2004 NRML 2002
Bioretention	Moderate	Low	Mowing/plant replacement	20–50	
Retention and Detention Basins	Moderate to High	Low	Moderate; annual inspection and debris removal	20– 50	
Infiltration Basin	Moderate	Moderate	High; sediment and debris removal from the surface	5–10 , before deep tilling is required	
Infiltration Trench	Moderate to High	Moderate	High; sediment and debris removal from the top	10–15	
Filtration Structures	Moderate to High	Moderate to High	High; biannual to annual media removal	5–20	
Vegetated Filter Strip (VFS)	Low	Low	Low; mowing and edge debris removal, scraping to maintain sheet flow	20–50	

Table 27. Typical Base Capital Construction Costs for BMPs (USEPA 1999)

BMP Type	Typical Cost* ($/cf)	Typical Cost ($/BMP)	Application	Notes	Source
Retention and Detention Basin	0.5–1.00	$100,000	50-ac Residential Site (Impervious Cover = 35%)	Cost range reflects economies of scale in designing this BMP. The lowest unit cost represents approx. 150,000 ft^3 of storage, while the highest is approx. 15,000 ft^3. Typically, dry detention basins are the least expensive design options among retention and detention practices	Brown and Schueler (1997)
Wetland	0.60–1.25	$125,000	50-ac Residential Site (Impervious Cover = 35%)	Although little data are available to assess the cost of wetlands, it is assumed that they are approx. 25% more expensive (because of plant selection and sediment forebay requirements) than retention basins.	Brown and Schueler (1997)
Infiltration Trench	4.00	$45,000	5-ac Commercial Site (Impervious Cover = 65%)	Represents typical costs for a 100-ft-long trench.	SWRPC (1991)
Infiltration Basin	1.30	$15,000	5-ac Commercial Site (Impervious Cover = 65%)	Represents typical costs for a 0.25-ac infiltration basin.	SWRPC (1991)
Sand Filter	3.00–6.00	$35,000 - $70,000	5-ac Commercial Site (Impervious Cover = 65%)	The range in costs for sand filter construction is largely due to the different sand filter designs. Of the three most common options available, perimeter sand filters are moderate cost whereas surface sand filters and underground sand filters are the most expensive.	Brown and Schueler (1997)
Bioretention	5.30	$60,000	5-ac Commercial Site (Impervious Cover = 65%)	Bioretention is relatively constant in cost because it is usually designed as a constant fraction of the total drainage area.	Brown and Schueler (1997)
Grass Swale	0.50	$3,500	5-ac Residential Site (Impervious Cover = 35%)	Based on cost per ft^2, and assuming 6 in. of storage in the filter	SWRPC (1991)
Filter Strip	0.00–1.30	$0-$9,000	5-ac Residential Site (Impervious Cover = 35%)	Based on cost per ft^2, and assuming 6 in. of storage in the filter strip. The lowest cost assumes that the buffer uses existing vegetation, and the highest cost assumes that sod was used to establish the filter strip.	SWRPC (1991)

*Base year for all cost data: 1997

5.2 COST ANALYSIS METHODOLOGY

This study estimates the construction cost, maintenance cost, and the expected life of three BMPs: infiltration trench, bioswale, and vegetated filter strip. Construction costs were determined based on the price that a qualified subcontractor would submit to a general contractor for a project of at least two weeks' duration, (at least 6,000 linear ft of infiltration trench or bioswale and at least 60,000 linear ft of vegetative filter strip). The cost estimates are exclusive of general conditions, profits, inspections, design, sales tax, mobilization, and traffic control. The estimated costs are for the BMP only and do not include demolition, drain connections, mass grading, de-watering, or any other ancillary work that a subcontractor performing this type of work would likely include based on the details of a particular project. Costs are based on June 2015 Illinois prevailing wage rates and equipment cost, $3.00 per gallon diesel fuel, and current material price quotes for seed, plants, geotextiles, drain pipe, aggregate, and growing medium.

For comparative purposes a standard width, the idealized cross-section was used to develop an appropriately sized BMP for that cross-section; costs and expected life calculations were determined based on the resulting design. The idealized cross-section consists of a 58-ft-wide, single sloped, four-lane pavement; a 20-ft-wide grass foreslope from the edge of the pavement to the edge of the BMP; a BMP of appropriate width for the cross-section and a back slope from the edge of the BMP to the edge of the right-of-way. The back slope width varies as necessary to provide a consistent total cross-section width of 96 ft. In the case of a vegetative filter strip, the strip extends the entire width from the toe of the foreslope to the edge of the right-of-way. The following assumptions were employed to size and analyze BMPs with the capacity to store 1 in. of runoff depth from the cross-section:

- Stormwater volume equals precipitation volume
- BMP only receives stormwater from the idealized catchment
- 100% of the stormwater sediment load is deposited within the BMP
- 1 ft^3 of sediment weighs 100 lb

The storage volume of a BMP is calculated by multiplying the volume of the BMP's storage area by the void ratio of the storage area's material. Void ratio measurements were performed on limestone chips (CA 15), 2" clean limestone (CA 1), and a proprietary growing medium mix (St. Louis Composting – Rain Garden Mix). The following void ratios were determined (see Figure 25) and subsequently used to appropriately size BMPs analyzed in this cost analysis:

- CA 15: 44%
- CA 11: 44%
- CA 1: 44%
- Growing medium: 18%

Figure 25. CA 15 void ratio determination.

Gateway Infrastructure Services Inc. (GISI) provides site work construction services for the public and private sector market in Illinois. GISI has extensive experience with road and bridge construction, temporary and permanent BMP construction, and contracting with IDOT and Illinois municipalities. The senior estimator for GISI, acted as a consultant for this project, providing work crew composition, construction equipment selection, work activity logic, productivity data, and cost history data. Details provided by GISI were broken down into discrete units, adjusted over a range of BMP geometry variations, and compiled into spreadsheet based cost calculators capable of generating BMP unit cost based on a range of BMP dimensions. All estimated costs are shown based on cost per 100 linear ft of BMP appropriately sized for the idealized cross-section. BMP cost for alternate cross-sections and BMP geometries may be quickly determined by altering appropriate values in the BMP sizing and BMP cost determination spreadsheets.

Life expectancy is an important component of BMP selection. When life expectancy factors are included, a BMP that is relatively expensive to construct may be superior to a less expensive BMP with a short life expectancy. USEPA does not have numerically defined BMP end of life criteria, (Bob Newport, personal communication, 2015). BMPs commonly fail due as a result of internal storage volume caused by accumulated sediment, or they fail because of restricted inflow to the BMP caused by surface clogging. For the purposes of our analysis, we have arbitrarily selected 40% internal void loss as the value for determining BMP failure.

Finally, this study creates and evaluates a management tool for preparing unit cost estimates for permanent BMPs appropriate for linear project applications. The management tool calculates construction cost, maintenance cost, and life expectancy of three BMPs: infiltration trench, bioswale, and vegetated filter strip. Cost details are compiled into a spreadsheet based cost calculator capable of generating BMP unit cost based on a range of BMP dimensions. A Microsoft Excel spreadsheet with macros and user interface performs the analysis. Project planners must consider hydraulics, project geometry, cost, and life cycle in order to select an appropriate BMP. Figure 26 illustrates the cost analysis planning process.

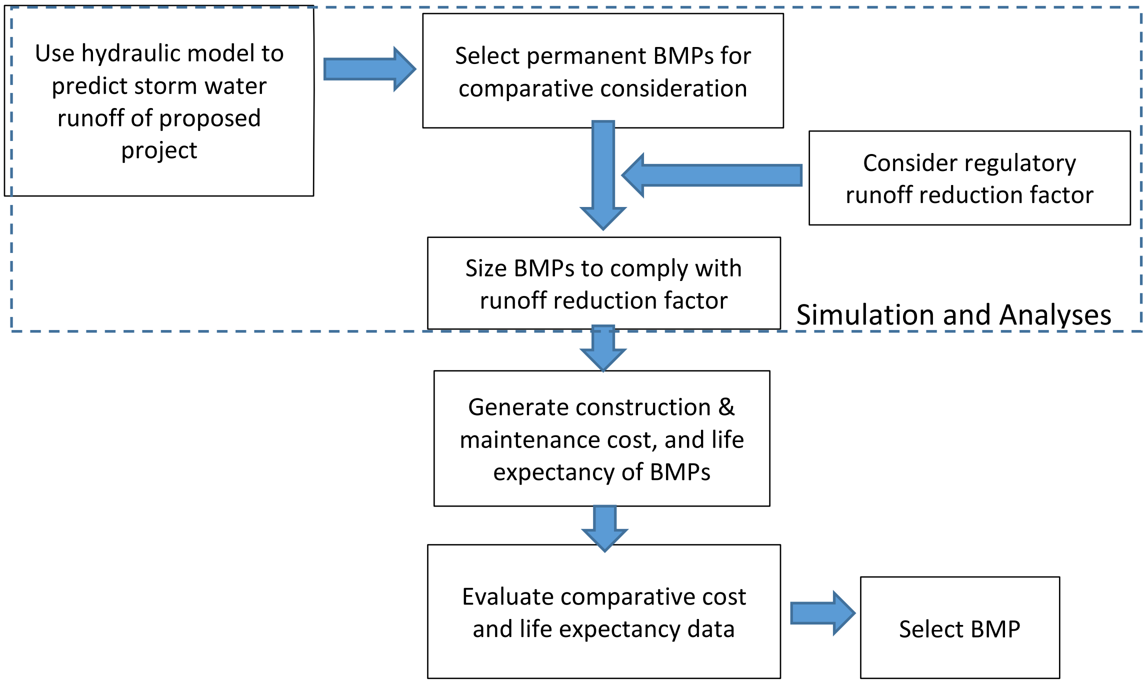


Figure 26. Planning process for cost level decision approach.

5.3 BIOSWALE

A bioswale functions by accepting run-off from its catchment area, filtering the run-off through a highly permeable growing medium, and temporarily storing run-off in an underlying infiltration bed. The growing medium also stores run-off and supports vegetation. While specified growing mediums have a higher infiltration rate than most native soils, growing medium infiltration rates will not likely be high enough to accept 100% of the design storm run-off. To overcome this limitation, many bioswales are constructed to include temporary surface storage above the growing medium. Surface storage is generally achieved with low berms capable of impounding run-off to a depth of up to several feet. Cost estimates generated in this study do not include impoundment berms or other means of surface storage other than depressing the bioswale 0.5 ft below the immediate grade.

Bioswale design is driven by vegetation type, growing medium characteristics, required storage volume, surrounding soil infiltration rate, trench depth considerations, and trench width. Bioswale volume must accommodate the fill material and the anticipated run-off volume. Bioswale volume in this study is based on the assumption that growing medium volume is occupied by 82% growing medium and 18% void space, and that the underlying infiltration area volume is occupied by 56% aggregate and 44% void space. In this study, 1 ft was selected for the growing medium depth, and 3 ft was selected for infiltration layer depth; surface storage is provided by depressing the bioswale 0.5 ft below surrounding grade. Excavations deeper than 4 ft require special conditions for worker safety, adding cost and complexity. Deep excavations may also encounter groundwater issues that affect construction cost and reduce capacity during periods of wet weather. Relatively wide bioswales provide a larger bottom area for infiltration. Applying these considerations to the idealized cross-section results in a bioswale 3.5 ft deep and 8 ft wide.

Bioswales may be equipped with a permeable pipe subdrain. The subdrain functions to slowly draw down internally stored run-off during wet periods when the soil infiltration rate is not sufficient to keep up with run-off entering the system and to discharge run-off in excess of the design storm. During extended periods of wet weather and during precipitation events in excess of the design storm a bioswale without a subdrain will not be able to internally accept run-off and surface flow will occur at rates higher than would be the case if a subdrain was provided. The cost estimating spreadsheet provides the option of pricing a subdrain. Outlet structure and connection costs are not included in the estimated cost.

Geotextile fabric may be specified as a liner for the sides and bottom of bioswale excavations. The fabric is intended to act as a barrier to soil fines migration into the BMP's void space. The option of determining the cost of a side and bottom geotextile liner has been provided in the cost calculation spreadsheet.

Fine material in the growing medium and solids in stormwater run-off will likely migrate into the underlying infiltration bed. Over time the accumulated solids will reduce the space available for stormwater storage. A geotextile fabric may be specified to separate the growing medium and infiltration bed. Installation of this detail requires material and labor to install the geotextile barrier. The option of determining the cost of a separating barrier has been provided in the cost calculation spreadsheet.

Permanent vegetation is an important component of bioswale design. Vegetation may be established by transplanting mesically adapted plants into the growing medium. *Aster punicus* (Swamp Aster), *Eupatorium maculatum* (Spotted Joe Pye Weed), *Glyceria striata* (Fowl Manna Grass), and *Spartina pectinata* (Prairie Cord Grass) are mesic plants often specified for bioswales. The horticultural industry has responded to this market and currently produces starter plants purposely grown for the bioswale market at $3.00 per plant. Typical planting specifications require 1.33 plants per ft^2. Associated labor and maintenance costs necessary to plant and start transplants are a significant fraction of bioswale cost.

Permanent vegetation may also be provided by establishing vegetation by seed rather than transplanting. Seed cost and associated labor and maintenance costs are significantly lower than vegetating by transplanting. Seed established vegetation would be the likely choice in a highway environment, while transplant established vegetation is often used in urban, decorative settings. Options to price either method are provided in the bioswale cost calculation spreadsheet. Figure 27 shows a generalized bioswale design with geotextile, subdrain, and vegetation options.

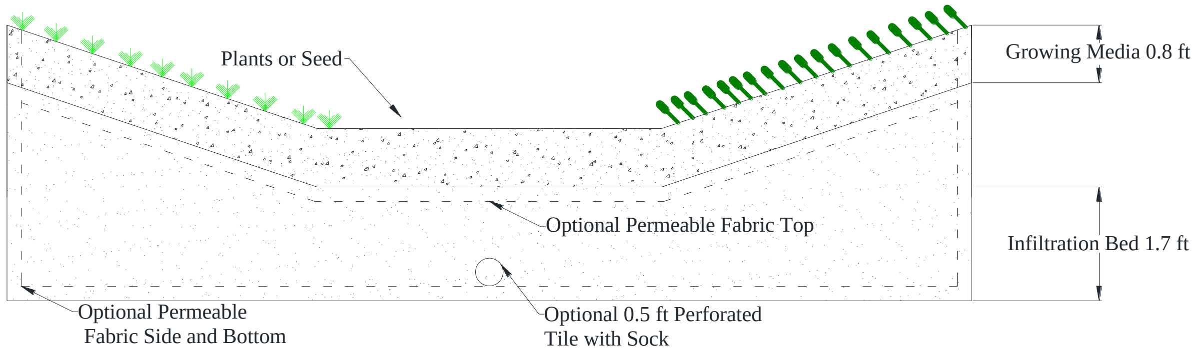


Figure 27. Cross-sectional area of a bioswale.

5.3.1 Bioswale Construction Cost

Workflow analysis indicates that a productivity rate of 600 linear ft per day may be achieved for bioswale construction in a highway environment. This work rate will require two excavators, two wheel loaders, two skid steer loaders, six laborers (eight, depending on options), four spoils haul-off trucks, and foreman, along with deliveries of aggregate, growing medium, (and if included) geotextile fabric, drain pipe, and plant materials. The considered variables of bioswale construction cost are described in Equation 3. Generally, construction cost is driven by bioswale dimensions, unit prices including labor, excavation, aggregate and vegetation and construction factors such as waste and transportation factors. As presented in Table 28, cost estimations are described as a function of volume or area, unit prices (U_n) and construction factors. Unit prices based on 2015 cost, are presented in Table 29.

Bioswale construction cost = f (excavation, haul off, aggregate , growing medium, fabric, drain pipe, plant, supervision) (3)

Table 28. Bioswale Construction Cost Estimation per Item

Pay Item	Estimation Formulation
Excavation + Haul Off	$U_1 \times (V_1 + V_2)$
Total aggregate cost	$U_2 \times (V_1 \times \rho) + U_3 \times V_1$
Total growing medium	$U_4 \times V_2 \times W_F \times C_F \times M + U_5 \times V_2$
Total fabric side, bottom & top*	$U_6 \times A_{S\&B} + U_6 \times A_t \times W_F + U_7 * A_t$
Drain pipe*	$100 \times U_8 \times W_F \times O + U_9$
Total seed	$U_{10} \times A_t$
Total plant cost	$U_{11} \times A_t \times N \times O \times P + U_{12} \times A_t \times M + A_t \times N/60 \times U_{13} \times O \times 2$
Supervision	$U_{14} \left(\frac{\$}{100\ ft}\right)$

Table 29. Unit Prices in Bioswale Construction Cost, Based on 2015

Pay Item	Description	Unit price
U_1	Equipment and labor	7.66 $\left(\frac{\$}{yd^3}\right)$
U_2, U_3	Aggregate and haul in cost, placement cost	16.5 $\left(\frac{\$}{ton}\right)$, 11.28$\left(\frac{\$}{yd^3}\right)$
U_4, U_5	Growing medium cost and haul in, placement cost	26 $\left(\frac{\$}{yd^3}\right)$, 14.7 $\left(\frac{\$}{yd^3}\right)$
U_6, U_7	Fabric cost, labor cost	1.15 $\left(\frac{\$}{yd^2}\right)$, 0.30 $\left(\frac{\$}{yd^2}\right)$
U_8, U_9	Pipe cost, constant cost per 100 ft for equipment, supervision, and labor	2.49 $\left(\frac{\$}{ft}\right)$, 119.7 $\left(\frac{\$}{100\ ft}\right)$
U_{10}	Seed price and seed establishment	6000 $\left(\frac{\$}{acre}\right)$
U_{11}, U_{12}, U_{13}	Plant cost, labor cost, establishment cost	3 $\left(\frac{\$}{plant}\right)$, 0.63 $(\frac{\$}{ft^2})$, 60 $\left(\frac{\$}{hour}\right)$
U_{14}	Supervision	166.7 $\left(\frac{\$}{100\ ft}\right)$

For example, the bioswale catchment area shown in Figure 28 depicts the idealized cross-section. Table 30 itemizes construction costs. Computed values are provided in dollars per 100 linear ft for the study specified a 3.5-ft-deep, 8.0-ft-wide bioswale. With a subdrain, geotextile liners, and seeding options, construction cost is $62 per linear ft. Replacing seed with transplanted mesic plants raises the construction cost to $118 per linear ft.

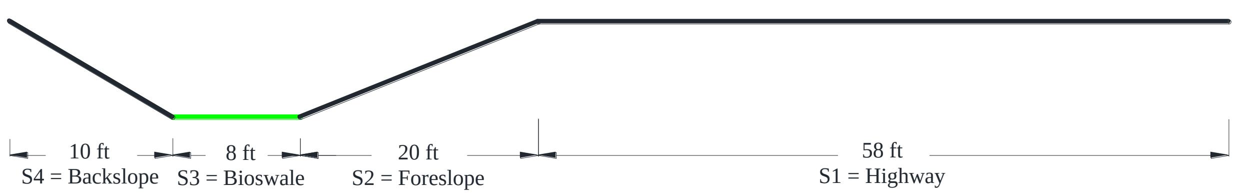


Figure 28. Bioswale draining an idealized catchment.

Table 30. Bioswale Construction Cost

Width (ft)	Infiltration Bed Depth (ft)	Growing Medium Depth (ft)
8	2	1
Pay Item / Per 100 Linear Ft		
Excavation	$334.35	
Haul Off	$481.30	
Aggregate	$1,037.86	
Haul In	$559.29	
Placement	$668.44	
Growing Medium	$1,149.93	
Haul In	$185.48	
Placement	$250.37	
Fabric S&B	$214.15	
Fabric Labor	$200.00	
Fabric Top	$153.33	
Fabric Labor	$240.00	
Drain Pipe	$420.37	
Seed	$55.10	
Seed Establishment	$55.10	
Plants	$3,864.00	
Plant Labor	$705.60	
Plant Establishment	$1,182.22	$5,751.82
Supervision	$166.67	
Total (seed)	$6,172	
Total (plants)	**$11,813**	

Notes:

1. Growing medium cost is assumed $26 per loose cubic yard.
2. Aggregate cost is assumed $10.65 per ton.
3. Pipe cost is assumed $2.49 per ft.

The cost calculation spreadsheet may be used for bioswales ranging from 4 to 16 ft wide and from 2 to 4 ft deep. The cost calculation spreadsheet was used to estimate prices for a representative range of dimensions and the results are shown in Table 31.

Table 31. Bioswale Cost Range When Equipped with Subdrain and Geotextile Barriers

Width (ft)	Infiltration Bed Depth (ft)	Growing Medium Depth (ft)	$ Per Linear Ft Seed	$ Per Linear Ft Plants
4	1	1	$28.44	$56.65
4	2	1	$35.54	$63.74
8	1	1	$47.83	$104.24
8	2	1	$61.72	$118.13
12	1	1	$67.21	$151.83
12	2	1	$87.90	$172.52
16	1	1	$86.59	$199.42
16	2	1	$114.08	$226.91

5.3.2 Bioswale Maintenance Cost

Bioswales should be mown annually to promote mesic plant regrowth and exclude woody plants. Appropriately scheduling mowing operations is crucial to bioswale performance. Equipment should never be driven over bioswales as the growing medium is subject to compaction even when dry. Mowing operations should be conducted after the primary growing season (after mid-July, yet early enough that the bioswale plants can accumulate at least 1 ft of growth during the late summer/fall growing period, before mid-September). Nearly all rotary mowers require the tractor to drive over vegetation, pulling the rotary mower in tow. This is not an acceptable technique for bioswale mowing operations. Either a side mount, three point hitch supported rotary mower or a side-mounted sickle type or spinning disc type mower must be used for bioswale mowing.

Current mowing cost data was obtained from county and township highway departments and from private mowing contractors. Adjusted for bioswale conditions a price of $140 per mile of bioswale BMP up to 8 ft wide may reliably be used for planning purposes. For bioswales between 9 and 16 ft wide, mowing costs are estimated at $280 per mile.

Over time, bioswale effectiveness may be compromised by accumulated dead vegetation, trash, and surface sediment. When periodic inspections indicate this condition, the accumulated material should be removed. This cleanup operation must be performed carefully so as not to destroy the bioswale's previously established mesic vegetation. This cleanup task is estimated at $284 per 100 linear ft for all bioswales less than 16 ft wide.

5.3.3 Bioswale Expected Life

A bioswale reaches the end of its life because of a loss of internal void volume. A bioswale is considered to have failed when 40% of its internal void volume has been lost to accumulated solids or when the surface infiltration rate has been compromised by a layer of debris and sediment 0.1 ft or more in thickness. Both of these failure modes are driven by soil erosion and resulting sediment transport from the BMP's drainage area. Time of life calculations are based on a bioswale sized to receive, store, and infiltrate 1 in. of precipitation from the idealized subcatchment cross section.

Life expectancy formulas are based on linear equations. The arbitrarily defined 40% void loss value may be adjusted as a simple function. For instance, if the life expectancy at 40% void loss equals 20 years, life expectancy defined by 10% void loss would be one-quarter of that value, or 5 years.

Soil loss in the infiltration trench's catchment area directly affects life expectancy. Expected lifetimes associated with a range of catchment area soil loss rates have been calculated. Soil loss is expressed in T (soil loss in t/ac/yr). T values for well-maintained areas of established vegetation are generally accepted to be no more than 0.5 t/ac. Typical T values for level land in row-crop agriculture range from 2 to 4, for highly erodible, sloped cropland T values of 8 to 15 are routinely observed. T values as high as 700 have been reported for poorly managed construction sites. The Revised Universal Soil Loss Equation (RUSLE) is often employed to estimate T. To determine the life expectancy of a particular BMP, site-specific RUSLE calculations should be undertaken, and the resulting T value entered in the life expectancy spreadsheet algorithm. Life expectancy calculations provided in this report are based on the assumptions that:

- All precipitation in the idealized cross-section flows as run-off
- No run-off from outside of the idealized cross-section flows to the BMP
- All sediment that flows to the BMP is captured by the BMP

Life expectancies have been calculated for a range T values and a range of bioswale sizes subject to run-off from the idealized cross-section, see Table 32. Life expectancies of at least six decades can be expected when T values are less 0.5 t/ac. Bioswales will function well for a few years to a decade when T values exceed 10. Bioswales may fail after a single event if they are subject to run-off from steep, highly disturbed slopes.

Table 32. Bioswale Time to Failure Caused by Void Loss

Bioswale Width (ft)	Infiltration Layer Depth (ft)	Back Slope Width (ft)	Foreslope Width (ft)	Pavement Width (ft)	RUSLE - T (t/ac)	Years to 40% Void Capacity Loss
4	2	14	20	58	0.5	67
4	2	14	20	58	1.0	33
4	2	14	20	58	10.0	3
6	2	12	20	58	0.5	102
6	2	12	20	58	1.0	51
6	2	12	20	58	10.0	5
8	2	10	20	58	0.5	139
8	2	10	20	58	1.0	70
8	2	10	20	58	10.0	7
12	2	6	20	58	0.5	219
12	2	6	20	58	1.0	110
12	2	6	20	58	10.0	11

Failure occurs when accumulated sediment = 40% of infiltration bed storage volume.

5.4 INFILTRATION TRENCH COST

Infiltration trench design is driven by required storage volume, surrounding soil infiltration rate, trench depth considerations, and trench width. The volume of the infiltration trench must accommodate the fill material and anticipated run-off volume. For this reason clean, course aggregates of uniform size, passing a quarter-inch screen or larger are used for infiltration trench material. Infiltration trench volume in this study is based on the assumption that trench volume is occupied by 56% aggregate and 44% void space. In this study, a depth of 4 ft was selected for infiltration trench. Trenches deeper than 4 ft require special conditions for worker safety, adding cost and complexity. Deep trenches may also encounter ground water issues that affect construction cost and reduce capacity during periods of wet weather. Relatively wide trenches provide a larger bottom area for infiltration.

Infiltration trenches may be equipped with a permeable pipe subdrain. The subdrain functions to slowly draw down internally stored run-off during wet periods when the soil infiltration rate is not sufficient to keep up with run-off entering the system and to discharge run-off in excess of the design storm. During extended periods of wet weather and during precipitation events in excess of the design storm an infiltration trench without a subdrain will not be able to internally accept run-off and surface flow will occur at rates higher than would be the case if a subdrain was provided. The cost estimating spreadsheet provides the option of pricing a subdrain.

Geotextile fabric may be specified as a liner for the sides and bottom of infiltration trenches. The fabric is intended to act a barrier to soil fines migration into the infiltration trench's void space. Geotextile fabrics are routinely used for a similar purpose in pavement construction, separating soil from rock base materials. However, in these applications, the rock base is relatively thin, usually a foot or less, and is subjected to repeated wheel loads from vehicle traffic. There are multiple anecdotal reports of clean aggregate backfill in deep fills surrounded by fine soils that have not been contaminated by migrating fines over extended periods. None-the-less the option of determining the cost of a side and bottom geotextile liner has been provided in the cost calculation spreadsheet.

Solids in stormwater run-off will be transported to and into the infiltration trench. Over time, the accumulated solids will reduce the space available for stormwater storage. Some designers provide a geotextile barrier across the width of the infiltration trench near its surface. When this strategy is employed, accumulated fines are largely confined to the upper layer. When the storage volume of the upper layer has been reduced, recurring maintenance may be used to remove and replace the upper layer, restoring the majority of the BMP volume to full effectiveness. Installation of this detail requires material and labor to install the geotextile barrier and an additional surface grading operation. The option of determining the cost of a surface layer barrier has been provided in the cost calculation spreadsheet. A generalized infiltration trench design with geotextile and subdrain options is shown in Figure 29.

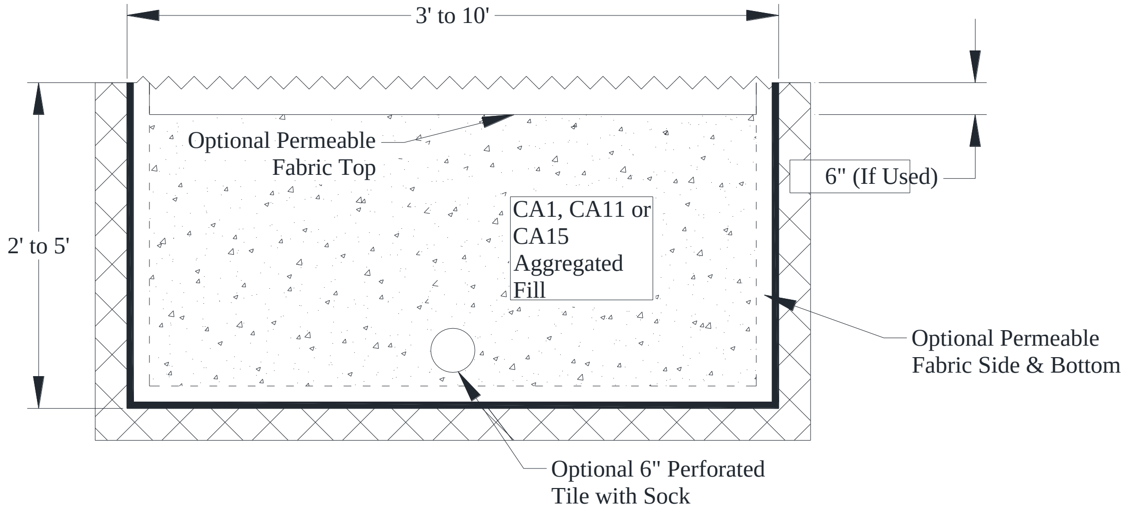


Figure 29. Cross-sectional area of an infiltration trench.

5.4.1 Infiltration Trench Construction Cost

Workflow analysis indicates that a productivity rate of 600 linear ft per day may be achieved for infiltration trench construction in a highway environment. This work rate will require an excavator, wheel loader, two skid steer loaders, four laborers (five, depending on options), four spoils haul-off trucks, and foreman, along with deliveries of aggregate, (and if included) geotextile fabric, and drain pipe.

The general items of infiltration trench construction cost are described in Equation 4. Generally, construction cost is driven by BMP dimensions, unit prices including labor, excavation and aggregate and construction factors such as waste and transportation factors. As presented in Table 33, cost estimations are described as a function of volume or area, unit prices (U_n) and construction factors. Unit prices based on 2015 costs are presented in Table 34.

$$\textit{Infiltration trench construction cost} = f\,(\textit{excavation, haul off, aggregate, fabric, drain pipe, supervision}) \qquad (4)$$

Table 33. Infiltration Trench Construction Cost Estimation per Item

Pay Item	Estimation Formulation
Excavation + Haul Off	$U_1 \times V$
Total aggregate cost	$U_2 \times (V \times \rho) + U_3 \times V$
Total fabric side, bottom & top*	$(U_4 \times A_{S\&B} + U_5) \times W_{F1} + U_4 \times A_t \times W_{F2} + U_6 \times A_t + U_7 \times A_t$
Drain pipe*	$100 \times U_8 \times W_F \times O + U_9$
Supervision	$U_{10} \left(\frac{\$}{100\ ft}\right)$

*Optional items

where

V: Volume (ft^3) of infiltration bed in 100 linear ft

W_F: Waste factor (fabric: 1.15, 1.2, pipe: 1.05)

$A_{S\&B}$: Area (ft^2) of bottom and side of infiltration bed in 100 liner ft

A_t: Area (ft^2) of top of infiltration bed in 100 linear ft

O: Overhead and profit (1.15)

Table 34. Unit Prices in Infiltration Trench Construction Cost, Based on 2015

Pay Item	Description	Unit Price
U_1	Equipment and labor	7.66 $\left(\frac{\$}{yd^3}\right)$
U_2, U_3	Aggregate and haul in cost, placement cost	16.5 $\left(\frac{\$}{ton}\right)$, 8.86 $\left(\frac{\$}{yd^3}\right)$
U_4, U_5, U_6, U_7	Fabric cost, fabric staples, labor cost, top grading cost	1.15 $\left(\frac{\$}{yd^2}\right)$, 7.33 $\left(\frac{\$}{100\ ft}\right)$, 0.30 $\left(\frac{\$}{yd^2}\right)$, 3.23$\left(\frac{\$}{yd^2}\right)$
U_8, U_9	Pipe cost, constant cost per 100 ft for equipment, supervision, and labor.	2.49 ($/ft), 119.7 $\left(\frac{\$}{100\ ft}\right)$
U_{10}	Supervision	166.7 $\left(\frac{\$}{100\ ft}\right)$

For example, for an idealized cross-section with a 96-ft-wide catchment area, shown in Figure 30, an infiltration trench 4 ft deep and 5 ft wide is considered. Table 35 itemizes construction costs. Computed values are provided in dollars per 100 linear ft for the specified 4-ft-deep, 5-ft-wide infiltration trench. With subdrain and geotextile liners, construction cost is $47 per linear ft; without these options, the infiltration trench construction cost is $34 per linear ft.

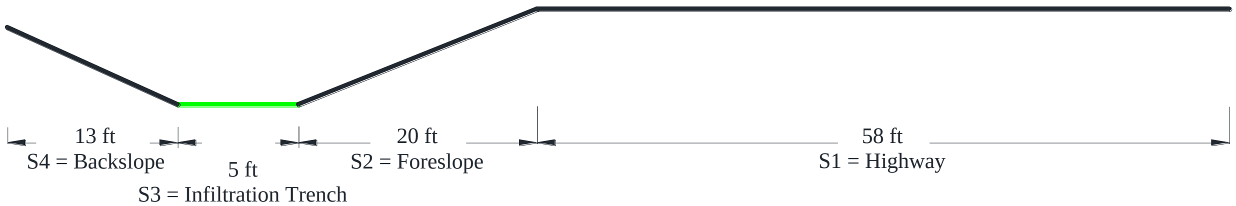


Figure 30**. Infiltration trench draining an idealized catchment.**

Table 35. Infiltration Trench Construction Cost

Width (ft)	**Depth (ft)**	**Aggregate Cost ($/ton)**	**Pipe Cost ($/ft)**
5	4	10.65	2.49
Pay Item / Per 100 Linear Ft			
Excavation	$232.59		
Haul Off	$334.81		
Aggregate	$1,297.33		
Haul In	$669.98		
Placement	$656.30		
Fabric S&B	$228.85		
Fabric Labor	$200.00	$428.85	
Fabric Top	$107.33		
Fabric Labor	$150.00		
Top Grading	$179.44	$436.78	
Drain Pipe	$420.37	$420.37	
Supervision	$166.67		
Total	**$4,644**	**$1,286**	**$3,358**

The cost calculation spreadsheet may be used for infiltration trenches ranging from 3 to 10 ft wide and from 2 to 4 ft deep. The cost calculation spreadsheet was used to estimate prices for a representative range of dimensions and the results are shown in Table 36.

Table 36. Infiltration Trench Cost for Different Widths and Depths

Width (ft)	Infiltration Depth (ft)	$ Per Linear Ft
4	2	$25.74
4	3	$32.42
4	4	$39.10
6	2	$34.04
6	3	$43.91
6	4	$53.78
8	2	$42.34
8	3	$55.40
8	4	$68.46
10	2	$50.64
10	3	$66.89
10	4	$83.14

5.4.2 Infiltration Trench Maintenance Cost

Over time infiltration trench effectiveness may be compromised by accumulated dead vegetation, trash, and surface sediment. When periodic inspections indicate this condition, the accumulated material should be removed and the contaminated surface aggregate replaced. This cleanup operation must be performed carefully so as not to destroy the infiltration trench's geotextile surface barrier. Removal of debris and contaminated aggregate is estimated at $284 per 100 linear ft for all infiltration trenches between 4 and 10 ft wide. Replacement costs for the surface aggregate are dependent on infiltration trench width:

- 4 ft wide $262 per 100 linear ft
- 6 ft wide $394 per 100 linear ft
- 8 ft wide $524 per 100 linear ft
- 10 ft wide $656 per 100 linear ft

The ability of infiltration trenches to rapidly accept run-off will likely be negatively affected if vegetation is allowed to grow in or over the trench surface. Routine infiltration trench maintenance should include herbicide applications to control vegetation and maintain the open nature of the infiltration trench surface. Herbicide application will likely be required at least three times annually to maintain a vegetation-free surface. The first application should be scheduled at least two weeks after the frost-free date and before the end of May. The second application should occur at mid-summer. A third application should be applied during October and, in addition to a burndown herbicide, this fall application should include a winter annual suppressing herbicide. Each herbicide application will cost approximately $55 per mile of infiltration trench or a total of $165 per year assuming three applications.

5.4.3 Infiltration Trench Expected Life

An infiltration trench reaches its end of life as a result of loss of internal void volume. The infiltration trench is considered to have failed when 40% of its internal void volume has been lost to accumulated solids or when the surface infiltration rate has been compromised by a layer of debris and sediment 0.1 ft or more in thickness. Both of these failure modes are driven by soil erosion and resulting sediment transport from the BMP’s drainage area. Time of life calculations are based on an infiltration trench sized to receive, store, and infiltrate 1 in. of precipitation from the idealized subcatchment cross section.

Life expectancies have been calculated for a range of T values and a range of infiltration trench sizes subject to run-off from the idealized cross-section (see Table 37). Life expectancies of a century or more can be expected when T values are less 0.5 t/ac. Infiltration trenches will function well for a decade or less when T values exceed 10 t/ac. Infiltration trenches may fail after a single event if they are subject to run-off from steep, highly disturbed slopes.

Table 37. Infiltration Trench Time to Failure Because of Void Loss

Trench Width (ft)	Trench Depth (ft)	Back Slope Width (ft)	Foreslope Width (ft)	Pavement Width (ft)	RUSLE - T (t/ac)	Years to 40% Void Capacity Loss
4	3	14	20	58	0.5	100
4	3	14	20	58	1.0	50
4	3	14	20	58	10.0	5
6	3	12	20	58	0.5	153
6	3	12	20	58	1.0	77
6	3	12	20	58	10.0	8
8	3	10	20	58	0.5	209
8	3	10	20	58	1.0	105
8	3	10	20	58	10.0	10
10	3	8	20	58	0.5	267
10	3	8	20	58	1.0	134
10	3	8	20	58	10.0	13

Failure occurs when accumulated sediment = 40% of original storage volume

5.5 VEGETATED FILTER STRIP

Vegetative filter strips function by slowing sheet flow velocity, filtering sheet flow, improving infiltration, and removing soil moisture through evapotranspiration. A well-designed vegetative filter strip includes an improved topsoil layer that encourages soil infiltration, a dense mat of sod and thatch acting as a filter, and a vigorous stand of vegetation to resist erosion. Vegetative filter strips are usually provided as a water quality and erosion prevention BMP between a catchment area and a water course or used to pretreat sheet flow before run-off enters another BMP. In agricultural practice vegetative filter strips are installed between row-crop fields and streams, typically specified a minimum of 30 ft wide. In the transportation environment, vegetative filter strips may be used to pretreat run-off before entering another BMP or before discharge to a waterway.

Soils within the highway right-of-way are usually highly compacted, either from construction activities or from repeated mowing during periods when the soils are in a wet condition. This compacted condition greatly restricts soil infiltration. Soil compaction must be remediated as part of vegetative filter strip establishment. Special, vertical deep tillage tools are available to open up, loosen, and de-compact soil. These tools have minimum impact to the soil surface and can be operated through existing vegetation. The cost of performing deep vertical tillage is included in our vegetative filter strip cost analysis.

Undesirable existing vegetation may be present where a vegetative filter strip is to be installed. In this case, the existing vegetation must be eliminated. The cost of eliminating existing vegetation with herbicides is included as an option in our cost analysis.

Several options for plant varieties are available for vegetative filter strips. Cool season grasses, *Bromus inermis* (smooth brome) and *Festuca arundinacea* (tall fescue) are common species that are often specified; alternatively, native grasses and forbs may be specified for projects that combine vegetative filter strip functions with native prairie establishment criteria. Seeding practices and cost for cool season grass and native prairie establishment or similar, though some specialized native plant seeds are relatively expensive and difficult to establish. The cost of seeding using a specialized grass seed drill capable of operating in no-till or tilled conditions and capable of simultaneously seeding a companion crop is included in our analysis.

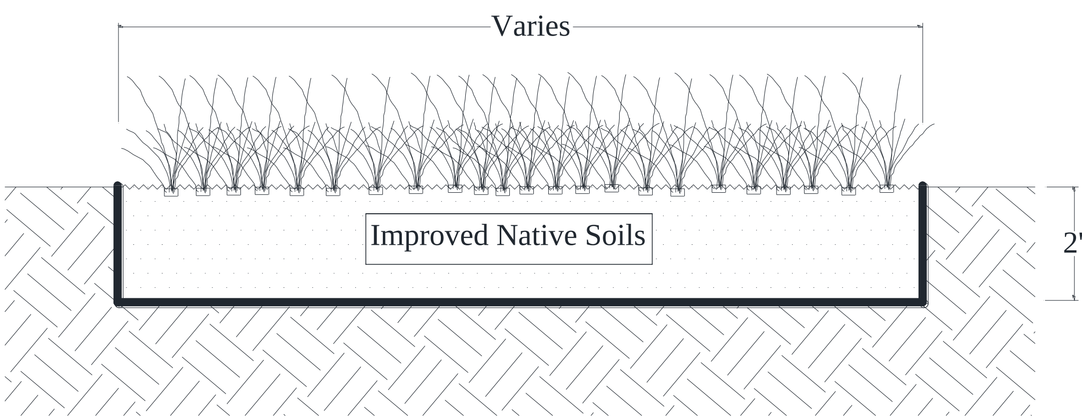


Figure 31. Cross-sectional area of a vegetated filter strip.

5.5.1 Vegetative Filter Strip Construction Cost

Workflow analysis indicates that a productivity rate of 6,000 linear ft per day may be achieved for vegetative filter strip construction in a highway environment. This work rate will require a tractor equipped with a rubber-track, a vertical tillage tool, a no-till seeder pulled by a low ground-pressure-tire equipped tractor, an herbicide spray truck, one laborer, and a foreman.

The general items of construction costs are described in Equation 5. Construction cost is derived from unit prices including herbicide, labor, vertical tillage, and seeding. As presented in Table 38, cost estimations are described as a function of area and unit prices (U_n). Unit prices based on 2015 costs are presented in Table 39.

$$\textit{Vegetative filter strip construction cost} = f\,(\textit{vertical tillage, herbicide, seeding, labor, supervision}) \quad (5)$$

Table 38. Vegetative Filter Strip Construction Cost Estimation per Item

Pay Item	Estimation Formulation
Vertical tillage	$U_1 \times A$
Herbicide	$(U_2 \times 100)) + U_3 \times \ A$
Seeding	$U_4 \times A$
Labor	$U_5 \left(\frac{\$}{100\ \text{ft}}\right)$
Supervision	$U_6 \left(\frac{\$}{100\ ft}\right)$

Table 39. Unit Prices in Vegetative Filter Strip Construction Cost, Based on 2015

Pay Item	Description	Unit Price
U_1	Equipment and labor	250 $\left(\frac{\$}{yd^3}\right)$
U_2, U_3	Truck cost, placement cost	116 $\left(\frac{\$}{ft}\right)$, 7.23 $\left(\frac{\$}{yd^3}\right)$
U_4	Seed cost	3000 $\left(\frac{\$}{acre}\right)$
U_5	Labor	20 $\left(\frac{\$}{100\ \text{ft}}\right)$
U_6	Supervision	14.33 $\left(\frac{\$}{100\ ft}\right)$

For example, a vegetated filter strip with 18 ft width as shown in Figure 32 is considered as an idealized catchment. Table 40 itemizes construction costs. Computed values are provided in dollars per 100 linear ft for the study specified 18-ft-wide vegetative filter strip. Construction cost for an 18-ft-wide filter strip is $1.58 per linear ft, the equivalent of $3,835 per ac.

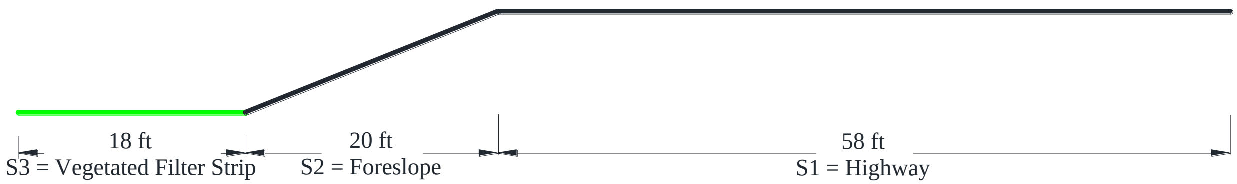


Figure 32. Vegetated filter strip draining an idealized catchment.

Table 40. Itemized Costs for an 18-Ft-Wide Vegetative Filter Strip

Pay Item	Per 100 Linear Ft
Vertical Tillage	$6.89
Herbicide	$0.94
Seeding	$123.97
Labor	$10.00
Supervision	$16.67
TOTAL	$158.47

The cost calculation spreadsheet may be used for vegetative filter strips ranging from 12 to 60 ft wide. The cost calculation spreadsheet was used to estimate prices for a representative range of dimensions and the results are shown in Table 41.

Table 41. Vegetative Filter Strip Cost Range

Strip Width (ft)	$ Per Linear Ft	$ Per Ac
12	$1.15	$4,174
20	$1.73	$3,768
30	$2.57	$3,732
40	$3.34	$3,637
50	$4.11	$3,581
60	$4.87	$3,535

5.5.2 Vegetative Filter Strip Maintenance Cost

Vegetative filter strips should be mown and inspected for rills and gullies annually to promote stand health and exclude woody plants and sediment build-up. Appropriately scheduling mowing operations is crucial to vegetative filter strip performance. Equipment should never be driven over vegetative filter strips during wet conditions. If soil moisture levels are high enough that vehicle tires leave visible indentations the ground is too wet. In addition to mowing exclusively during dry weather, mowing operations should be conducted after the primary growing season (i.e., after mid-July, yet early enough that the stand can accumulate at least 1 ft of growth during the late summer/fall growing period, or before mid-September). Once-a-year mowing operations require mowing equipment to handle large quantities of vegetation at a time—up to 4 t of dry matter per ac may accumulate.

Mowing this quantity of material with a rotary mower may be difficult to achieve without clumping and irregular cutting. Also, nearly all rotary mowers require the tractor to drive over vegetation prior to mowing, when vegetation is very tall; dense tractor tires tend to knock over and hold down vegetation, and the mower behind it will likely miss much of the vegetation in the resulting wheel track. To eliminate these issues a side-mounted sickle type or spinning disc type mower is recommended for once annual mowing operations. This type of mower does not chop the vegetation. Instead, it cuts the plant stems once and lays the intact plant down in an even layer. Plant regrowth is facilitated by the even mulch and wheel tracking, clumping, and uneven cutting issues associated with rotary mowers operated in very heavy vegetation are eliminated. Sickle type mowers and rotary mowers have similar operating costs though sickle type mowers may require more frequent periodic maintenance than rotary mowers.

Current mowing cost data was obtained from county and township highway departments and from private mowing contractors. Adjusted for vegetative filter strip conditions a price of $55 per ac may reliably be used for planning purposes.

5.5.3 Vegetative Filter Strip Life-Cycle Analyses

A vegetated filter strip reaches the end of its life when accumulated sediment exceeds the mowing height. For purposes of this analysis, we have selected a mowing height of 5 in. typically used for practices where mowing operations are performed once per year. Vegetative filter strip failure is directly related to soil erosion and resulting sediment transport from the BMP's drainage area. Time of life calculations are based on a vegetative filter strip sized to occupy all available space from the toe of foreslope to edge of right-of-way (18 ft wide).

Life expectancies have been calculated for a range of T values for an 18-ft-wide vegetated filter strip subject to run-off from the idealized cross-section, see Table 42. Life expectancies of several centuries can be expected when T values are less than 0.5 t/ac. Vegetative filter strips will function well for half of a century when T values do not exceed four. Vegetative filter strips may fail within a decade if they are subject to run-off from steep, highly disturbed slopes.

Table 42. Vegetated Filter Strip Time to Failure Because of Accumulated Sediment

Filter Strip Width (ft)	Back Slope Width (ft)	Foreslope Width (ft)	Pavement Width (ft)	RUSLE - T (t/ac)	Years to 5 in. Accumulation
18	0	20	58	0.5	422
18	0	20	58	1.0	211
18	0	20	58	4.0	53
18	0	20	58	7.0	30
18	0	20	58	10.0	21
18	0	20	58	15.0	14

Failure occurs when accumulated sediment height = mowing height of 5 in. = 0.42 ft

5.6 PLANNING TOOLS

5.6.1 Cost Levels

BMP comparative evaluation is performed by employing a spreadsheet-format computational aid that provides construction and maintenance cost estimates and life-cycle predictions. The construction costs are derived from Equation 3 to Equation 5. Also, a summary of maintenance cost is shown in Table 43 and is used for cost comparisons.

Table 43. Maintenance Costs

Bioswale		Infiltration Trench		Vegetative Filter Strip	
Annual mowing:	Up to 8 ft wide: $140/mi/yr	Annual:	$165/mi/yr	Annual:	$120/mi/yr
	9 to 16 ft wide: $280/mi/yr				
Periodic cleanup:	Up to 8 ft wide: $284/100 ft	Periodic clean up:	$284/100 ft + width × $65/100 ft		
	9 to 16 ft wide: $426/100 ft				

Figure 33 compares construction and maintenance costs of different BMPs. To provide long-term planning, maintenance cost from ten year period is estimated based on annual and periodically maintenance costs. Construction costs for a 14-ft-wide bioswale, 3-ft-wide infiltration trench, and 25-ft-wide vegetative filter strip are $16,291, $3,233, and $207 per 100 linear ft, respectively. Bioswale construction cost significantly exceeds infiltration trench and vegetative filter strip construction cost. Ten-year maintenance costs are $4,313, $4,821, and $32 per 100 linear ft, respectively. Maintenance costs for a 10 year period are 26.5%, 149%, and 15% of the construction cost for bioswales, infiltration trenches, and vegetative filter strips, respectively.

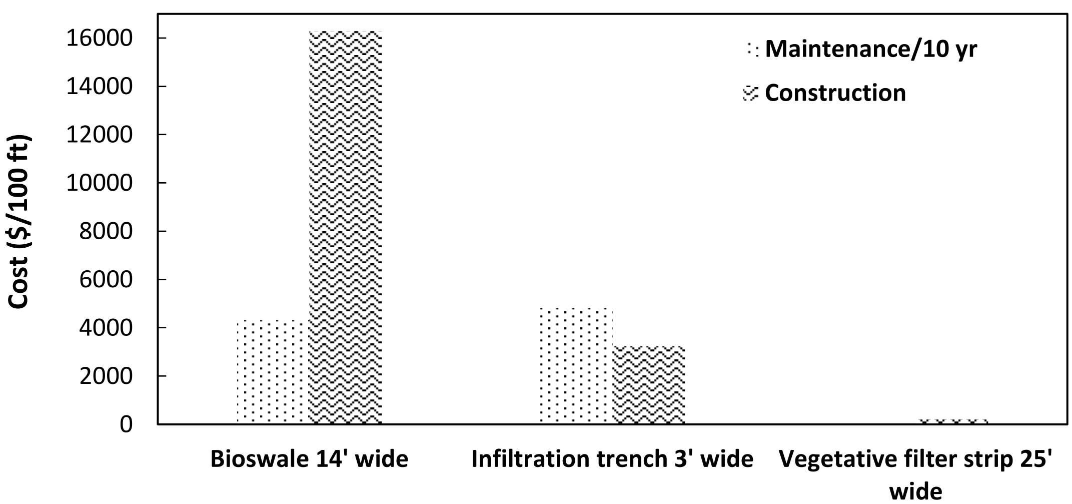
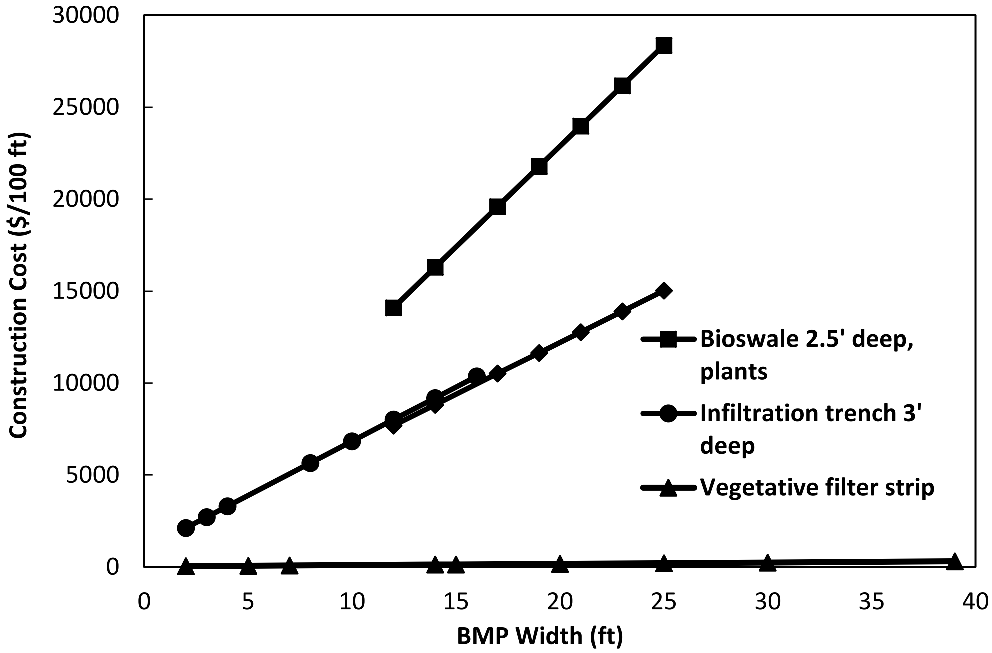


Figure 33. Comparison of construction cost and 10-year maintenance cost of three BMPs.

To aid planners, several cost estimates are produced for BMPs over a representative range of dimensions. Figure 34 provides the variation of construction cost with width for three types of BMPs. All construction costs are a linear function of width.



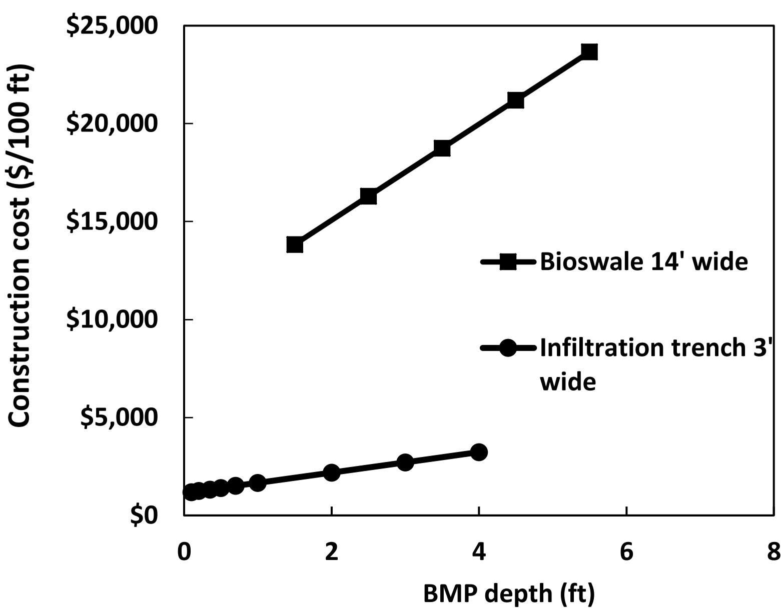


Figure 34. Variation of the construction cost with BMP width (top), and BMP depth (bottom).

Bioswales vegetated with transplanted plants are the most costly BMPs considered. Increasing bioswale width from 12 ft to 25 ft would increase the construction cost from $14,096 to $28,363 per 100 linear ft. Vegetative filter strips have the lowest cost. In Figure 34b, construction cost variation with BMP depth is shown. Because vegetative filter strip cost is not dependent on depth, it is not included in Figure 34.

5.6.2 Cost Assessment and Comparison

Even though construction costs vary based on drainage area, region, and site conditions, a comparison may be made between our study results and cost values in the literature. Table 44 presents bioswale cost estimation proposed by Brown and Schueler (1997). Their study provides estimates based on dollars per ft^3 of BMP volume. The current study's estimation of bioswale construction cost ranged between $\$6/ft^3$ and $\$6.4/ft^3$, which appears reasonable in comparison with Brown and Schueler's 1997 cost of $\$5.3/ft^3$.

As presented in Table 44, construction cost for infiltration trenches is calculated from historical equations. Wiegand et al. (1986) proposed an exponential formulation, while Brown and Schueler in 1997 developed a linear cost function (Brown and Schueler 1997). Our current study cost estimate for an infiltration trench is a linear function and ranged above the two historical equation values. The Wiegand equation and Brown and Schueler equation may underestimate the current study cost as they are based on 1986 and 1997 prices. The advantage of our current study is that it allows for updating the cost estimate based on current unit prices.

Table 44. Comparison of Current Cost Estimation to Typical Construction Cost for BMPs

BMP type	Equation ($)	Estimated cost	Source
Bioretention	$\$5.3 \times V$	$\$5.3/ft^3$	Brown and Schueler (1997)
Bioswale	Equation 1	$\$6\text{-}\$6.4/ft^3$	Current study
Infiltration trench	$\$33.7 \times V_t^{0.63}$	$1,749/100 ft (3-ft-wide and 4-ft-deep infiltration trench)	Wiegand (1986)
	$\$2.5 \times V_t$	$1,320/100 ft (3-ft-wide and 4-ft-deep infiltration trench)	Brown and Schueler (1997b)
	Equation 2	$3,233/100 ft (3-ft-wide and 4-ft-deep infiltration trench)	Current study
Vegetative filter strip	-----	Up to $\$1.30/ft^3$	SWRPC (1991)
	Equation 3	$\$0.08\text{-}\$0.20/ft^3$	Current study

V_f: The treatment volume (ft^3) within the trench = Trench volume * 0.44

In Southeastern Wisconsin, costs were predicted applying standardized unit costs for different elements of the BMPs (SWRPC). In Table 44, the current construction cost for filter strips is compared to SWRPC estimates. The current cost estimation, \$0.08-\$0.20/ft^3, is in agreement with the lower bound of the SWRPC estimation, up to \$1.30/ft^3. The upper value in the SWRPC assumes sod for filter strip establishment which is more costly than seed vegetative methods in current estimation.

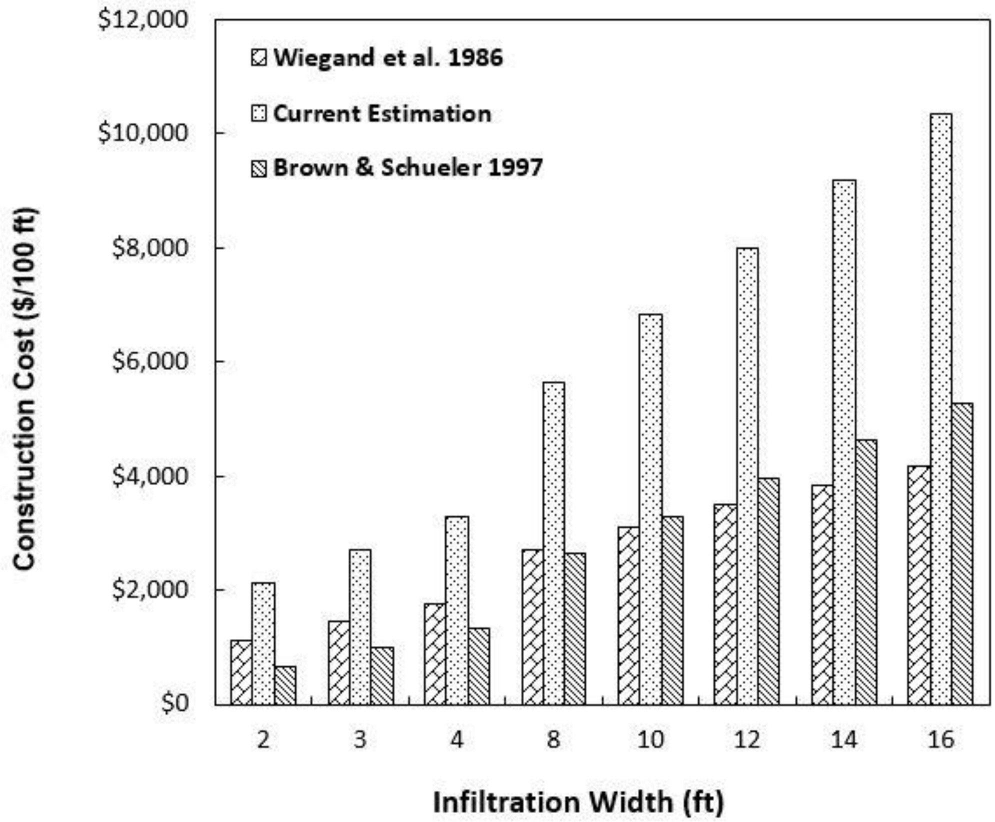


Figure 35. Comparison of current construction cost estimation with typical methods in infiltration trench.

CHAPTER 6: FULL-SCALE BIOSWALE AND INFILTRATION TRENCH TESTS

To examine the efficiency of the BMPs, a set of BMPs were constructed at SIUE campus and tested for various rainfall event conditions.

6.1 GENERAL CONSTRUCTION BMP RESTRICTIONS AND CONSIDERATIONS

6.1.1 Site Area

The site is located in the northwest quadrant of the SIUE campus as shown in Figure 36. The locations of the BMP test cells, water supply tanks, and delivery pipes are shown in Figure 37. The elevation difference between BMP test cells and water level in the supply tanks varied from 11.0 ft to 9.0 ft as the tanks were discharged during test events. The resulting nominal 10 ft of hydraulic head conveyed simulated stormwater run-off flows to BMP test cells via gravity.

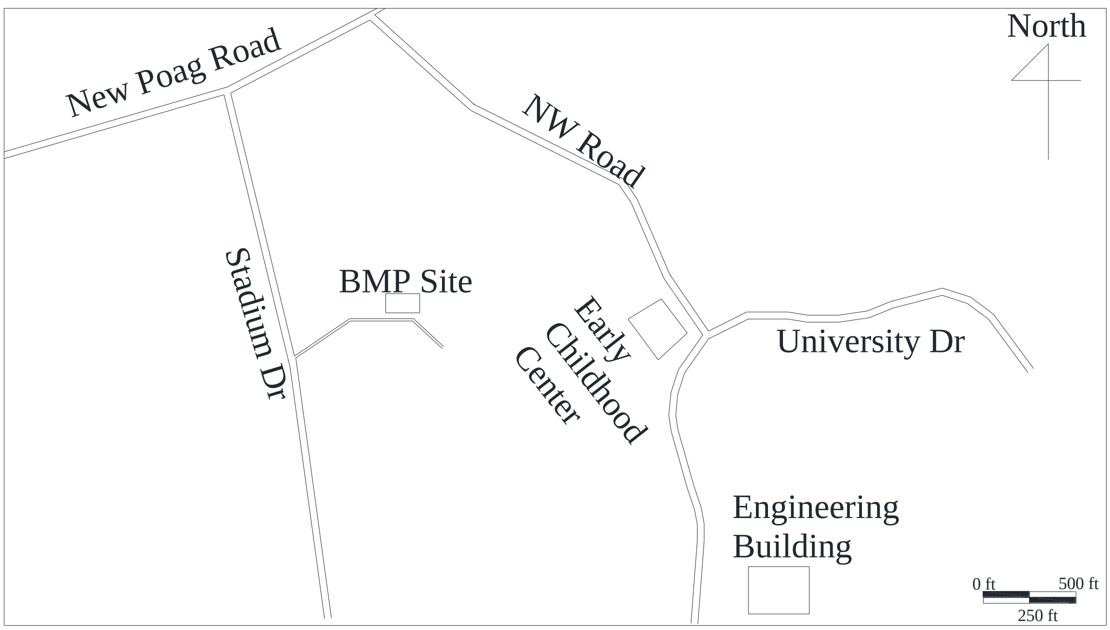


Figure 36. Location of the BMP site.

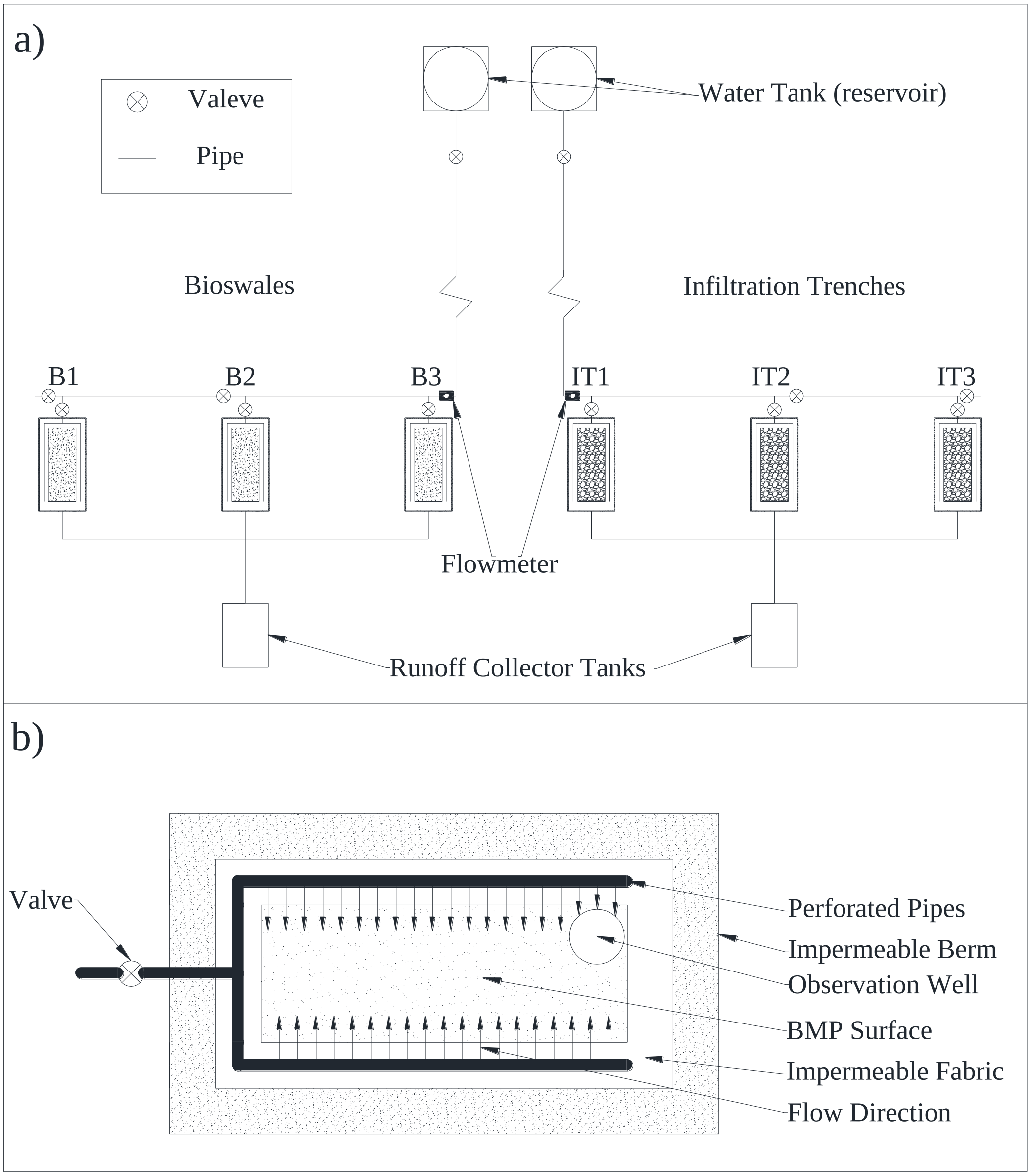


Figure 37. (a) Schematic plan view of the BMPs and test layouts; (b) magnified version of a representative cell.

6.1.2 Construction

6.1.2.1 Water Tanks

Two 300-gal water tanks were installed on a scaffold to raise their level by 6 ft. Each tank through a pipe supplied water for either bioswale or infiltration trench cells (see Figure *38*).

Figure 38. Two 300-gal water tanks on scaffold.

6.1.2.2 Creating the Test Cells

The site was mown, cleared, and leveled (see Figure 39). Six test cells 4 ft deep, 3 ft wide, and 8 ft long were excavated with mini excavator equipped with a 3-ft, smooth bucket. A perforated 8-in.-diameter pipe was installed vertically in each cell to monitor water levels during and after the test. Three infiltration trench test cells were filled with clean limestone rock. Three bioswale tests cells were constructed by installing 3 ft of clean limestone rock and a 1-ft-thick growing medium layer, separated by a layer of geotextile fabric (see Figure 40). A 1-ft-high berm was installed around the perimeter of each test cell to prevent precipitation run-off from entering the test cells. The perimeter edge of each test cell was protected with geotextile fabric as shown in Figure 41. The edge protection fabric prevented infiltration and contamination of simulated run-off as it flowed from distribution manifold into the BMP test cell. Surrounding berms were also covered with plastic sheet to provide protection from rainfall and surface flow. BMP test cells were covered with plastic tarps when tests were not in progress as shown in Figure 42.

Figure 39. Clearing and leveling off the ground.

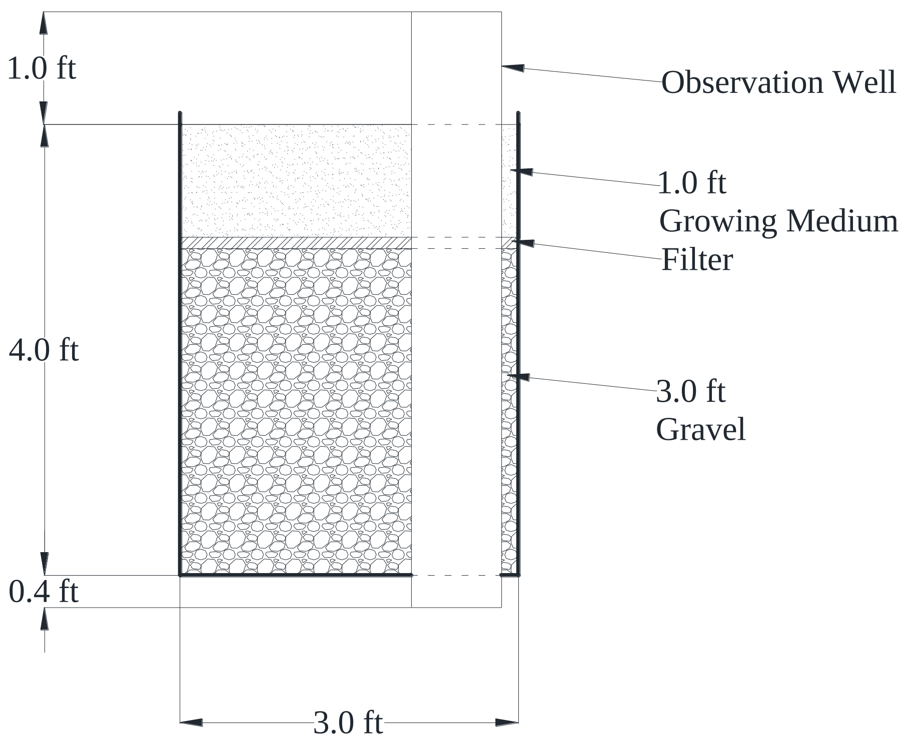


Figure 40. Cross-section of a bioswale showing
3 ft bottom gravel, filter, and 1 ft top growing medium.

Figure 41. A test cell with observation well and protection fiber.

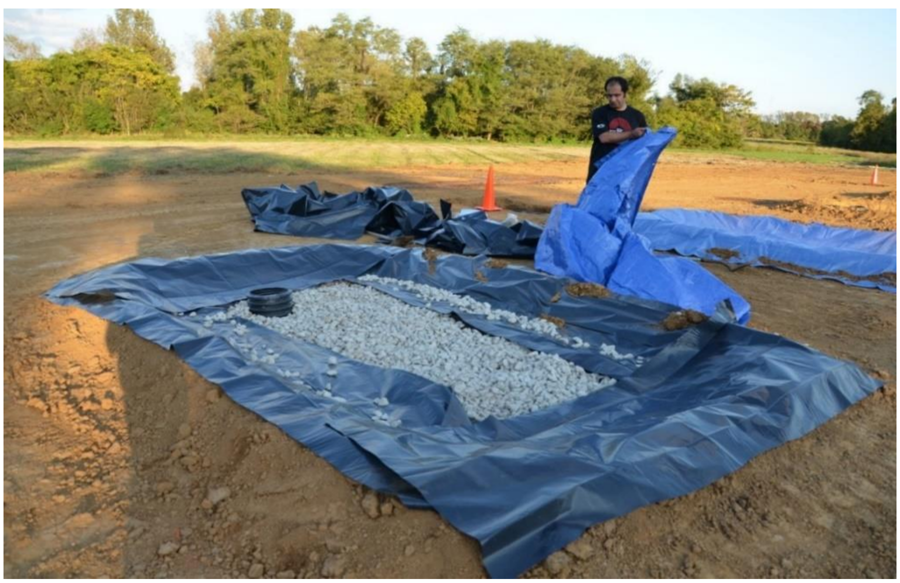


Figure 42. Heavy-duty plastic to cover perimeter berm and tarp to cover the entire test cell.

6.1.3 Natural Soil

For the classification of the soil, three samples were collected from three different locations of the site. Grain size distribution is shown in Figure 43.

The liquid limit and the plastic limit of the soil were 30% and 20%, respectively. The soil was classified as Sandy Lean Clay per Unified Soil Classification System (USCS). The gradation curve of the aggregates used is shown in Figure 43. In a loose state, the specific gravity of the aggregate was 2.53 with a bulk density of 91 pcf and a void ratio of 42%. On-site native soil passing a No. 8 sieve were used to simulate sediment loads.

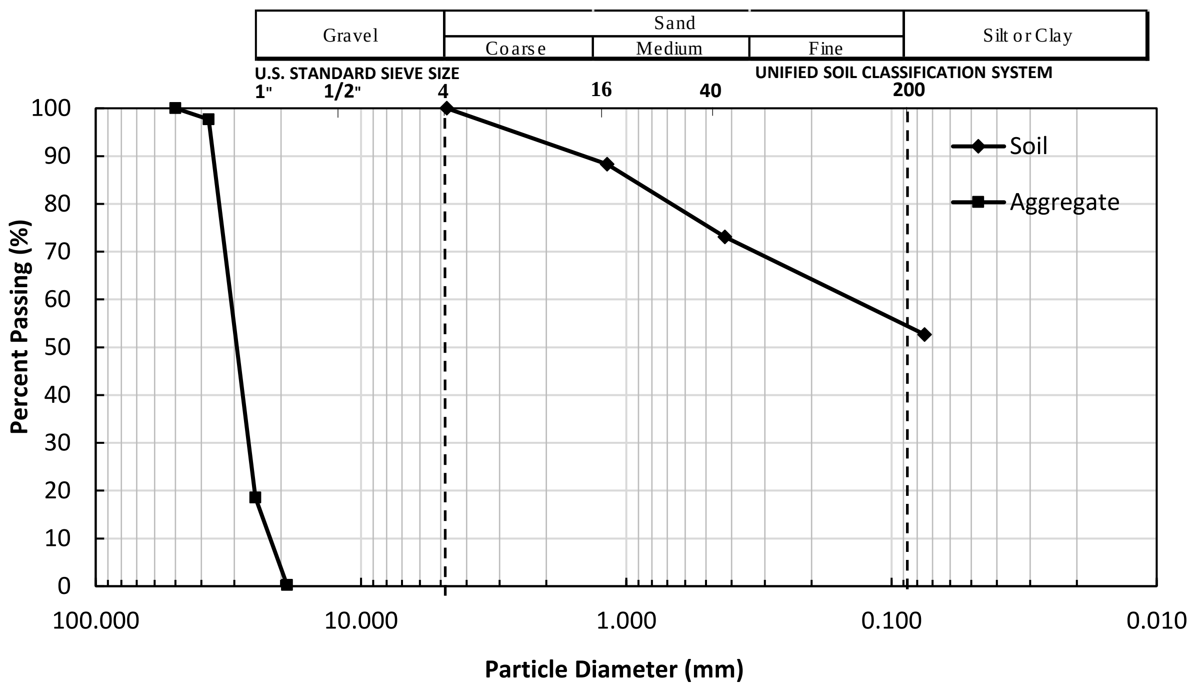


Figure 43. Native soil and aggregate particle size distribution.

The infiltration rate of sieved soil in a loose state was determined using a Turf-Tec Infiltrometer (see Figure 44). Infiltration rates of 0.46 in. per minute, and 0.13 in. per minute in unsaturated and saturated conditions were determined, respectively. The infiltration rate of in situ native soil was tested at the test cell bottom using the same device. The in situ infiltration rate was measured at 0.18 in. and 2.1 in. per minute, respectively, in high- and low-saturated conditions.

Figure 44. Turf Tech Infiltrometer.

6.1.4 Rainfall Scenarios

Five different rainfall scenarios were considered for these tests. Table 45 shows the intensity-duration-frequency (IDF) of storms with 9-month, 2-year and 10-year frequencies occurring in southwestern Illinois. Besides these three selected rainfall scenarios, two other scenarios representing medium and high rainfall event were selected based on rainfall data from the last 10 years reported at Belleville, IL. Each BMP test cell provides 250 gal of stormwater run-off storage. Tests were designed to represent the scenarios shown in Table 45. All test scenarios simulated 50 ft of catchment width. Multiple possible highway layout scenarios are shown in Figure 45.

To evaluate BMP performance over a range of precipitation events medium and high-intensity scenarios were included in the test plan. The frequency of the reported medium and high rain events are shown in Table 46. As shown in this table, the intensities of these events were less than those from IDF table. For example, 88% and 99.7% of the recorded rains had less than 1 and 6 in. of rain with an average duration of 8 and 6.8 hours, respectively. It is worth mentioning that although the intensity of the medium and high-intensity rains are lower than those derived from IDF table, the total volume of stormwater run-off was approximately 1000 gal, which is four times larger than the simulated rainfalls based on IDF table. A graphical representation of the simulated rainfall scenarios with associated duration and flow rate are shown in Figure 46.

Table 45. Rainfall Simulation Based on IDF for 1 in. of Precipitation

Event Type	Storm Return Period			10-year data of Belleville Rain Gauge Station	
	9-month	2-year	10-year	Medium	High
Rainfall Depth (in.)	1	1	1	1	4
Volume (gal)	249	249	249	249	997
Duration (min)	45	20	10	480	408
Intensity (in./hr)	1.3	6	6	0.13	0.59
Flowrate (gal/min)	6	12.5	25	0.52	2.44

Table 46. 10-year Rainfall Data Belleville, IL

No. of events	% of events	Percentile	Accumulated daily precipitation (in.)	Avg. Duration (hr)
470	43	43	0.1-0.2	8.9
153	15	58.2	0.2-0.3	7.5
66	6	64	0.3-0.4	6.4
65	6	70.4	0.4-0.5	7.1
49	4	74.6	0.5-0.6	7.9
50	5	79.2	0.6-0.7	7.6
41	4	83	0.7-0.8	7.3
28	3	85.6	0.8-0.9	9.4
27	**3**	**88.2**	**0.9-1**	**8**
89	8	96.4	1 - 2"	9.2
26	2	98.7	2-3"	11.4
4	0.5	99.2	3-4"	12.8
7	**0.5**	**99.7**	**4-6"**	**6.8**
1	0.1	99.8	6-8"	6.4
1	0.1	99.9	8-11"	5

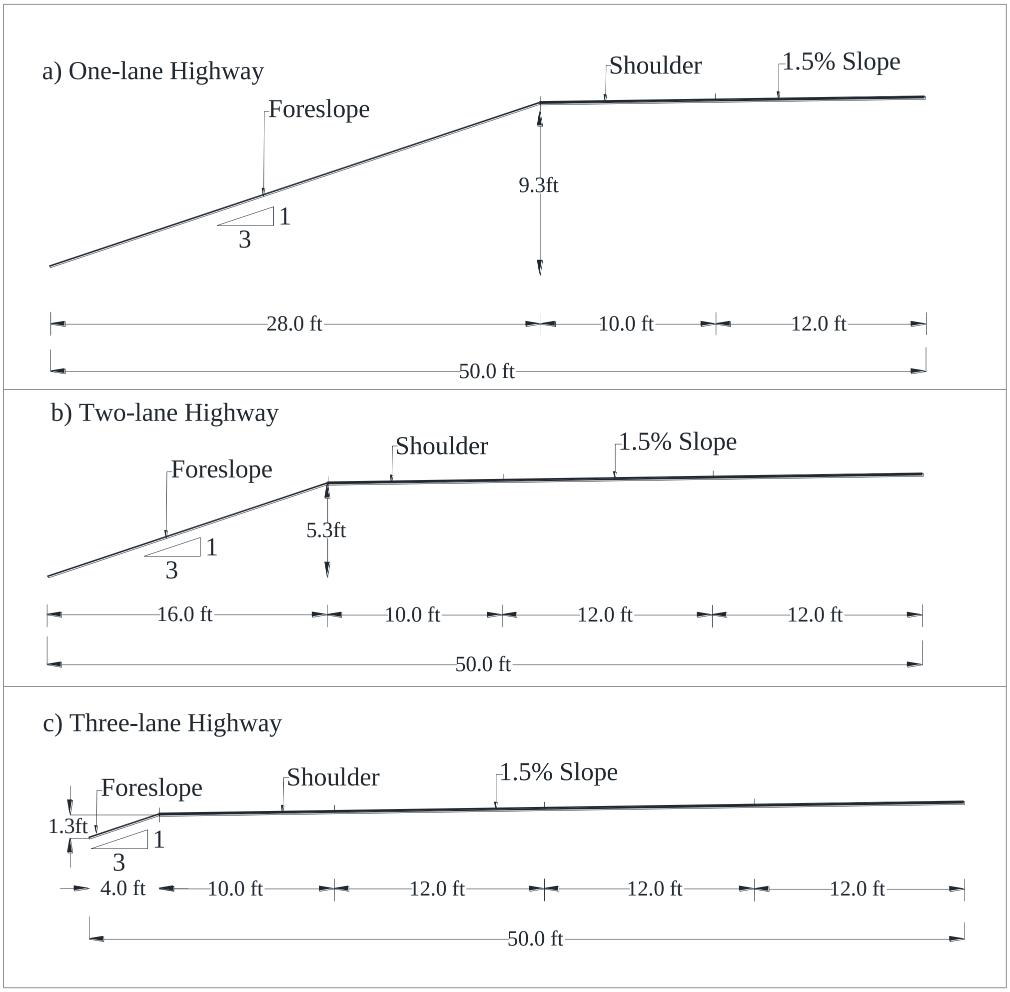


Figure 45. Different possible highway layout scenarios within the considered 50-ft width.

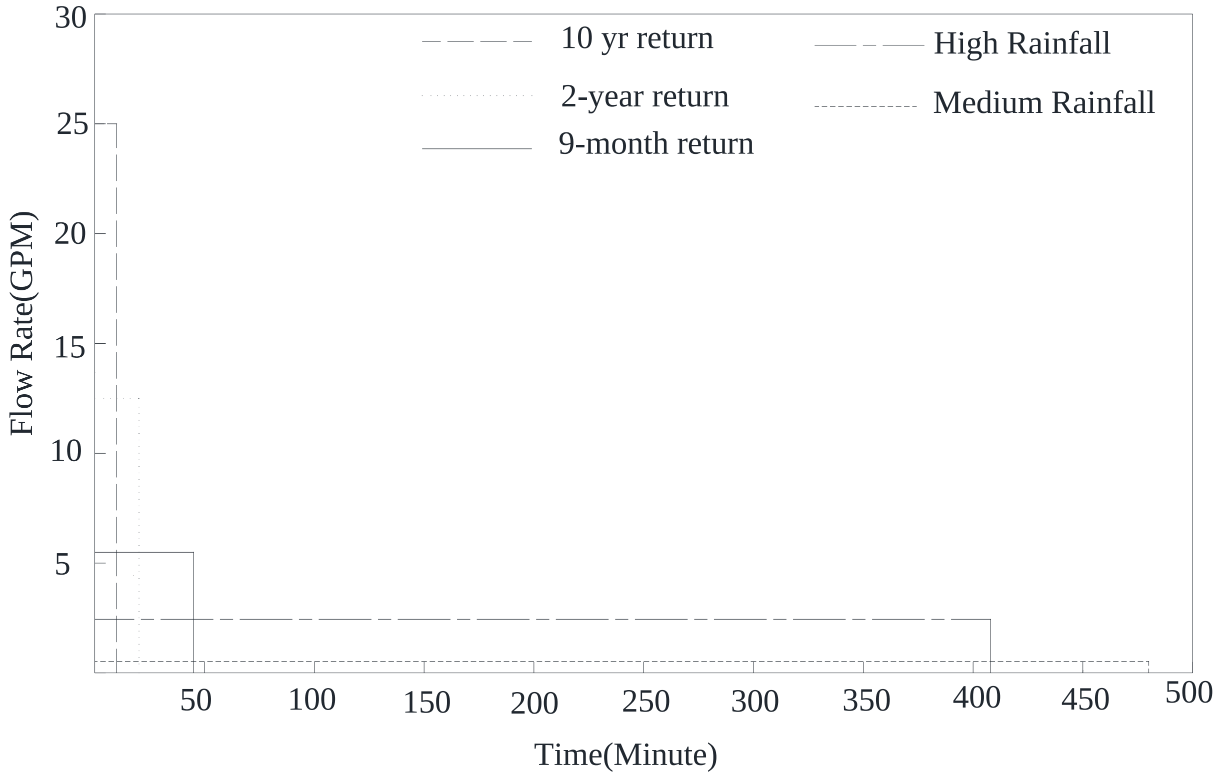


Figure 46. Rainfall scenarios.

6.1.5 Impact of Sediment Buildup on BMP Performance (Aging)

To represent different ages of the BMP or different levels of regular maintenance, transported sediments were artificially deposited on the test cell surface. The amount of sediment deposited on the bioswale was estimated by calculating the soil loss for the highway based on the USLE equation (NRCS, 1997). The estimated soil loss was 1 ton/ac per year. According to information from Environmental & Resource Policy, Madison County SWCD and the National Conservation District Employees Association (NCDEA), soil loss can range from 1, 5, 12, and more than 80 t/ac per year for stabilized small watersheds, areas with fine textured soils, agricultural areas, and construction sites, respectively. A minimal sediment accumulation based on 1 t/ac per year soil was considered for this study. The corresponding equivalent amount of sediments from 50 ft width of highway and its right-of-way was estimated to be 30 kg and 6 kg for a 10-year-old and 2-year-old BMP, respectively. The calculated thickness of the sediment layer covering the 10- and 2-year-old BMP were 0.7 and 0.1 in., respectively. Observed infiltration rates based on in situ infiltrometer measurements (see Figure 44) for a 10-year-old bioswale and a 2-year bioswale was determined 0.235 in. per minute and 0.355 in. per minute in fully saturated condition, respectively. The test cells B1/IT1, B2/IT2, B3/IT3 in Figure 37 represent the 10-year-old, 2-year-old, and new bioswale/infiltration trench.

A tentative test matrix including all the desired field tests was developed as shown in Figure 47. After starting the tests, it was determined some tests were not necessary. The tests that were conducted are shown with bold fonts in this figure. The tests in the matrix included two types of BMPs: bioswale and infiltration trench. For each BMP type, the performance of the BMP was analyzed for newly constructed, 2-year-old, and 10-year-old conditions. The matrix also includes all considered rainfall events shown in Table 45.

All scenarios shown in the test matrix are single rainfall events occurring during a 24-hour period. To monitor the performance of BMPs in cases where two rainfall events occur subsequently in a day, a set of sequential test was also conducted. For sequential tests, the 5-year return rainfall event was repeated 3 to 4 hours after the first simulated event and only on BMPs representing newly constructed.

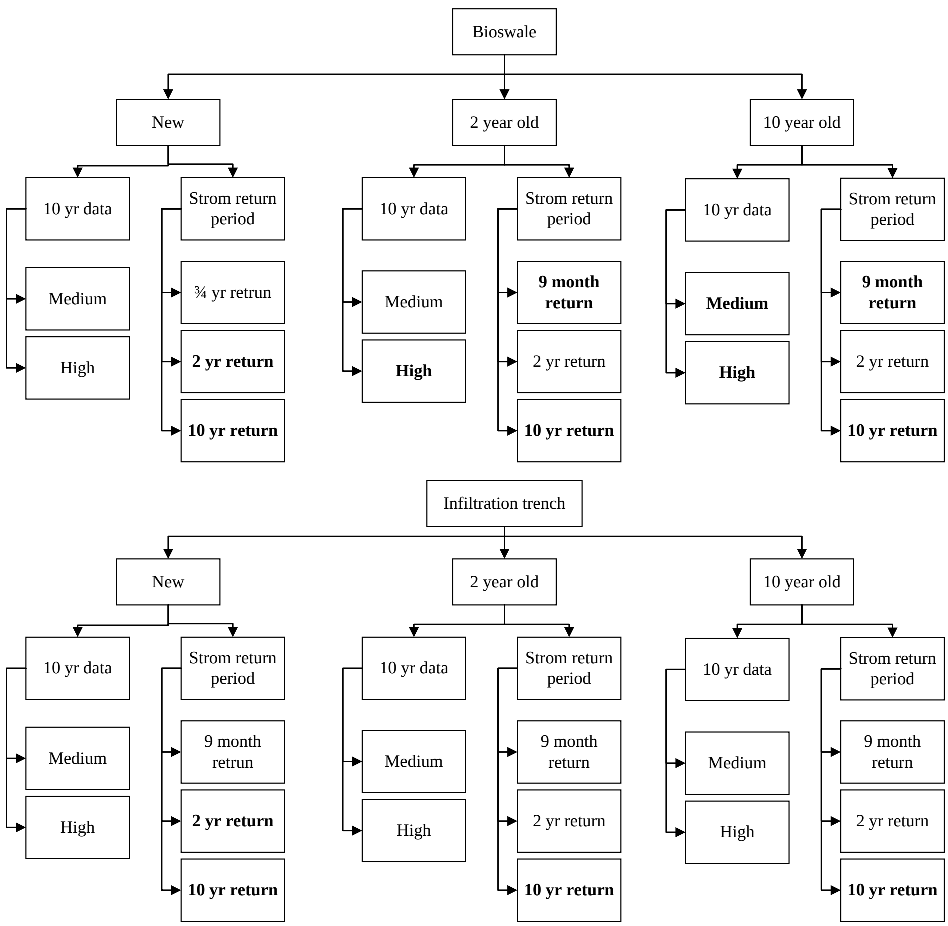


Figure 47. **Tentative test matrix.**

6.1.6 Methodology

The tests were designed to simulate BMP behavior during a rainfall event. Water was conveyed through 1.5 in. PVC SCH 40 pipes from the elevated storage tank to the BMP test cells by gravity. Two perforated pipes (8 ft long and 1.5 in. diameter) were installed along each side of the BMP test cell as shown in Figure 48. A flowmeter was installed in the main just before entering the BMP as shown in Figure 49 to monitor the amount of water inputs into the BMP. The flow meter was constantly monitored during the test to ensure the cell is exposed to the flow rate specified in Table 45.

Figure 48. Piping system and bioswale during a control test.

Figure 49. Flowmeter installed in the pipeline.

An 8-in. diameter perforated monitoring well was installed at the corner of each BMP cell to record the stored stormwater level in the BMP (see Figure 48). During the test, the water level in the well was measured manually every 1 minute until the inflow stopped. After that, readings were taken at longer intervals. In addition, water level sensors were placed at the bottom of the monitoring wells (Figure 50). These sensors were left in place until the well became dry. A camcorder was also used to record the performance of BMP during the tests.

Figure 50. Pressure sensor used to measure water depth.

If the intensity of rain is more than the infiltration capacity of the BMP, stormwater accumulates on the BMP surface and run-off will occur. For tests with water accumulation of more than 2 in., surface-ponded water was considered run-off and was pumped out and stored in 100-gal capacity tanks adjacent to BMP cells as shown in Figure 51.

Figure 51. Pumping run-off into the collecting tanks.

6.2 RESULTS

6.2.1 Bioswales

From the amount of run-off observed, it was clear that run-off from test cell increases with aging of the BMP. The infiltration rate of the bioswale depends on the sediment thickness and clogging. The total inflow to and run-off from a 10-year-old (Cell B1) and a 2-year-old (Cell B2) old bioswale in different rainfall events is shown in Figure 52 and Figure 53, respectively. It should be noted that no run-off was observed for the new bioswale scenario (B3). Therefore, the efficiency of the bioswale B3 in handling the stormwater run-off from considered rainfall events was 100%. The efficiency of the bioswale B1 and B2 are shown in Figure 54. According to this figure, the efficiency of the bioswales is 27%, 44%, and 57% for a 10-year-old bioswale during 10- year, 2-year, and 9-month return storms, respectively. The efficiency of a 10-year-old bioswale in capturing stormwater run-off from medium and high rain events (see Table 45) was 100 % and 37%, respectively. A similar trend was observed for the B2 bioswale, which represented 2-year-old bioswale, although the efficiencies generally were 20% to 45% higher than those for the 10-year-old bioswale depending on the intensity of rainfall. In the case of the sequential test on a new bioswale (B3), there was no run-off in the first part of the test, but there was runoff in the second part. The run-off on the second part is shown in Figure *55*.

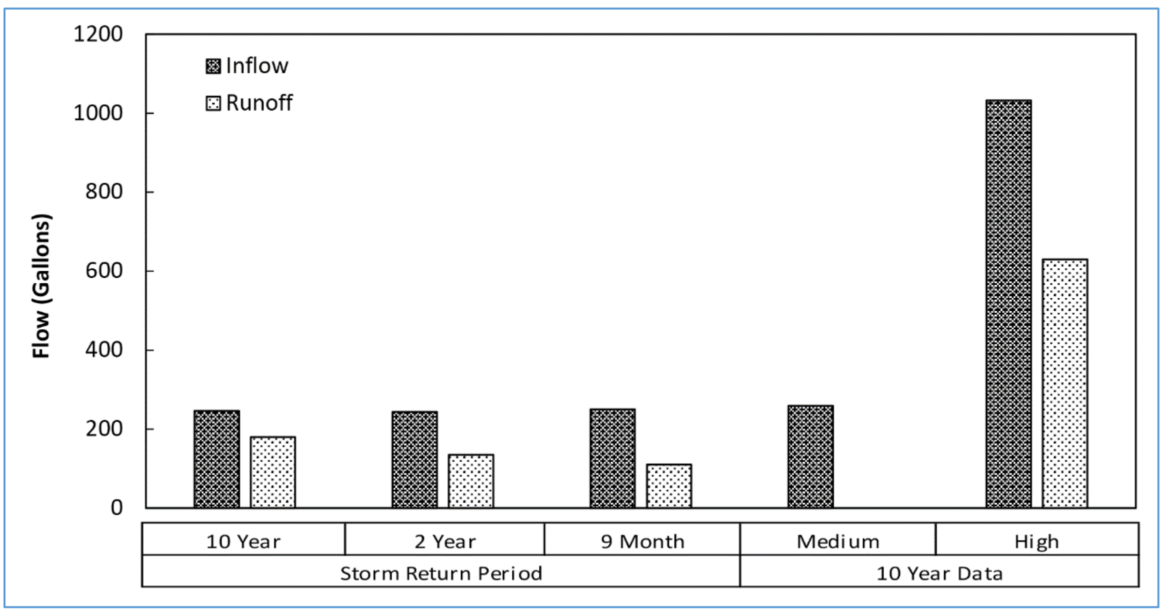


Figure 52. Test on cell B1 on different rainfall scenarios.

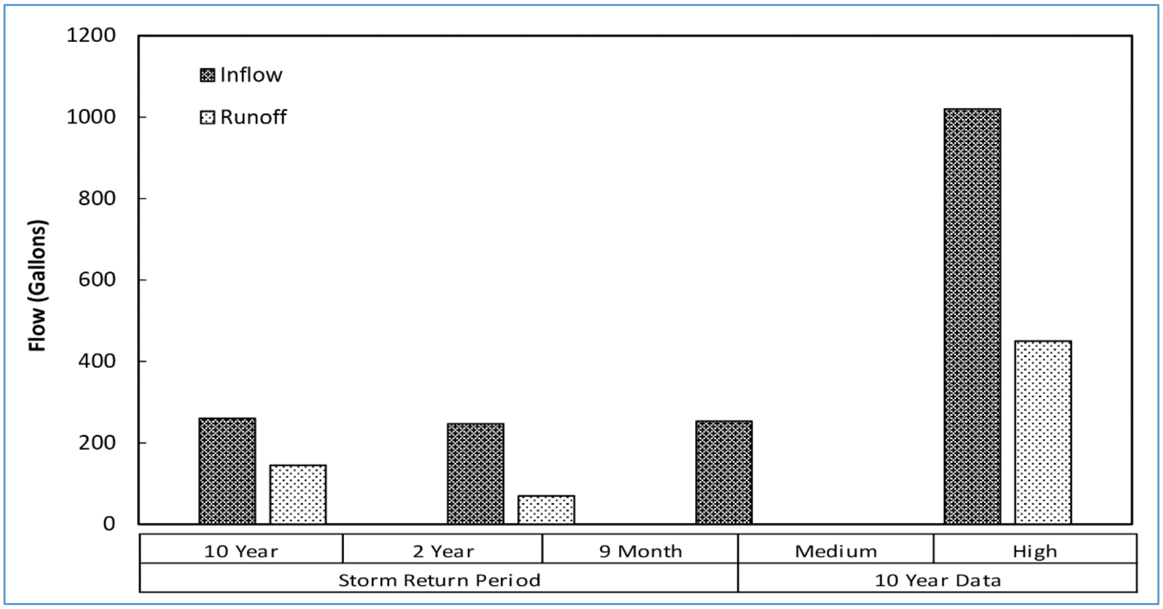


Figure 53. Test on Cell B2 on different rainfall scenarios.

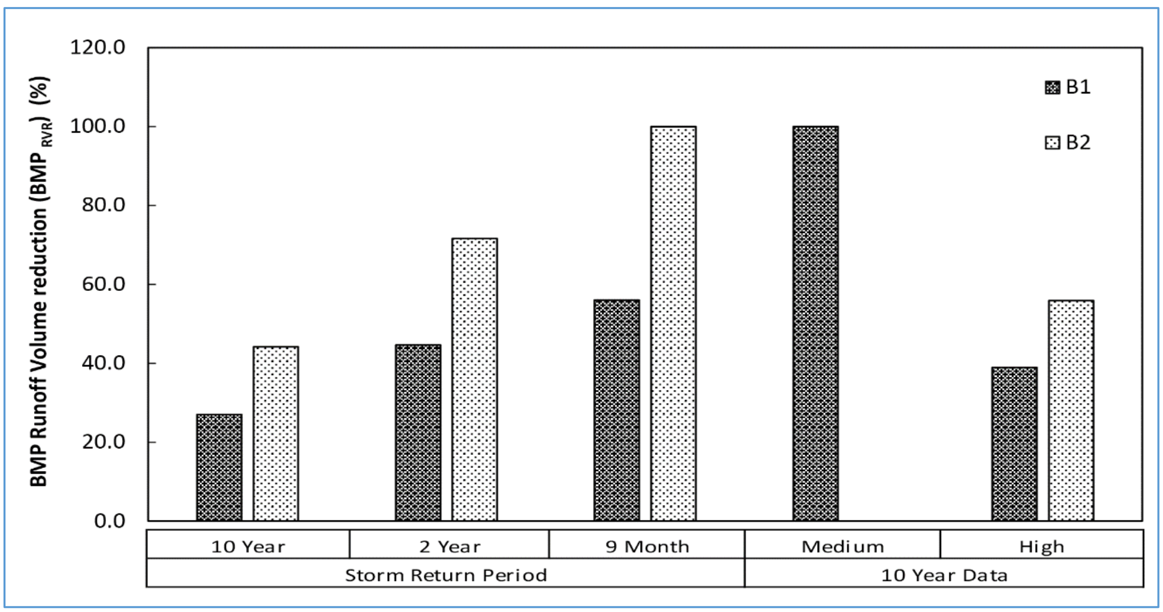


Figure 54. BMP $_{RVR}$ of different cell on different rainfall scenarios.

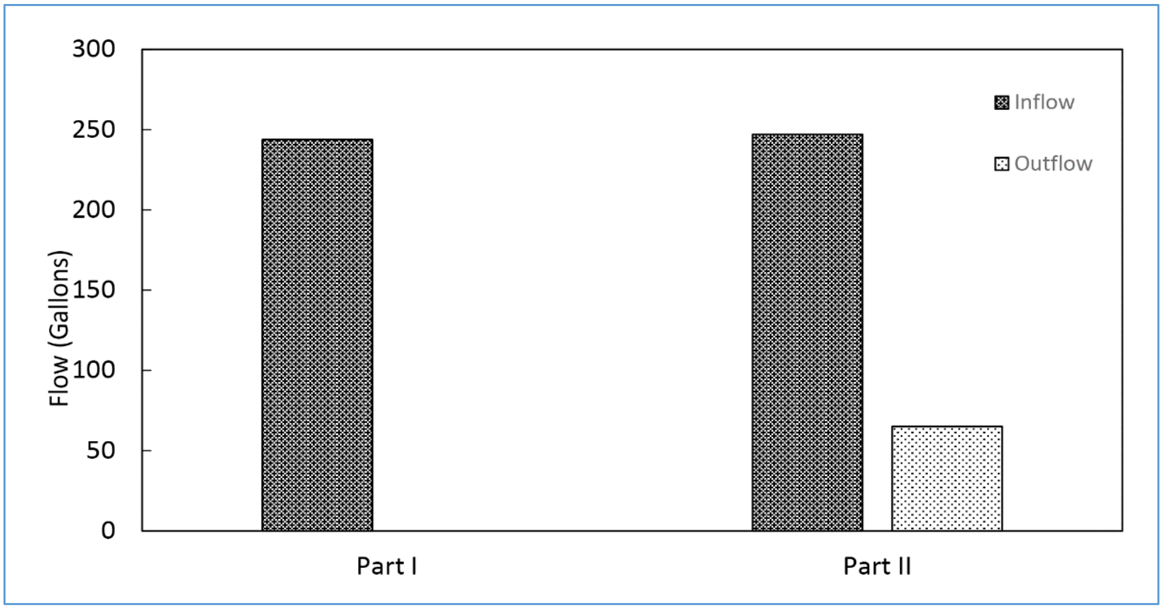


Figure 55. Five-year return period storm sequential test performed at 5-hour interval on test cell B3.

6.2.2 Infiltration Trench

The infiltration trench tests showed there was no run-off regardless of rainfall event and age of infiltration trench. The void ratio for the infiltration trench was high. Thus the inflow water infiltrated through the gravel storage zones and there was no run-off. The appearance of the BMP surface after placing sediment to represent the 2- and 10-year-old infiltration trenches is shown in Figure 56 and Figure 57, respectively. It was observed that the inflow water washed the sediment placed at the surface. The BMP will capture all run-off up to its void capacity, which will decrease as sediment and debris occupy the void space. It should be noted that there was no run-off observed during a sequential rain event.

Figure 56. Sediment on 2-year-old infiltration trench.

Figure 57. Sediment on 10-year-old infiltration trench.

6.3 MONITORING WELL READINGS

The graph obtained from the sensor shows the pattern of rise of the water head at the monitoring well during the test and its fall after the test until it reaches zero. The sharp rise in the water head is due to a high influx of water inflow to the BMP during the rain event. The rate of fall of water level in the observation well reflects the infiltration rate capacity of the soil.

6.3.1 Infiltration in Bioswale Cells

Figure 58 shows the monitored water levels for tests conducted in the 10-year-old bioswale. The rate of water level increase in the well can indicate the infiltration rate of the bioswale. The rate of decrease in water level can provide a rough estimate of the infiltration rate of the native bottom soil.

Five tests with 9-month, 2-year, 10-year return storms as well as medium and high rain events were conducted for a 10-year-old bioswale. The infiltration rate of the bioswale is estimated at 0.994, 0.873, and 0.309 in. per minute for 10-year-return, 2-year-return, and 9-month-return storm events, respectively.

The first 3 hours on the descending part of the curves in Figure 58 show the maximum infiltration rates into native soil under a full water head. These rates are 0.053, 0.051, and 0.045 in. per minute for 10-year-return, 2-year-return, and 9-month-return storm events, respectively. For a medium rain event, the infiltration rate into the bioswale varies non-linearly from 0.404 in. per minute to 0.013 in. per minute over 8 hours. The infiltration rate into the native soil is almost constant at a rate of 0.035 in. per minute. For the high rain event, the infiltration rate into the bioswale and native soil is 0.619 and 0.06 in. per minute, respectively. The reason for the variation might be compaction of the material as water infiltrates. The figure shows that storms with higher intensities will infiltrate into the bioswale and occupy a larger volume of void space. It is also concluded that if the medium rain event is repeated immediately after the first event, the bioswale would have the capacity to capture all rainfall from both events.

The duration of the medium events was longer; therefore the intensity of rainfall was lower compared to high events. The low-intensity inflow and simultaneous infiltration to the bottom soil will result in a much slower rate of water level rise in the monitoring well. In this particular test, the increasing slope is not a reliable representation of the infiltration rate of the bioswale because there is no full head of water to force flow through the bioswale growing medium layer.

For the high rain event, the intensity was higher (2.45 gpm) and had a longer duration (6.8 hours). A noticeable point in this test is that the peak water level is observed for a longer period (6 hours). The reason is that after about 90 minutes from the beginning of the test, the bioswale filled up with stormwater, and there was no room for accommodating additional inflow. Therefore, a run-off condition occurred, and surplus water was pumped out and stored until the end of the test.

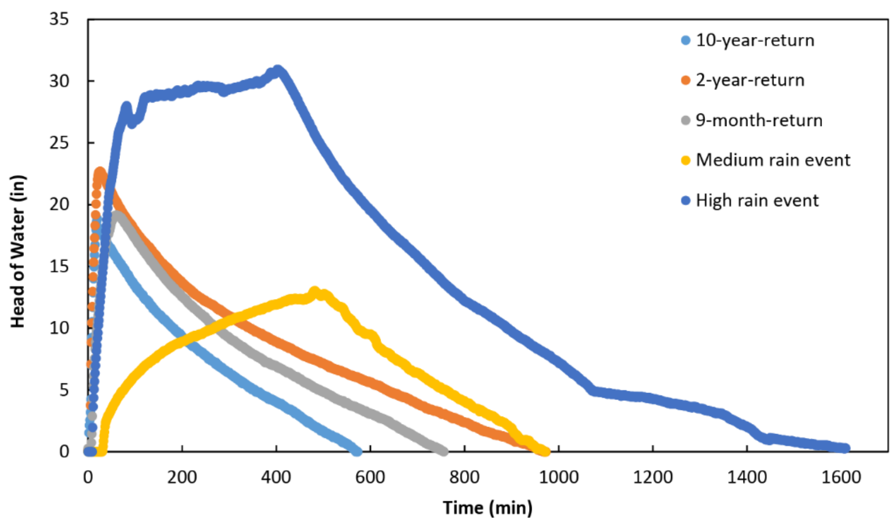


Figure 58. Water head in observation well for 10-year-old bioswale.

The 2-year-old bioswale was also tested using similar storm events, as shown in Figure 59. The rates of water head increase in the monitoring well during 10-year and 2-year storm events are very similar to the ones in 10-year-old bioswale. However, because of reduced intensity in the 9-month return rainfall event, the peak of the water head in the well is higher, and the bioswale can promote more infiltration. The infiltration rate of the bioswale for 10-year-return, 2-year-return, 9-month-return, and high rain events are 1.356, 0.795, 0.614, and 0.255 in. per minute, respectively. The infiltration rates into native soil are 0.083, 0.057, 0.080, and 0.139 in. per minute, respectively.

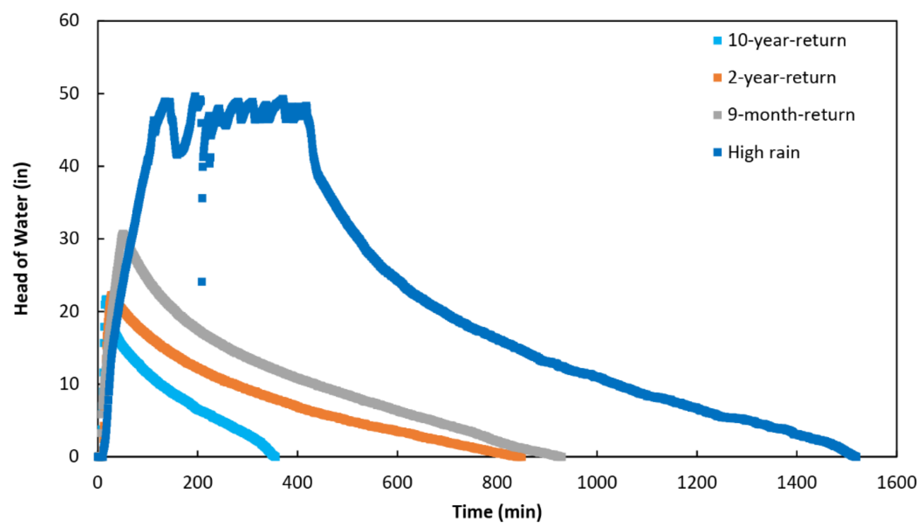


Figure 59. Water head in observation well for 2-year-old bioswale.

The behavior of the bioswale when two events happened consecutively was investigated by running a sequence test using 2-year-return storm event on a new bioswale. The monitoring well reading results are shown in Figure 60. The ascending part of the figure for the first and second parts shows slopes of 1.65 and 1.51 in. per minute, respectively. The descending slopes of the water level in this figure show slopes of 0.096 and 0.115 in. per minute for the first and second part of the test, respectively.

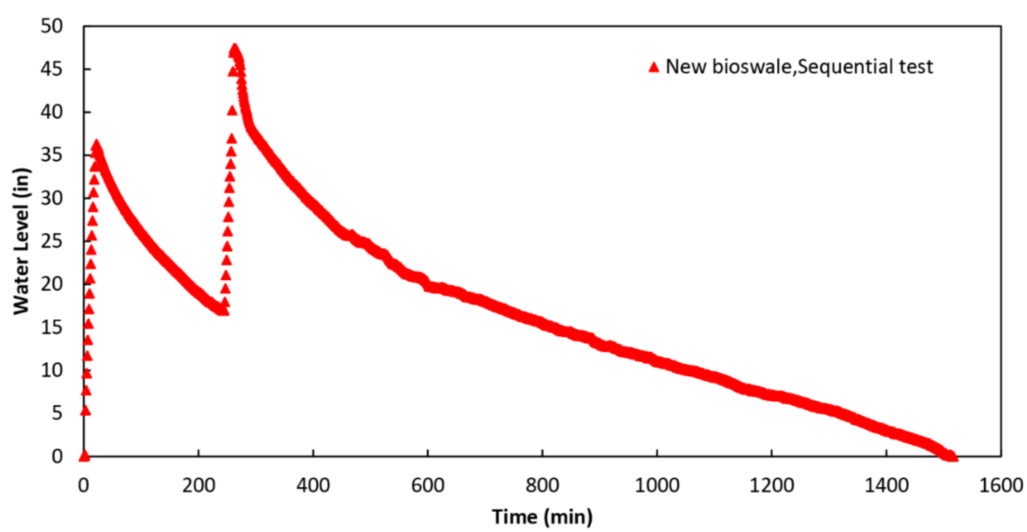


Figure 60. Water head in observation well for a new bioswale in a sequential test using 2-year return storm event.

6.3.2 Infiltration in Infiltration Trench Cells

The same scenarios were repeated for infiltration trench test cells. In these tests, aging of the infiltration trench had no effect on the infiltration rate of the BMP because the simulated stormwater washed out all the sediment. However, over time, sediment will eventually fill up the infiltration trench void space.

Figure 61 illustrates the results of tests for the 10-year-return storm event. The infiltration rate into infiltration trench test cell was measured at 2.9, 3.2, and 3.4 in. per minute in new, 2- and 10-year-old infiltration trenches, respectively. The infiltration rate into native soil at the bottom of the trench was measured as 0.12 in. per minute for all three tests.

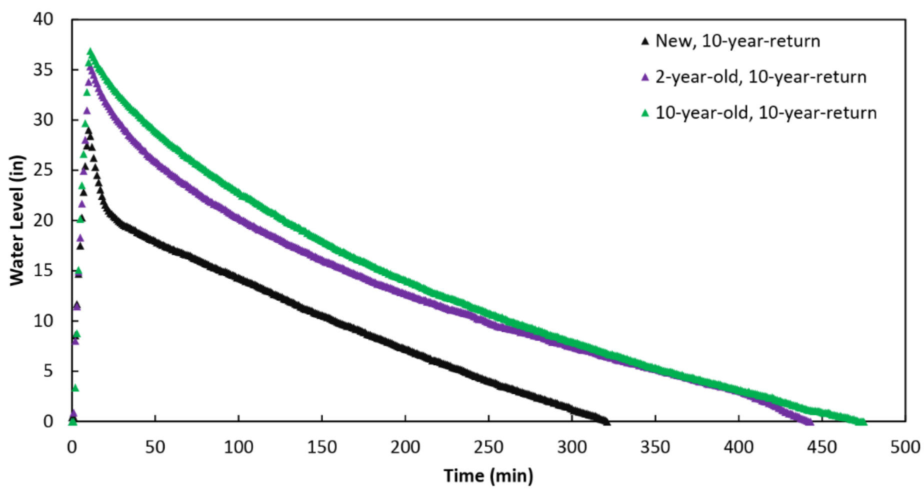


Figure 61. Water head in observation well for 10-year-return event in infiltration trenches.

To observe the behavior of the infiltration trench during two consecutive events, a sequential test of a 2-year-return storm event with an interval of 4 hours was conducted on a 10-year-old infiltration trench. The water level reading for this test is shown in Figure 62. If a different interval between two events is desired, the response of second rain event can be shifted and superimposed on the response of first part to obtain the full response. In this test, the infiltration rate into the test cell was 1.7 and 1.4 in. per minute for first and second parts of the test, respectively. The infiltration rate into native soil was about 0.1 in. per minute during both events.

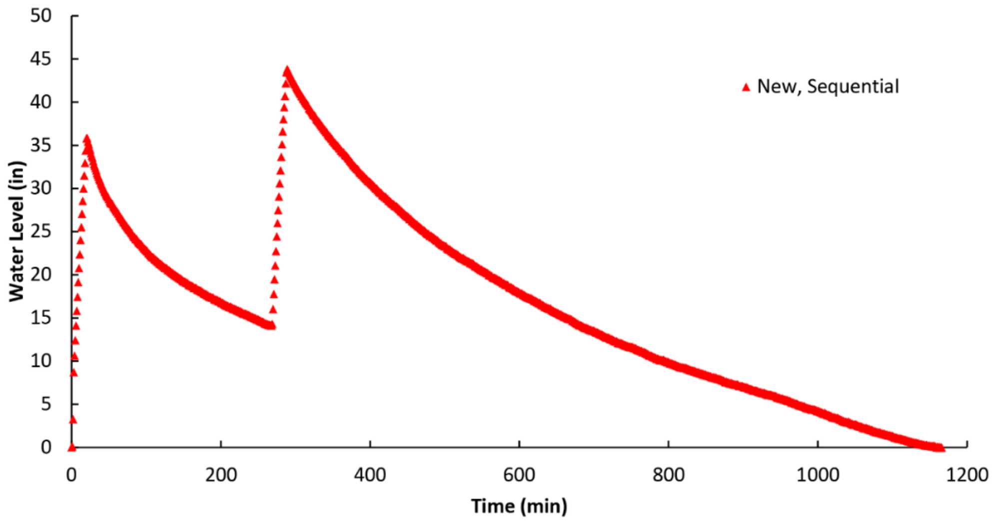


Figure 62. Head of water in observation well for new infiltration trench, sequential test.

CHAPTER 7: SEDIMENT ACCUMULATION EFFECT ON IDEALIZED CATCHMENT SIMULATIONS

As noted earlier, the simulations discussed in Chapters 3 and 4 considered newly constructed BMPs or very well-maintained BMPs. In this chapter, the aim is to identify the effect of aging or poor maintenance and/or clogging effects or sediment accumulation on bioswale simulations based on findings from the field tests.

Section 7.1 addresses field tests that were modeled using the simulation methodologies discussed in Chapter 3 to calibrate the simulations results. Section 7.2 presents the findings from two specific simulations with an idealized catchment that had silty clay and silty loam native soils (discussed in Section 4.3) to show how aging and sediment clogging can affect the performance of those configurations. This linkage would provide an understanding about how the other simulations would be affected if the aging of BMPs is considered.

7.1 FIELD TEST MODEL AND CALIBRATION

The methodology discussed in Chapters 3 and 4 was used to simulate the field tests. The field test model represents two subcatchments—bioswale and upstream. As noted earlier, the upstream subcatchments that contribute stormwater to the BMP are 50 ft wide in the field tests. The possible layouts for a 50-ft-wide upstream subcatchment are shown in Figure 63. Therefore, the simulation model was set up with a 50-ft width and 8-ft length to represent the upstream subcatchment and BMP. Because all the stormwater run-off from the upstream subcatchment was directed to the BMP, the imperviousness of the upstream subcatchments was considered 100%. The bioswale subcatchment has the same characteristics as discussed in Chapter 3, except its area is 24 ft^2 and its depth is 4 ft.

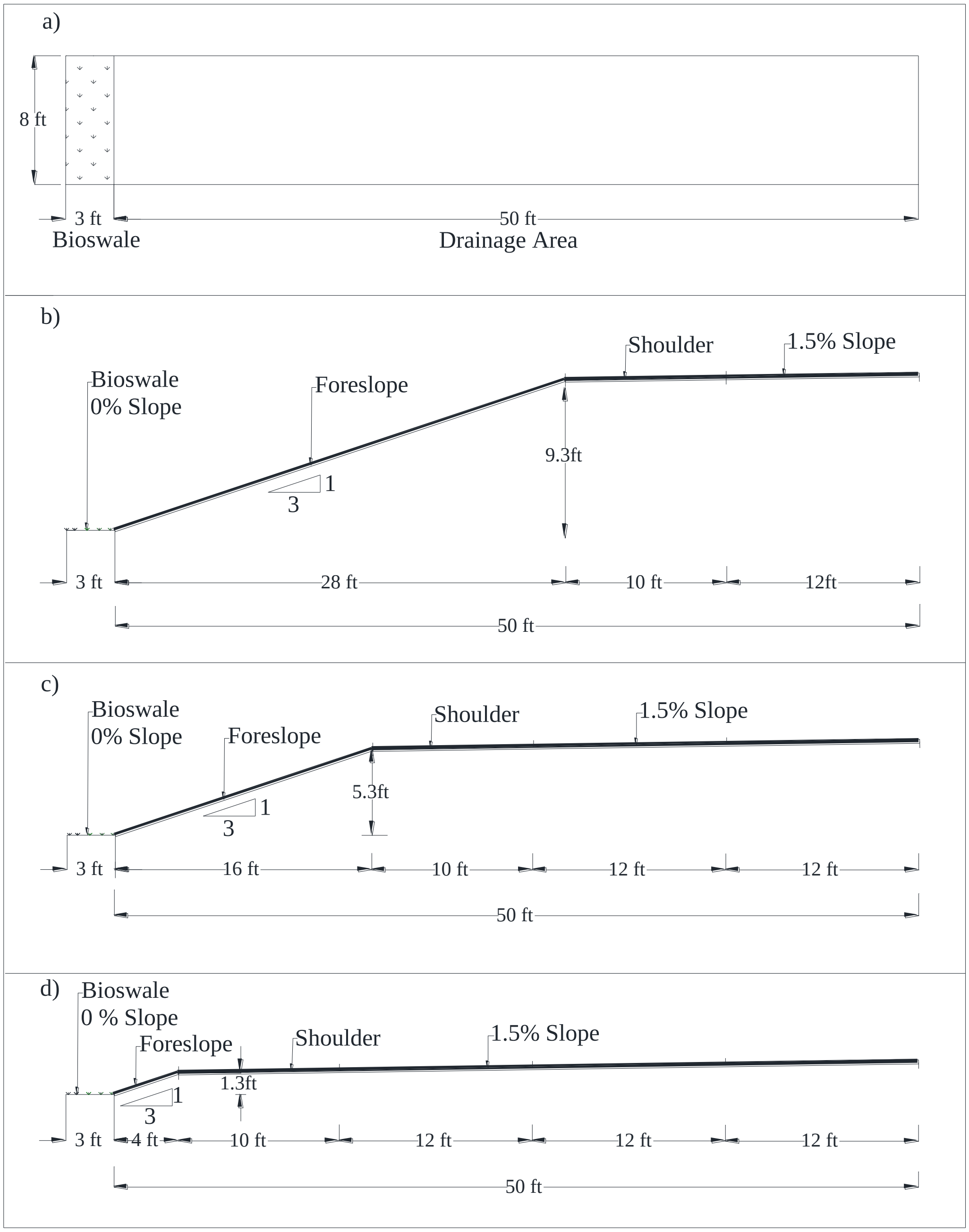


Figure 63. Sketch showing (a) plan view of field test layout; and cross section of (b) one-lane highway, (c) two-lane highway, and (d) three-lane highway.

To calibrate the PCSWMM model, the SRTC tool of PCSWMM was used. The first step was to import the observed run-off data through a time series and integrate it with the specific simulation scenario. Then the uncertainty percentage for parameters such as watershed area, width, slope, N Imperv, N Perv, Dstore Imperv, Dstore Perv, conductivity, etc. were set based on

Table 47, which is suggested in the SWMM manual (James 2005). The simulation is run using the uncertainty ranges for the parameters to identify to which one it is most sensitive.

Table 47. Uncertainty Percentages for Subcatchment Parameters

Parameter	Uncertainty %
Area (ha)	5
Width (m)	200
Slope (%)	50
Imperv (%)	30
N Imperv	20
N Perv	50
Dstore Imperv (mm)	20
Dstore Perv (mm)	50
Zero Imperv (%)	60
Percent Routed (%)	35
Suction Head (mm)	50
Conductivity (mm/hr)	65
Initial Deficit (frac.)	25
Conduit Parameter Roughness	60

After the uncertainty percentage was set, the SRTC was applied; infiltration rate (conductivity) was identified as the most sensitive parameter that affects the model's run-off and infiltration volume. Therefore, for simplicity, instead of calibrating all input parameters, the calibration was focused only on the infiltration rate so that it provides run-off volumes that matched field measurements. The main purpose was to connect these field tests with the numerous simulations discussed in Chapters 3 and 4. If more of these field test results had been available in the early stages of the project, a thorough calibration of parameters would have been possible.

The infiltration rates that were measured on-site for new and for 2- and 10-year-old bioswales were used in simulations of bioswales subjected to a 1-in. rainfall event with a 10-year return. As Table 48 shows, calibration demonstrated that the infiltration rate used for simulation should be increased by 2.7 to 3.2 times of the original measured values to match the simulated and measured run-off reductions.

Table 48. Calibration Results for Infiltration Rate When Bioswale Is Subjected to a 1-in. Rainfall with 10-Year Return

Bioswale Age	Measured Infiltration Rate On-Site (mm/hr)	Calibrated Infiltration Rate in PCSWMM (mm/hr)	Ratio of Calibrated to Measured Infiltration Rate
New	1812	5700	3.2
2 yr	544	1451	2.7
10 yr	191	601	3.1

Based on the field test calibrated infiltration rate, the change in the ratio of infiltration rate from new to the 2- and 10-year-old BMP is shown in Table 49. The ratios were applied to the sand layer as the soil in the bioswale subcatchment to consider the aging effect of bioswales.

Table 49. New Infiltration Rate for Idealized Catchment Modeling

Bioswale age (yr)	Ratio of new/aged based on calibrated field test
0	1
2	3.9
10	9.5

Considering these calibrated ratios of the infiltration rates, the simulations of bioswales subjected to a 1-in. rain event with 9-month and 2-year return rainfalls were conducted, and the resulting run-offs were compared to observed run-off in the field under these rainfall events.

As shown previously in Table 48, it was observed that if the infiltration ratio measured in the field increases about three times, the simulated and measured run-off under a rain event of 1-in. depth with 9-month return and 2-year return would also match. For example, as shown in Table 50, the simulation results for a 2-year old bioswale with a soil with a 1451 mm per hour infiltration rate show run-off volumes of 135, 76, and 16 gal in a 1-in. a rainstorm with 10-year, 2-year, and 9-month returns, respectively. The results reasonably match with the run-off values of 145, 70, and 0 gal measured in the field, respectively.

Table 50. Comparison of Field Test and Calibrated Simulation Results

Bioswale Age (yr)	Rainfall Storm (Return Time)	Field Test Result		Simulation Results					
				Infiltration Rate (mm/hr)	BMP Unit Performance				BMP $_{RVR}$ (%)
		Run-Off (gal)	Infiltration (gal)		Rainfall (gal)	Run-On (gal)	Infiltration (gal)	Run-Off (gal)	
0	10 years	0	250	5700	15	251	239	33	87.72
	2 years	0	250		15	243	227	19	92.47
	9 months	0	250		15	231	226	16	93.62
2	10 years	145	105	1451	15	251	136	135	49.29
	2 years	70	180		15	243	186	76	70.63
	9-months	0	250		15	231	227	16	93.46
10	10 years	180	70	601	15	251	76	192	27.71
	2 years	135	115		15	243	103	158	38.59
	9 months	110	140		15	231	160	86	64.82

7.2 THE EFFECT OF AGING ON SIMULATIONS OF IDEALIZED CATCHMENT

The simulation results of newly constructed bioswales in the idealized catchment with soil types of silty clay and silt loam were discussed in Section 4.3. A cross-section of the idealized catchment was previously shown in Figure 1. These two simulations will be considered herein as examples to show how aging would affect their performance and efficiency. It is worth noting that these two soil types are the natural soils in the area of foreslope, ground level, and backslope area with a turfgrass as the vegetated cover. Moreover, the selected scenarios were simulated for a 1-in. rainfall during 24 hours with a storm Type II pattern.

To simulate the lower infiltration rate of aged bioswales, the infiltration rates of a newly constructed bioswale (120.4 mm per hour for sand as the soil applied in bioswale) was reduced using the ratios shown previously in Table 49. Therefore, infiltration rates of 31 and 13 mm per hour were used for simulating the 2- and 10-year-old bioswales in the idealized catchment.

7.2.1 Results for Silty Clay Soil Type

As Figure 64 illustrates, a 1-in. rainfall within 24 hours results in a total of 37,046 gal precipitation in the idealized catchment. As the bioswale gets older and more sedimentation accumulates on its surface, the volume of infiltrated water by the bioswale decreases from 26,845 gal in the new bioswale to 17,120 and 9,261 gal in the 2- and 10-year-old bioswales, respectively. System infiltration is higher than the infiltration occurring in the bioswale because the system includes the foreslope, backslope, and ground level, which are pervious surfaces covered with turfgrass.

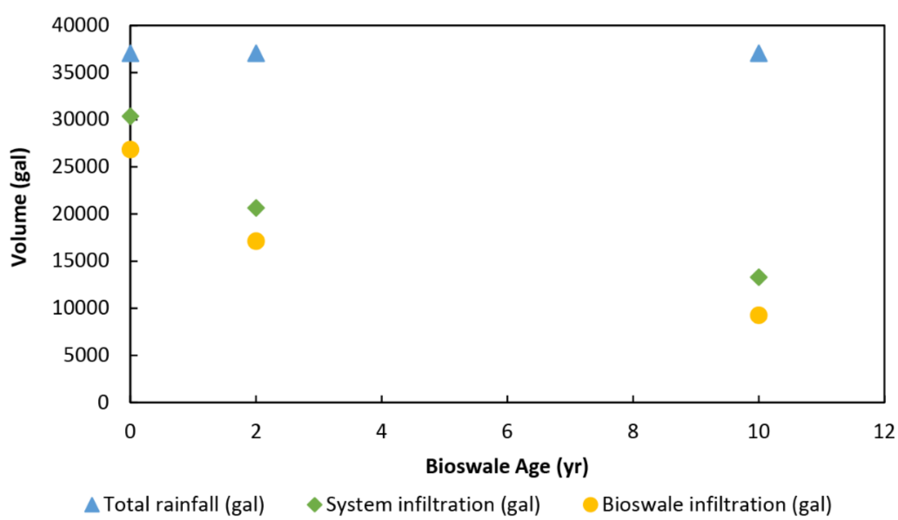


Figure 64. The model result for infiltration and run-off volume for the silty clay soil type.

As Figure 65 displays, the percentage run-off reduction decreases from 86% to 60% and 40% from the new bioswale to the 2- and 10-year-old bioswales, respectively. In other words, in 10 years, the performance of the bioswale in run-off volume reduction of the system in an area with silty clay natural soil decreased to 50% of its performance when it was new.

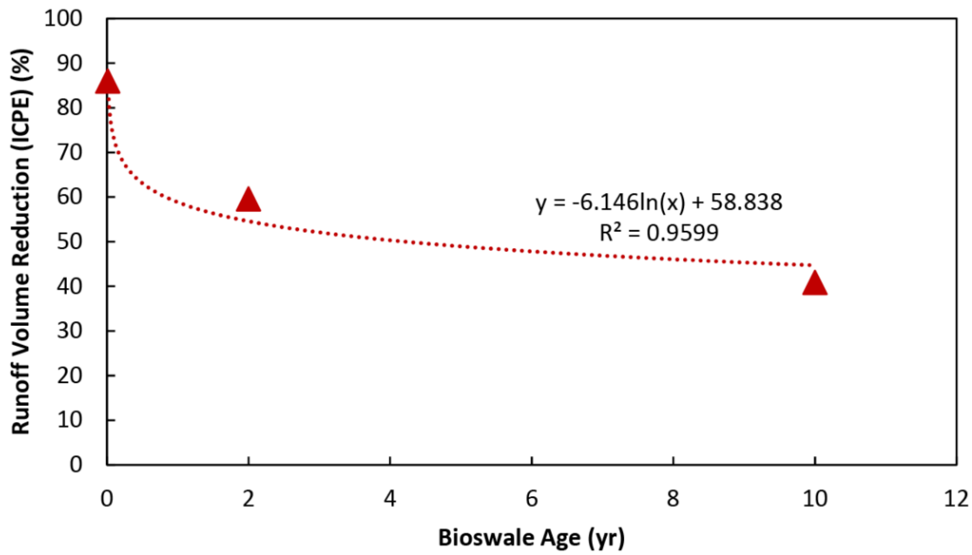


Figure 65. Variation of ICPE for the idealized catchment for a site with silty clay native soil with bioswale aging.

7.2.2 Results for Silty Loam Soil Type

Figure 66 presents the simulation results for a site with silty loam type soil. As the bioswale gets older and more sedimentation accumulates on its surface, the volume of infiltrated water by the bioswale decreases from 18,476 gal in the new bioswale to 12,072 and 7,813 gal in the 2- and 10-year-old bioswales, respectively. As with the silty clay soil, system infiltration is higher than the infiltration occurring in the bioswale because the system includes the foreslope, backslope, and ground level, which are pervious surfaces covered with turfgrass. The difference between the volume of infiltrated water in the whole system and the bioswale unit is much more than what was observed at the silty clay site, as shown in Figure 64. The reason is that the silt loam at this site promotes more infiltration in non-BMP areas of the idealized catchment.

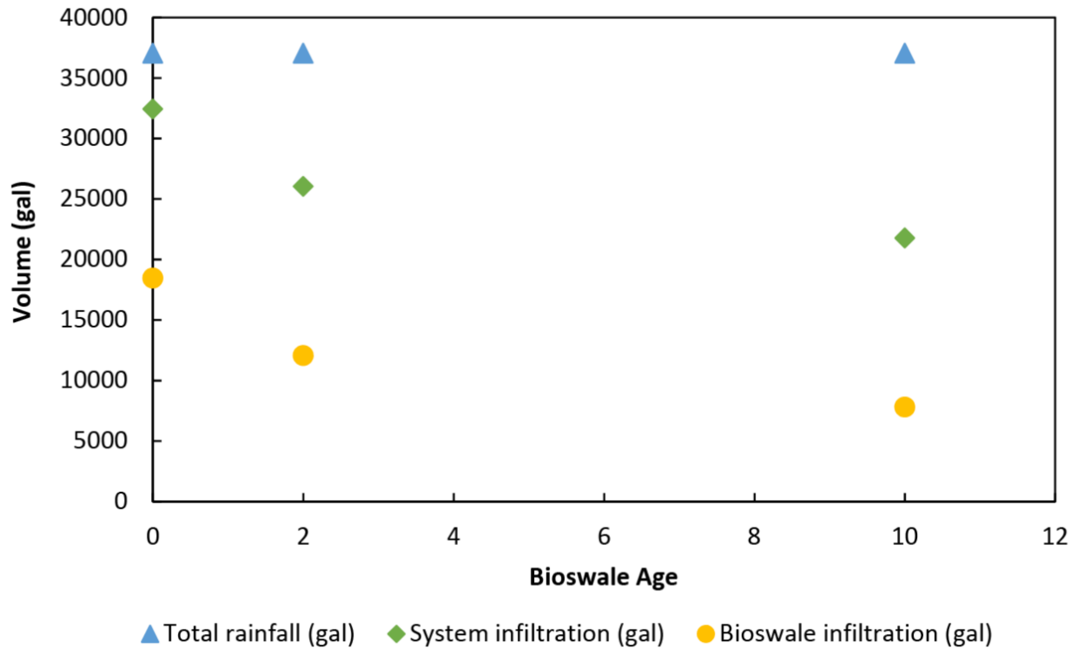


Figure 66. Model result for infiltration and run-off volume for the silt loam soil type.

As Figure 67 shows, the ICPE of a highway system is 90%, 72%, and 61% for the new, 2-year-old and 10-year-old bioswales, respectively. In other words, in 10 years, the performance of the bioswale in run-off volume reduction in an area with silt loam natural soil decreased 33%. These results demonstrate that the default SWMM infiltration rate provides the performance of a new bioswale and that for an older BMP, a reduction of the infiltration rate by as much as 90% is possible. It is worth noting that the suggested reductions in infiltration rates of the bioswale site in Charlottesville, Virginia (see Section 3.5.1) are within this limit.

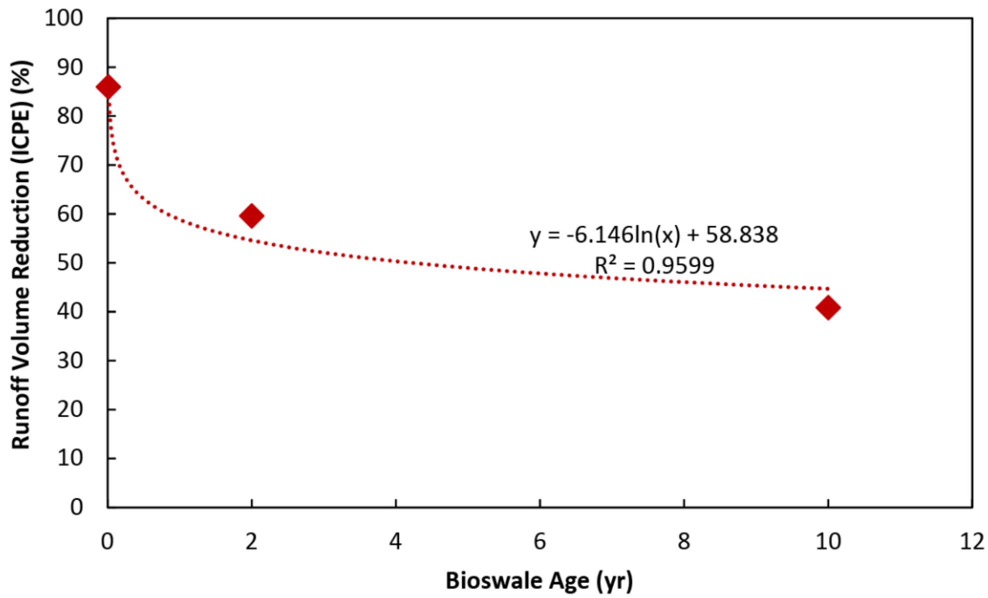


Figure 67. Variation of ICPE for the idealized catchment for a site with silt loam native soil with bioswale aging.

For the other simulation scenarios discussed in Section 4.3 and for other soil types, a similar reduction in BMP performance is expected if they are not well maintained. It is also concluded that poor maintenance of bioswales in sites with low permeable native soils would affect the performance of the bioswales significantly.

CHAPTER 8: BMP SELECTION, INSTALLATION, COST, AND MAINTENANCE GUIDE

8.1 GENERAL POST-CONSTRUCTION BMP RESTRICTIONS AND CONSIDERATIONS

Physical site constraints such as the infiltration capacity of the soil, depth to groundwater table, size of the drainage area, type of vegetation, and slope can limit the implementation of stormwater run-off BMPs at a site. Overcoming these restrictions may incur high costs for BMP installation.

8.1.1 Site Area

Larger drainage areas are accompanied by greater volume and possibly higher velocity stormwater run-off than small drainage areas. Some BMPs can be designed to accommodate run-off volume from both small and large drainage areas; other BMPs may generally be better adapted for small drainage areas. Therefore, a determination of BMP drainage area is necessary to select and design appropriate BMP storage and treatment volume capacity.

In urban areas where the available BMP footprint is limited, BMPs may be broken up into smaller structures to accommodate such restrictions. On the other hand, in areas where a larger BMP footprint is available, there are fewer BMP design restrictions and more cost-effective BMPs may be implemented. Because roadways are linear structures, BMPs such as vegetated filter strips and swales are often the most advantageous practices.

8.1.2 Soil

Surface and subsurface soil characteristics are very important considerations for successful BMP performance. The collected water in the BMP eventually has to be infiltrated into the soil beneath. Therefore, the infiltration rate of the soil would determine how long after a storm event the implemented BMP will be again available to control run-off.

Subsurface soil characteristics must be determined properly at appropriate depths in order to design infiltration-dependent parameters. In cases where the subsurface soil infiltration is low, the upper 3 to 4 ft of subsoil must be modified to provide an adequate infiltration rate, or an alternate BMP will be required to serve the site (Burack et al. 2008). It should be noted that during the design and construction process, additional geotechnical tests are often required to confirm predicted BMP design assumptions.

Soil evaluation is based on hydrologic soil group (HSG) classifications, as defined by the National Resource Conservation Service (NRCS). Soil types from NRCS are classified as clay (particle size smaller than 0.002 mm in diameter), silt (particle size between 0.002 and 0.05 mm in diameter), and sand (particle size from 0.05 to 2.0 mm in diameter). The NRCS also categorizes soils into one of four HSGs: A, B, C, and D (see Table A1-5 of Appendix 1):

Group A—Soils have high infiltration and transmission rates when thoroughly wet. This group has good drainage underneath, especially when associated with layers of sand and gravel.

Group B—Soils have moderate infiltration and transmission rates when thoroughly wet. This group has moderate drainage underneath, where soils have fairly fine to fairly coarse texture.

Group C—Soils have slow infiltration and infiltration rates when thoroughly wet. This group has a characteristic that hinders water movement through its fine-textured subsurface soils.

Group D—Soils have very slow infiltration and transmission rates when thoroughly wet. This group is composed primarily of clays with high shrink–swell potential.

8.1.3 Slope
Sites with steep slopes along a run-off pathway are vulnerable to surface erosion. Steep slopes are subject to higher erosive potential than gently sloped or flat terrain. BMPs on sites with steep slopes may experience frequent clogging, increased maintenance requirements, and early failure. The slope at and/or abutting a BMP and the slope of drainage area should be considered during the BMP selection process (Burack et al. 2008).

8.1.4 Depth to Groundwater
Determination of depth to groundwater from the surface is critical in the selection process of BMPs, particularly for infiltration practices. Groundwater recharge through infiltration of stormwater may exacerbate contamination in shallow aquifers. Furthermore, sites with shallow groundwater have significantly reduced downward percolation and infiltration of stormwater run-off. For example, if an infiltration trench with a depth of 10 ft is installed in an area with a seasonally high groundwater table, a portion of the capacity of the infiltration trench will not be available during periods of wet.

8.1.5 Temperature Extremes
Another element that can significantly affect the performance and applicability of BMPs is temperature extremes. The efficiency of infiltration BMPs can substantially be reduced as a result of frost. In addition, vegetative BMPs must accommodate temperature-sensitive conditions: freeze/thaw cycles, deep frost, deicing salt associated with snow removal, and drought. Table 51 shows peak flow reduction capacity and temperature extreme maintenance guidelines for each type of BMP (ADOT 2009).

Table 51. Climate Zone Restrictions

Water Quality or Treatment BMP	Peak Flow Reduction	Cold Climate
Bioretention	Low to moderate; 40% reduction in the total run-off volume (influent to effluent)	Protect inlet/outlet pipes Use large-diameter (>8 in.) gravel in underdrain of outfall protection Provide ice storage volume Use freeze- and salt-tolerant vegetation
Retention and Detention Basins	Ideally suited for peak flow reduction and flood control Retention and detention ponds may increase the risk of downstream flooding in some cases	
Infiltration Trench/Basins	Moderate; when designed with sufficient capacity, all run-off collected is infiltrated	Monitor groundwater for chloride and do not allow infiltration if chlorides are a concern for the groundwater in the area Increase soil permeability requirements Use a 20 ft minimum setback between the road subgrade and the BMP structure
Filtration Structures	None to low peak flow reduction	Reduced filtration occurs during cold weather Underground filters are effective if only placed below the frost line Peat/compost (organic) media is ineffective during cold weather and may become impervious if frozen
Vegetated Filter Strip (VFS)	Low to moderate; 30% to 40 % reduction in the total run-off volume (influent to effluent)	Small setback may be required between the VFS and the edge of the road if frost heave is a concern Use cold- and salt-tolerant vegetation Plowed snow can be stored in the VFS

8.2 BMP OPTIONS FOR LINEAR PROJECTS IN URBAN AREAS

BMP options for controlling urban-area linear project stormwater run-off are likely limited in comparison to BMPs feasible in rural areas. Compared to rural areas, urban-area linear projects usually have a very limited non-pavement right-of-way and a greater ratio of paved area per linear foot of roadway.

For linear projects in urban areas, bioswales, vegetated filter strips, and infiltration trenches are likely the most effective on-site structural BMPs for controlling stormwater run-off. These BMPs may be employed alone or in combination. Infiltration basins may be another option; however, their use would typically require a larger footprint than is commonly available in an urban area. The best locations for implementing infiltration basins are in highway interchange infield areas.

Detention and retention basins, when combined with infiltration practices, have the potential to retain run-off on-site. However, the main purpose of detention and retention basin design is to reduce and delay the peak run-off—not to capture and infiltrate stormwater.

Other BMPs, such as wetland channels or basins, are not typically feasible in urban areas because of limited space.

Permeable pavements are not currently suitable because their use is very limited in urban roads with high traffic loads.

As discussed earlier, many BMPs may be designed with an underdrain. However, if the purpose of the BMP is to retain run-off volume, relying on the capacity of an underdrain as a volume reduction practice would not help because the collected run-off would be discharged by the underdrain and would not be retained on-site. This does not mean that practices should not have underdrains.

Vegetation root systems promote infiltration. In this study, prairie grass cover provided 40% more run-off volume reduction for a 1-in./24-hour event than the same site without vegetative cover. The inclusion of turfgrass cover marginally improves the infiltration capacity of the system. Even when improving the infiltration rate is not a key consideration, vegetation cover is likely justified for sediment/erosion control and aesthetic purposes.

Simulations of individual BMPs revealed that they are effective in controlling a large percentage of catchment area run-off from a 1-in. rainfall. The average percentage run-off volume reduction for simulated newly constructed sites with no vegetative surface cover was 89% for bioswales, 100% for infiltration trenches, and 86% for vegetated filter strips. For turfgrass scenarios, run-off volume reduction was 90% for bioswales, 100% for infiltration trenches, and 88% for vegetated filter strips. Simulation of prairie grass cover demonstrated that run-off of a 1-in. rainfall was reduced by 92% for bioswales, 100% for infiltration trenches, and 90% for vegetated filter strips. The analysis showed that prairie grass would reduce more run-off than turfgrass.

Simulation of two combined BMPs revealed that the average run-off volume reduction for a 1-in. rainfall routed through a vegetated filter strip and bioswale combination, a vegetated filter strip and infiltration trench combination, or a bioswale and infiltration trench combination resulted in a greater than 94% reduction of stormwater run-off. In addition, the use of turfgrass or prairie grass in combination with the BMPs produced an increased runoff volume reduction.

Furthermore, the analysis confirmed that in pre-BMP scenarios, the implementation of prairie grass as surface cover would reduce more run-off than turfgrass. The run-off volume reduction for prairie grass was different for various soil types. For example, in pre-BMP scenarios on sandy loam sites, having prairie-vegetated cover resulted in an 87% run-off volume reduction and having turfgrass resulted in a 71% run-off volume reduction, while in scenarios with no vegetative surface cover, the run-off volume reduction of the 1-in. rainfall was 58%.

Also, in pre-BMP scenarios on silt loam sites, the prairie grass cover resulted in a 74% run-off volume reduction of the 1-in. rainfall, while turfgrass and no vegetative surface cover led to 47% and 36% run-off volume reductions, respectively.

For pre-BMP scenarios on silty clay sites, having prairie-vegetated cover resulted in a 42% run-off volume reduction, and having turfgrass resulted in 17% run-off volume reduction. However, in scenarios with no vegetative surface cover, the run-off volume reduction for a 1-in. rainfall was only 8%.

The effect of BMP sizing in capturing run-off was also investigated. For a bioswale site that has no vegetative surface cover on other subcatchments, the run-off reduction from a 1-in. rainfall event varied from 87% to 95% if the bioswale with a 3:1 side slope and 3-ft bottom width is replaced with a BMP that has a 5:1 side slope and a bottom width of 8 ft. For the bioswale site that has turfgrass and prairie grass cover on other subcatchments, similar volume reductions were expected. The run-off reduction for the sites with a vegetated filter strip varies from 36% to 96% as the VFS width changes from 5 ft to 25 ft.

It should be noted that the results shown for new BMPs may overestimate the performance of the BMPs when compared to field observations—because of factors such as aging, clogging, and poor maintenance. The limited field test results on bioswales show that the run-off volume reduction of an idealized catchment with a 10-year-old bioswale may be half of the one resulting from a new bioswale.

This study indicates that a 5-ft-wide bioswale or a 25-ft-wide vegetated filter strip will not capture all run-off produced by 1-in. rainfall except for sites that have sandy native soils. The performance efficiency (ICPE) of these sites are typically more than 80%. However, a newly constructed infiltration trench with 5 ft depth and 3 ft width can capture all run-off from a 1-in./24-hour rainfall event. BMP volume control performance is significantly reduced when subsequent rainfall events occur before the BMP infiltrates internally stored run-off. If the native soil is a low permeable material, the BMP will not be effective for a few days after a rain event. For these cases, the analyses showed that a combination of the BMPs may be designed to capture all run-off produced by 1 in. of rainfall.

BMP costs may be a significant portion of the project cost. However, BMP costs should be weighed against the benefits they offer. Regarding run-off reduction factors, a simulated model revealed that the averages of percentage stormwater run-off reduction from 1-in. rainfall event were 80% for bioswales, 100% for infiltration trenches, and 76% for vegetated filter strips, implying that vegetative filter strip performance is the lowest among considered BMPs. However, filter strip construction and maintenance costs are substantially lower than costs for bioswales or infiltration trenches, indicating that, in cases where capital is limited, vegetative filter strips may be a superior choice. While the relatively costly bioswale may be the proper choice when hydraulic performance, biodiversity, wildlife habitat, nutrient capture, evapotranspiration, and carbon capture are considered.

REFERENCES

2IM group, LLG (2009). I-294 Tri-state tollway bioswale storm water/water quality treatment from TOUHY Avenue to Sanders road overpass contract plans, the Illinois state toll highway authority, Volume I and II.

Abi Aad, M., Suidan, M., and Shuster, W. (2010). Modeling techniques of Best Management Practices: rain barrels and rain gardens using EPA SWMM-5. Journal of Hydrologic Engineering, 15(6), pp. 434-443.

Ackerman, D., and Stein, E. D. (2008). Evaluating the effectiveness of best management practices using dynamic modeling. Journal of Environmental Engineering, 134, 628–639.

Ahiablame, L. M., Engel, B. A., and Chaubey, I. (2012). Representation and evaluation of low impact development practices with L-THIA-LID: An example for site planning. Environment and Pollution, 1(2), 1.

American Association of State Highway and Transportation Officials (AASHTO) (2005). A Policy all Design Standards Interstate System, Standing Committee on Highways AASHTO Highway Subcommittee on Design Technical Committee on Geometric Design.

Arizona Department of Transportation (ADOT) (2009, July). Post-Construction Best Management Practices Manual. Prepared by AMEC Earth & Environmental, Inc.

Arnalds, Ó., and Archer, S. (Eds.) (2013). Rangeland desertification (Vol. 19). Springer Science & Business Media.

Aryal, R. K., and Lee, B. K. (2009). Characteristics of suspended solids and micropollutants in first-flush highway runoff. Water, Air, & Soil Pollution: Focus, 9(5-6), 339-346.

Barr Engineering Company (BEC) (2010). Interception and Depression Storage, 23/62 1050 MIDS.

Barrett, M., Walsh, P. Jr., and Charbeneau, R. (1998). Performance of Vegetative Controls for Treating Highway Runoff. J. Environ. Eng., 10.1061/(ASCE)0733-9372(1998).124:11(1121), 1121-1128.

Borah, D., and Weist, J. (2008). Watershed Models for Storm Water Management: A Review for Better Selection and Application. World Environmental and Water Resources Congress 2008: pp. 1-10.

Brix, H. (1997). Do macrophytes play a role in constructed treatment wetlands? Water science and technology, 35(5), 11-17.

Brown, W., and Schueler, T. (1997). The Economics of Storm Water BMPs in the Mid-Atlantic Region. Center for Watershed Protection. Ellicott City, MD.

Burack, T. S., Walls, M. J., and Stewart, H. (2008, December). New Hampshire Storm Water Manual. Post-Construction Best Management Practices Selection and Design. New Hampshire.

Caltrans (2004). BMP Retrofit Pilot Program Final Report, California Department of Transportation, CTSW-RT 01-050.

Emanuel, R., and Powers, T. H. (2014). City of Chicago storm water management ordinance manual. City.

Christian-Roge & Associates. Inc. (2011), Highway Plans F.A.P RTE. 365/ IL RTE.56 (Butterfield Road) section (58&59) WRS-3, west of IL RTE 59 to East of Winfield Road Roadway Widening, Reconstruction, Bridge replacement and traffic signal installation with interconnect, Project County DuPage, IDOT Division of Highways, C-91-127-02.

Clary, J., Leisenring, M., Quigley, M., Jones, J., and Strecker, E. (2012). International Storm Water Best management Practices (BMP) Database, Narrative Overview of BMP Database Study Characteristics, Wright Water Engineers, Inc., GeoSyntec Consultants.

Cooper, D., Griffin, P., and Cooper, P. (2005). Factors affecting the longevity of sub-surface horizontal flow systems operating as tertiary treatment for sewage effluent. Water Science and Technology 51: 127–135.

GeoSyntec (2008). Post-Construction BMP Technical Guidance Manual, Storm Water BMP Guidance Manual, City of Santa Barbara.

Grenz, N. S (2007). Efficiency of bioswales in positively affecting storm water quality (Doctoral dissertation).

Haan, C. T., Barfield, B. J., and Hayes, J. C. (1994). Design hydrology and sedimentology for small catchments. Elsevier.

Han, J., Wu, J. S., and Allan, C. (2005). Suspended sediment removal by vegetative filter strip treating highway runoff. Journal of Environmental Science and Health, Part A, 40(8), 1637-1649.

Herrera Environmental Consultants (2007). Untreated Highway Runoff in Western Washington, Prepared for Washington State Department of Transportation, Seattle, Washington.

Hunt, W., Hathaway, J., Winston, R., and Jadlocki, S. (2010). Runoff Volume Reduction by a Level Spreader–Vegetated Filter Strip System in Suburban Charlotte, N.C. J. Hydrol. Eng. 15, SPECIAL ISSUE: Low Impact Development, Sustainability Science, and Hydrological Cycle, 499–503.

Illinois Environmental Protection Agency (IEPA) (2013). Storm Water Performance Standards Recommendations, Prepared by: Post-Development Storm Water Runoff Standards (PDSWRS) Workgroup and Association of Illinois Soil and Water Conservation Districts (AISWCD).

Illinois Urban Manual. (2002). Prepared by Illinois Environmental Protection Agency and U.S. Department of Agriculture. A Technical Manual Designed for Urban Ecosystem protection and Enhancement. Springfield, Illinois, USA: Natural Resources Conservation Service.

James, W., Rossman, L.E., and James W.R. (2010). User's Guide to SWMM 5, 13th Edition, CHI Press Publication.

Kale, R. V., and Sahoo, B. (2011). Green-Ampt infiltration models for varied field conditions: a revisit. Water resources management, 25(14), 3505-3536.

Lee, R. (2011). Modeling Infiltration in a Storm Water Control Measure Using Modified Green, MSC thesis, Villanova University.

Liu, Y., Ahiablame, L. M., Bralts, V. F., and Engel, B. A. (2015). Enhancing a rainfall-runoff model to assess the impacts of BMPs and LID practices on storm runoff. Journal of environmental management, 147, 12-23.

McCuen, R. (2005). Hydrologic analysis and design, 3rd edition.

McCutcheon, M., and Wride, D. (2013). Shades of Green: Using SWMM LID Controls to Simulate Green Infrastructure. In 2012 Storm Water and Urban Water Systems Modeling Conference. Pragmatic Modeling of Urban Water Systems, Monograph (Vol. 21, pp. 289-301).

Natura, H. (1995). Illustration of the Root Systems of Prairie Plants, the Conservation Research Institute.

National Cooperative Highway Research Program (NCHRP) (2006). Evaluation of Best Management Practices for Highway Runoff Control (Report 565). Washington, D.C.: Transportation Research Board.

National Cooperative Highway Research Program (NCHRP) (2012). Guidelines for Evaluating and Selecting Modifications to Existing Roadway Drainage Infrastructure to Improve Water Quality in Ultra-Urban Areas (Report 728). Washington, D.C.: Transportation Research Board.

National Cooperative Highway Research Program (NCHRP) (2014). Long-Term Performance and Life-Cycle Costs of Storm Water Best Management Practices (Report 792). Washington, D.C.: Transportation Research Board.

Harwood, D. W., Hutton, J. M., Fees, C., Bauer, K. M., Glen, A., and Ouren, H. (2014). Evaluation of the 13 Controlling Criteria for Geometric Design. NCHRP 783 (No. Project 17-53).

Pellant, M., Shaver, P., Pike, D., and Herrick, J. (2005). Interpreting Indicators of Rangeland Health, United States Department of the Interior, Bureau of Land Management, Technical Reference 1734-6.

Pennsylvania Department of Environmental Protection (DEP) (2006). Pennsylvania Storm Water Best Management Practices Manual. Commonwealth of Pennsylvania.

Poresky, A., Bracken, C., Strecker, E., and Clary, J. (2011). International Storm Water Best Management Practices (BMP) Database, Technical Summary: Volume Reduction, GeoSyntec Consultants & Wright Water Engineers, Inc.

Prince George County, Maryland (PGC) (1999). Low-Impact Development Design Strategies: An Integrated Design Approach. Prince George County, MD.

Roess R. P., Prasses, E.S., and McShane, W.R (2011). Traffic Engineering, 4th edition, Prentice Hall, ISBN-13: 978-0136135739

Selbig, W.R., and Balster, N. (2010). Evaluation of Turf-Grass and Prairie-Vegetated Rain

Gardens in a Clay and Sand Soil, Madison, Wisconsin, Water Years 2004–08, Scientific Investigations Report 2010–5077, U.S. Department of the Interior, U.S. Geological Survey.

Simon, A., Cordova, T., Cooke, J., Aguilera-Harwood, P., and Miera, B. A. (2004). dialogue for sustainability: people, place and water.

Southeast Michigan Council of Governments (SEMCOG) (2008). Low Impact Development Manual for Michigan, A Design Guide for Implementers and Reviewers.

Southeastern Wisconsin Regional Planning Commission (SWRC) (1991) Costs of Urban Nonpoint Source Water Pollution Control Measures. Waukesha, WI.

Strecker, E., Poresky, A., Roseen, R., Soule, J., Gummadi, V., Dwivedi, R., and Littleton, C. O. (2015). Volume Reduction of Highway Runoff in Urban Areas: National Cooperative Highway Research Program (NCHRP) Report 802, Transportation Research Board (TRB).

Sun, Y. W., Li, Q. Y., Liu, L., Xu, C. D., and Liu, Z. P. (2014). Hydrological simulation approaches for BMPs and LID practices in highly urbanized area and development of hydrological performance indicator system. Water Science and Engineering, 7(2), 143-154.

Terzaghi, K., Peck, R. B., and Mesri, G. (1996). Soil Mechanics in Engineering Practice, John Wiley & Sons, Inc., New York.

United States Department of Agriculture (USDA) (2016). Web Soil Survey, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online.

United States Environmental Protection Agency (USEPA) (1999a). Storm Water Technology Fact Sheet Infiltration Trench, EPA 832-F-99-019

United States Environmental Protection Agency (USEPA) (1999b). Preliminary Data Summary of Urban Storm Water Best Management Practices, Office of Water (4303). Washington: EPA-821-R-99-012.

United States Environmental Protection Agency (USEPA) (2000). Low Impact Development (LID): A Literature Review. Washington, DC. http://water.epa.gov/polwaste/green/upload/lid.pdf Accessed Sept. 7, 2014

United States Environmental Protection Agency (USEPA) (2015). NPDES Storm Water Permit Program, http://www.epa.gov/region1/npdes/storm water/. Accessed June 10, 2015

Urban Drainage and Flood Control District (UDFCD) (2008). Urban Strom Drainage-Criteria Manual, V.1.

Vettel, P. (1986). Highway To Lush Lawns Is Paved With Short Cuts, Chicago Tribune.

White, M. J., and Arnold, J. G. (2009). Development of a simplistic vegetative filter strip model for sediment and nutrient retention at the field scale. , Hydrol. Process. 23, 1602–1616.

Wiegand, C., T. Schueler, W. Chittenden, and D. Jellick (1986). Cost of Urban Runoff Controls. Urban Runoff Quality Impact and Quality Enhancement Technology. Proceedings of an Engineering Foundation Conference.

Wisconsin Department of Transportation (WisDOT) (2008). BMP Effectiveness Assessment for Highway Runoff in Western Washington, Prepared for Washington State Department of Transportation, http://www.wsdot.wa.gov/NR/rdonlyres/195AF37F-1AA3-43AE-B776-B4A616CC5C7B/0/BMP_EffectivHwyRunoffWestWA.pdf.

Wu, J. S., and Allen, C. J. (2006). Evaluation and Implementation of BMPs for NCDOT's Highway and Industrial Facilities, NCDOT, Research Project No. 2003-19 , HWA/NC/2006-02.

Xiao, Q., and McPherson, G. E. (2009). Testing a Bioswale to Treat and Reduce Parking Lot Runoff, University of California, Davis and USDA Forest Service.

Zimmerman, M. J., Barbaro, J. R., Sorenson, J. R., and Waldron, M. C. (2010). Effects of selected low-impact-development (LID) techniques on water quality and quantity in the Ipswich River Basin, Massachusetts—field and modeling studies. U.S. Geological Survey Scientific Investigations Report, 2010–5007 p. 113.

APPENDIX

Table A1-1. Subcatchments Parameters of Idealized Catchment Area in PCSWMM

<table>
<tr><th>Parameters</th><th>S1 (Highway)</th><th>S2 (Foreslope)</th><th>S3 (level ground)</th><th>S4 (Backslope)</th><th>Reference</th></tr>
<tr><td>Slope (%)</td><td>1.5</td><td>3H:1V = 33</td><td>0.5</td><td>6H:1V (16.7)</td><td>(James et al. 2010)
(Roess et al. 2011)
(Harwood et al. 2014)</td></tr>
<tr><td>Imperviousness%</td><td>100</td><td colspan="3">0</td><td></td></tr>
<tr><td>NImperv[1]</td><td colspan="4">0.011</td><td>(McCuen 2005)</td></tr>
<tr><td rowspan="3">Nperv[2]</td><td rowspan="3">0.011[3]</td><td colspan="3">Bare Land = 0.012</td><td rowspan="3">(McCuen 2005)
(Haan et al. 1994)</td></tr>
<tr><td colspan="3">Turfgrass = 0.24</td></tr>
<tr><td>-*</td><td colspan="2">Prairie Grass = 0.15</td></tr>
<tr><td>Dstore Imperv[4]</td><td colspan="4">1.3 mm (0.05 in.)</td><td>(UDFCD 2008)
(BEC 2010)
(James et al. 2010)</td></tr>
<tr><td rowspan="3">Dstore Perv[5]</td><td rowspan="3">1.3 mm</td><td colspan="3">Bare land= 2.5 mm (0.10 in.)</td><td rowspan="3">(UDFCD 2008)
(BEC 2010)
(James et al. 2010)</td></tr>
<tr><td colspan="3">Turfgrass = 6.35 mm (0.25 in.)</td></tr>
<tr><td>-*</td><td colspan="2">Prairie Grass = 10.16 mm (0.40 in.)</td></tr>
<tr><td>Soil</td><td>Clay Soil parameters</td><td colspan="3">Soil Parameters Based on the USDA soil type</td><td>(James et al. 2010)</td></tr>
</table>

[1]Manning’s n for overland flow over the impervious portion of the subcatchment
[2]Manning's n for overland flow over the pervious portion of the subcatchment
[3]Because the imperviousness percentage is 100, it does not matter what value is selected
[4]Depth of depression storage on the impervious portion of the subcatchment. This value would be factored by impervious percentage ratio depending on the subcatchment.
[5]Depth of depression storage on the pervious portion of the subcatchment
*Foreslope is supposed to have two conditions in scenarios, having no surface cover (bare soil), or covered with turfgrass (no prairie grass is considered on the foreslope because of maintenance issues and general guidelines and practices)

Table A1-2. Soil Parameters for USDA Soil Type (James et al. 2010)

USDA Soil Type	Conductivity (mm/hr)	Suction Head (mm)	Initial Deficit (fraction)
Sand	120.4	49.02	0.024
Loamy Sand	29.97	60.96	0.047
Sandy Loam	10.92	109.98	0.085
Sandy Clay Loam	3.3	88.9	0.116
Sandy Clay	6.6	169.93	0.135
Loam	1.52	219.96	0.136
Silt Loam	1.02	219.06	0.187
Clay loam	1.02	270	0.21
Silty Clay Loam	0.51	240.03	0.221
Silty Clay	0.51	290.07	0.251
Clay	0.25	320.04	0.265

Table A1-3. BMPs Subcatchment Parameters in PCSWMM

Parameters	Bioswale	Infiltration Trench	Vegetated Filter Strip	Source
Slope (%)	0.5	0.5	0.5	(James et al. 2010) (Roess et al. 2011) (Harwood et al. 2014)
Imperviousness%	0	0	0	
NImperv[1]	0.011			McCuen (28)
Nperv[2]	Turfgrass = 0.24	0.015	Turfgrass = 0.24	(McCuen 2005)
Dstore Imperv[3]	1.3 mm (0.05 in.)			UDFCD (29) (BEC 2010) James et al. (2010)
Dstore Perv[4]	Turfgrass = 6.35 mm (0.25 in.)	Bare land= 2.5 mm (0.10 in.)	Turfgrass = 6.35 mm (0.25 in.)	(UDFCD 2008) (BEC 2010) (James et al. 2010)
Soil	Sand parameters	Sand parameters	Sandy Loam Soil (Engineered Soil)	(UDFCD 2008) (BEC 2010) (James et al. 2010)

[1]-Manning's n for overland flow over the impervious portion of the subcatchment
[2]-Manning's n for overland flow over the pervious portion of the subcatchment
[3]-Depth of depression storage on the impervious portion of the subcatchment
[4]-Depth of depression storage on the pervious portion of the subcatchment

Table A1-4. BMP Design Parameter Values (SEMCOG 2008; James et al. 2010; Harwood et al. 2014; McCuen 2005; DEP 2006, Emanuel and Powers 2014)

Parameters	Bioswale	Infiltration Trench	Vegetated Filter Strip
Surface			
Storage Depth (mm)	305 mm (12 in.)	76.2 mm (3 in)	25 mm (1 in.)
Vegetative Volume (fraction)	0.2	0	0.2
Surface Roughness (Manning's n)	0.15	0	0.15
Surface Slope (%)	1 (Longitudinal)	0	2
Swale Side Slope (run/rise)	3	-	-
Storage			
Height (mm)	-	2133.6 mm (7 ft)	0.1 mm
Void ratio (voids/solids)	-	40%	0.8
Conductivity (mm/hr)	-	0.1 m/s (360,000 mm/hr)	11 mm/hr
Clogging factor	-	0	0
Soil			
Thickness (mm)	-	-	457 mm (18 in.)
Porosity (volume fraction)	-	-	0.453
Field Capacity (volume fraction)	-	-	0.190
Wilting Point (volume fraction)	-	-	0.085
Conductivity (mm/hr)	-	-	11 mm/hr (0.43 in/hr)
Conductivity Slope	-	-	10
Suction Head (mm)	-	-	110 mm (4.33 in.)

Table A1-5. Characteristics of Soil Assigned to Soil Group (McCuen 2005)

Hydrologic soil group	Soil type
A	Deep sand, deep loess, aggregated silts
B	Shallow loess, sandy loam
C	Clay loam, shallow sandy loam, soils low in organic content, soil usually high in clay
D	Soils that swell significantly when wet, heavy plastic clays, certain saline soils

Table A1-6. Run-Off Curve Numbers Table (McCuen 2005)

Cover Description	**Hydrologic Soil Groups**			
Cover Type and Hydrologic Condition	**A**	**B**	**C**	**D**
Open space (Parks, Cemeteries, etc.):				
Poor Condition (grass cover < 50%)	68	79	86	89
Fair Condition (grass cover 50% - 75%)	49	69	79	84
Good Condition (grass cover>75%)	39	61	74	80
Imperious areas (Parking lots, etc.)	98	98	98	98

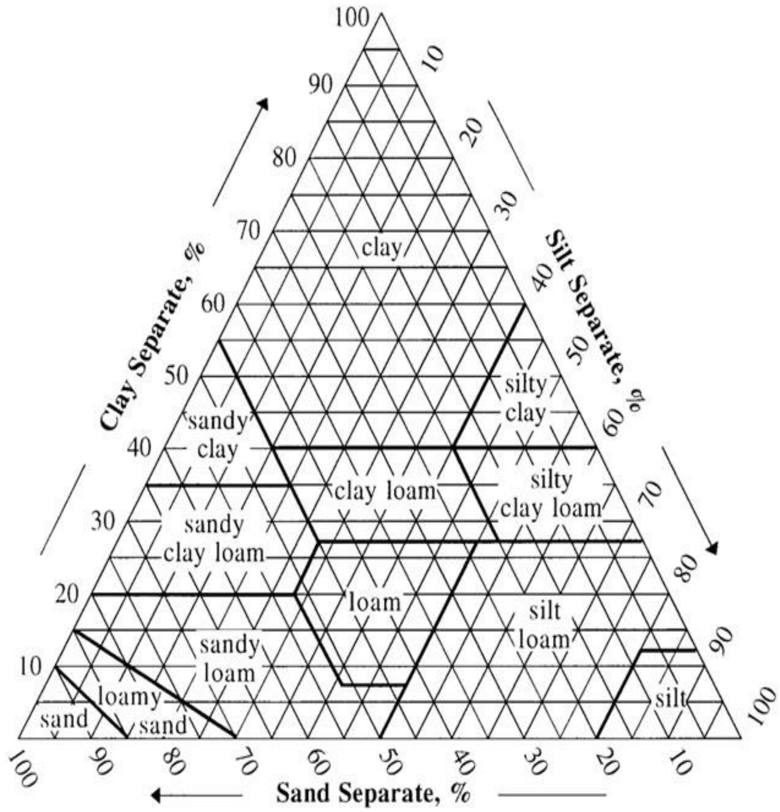


Figure A1-1. Guide for textural classification by the USDA (McCuen 2005).