NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 922

Stormwater Infiltration in the Highway Environment: Guidance Manual

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the Federal Highway Administration. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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FOREWORD

By William C. Rogers
Staff Officer
Transportation Research Board

NCHRP Research Report 922: Stormwater Infiltration in the Highway Environment: Guidance Manual (Guidance Manual) provides information, guidance, and tools for planners, designers, regulators, and policymakers to determine when it is appropriate to use infiltration approaches to manage stormwater in the highway environment. The limitations, risks, and benefits of infiltration best management practices (BMPs) are examined in the context of the built and natural environments (e.g., surface water, groundwater, soils, and infrastructure). The Guidance Manual supports decision-making about the siting, selection, and design of stormwater infiltration BMPs, including effective system design in cases when projects include infiltration.

While stormwater permits and other regulations have increasingly prioritized or mandated the consideration of infiltration BMPs, there is growing concern that requiring infiltration BMPs may inadvertently lead to other consequences to the natural and built environments. For instance, research has shown that the upper layers of soil generally capture heavy metals and hydrocarbons, but there is potential for groundwater contamination from stormwater infiltration in some conditions and for some pollutants. Additionally, research has shown that infiltration BMPs can be susceptible to premature failure or substandard performance because of excessive sedimentation, soil compactions, groundwater mounding, and other issues. The results of this project will help practitioners better understand the capabilities of infiltration BMPs in different environmental settings and identify the potential limitations and overall environmental effects of infiltration BMPs.

In NCHRP Project 25-51, Geosyntec Consultants and its team were asked to develop guidance to address a broad range of issues and needs associated with selecting, siting, and designing infiltration BMPs for mitigating roadway stormwater that may include but not be limited to the following: (1) limitations (e.g., cost, maintenance, regulatory, receiving waters, and geotechnical); (2) effects of climate, soils, topography, geology, vegetation, and land use; (3) effects of pollutants of concern on surface water and groundwater quality; (4) effects on surface water and groundwater quantity (e.g., recharge, baseflow augmentation, and groundwater mounding); (5) identification of gaps in the body of knowledge; and (6) options for improving effectiveness and reducing risk.

The report contains a decision-making framework for the various phases of the project design and delivery process. Several topical appendices provide focused technical guidance on key steps in the framework, including extensive guidance on the appropriate investigations to conduct; three software tools to support users with efficient calculations to address groundwater mounding, groundwater quality, and BMP clogging; and a PowerPoint presentation. These additional products can be found on the TRB website (www.trb.org) by searching for "*NCHRP Research Report 922*".

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* Appendices B through J can be found on the TRB website (www.trb.org) by searching for "*NCHRP Research Report 922*".

CHAPTER 1

Introduction and Orientation

The purpose of this Guidance Manual is to support evaluation, selection, siting, design, and construction of infiltration best management practices (BMPs) in the highway environment. It is also intended to identify limitations on the use of infiltration and determine the need for alternative non-infiltration-based stormwater management approaches. This Guidance Manual is intended to complement and inform local guidance and serve as a resource for planners, designers, regulators, and policymakers. The goal of this Guidance Manual is to support responsible decisions about stormwater infiltration in the highway environment. The Guidance Manual contains effective system designs for projects that include infiltration.

In preparing this Guidance Manual, the research team considered a broad range of issues that can limit infiltration. The research team identified approaches for assessing and overcoming these limits for each phase of the project delivery process. These research findings supported the development of practical guidance. The Guidance Manual includes approaches (e.g., frameworks and underlying principles) to overcome conceptual limitations and also provides detailed guidance (e.g., topical guides, tools, design adaptations, construction, and checklists) that focuses on more specific limitations.

This Guidance Manual is accompanied by a Project Summary Report. These documents are intended to serve complementary roles. The Guidance Manual provides technical guidance to targeted users, including transportation planners, designers, regulators, and policymakers. The Project Summary Report provides documentation of the research efforts and methods used to support development of this Guidance Manual and the associated software tools. The Project Summary Report can be found on the TRB website (www.trb.org) by searching for "*NCHRP Research Report 922*".

1.1 Key Features and Uses of this Guidance Manual

This Guidance Manual includes five chapters, organized into a stepwise decision-making framework. The main body of this Guidance Manual serves as an efficient resource and provides an orientation to key issues. Appendices and Microsoft Excel-based user tools provide focused technical references on selected issues. Appendix A is published herein and Appendices B through J can be found on the TRB website (www.trb.org) by searching for "*NCHRP Research Report 922*". Table 1 highlights the key features of this Guidance Manual.

The following paragraphs summarize the organization of the Guidance Manual and the intended uses of each section.

Chapter 1 provides an overview of infiltration approaches to stormwater management and provides a summary of the key factors influencing infiltration feasibility and desirability. This chapter serves as a reference of the primary decisions and factors associated with infiltration

Table 1. Key features of this Guidance Manual.

Feature	Description	Location
Stepwise Decision-Making Framework	A framework and guidance for conducting investigations, organizing data, and scoping analyses to support BMP selection, siting, design, and construction. Includes flow charts, worksheets, example criteria, and distilled guidance to support each step	Overview in Section 1.7 Details in Chapters 2, 3, and 4 Examples in Chapter 5
BMP Fact Sheets	Fact sheets summarizing characteristics, key considerations, design schematics, and example design criteria for 10 infiltration BMPs	Appendix A
Detailed Technical Guides	Technical guides providing detailed information on key topics including the following:	
	• Infiltration estimation methods (including 10 fact sheets on testing methods)	Appendix B
	• Groundwater mounding	Appendix C
	• Water balance and groundwater quality	Appendix D
	• Geotechnical issues	Appendix E
	• Cold and arid climate issues	Appendix I
Microsoft Excel-Based User Tools	Three new software tools intended to streamline key analyses that project teams may need to conduct include the following:	These can be found on the TRB website (www.trb.org) by searching for "*NCHRP Research Report 922*".
	• Roadside BMP Groundwater Mounding Assessment Guide and User Tool	Appendix C
	• Guide for Assessing Potential Impacts of Highway Stormwater Infiltration on Water Balance and Groundwater Quality in Roadway Environments	Appendix D
	• BMP Clogging Risk Assessment Tool	Appendix F
Case Studies	Case study applications of this Guidance Manual to three real projects	Chapter 5
	Case studies of whole lifecycle cost and performance analysis tools	Appendix G
	Case studies of infiltration BMPs constructed by DOTs, weighted toward BMP failures that can serve as a learning opportunity	Appendix J

approaches. This chapter also introduces the decision-making framework that provides structure for the remaining chapters. The steps in this framework are as follows:

Step 1: Perform Project Scoping and Preliminary Planning for Stormwater Infiltration
Step 2: Tentatively Select BMP Locations and Types
Step 3: Conduct Prioritized Site Investigations and Analyses to Confirm BMP Selection and Sizing
Step 4: Design, Construct, and Maintain BMPs

Section 1.7 explains these steps.

Chapter 2 provides guidance for Steps 1 and 2 of the decision-making framework. The guidance in this chapter helps a user select a general strategy for stormwater infiltration and identify tentative BMP types and locations. This chapter introduces screening-level methods for reaching preliminary determinations and helps determine the need for conclusive methods to confirm feasibility. Chapter 2 is supported by several appendices, designed to address specific topics that may be relevant for selection of an infiltration strategy:

Appendix A: Infiltration BMP Fact Sheets
Appendix B: Infiltration Estimation Method Selection and Interpretation Guide
Appendix C: Roadside BMP Groundwater Mounding Assessment Guide and User Tool (Excel-based tool)
Appendix D: Guide for Assessing Potential Impacts of Highway Stormwater Infiltration on Water Balance and Groundwater Quality in Roadway Environments
Appendix E: Guide to Geotechnical Considerations Associated with Stormwater Infiltration Features in Urban Highway Design

Chapter 3 supports Step 3 of the framework. This chapter provides guidance for scoping and performing site investigations and preliminary design analyses intended to result in confirmation of the selected BMP types, locations, and overall infiltration strategy. Appendices A through E also support Step 3 (each appendix describes both preliminary and confirmatory assessment methods).

Chapter 4 provides guidance on BMP design, construction, operations and maintenance (O&M), and post-construction monitoring in support of Step 4 (Design, Construct, and Maintain BMPs). This section supports projects that include an infiltration-based approach. This chapter is also supported by appendices that address specific topics:

Appendix F: BMP Clogging Risk Assessment Tool
Appendix G: Whole Lifecycle Cost and Performance Example
Appendix H: Example Construction-Phase Checklists for Inspector and Contractor Training
Appendix I: Summary of Infiltration Issues Related to Cold and Arid Climates

Note that Appendices A through E also include guidance supporting Step 4 (BMP-specific design decisions).

Chapter 5 provides brief summaries of how the steps in this Guidance Manual could apply to example projects. Appendix J provides BMP case study reports (with an emphasis on infiltration failures and lessons learned) that may be of interest to users.

The decision-making framework and criteria presented in this Guidance Manual can be adapted to an agency's project delivery processes and accommodate project-specific issues.

1.2 Introduction to Infiltration Approaches for Stormwater Management in the Highway Environment

The infiltration approach to stormwater management involves the design, construction, and O&M of engineered systems that infiltrate stormwater runoff into soils. These systems, referred to as "infiltration BMPs," are intended to reduce the volume of stormwater runoff and associated pollutants that discharge to stormwater systems and receiving waters via surface runoff.

The concept of stormwater infiltration in the built environment is inherently different from the natural rainwater/snowmelt infiltration that occurs on pervious lands. In the built environment, stormwater runoff from impervious surfaces is routed to a pervious BMP area (often designed to pool water), resulting in greater levels of hydraulic and pollutant loading in this area than would occur via precipitation alone. As a result, a greater portion of stormwater percolates to deeper groundwater and discharges to surface runoff than would occur in natural reference conditions in which evapotranspiration (ET) tends to have greater influence on the water balance (Strecker et al. 2015).

As a result, a range of conditions can develop in engineered stormwater infiltration systems that are less frequently observed on natural pervious lands, including ponded water, soil saturation, localized groundwater mounding, pollutant accumulation, and surficial clogging. Where site conditions do not support the intended level of infiltration or pose risks to infrastructure or the surface or sub-surface environment, an infiltration approach may be infeasible or not desirable. Identifying where limits exist for a given site is a key step in responsible application of stormwater infiltration.

In addition to physical limits, there are regulatory limits associated with infiltration of stormwater runoff from the built environment. State regulators may classify stormwater as discharge to a receiving water (e.g., groundwater), and local groundwater management entities may establish groundwater protection criteria that apply to stormwater infiltration. Project teams need to consider these issues as part of selection, siting, design, operation, and monitoring of stormwater infiltration BMPs.

However, the same underlying processes that pose risks in some cases can also provide benefits. For example, in suitable conditions, the use of infiltration can help project teams efficiently comply with surface water requirements while lessening the need for downstream conveyance infrastructure. In some cases, infiltrated stormwater can also be a desirable resource for groundwater augmentation.

There is not a single "infiltration approach" that has categorical benefits or limitations. Rather, this Guidance Manual considers a range of infiltration-based stormwater management approaches. These approaches target different levels of infiltration, have different levels of sensitivity to site conditions, pose different risks, and have different limitations. One of the goals of this Guidance Manual is to assist users in (a) evaluating a range of potential infiltration approaches, (b) selecting and implementing one that is appropriate for the objectives and constraints that apply to a given site, and (c) identifying the need for alternative non-infiltration approaches to be considered.

1.3 Rationales for Considering Stormwater Infiltration

There are numerous reasons for DOTs and project designers to consider some form of stormwater infiltration as part of a stormwater management approach. Examples include the following:

- Infiltration of stormwater may need to be considered or implemented to comply with applicable regulations, such as National Pollutant Discharge Elimination System (NPDES) permits or Total Maximum Daily Loads (TMDLs).
- Pollutant removal performance of BMPs can be improved when volume reduction is increased.
- Infiltration can be more cost-effective than other stormwater management approaches under favorable conditions and can sometimes help reduce the cost of overall stormwater management design (e.g., via fewer storm inlets and less piping). In many cases, some level of infiltration occurs incidentally at no additional cost.
- Multiple benefits can be realized such as groundwater augmentation and reduction of hydraulic load to streams; water that infiltrates and later enters receiving waters as interflow or baseflow tends to be cleaner and mimics natural flow regimes compared with direct surface runoff.

Given these potential motivations and advantages, an approach involving some level of infiltration warrants consideration for stormwater management applications in the highway environment.

1.4 Key Limitations to Infiltration as a Stormwater Management Approach

Stormwater infiltration approaches have potential limitations. There are five general categories of limits to infiltration.

1. Physical Feasibility. Can you do it (feasibility)? Key limits related to physical feasibility include the following:

- Soil infiltration rate at the intended infiltration surface (i.e., the interface between more permeable media and the underlying native soil) including the effects of compaction (intentional or unintentional) on infiltration.
- Capacity of the soil/groundwater receptor to receive infiltrated volume including limiting layers, potential for groundwater mounding, and associated degradation of infiltration rate.
- Amount of space available for an infiltration surface within the highway environment.

2. Impacts to Infrastructure or the Environment. Should you do it (desirability)? Infiltration of stormwater poses potential risks, including the following:

- Geotechnical hazards related to structures, foundations, and slopes.
- Roadway damage, such as impacts to the integrity of base, subbase materials, and pavements.
- Deterioration of groundwater quality from stormwater-borne pollutants and mobilization of pollutants in soil or groundwater.
- Unnatural water balance effects involving artificially elevated groundwater tables can result in a change of stream systems from ephemeral or intermittent to perennial (with possible habitat changes) in arid areas.

3. O&M Limits. Can performance be sustained? Infiltration BMPs can be susceptible to O&M issues including the following:

- Clogging of systems as a result of sediment loading
- Challenges in accessing surfaces that have become clogged
- Uncertainty in what remedial efforts will be effective to restore function if clogging or other issues occur
- Maintaining acceptable levels of vegetation
- Other challenges to safely and consistently perform maintenance at an acceptable cost

4. Practical Limits. This category of limits pertains to practical factors associated with planning, designing, implementing, and operating infiltration BMPs, including the following:

- Cost and time requirements. Assessing the feasibility and desirability of infiltration approaches can require substantial cost and time. This is particularly true if there are complex factors at a site, or if the design must ensure that a certain reliable amount of infiltration will occur. In practice, a single missed factor from one of the three categories (numbers 1 through 3 in this list) can lead to failure or unintended consequences requiring an alternative approach to be implemented. While some level of geotechnical investigation is needed for most BMP types, there are often extra costs associated with investigation for infiltration BMPs, including the need for reliable infiltration tests, greater number of tests, and longer periods of monitoring to determine seasonal hydrogeologic conditions.
- Unknowns in design and construction. Even with a thorough investigation and assessment as part of the design, uncertainties remain in predicting as-built infiltration rates of full-scale facilities. This is due to limitations in infiltration measurement techniques as well as the potential for changes in infiltration properties during construction and post-construction activities. Developing designs and construction plans to accommodate these inherent unknowns, while still ensuring the survivability of the system, can be more challenging.

- Project delivery and contracting methods. Successful implementation of infiltration approaches can require careful control through the design, construction, and post-construction phases of the project. This may require adjustment of typical project delivery approaches, for example, specifying "means and methods" of construction, allowing for design contingencies/modification based on construction-phase tests, and providing for a longer warranty/bonding period for system establishment.
- Unknowns in maintenance needs. Limited data are available regarding the maintenance needs of infiltration BMPs, particularly how maintenance needs are affected by site-specific factors. This can have major implications on lifecycle costs and budgeting.
- Regulatory uncertainty for groundwater receptors. It can be unclear what limits apply to infiltration discharges to groundwater, and how these limits may change in the future. Additionally, due to limits in available scientific understanding and contaminants of emerging concern, there are cases for which it may not be possible to quantify potential long-term effects of infiltration on groundwater quality.

The framework for infiltration evaluation and implementation presented in this Guidance Manual is designed to address and overcome these practical limitations, where possible.

5. Program Management Limits. This class of limits pertains to program management issues that can be associated with the broadening use of infiltration in the highway environment. During interviews and communication with DOT program managers, several issues were identified, including the following:

- Long-term liability. Broader use of infiltration BMPs can increase DOT liability related to inventorying features, reporting compliance, funding long-term O&M, developing memoranda of understanding (MOUs) with local government, and associated staffing needs. These issues apply to any stormwater control approach. However, uncertainties in the lifecycle cost and management needs of some infiltration BMPs can make it more challenging to quantify long-term liability compared with conventional stormwater management approaches that have more defined costs and operating requirements.
- Legal liability. Even with a careful screening and design process, infiltration BMPs have the potential to pose legal liability related to groundwater contamination, geotechnical failures, water rights, and other issues. While DOTs can limit these risks with effective technical guidance and project review processes, the elimination of legal liability arising from stormwater infiltration is not realistically possible in all cases.
- Compliance monitoring. Depending on types of BMPs used and applicable regulations, a compliance monitoring program may be needed to evaluate performance and impacts.
- Compatibility with land use plans. The infiltration approach may be incompatible with local land use plans, such as source water protection zones and wellhead protection zones.

DOT program managers should consider these factors when establishing agency policies and technical guidance. These issues differ with different classes of infiltration approaches (as described in Section 1.5). Additionally, the framework is designed to guide appropriate BMP selection, design, construction, and maintenance to reduce these organizational risks.

1.5 Classes of Infiltration Approaches

The decision-making and implementation framework is organized around three overall classes of infiltration approaches:

1. Full Infiltration. This class involves infiltration BMPs that rely solely on infiltration into underlying soils. Full Infiltration does not imply that all stormwater runoff is infiltrated. The amount of water infiltrated is a function of BMP size and site conditions. However, these BMPs do not have a design discharge to surface waters except when the system overflows or bypasses. The key distinguishing trait of these BMPs is that they depend on a certain minimum infiltration rate to meet their intended functions and avoid unintended consequences (e.g., nuisance conditions, vegetation mortality, vector issues, safety concerns, excessive bypass, or overflow levels). Examples include the following:

- Infiltration basins
- Infiltration trenches
- Bioretention without underdrains
- Permeable pavement and shoulders
- Infiltration galleries

Within this category, systems can be designed with or without features that could allow them to be adapted to a Partial Infiltration design (e.g., capped underdrains).

2. Maximized Partial Infiltration. This approach involves BMPs designed specifically to maximize infiltration of a portion of the applicable design volume while also providing other treatment mechanisms. These BMP types are not wholly reliant on infiltration to maintain an operable condition and meet water quality and flow control requirements but are expected to result in significant levels of infiltration. Examples include the following:

- Vegetated filter strips with amended soils
- Vegetated swales with shallow subsurface retention storage
- Media filter drains
- Bioretention with underdrains and internal retention storage
- Permeable pavement and shoulders with supplemental drains

These approaches share common design attributes: (1) subsurface storage compartments dedicated to infiltration only and (2) freely draining surface storage compartments that do not rely on infiltration to be operable. These systems can be designed to meet a specific volume reduction goal if the underlying soil infiltration rates are well understood.

3. Incidental Infiltration. This approach involves the use of BMPs designed principally for treatment and flow control of stormwater but with design considerations that allow for incidental infiltration of stormwater. Examples are similar to the Maximized Partial Infiltration category, but without design features specifically intended to maximize infiltration. These approaches are generally not designed for a given level of volume reduction.

These classes vary principally in (1) the degree to which they rely on a certain minimum infiltration rate to remain operable, (2) the degree of infiltration provided, and (3) their design approach relative to the specificity of infiltration goals. These distinctions have a significant effect on the planning, evaluation, and design processes described in this Guidance Manual.

1.6 Menu of Infiltration BMPs

This Guidance Manual presents a decision-making framework based first on the class of infiltration approach and then on the characteristics of the individual BMP type. Knowledge of the attributes and applicability of individual BMPs can support reasonable planning-level decisions about BMP feasibility and tentative selection of BMPs. Table 2 summarizes the menu of infiltration BMPs supported by this Guidance Manual (common alternative terminology is given in parentheses). Fact sheets for each are provided in Appendix A.

Table 2. Introduction to primary menu of infiltration BMPs.

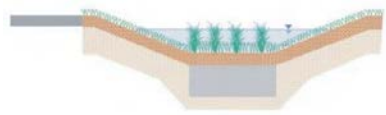
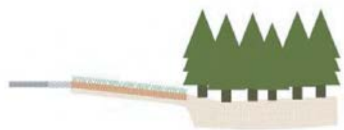
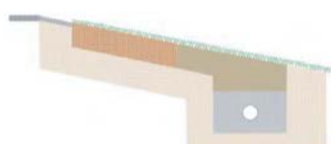
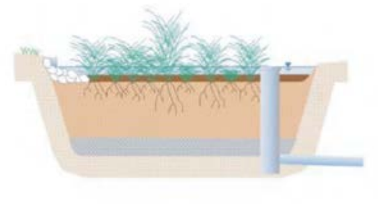
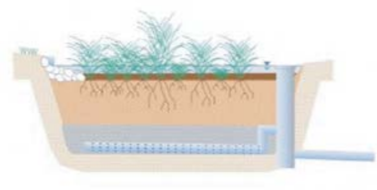
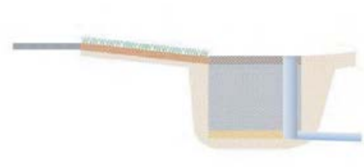
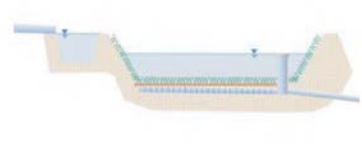
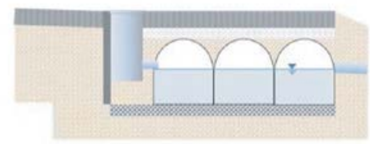
BMP 01 Vegetated Conveyance This BMP type includes engineered vegetated swales and other vegetated drainage features that serve the purpose of conveying stormwater runoff and can also provide treatment and significant reduction of stormwater runoff volume. Variations on this approach can include an amended soil or stone storage layer to increase storage capacity and promote infiltration. This BMP type is usually designed as an Incidental Infiltration BMP. Robust vegetative growth is important to maintain infiltration rates, slow water, and stabilize the surface to prevent scour.	
BMP 02 Dispersion This BMP type consists of the dispersion of runoff toward existing or restored pervious areas including road shoulders amended with compost and additional materials such as sand (if needed), designed to convey runoff as sheet flow over the surface or as shallow subsurface flow through amended soil layers. Dispersion reduces overall runoff volume by promoting infiltration and ET. Volume reduction performance can be improved with flow spreaders, shallow slopes, and soil amendments. This BMP type could qualify as Full Infiltration, Maximized Partial Infiltration, or Incidental Infiltration, depending on design and site conditions. Robust vegetative growth in dispersion areas is important to stabilize the surface and maintain good infiltration rates.	
BMP 03 Media Filter Drain This BMP consists of a stone vegetation-free zone, a grass strip, a storage reservoir filled with specialized media, and a conveyance system for flows leaving the reservoir. The conveyance system usually consists of a gravel-filled underdrain trench or a layer of crushed surfacing base course. The stone vegetation-free zone is intended to promote sheet to spread the water before it flows across the grass strip. It is then captured by the storage reservoir, where it infiltrates into the subsoil or is discharged through the underdrain. This BMP type is typically designed as a Maximized Partial Infiltration BMP. This BMP is typically installed between the road surface and a ditch or other conveyance located downslope. This BMP is based specifically on designs developed and applied by Washington State DOT.	
BMP 04 Permeable Shoulders This BMP type includes a permeable pavement surface course (asphalt, concrete, or interlocking pavers) along the shoulders of a roadway, underlain by a stone reservoir. Precipitation falling on the permeable pavement as well as stormwater flowing onto permeable pavement from adjacent travel lanes infiltrates through the permeable pavement top course into the stone reservoir where it infiltrates into the subsoil or is discharged through an underdrain and outlet control structure. With an underdrain and flow control outlet to augment infiltration capacity, permeable shoulders can be applied in a wide range of soil conditions and could also be used when soil conditions are less favorable for other infiltration BMPs. They could qualify as Full Infiltration or Maximized Partial Infiltration BMPs.	

Table 2. (Continued).

BMP 05 Bioretention without Underdrains Bioretention consists of a shallow surface ponding area underlain by porous soil media storage reservoirs and an optional porous stone storage layer. Captured runoff is directed to the bioretention area where it infiltrates into an engineered soil medium and then infiltrates into the subsoil. They would typically qualify as Full Infiltration BMPs. Engineered soil media is a central element of bioretention design and typically includes a mixture of sand, soils, and organic components (e.g., compost) that are designed to provide permeability, promote plant growth, and provide treatment. When infiltration is exceeded, water is conveyed to a surface discharge via an overflow riser or via an overland flow pathway.	
BMP 06 Bioretention with Underdrains This BMP type is similar to BMP 05 but includes an underdrain system to supplement infiltration discharge. Where soil infiltration rates permit, volume reduction can be enhanced by installing a stone reservoir beneath the underdrain discharge elevation. An upturned elbow or outlet structure can be used to create a retention storage zone (e.g., internal water storage zone). This category of BMPs is suitable for a wider range of conditions than bioretention without an underdrain and can potentially be used to mimic natural baseflows via careful control of discharges from the underdrain. These could qualify as Maximized Partial Infiltration or Incidental Infiltration BMPs.	
BMP 07 Infiltration Trench This BMP type consists of a stone-filled trench that provides subsurface storage of stormwater runoff and allows water to infiltrate through the bottom and walls of the trench into subsoils. These could qualify as Full Infiltration or Maximized Partial Infiltration BMPs. Pretreatment for infiltration trenches is commonly provided via vegetated conveyance such as swales or filter strips. Infiltration trenches tend to be well suited to the linear highway environment, because they are generally constructed in a linear configuration and their surface tends to be nearly flush to existing grade or slightly removed when pretreatment is included.	
BMP 08 Infiltration Basin Infiltration basins are relatively large, shallow basins that discharge water primarily via infiltration. Their contours appear similar to detention basins, but they do not have a surface discharge point below their overflow elevation. Infiltration basins are typically located in relatively permeable soils. They would qualify as Full Infiltration BMPs. Infiltration basins can be designed with detention surcharge above the infiltration volume to provide a combination of volume reduction and peak flow mitigation. Infiltration basins are differentiated from bioretention basins, because they are typically built on a larger scale and typically do not include an engineered soil medium. Vegetative cover may also be different.	

(continued on next page)

Table 2. (Continued).

BMP 09 Infiltration Gallery Infiltration Galleries (aka underground infiltration systems) include a broad class of BMPs that consist of storage reservoirs located belowground preceded by pretreatment systems. Water is pretreated, routed into the systems, and infiltrated into the subsoil. They would typically qualify as Full Infiltration BMPs. A range of potential options are available for providing storage including use of open graded stone or a variety of engineered storage chambers (concrete, plastic, or metal). There are also a range of potential locations where infiltration galleries can be placed, such as below (a) parking areas, (b) access roads, or (c) travel lanes.	

Note that this Guidance Manual does not explicitly consider drywells. The use of drywells in the highway environment is rare. Many considerations related to infiltration trenches and infiltration galleries apply to drywells. Additionally, drywells are required to be registered as part of a federal Underground Injection Control program. Specific state and local standards may also apply.

1.7 Overall Infiltration Assessment and Decision-Making Framework

This Guidance Manual proposes a structured framework for conducting infiltration assessments, evaluating infiltration limits, and making decisions about infiltration approaches for a given site. This framework is intended to support efficient investigation and selection of appropriate infiltration approaches. It is designed to improve efficiency by focusing on the questions that are crucial for a given project and the site conditions. The overall objective of this framework is to match appropriate infiltration approaches to site conditions and infiltration objectives to efficiently comply with applicable regulations. Figure 1 provides an overview of this process. The steps shown in Figure 1 are further described in the following sections.

Step 1: Perform Project Scoping and Preliminary Planning for Stormwater Infiltration

One key to successful implementation of stormwater infiltration is early consideration of stormwater management in project planning. Ideally, this will occur as part of advanced planning and environmental permitting. In this step, the project team assembles readily available information and applies efficient planning-level screening methods to reach initial decisions about the potential types of infiltration BMPs or non-infiltration alternatives that would align with infiltration objectives and site conditions. While the data to support these decisions are not typically conclusive, these preliminary decisions can guide and improve the efficiency of subsequent efforts.

Information compiled and used by the project team in this step includes the following:

- Regulatory requirements (e.g., infiltration requirements, applicable alternatives or "offramps," underlying regulatory goals, and groundwater quality standards)
- Other volume reduction goals (e.g., groundwater augmentation, stream protection, and cost avoidance)
- Project constraints and opportunities (e.g., project type, cuts and fills, and available space)

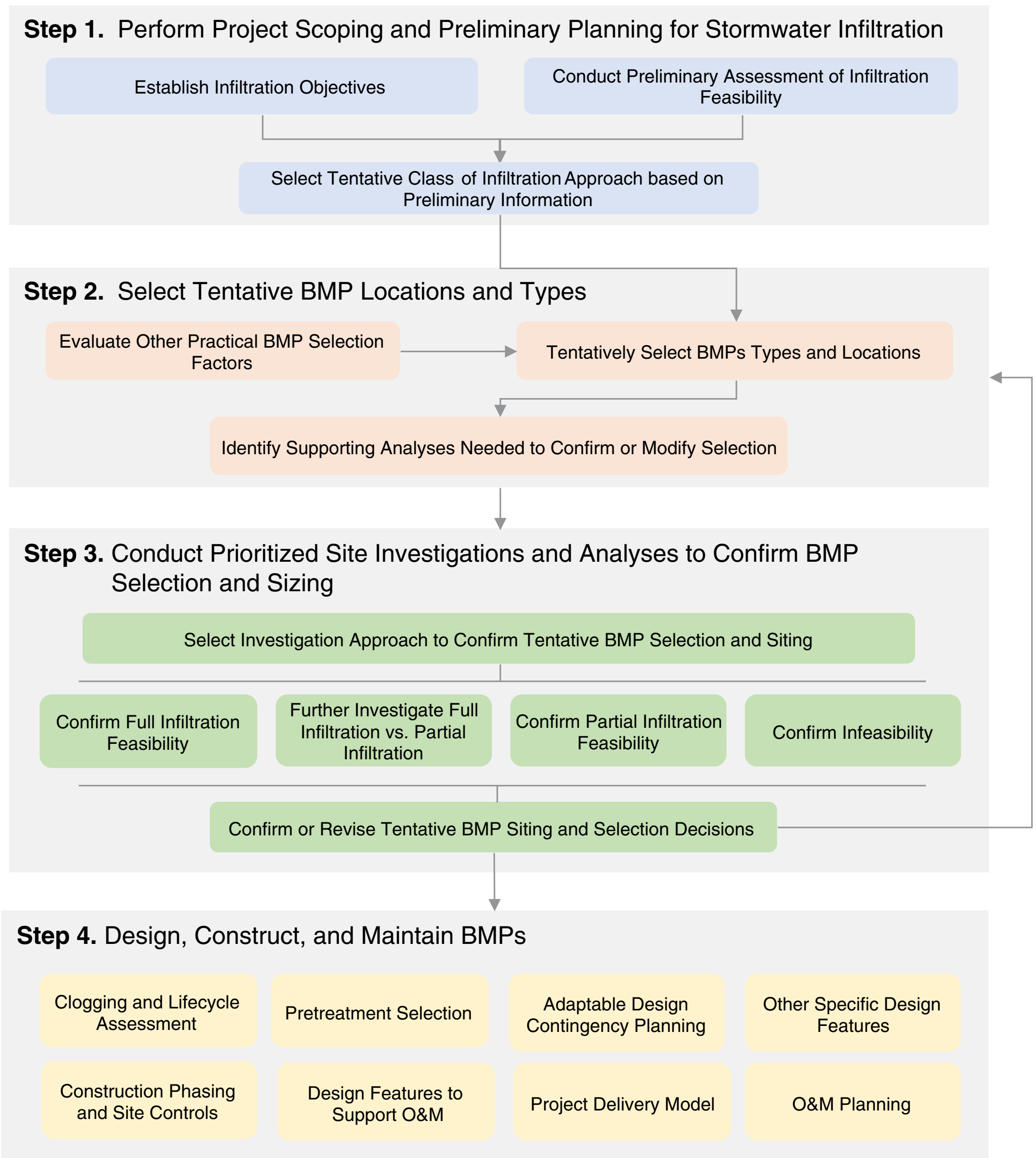


Figure 1. Overview of infiltration decision-making framework.

- Site conditions (e.g., readily available or efficiently obtained information about soil types, sensitive infiltration receptors, groundwater levels, slopes, and contamination)
- Local groundwater management criteria and guidance [e.g., wellhead protection programs, source water protection programs, and sole source aquifer (SSA) designation]
- Budget and schedule constraints and available sources of funding
- Capacity and preferences of O&M staff related to BMP types and maintenance needs

The outcomes of this step may include the following:

- Refinement of stormwater management goals pertaining to infiltration (or identification of alternative non-infiltration approaches that meet project goals)
- Identification of potential project areas to reserve for infiltration
- Identification of potential limits that may apply
- Preliminary selection of a class of infiltration approach (e.g., Full Infiltration, Maximized Partial Infiltration, or Incidental Infiltration)

- Identification of the primary risks and failure modes that could control decision-making for the site, and prioritization of issues for further consideration (e.g., the key factors that need to be resolved)
- Scoping and prioritization of the site investigations and analytical efforts necessary to confirm or refine the selected approach (e.g., soil infiltration testing at potential BMP locations, and groundwater and geotechnical analyses)
- Adaptation of the project delivery process (e.g., project-specific delivery approaches to mitigate risks)
- Determination of BMP types and locations that can be reasonably maintained

This step is intended to be relatively quick. It is not intended to be conclusive. This step is intended to promote efficiency in future steps and ensure that the decisions made will allow for infiltration options, where applicable and desired or required. This step helps focus the scope of future studies on the limits that may apply.

Step 2: Select Tentative BMP Locations and Types

In this step, the project team tentatively identifies BMP locations and tentatively selects the types of BMPs that will be evaluated for each location. These selections should be based on the findings from Step 1. While available data may not yet be conclusive to determine the feasibility of these BMPs, this step helps the project team narrow the scope of subsequent infiltration feasibility investigations. By narrowing the scope of these investigations and prioritizing investigation needs, this step helps the project team develop more reliable information about each location. Key questions in this step include the following:

- For the locations where infiltration could be implemented, which BMPs are applicable?
- Which BMPs will have the greatest potential to meet infiltration goals and limit risk to acceptable levels? Considerations include the following:
  - Overlay of infiltration feasibility category and infiltration objectives
  - Location, geometry, and size of available space
  - Adaptability needs
  - Whole lifecycle costs
  - O&M requirements and compatibility with DOT O&M capabilities

The intended outcomes of this step include the locations, types, and potential footprints of the BMPs, approximate tributary areas, and the overall conceptual design of each BMP (macro-level parameters, such as approximate depth, size, and discharge pathways). These parameters will support the confirmatory-level investigations in Step 3.

Step 3: Conduct Prioritized Site Investigations and Analyses to Confirm BMP Selection and Sizing

In this step, the project team conducts investigations and analyses intended to confirm or revise the feasibility of the selected BMPs. This step may vary considerably depending on the results of the project scoping and preliminary planning efforts (Step 1) and the types of BMPs tentatively selected (Step 2). **The key difference from Step 1 is that investigations and analyses in this step are intended to be confirmatory**. Project teams may need more rigorous investigation and analysis methods, particularly if Full Infiltration BMPs are under consideration. Note that depending on BMP selected, some elements may not be needed. For example, the project team may not need to determine design infiltration rates if BMPs will be designed for Partial Infiltration and will not depend on a certain minimum infiltration rate.

Key questions in this step include the following:

- Is it physically feasible to infiltrate stormwater at the target levels within the identified potential infiltration areas? Considerations include the following:
  - Design infiltration rates
  - BMP sizing calculations
  - Effect of groundwater mounding on reliable infiltration rates
  - Topography and space
  - Reasonable approaches to improve physical conditions for infiltration
- Is it desirable to infiltrate stormwater at the target rates? Are there sensitive receptors or conditions that would be affected? Considerations include the following:
  - Geotechnical/pavement/utilities
  - Groundwater or soil contamination
  - Adherence to local groundwater protection criteria
  - Local water balance issues (particularly in arid climates)
  - Reasonable approaches to mitigate issues
- Do these data confirm the selected infiltration strategy and associated BMPs? Or do the preliminarily selected BMP types and locations need to be revised based on the prioritized site investigation results?

This step should result in confirmation of the selected BMP locations and types or identification of the need for revisions to this strategy.

Step 4: Design, Construct, and Maintain BMPs

In this step, the project team develops detailed designs and construction plans, along with maintenance and monitoring protocols, for the selected BMPs. Design, delivery, and maintenance processes will inherently vary by project type but should generally consider the following:

- Development of design details to mitigate risks. The designer should consider and assess potential design variations based on site features, site conditions, project goals, and risk factors. The following are examples:
  - Pretreatment or isolation approaches
  - Design elements to improve resiliency (back-up plans and adaptability)
  - Supplemental treatment/drainage features built into the design (e.g., relief valves)
  - Design features needed to allow for maintenance of the BMP

  Project designers should consult with construction and O&M personnel during the development of the design to help ensure that the proposed system can be constructed and maintained.
- BMP construction. What construction-phase specifications and precautions should be used to minimize risks to infiltration and other functions of BMPs during construction and establishment phases? The following are examples:
  - What approaches can be used in designing, bidding, and contracting to reduce the risk of construction errors or construction-phase impacts to infiltration sites and infiltration BMPs?
  - What will be done to remediate infiltration rates if there are unavoidable or unforeseen construction impacts?
  - What contingency plans are needed for design adjustment based on conditions encountered during construction?
- BMP maintenance. How will the BMP be maintained and what specific provisions are needed to ensure that maintenance occurs? The following are examples:
  - How will the BMP be assessed to determine the need for maintenance? Do the design and site access support these assessments?

  - How will the BMP be maintained? Does the design allow for maintenance to occur?
  - What are the estimated timing and cost of key activities?
  - Is a BMP-specific O&M plan required, or will the BMP be covered under a standard maintenance procedure?
- Post-construction monitoring. Monitoring can help DOTs improve guidance, assess maintenance needs, evaluate performance, and assess impacts associated with infiltration BMPs.

Chapter 4 of the Guidance Manual is intended to help ensure that appropriate factors are considered in design, construction, and maintenance of BMPs. However, design, contracting and maintenance processes will vary considerably by agency. Therefore, this step is less structured than the previous steps.

Summary of Decision-Making Framework

This four-step process can serve as an overall road map to improve efficiency and reduce risks associated with evaluating and developing stormwater infiltration BMPs. This process is defined by (1) conducting early decision-making to focus the scope of subsequent investigations, (2) selecting BMPs based on their ability to meet project goals and their compatibility with site-specific conditions, (3) reserving more rigorous investigation methods for locations where they are needed, and (4) designing BMPs to reduce sensitivity to uncertain conditions (e.g., improving resiliency) and allow for maintenance to be performed. The remainder of this Guidance Manual is organized around this framework.

CHAPTER 2

Planning Framework for Early Decision-Making and Tentative BMP Selection

This chapter provides guidance to support decisions about infiltration approaches. The chapter supports the first two steps of the overall infiltration and assessment and decision-making framework: (1) goal-setting and preliminary planning investigations to support preliminary selection of an infiltration approach, and (2) tentative selection of BMP types (see BMP Fact Sheets in Appendix A) and locations.

While this chapter introduces a wide range of concepts that should be considered, this process is intended to be efficient and can be conducted primarily using “desktop” methods in most cases. The principal components of this process and associated evaluation tools are summarized in Table 3.

The decision-making tools in this chapter provide a means for organizing information to document initial decision-making. Figure 2 shows the relationship of these components to the infiltration assessment and decision-making process flowchart.

The framework described in this chapter emphasizes early project scoping and preliminary planning efforts including planning-level site assessments as the first steps in evaluating and developing an infiltration-based approach. The remaining steps build on these preliminary planning decisions. Conducting preliminary desktop investigations as part of the preliminary planning phase may deviate from typical project delivery. However, the advantages to undertaking these steps earlier include the following:

- Early identification can preserve potential high-quality infiltration areas when it is still possible to do so.
- Early identification of overriding constraints can eliminate the need for extraneous and costly site investigations.
- Preliminary screening can focus the scope of more rigorous design-phase assessments to only those areas where infiltration BMPs are likely to be placed, mitigating the necessity of performing detailed investigations over a larger scale.
- Early selection of tentative BMP types can focus the scope of design-phase assessments to answer questions that are specific to determining the feasibility of the selected BMP.

A phased site assessment framework may not be appropriate for all projects. The project team should consider project size, budget, timeline, soil variability, and existing information as part of scoping site assessments. In certain cases, a one-time mobilization may be appropriate to collect information that supports both preliminary screening and design-phase data needs. Project teams should adapt the recommendations in this chapter based on project-specific factors and local criteria.

Table 3. Description of preliminary infiltration site assessment and decision-making components and tools.

Component	Description	Evaluation Tools
Step 1a: Establish Infiltration Objectives (Section 2.1)	Users determine volume reduction objectives based on review of applicable regulations and site-specific goals.	• Table 4. Infiltration objectives checklist
Step 1b: Preliminary Infiltration Feasibility (Section 2.2)	Users perform initial site assessments to determine possible locations for infiltration practices, risk factors, constraints, or prohibitions associated with infiltration, and the potential physical capacity of the site for infiltration.	• Table 5. Checklist for preliminary review of infiltration conditions
Step 1c: Select Preliminary Infiltration Approach (Section 2.3)	Users select a preliminary infiltration approach based on the results of Steps 1a and 1b: • Full Infiltration, • Maximized Partial Infiltration, or • No/Incidental Infiltration. Users identify the need for additional investigation(s) if applicable.	• Table 10. Tentative infiltration approach
Step 2: Tentatively Select BMP Locations and Types (Section 2.4)	Users apply the findings from Step 1 to identify the following: • Tentative locations for BMPs and tributary areas, • Types of BMPs tentatively selected at each location, and • Conceptual design parameters for these BMPs.	• Section 2.4

2.1 Establishment of Infiltration Objectives

Planning and design teams should begin with an evaluation of the underlying objectives associated with infiltration. This can inform selection of BMP strategies and guide the level of effort of infiltration investigations in subsequent steps. Where objectives related to infiltration are more stringent, or there are considerable cost savings associated with successfully utilizing infiltration, greater effort may be justified for infiltration investigations. Where objectives are more flexible, or could be met with alternative approaches besides infiltration, it may be appropriate to use more efficient approaches for site investigation and BMP selection.

2.1.1 Categories of Project Objectives Related to Infiltration

Project objectives and requirements related to stormwater infiltration can originate from regulatory mandates or other stormwater management objectives, such as NPDES stormwater permits, TMDL implementation plans or watershed plans, water quality credit frameworks, local resource protection policies, capital improvement programs, and groundwater augmentation policies or incentives. Based on these drivers, project objectives associated with stormwater infiltration can fit within the following categories:

1. Opportunistic. Opportunistic objectives are those in which infiltration may be used as one option to meet stormwater management objectives such as permit compliance, water quality improvement, flood mitigation, and groundwater recharge. In these cases, regulatory requirements may not drive decision-making about whether to use infiltration. Rather, the relative cost-effectiveness of infiltration approaches (i.e., whether the use of infiltration can achieve objectives more cost-effectively than alternative approaches) is a primary driver in selecting an infiltration approach.

Examples scenarios include the following:

- Infiltration BMPs are one class of BMP in a menu of acceptable stormwater quality treatment approaches for meeting regulatory obligation. There is no hierarchy specified in this menu.

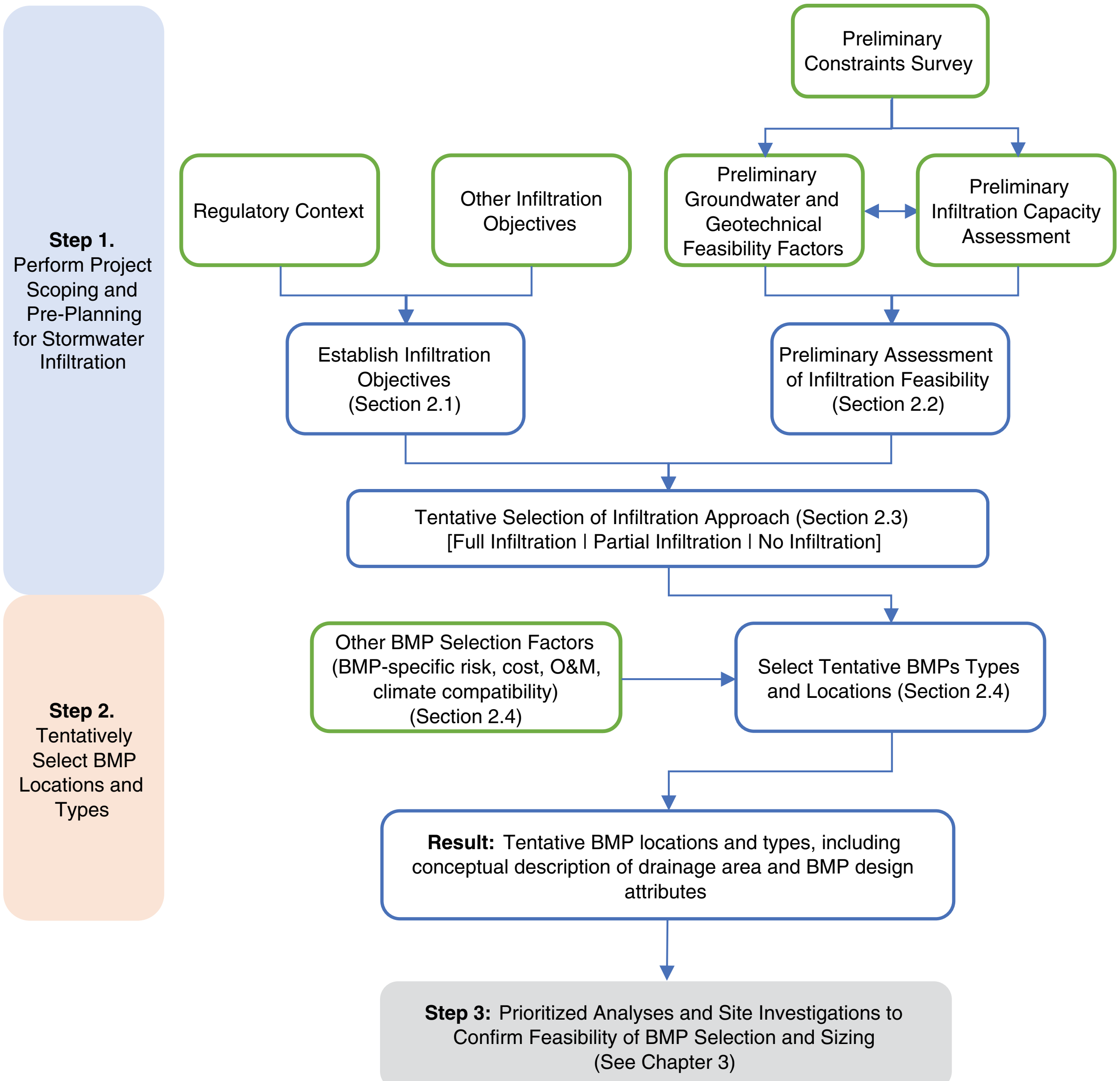


Figure 2. Preliminary infiltration assessment and decision-making process flow chart (Steps 1 and 2).

- Infiltration is being considered for flow control to reduce flooding and protect streams, but this could also be achieved by an extended-detention basin (flow-duration control).
- Infiltration could be used as a retrofit to make progress toward required load reductions or to secure water quality credits as part of TMDL implementation, but other options for achieving these load reductions or credits are also available.
- A local policy or incentive is in place that gives preference for stormwater management approaches that provide groundwater recharge in favorable areas, but this is not a mandate that applies to all projects.

2. Maximized Per Site Conditions. In this case, the project is required to evaluate and apply retention of stormwater runoff to a maximized level [e.g., "maximum extent practicable (MEP)"] based on site conditions, before considering other treatment methods. Under this framework, designers must work to maximize infiltration (or other surface runoff volume technique such as ET or harvest and use) within the site constraints, but the project is not required to achieve a certain minimum level of infiltration to comply. Often, stormwater permits that require consideration of infiltration approaches also include options such as biotreatment, biofiltration, conventional treatment, flow control, or alternative compliance that can be used to augment or replace infiltration, when justified.

Examples scenarios include the following:

- Infiltration BMPs are one class of BMP on a menu of acceptable stormwater quality treatment approaches that includes other BMPs. However, regulations require consideration of infiltration (or volume reduction overall) as the first priority and require that project-specific documentation be provided to justify decision-making, particularly if a "lower priority" class of BMP is deemed to be more appropriate (e.g., infiltration is infeasible).
- Applicable regulations require the use of infiltration if feasibility criteria are met but allow the level of infiltration to be reduced if infiltration rates are lower than a certain threshold (i.e., below a certain infiltration rate, BMPs do not need to be designed to fully infiltrate a design volume).
- Infiltration is identified to be a superior option to achieve project-specific goals, regardless of regulatory requirements. As a result, the project-specific policy direction is to attempt to find areas where infiltration will work because it would result in greater benefit, lower cost, or both than alternative approaches. Note, this is not based on compliance but has a similar "burden of proof" to exhaust opportunities for infiltration before evaluating alternative approaches.
- A water quality credit system is in place, but it only allows quantifications based on the volume of infiltration, so project teams are motivated to utilize approaches that achieve infiltration to accrue credits. However, accrual of credits is not mandated for a given project or location (i.e., credits could be accrued elsewhere if a site is not suitable).

3. Specified Performance Level: In this case, the regulatory framework requires the project to achieve a certain minimum level of volume reduction of surface runoff. This may also be applicable when very rigorous standards for BMP selection demand a high burden of proof for rejecting the use of Full Infiltration BMPs as well as when infiltration is the only viable method of drainage and water quality treatment. These cases tend to be relatively rare.

Examples scenarios include the following:

- The applicable stormwater permit requires projects to infiltrate stormwater as the only on-site option for compliance. If this is not feasible, the project must pursue a form of alternative compliance (e.g., off-site treatment or fee-in-lieu) or the project may not be able to proceed.
- An applicable TMDL is based on a volume-reduction surrogate, such that the only way to make progress toward TMDL implementation is through a volume reduction approach (note, this may not mandate infiltration on a specific project but can greatly increase the pressure to identify areas suitable for infiltration).
- A flat roadway segment and adjacent areas have no available storm drain pipe and not enough room along the side for a swale or not enough grade to drain stormwater to receiving waters. The most viable approach for water quality treatment and conveyance is to infiltrate.

These infiltration objective categories can be thought of as a continuum ranging from the least to the most stringent requirement or objective.

2.1.2 Guidance for Identifying Project Objectives Related to Infiltration

In most cases, the project team will be able to classify the project-specific objectives based on these definitions and examples. Table 4 provides set of questions that can be used to establish the underlying objectives.

Table 4. Infiltration objectives checklist.

Step	Response	Guidance
Regulatory Requirements for Roadway Construction Projects (e.g., new road, lane addition, interchange expansion)		
a. Do post-construction BMP regulations require infiltration to be considered and/or used at a certain minimum level?		If “a” and “b” are No, then this is likely an Opportunistic scenario. If “a” or “b” is Yes, and “c,” “d,” and “e” are also Yes, then this is likely a Maximized Per Site Conditions scenario. If “a” or “b” is Yes, and the answer to “c,” “d,” or “e” is No, then, then this may be a “Specified Performance Level” scenario. More research may be justified to determine what would happen if infiltration is found to be infeasible.
b. Are there other regulatory drivers that encourage or require infiltration?		
c. Are feasibility constraints recognized in the applicable regulations?		
d. Do other options exist if infiltration is not feasible?		
e. Are other options viable (i.e., available, not cost-prohibitive, compatible with the site)?		
Regulatory Objectives for BMP Retrofit Projects		
What are the regulatory motivations for the BMP retrofit?		This can vary greatly by region or watershed, including watershed plans, TMDL implementation, local resource protection ordinances, or other considerations.
What classes of BMPs can meet retrofit objectives?		Is infiltration the only way to meet the objectives? This can influence how rigorously infiltration needs to be considered.
How limited are the siting opportunities to meet these objectives?		The number of siting opportunities may dictate how important it is to try to achieve infiltration at a certain location or project.
Other Infiltration Objectives		
Are there other regulatory reasons [besides the Clean Water Act (CWA)] to consider infiltration?		*Examples include the following:* • Groundwater augmentation • Flood reduction • Avoiding new stormwater infrastructure • Endangered Species Act • National Environmental Policy Act (NEPA) or state environmental policy acts
Are there other means by which (i.e., other locations or projects where) these objectives could be achieved?		The number of siting opportunities may dictate how important it is to try to achieve infiltration at a certain location or project.
Establish Volume Reduction Objectives		
Select infiltration objective category. [This is relevant as part of the decision-making process described in Section 2.3.]		Opportunistic ☐ Maximized Per Site Conditions ☐ Specified Performance Level ☐
Summarize rationale(s) for selection of infiltration objective category.		

2.1.3 Implications of Infiltration Objectives on Subsequent Steps

The applicable infiltration objectives have several implications on subsequent steps:

- The project team can use an understanding of infiltration objectives to determine how rigorously and aggressively the project should pursue the assessment of infiltration feasibility. In other words, what is the burden of proof that infiltration assessments will need to support?
- The project team can use this information as part of scoping site investigations and interpreting site data.

- As outlined in Figure 2, the project team should combine the results of preliminary feasibility analyses with the established infiltration objectives to help make preliminary decisions about infiltration strategies for the project.

Section 2.3 provides guidance for integrating Steps 1 and 2 into preliminary decision-making.

2.2 Preliminary Feasibility Analyses to Support BMP Selection

The preliminary planning or preliminary stage refers to the early stages of project development, ideally prior to or concurrent with environmental permitting and clearance. At this stage, the project team knows the general scope of the project but is still working to determine project constraints, lay out the site, and determine stormwater management approaches. The project team can improve stormwater management outcomes by beginning evaluations of infiltration feasibility at this phase, including the following:

- Reserve space where conditions are most suitable.
- Focus subsequent investigations on relevant data needs to support and confirm decision-making.
- Determine the need for alternative approaches and alternative project delivery methods.

The purpose of this section is to outline planning-level infiltration-feasibility investigations that can be applicable at this phase. During this stage, the project team gathers information based on reviews of existing site information and low-effort site assessment techniques to support characterization of physical constraints, groundwater and geotechnical feasibility, and infiltration capacity. The project team then uses this information in Section 2.3, along with the established infiltration objectives, to select a preliminary infiltration approach for the project.

This section relies primarily on desktop methods and rapid field methods, where feasible. Field-level data may not always be feasible at this stage because of timing and site access limitations. If the project team can obtain field data to support initial decisions, this can reduce the potential that these decisions will need to be revised.

2.2.1 Categories of Constraints

Planners and designers can organize infiltration feasibility assessments into three categories of constraints.

Physical Constraints and Project Layout. Within the project area, where are infiltration BMPs potentially feasible? Can the site layout be adapted to support BMPs in these locations? The project team compiles and summarizes physical constraints and determines where (a) BMPs can be located and (b) infiltration could be feasible. This supports decision-making on the adaptation of site layouts to preserve areas with good infiltration opportunities. Factors such as structures, slopes, highway types, and drainage patterns may limit the locations where an infiltration practice can be located. At this phase, designers may be able to adjust the project layout and conceptual drainage plan to support infiltration objectives.

Infiltration Capacity. Can water be infiltrated reliably at an appreciable rate considering soil permeability and groundwater conditions? What effect would infiltration have on the localized groundwater table? The project team estimates the infiltration rate of the in-situ soils and the capacity of the infiltration receptor (groundwater depth and mounding) via desktop methods or rapid field methods to determine a preliminary infiltration capacity designation. At the planning phase, the focus is on using cost-effective methods to compare potentially feasible locations for initial assessment of infiltration approaches that can be supported.

Groundwater and Geotechnical Feasibility. Can water be infiltrated without introducing undesirable consequences or elevating risks to infrastructure or the environment? The project team coordinates with applicable agencies and conducts desktop research into groundwater protection criteria, site contamination, and other factors. The team also uses available data and tools to assess groundwater mounding, geotechnical, and other associated risks of infiltration. This can be potentially supported by low-effort site investigations at a level of detail adequate to support the tentative determination of infiltration feasibility. The team conducts these investigations for all portions of the site where infiltration BMPs could reasonably be located and considered.

The following sections describe these categories of constraints in more detail. Table 5 provides a preliminary assessment checklist. Key resources for these steps include the following:

- Appendix B: Infiltration Estimation Method Selection and Interpretation Guide
- Appendix C: Roadside BMP Groundwater Mounding Assessment Guide and User Tool
- Appendix D: Guide for Assessing Potential Impacts of Highway Stormwater Infiltration on Water Balance and Groundwater Quality in Roadway Environments
- Appendix E: Guide to Geotechnical Considerations Associated with Stormwater Infiltration Features in Urban Highway Design

Notes on Phasing and Scoping Site Investigations

This section and the supporting appendices are organized by distinct categories of constraints. However, the research team does not intend to imply a priority between these assessments. In practice, project teams may choose to investigate these constraints simultaneously as part of a single preliminary feasibility evaluation.

The project team should determine the scope of investigations necessary to adequately consider these factors. This can vary by project. For example, if the project team believes that soil contamination may affect infiltration feasibility, then it may be appropriate to investigate this issue first. If contamination is found to be present, then this could be the overriding factor in decision-making. Therefore, it would be unnecessary to conduct other investigations of infiltration feasibility.

2.2.2 Physical Constraints and Project Layout Assessment

In this step, the project team determines where infiltration practices could potentially be installed based on constraints related to project layout, topography, grading, drainage patterns, safety considerations, O&M access, and other factors. The primary goal of this step is to determine what limitation may exist and identify locations that can potentially support infiltration BMP while avoiding design conflicts. If the project team identifies constraints and opportunities during preliminary planning, then it can work to reserve areas that may be suitable for infiltration. Potential opportunities for land acquisition can also be considered. The following sections summarize factors that should be considered in assessing physical constraints and project layout.

Project Location and Watershed Characteristics

Preliminary site investigations should identify the location of the project and its connection to other watershed features.

Table 5. Checklist for preliminary review of infiltration conditions.

Step		Summary of Findings (if applicable)
Conduct Physical Constraints and Project Layout Assessment (2.2.2)		
Identify receiving water body connections and environmentally sensitive areas.	☐	
Identify portions of project layout that are inflexible versus flexible.	☐	
Identify potential opportunities for land acquisition.	☐	
Create conceptual drainage map with potential watershed bounds, flow directions.		
Identify potential BMP opportunity areas (a simple map with grading and topographic information as well as project layout is highly useful).	☐	
Conduct Preliminary Infiltration Capacity Assessment (2.2.3) (See Appendix B and Appendix C)		
Estimate infiltration rate and capacity, including evaluation of whether groundwater (GW) mounding could limit infiltration.	☐	
Create infiltration capacity site map.	☐	
Investigate Geotechnical Feasibility Factors (2.2.4) (See Appendix E)		
Describe and map site soil conditions (texture, hydrologic soil group, etc.).	☐	
Estimate underlying geology (depth to confining layer, soil stratification, etc.).	☐	
Identify possible soil stability concerns.	☐	
Identify structural setback requirements on infiltration opportunities map.	☐	
Evaluate potential for formation of a groundwater mound where it would pose a geotechnical hazard or limit drawdown time to a point where vector issues could be a concern.	☐	
Investigate Groundwater Feasibility Factors (2.2.5) (See Appendix D)		
Research applicable groundwater quality standards.	☐	
Estimate depth to seasonal high groundwater table.	☐	
Determine if groundwater protection criteria apply or if there are drinking water wells in the project vicinity.		
Determine if existing soil/groundwater contamination is a potentially concern for infiltration.	☐	
Assess risk of groundwater contamination due to infiltrating runoff.	☐	
Assess whether formation of a groundwater mound could reduce pollutant attenuation effects.	☐	

Connection to Receiving Water. Create a map to show the connection from the project site to each outfall location based on existing drainage infrastructure, including the following information:

- Receiving waterbody name
- Location of existing or new outfalls
- Proximity of project to existing or new outfalls
- Land ownership and space availability along flow path

Characteristics of Receiving Water. Because of the highly linear nature of highway projects, multiple receiving waters are often potentially impacted by the project. Assess whether different objectives apply to different parts of the project based on different receiving waters and their specific conditions and regulatory status.

Environmentally Sensitive Areas. Identify environmentally sensitive areas within the project area and along the downstream flow path. Determine if environmentally sensitive areas impact where infiltration practices can be reliably located.

Highway Type

The highway type can have inherent impacts on opportunities and limitations for infiltration BMPs. Highway segments can be characterized into eight representative types based on common geometric design variations for urban highways as described in AASHTO's *A Policy on Geometric Design of Highways and Streets* (*Green Book*) (AASHTO 2011a).

Ground-Level Highway Segments. Slightly elevated roadways with wide vegetated medians and shoulders (common in suburban and rural areas).

Ground-Level Highway Segments with Restricted Cross Sections. Slightly elevated roadways with narrow medians and shoulders because of topographic and development constraints (common in urban areas).

Highway Segments on Steep Transverse Slopes. Cross-sectional slopes are greater than 10% because of traversing hilly or mountainous terrain resulting in restricted cross sections.

Highway Segments with Steep Longitudinal Slopes. Longitudinal slopes are greater than 5% because of traversing hilly or mountainous terrain. Adjacent land inside and outside of the ROW also tends to be relatively steep.

Depressed Highway Segments. Roadways are depressed below adjacent ground surfaces to allow for overpassing surface streets common in urban areas. Sloped embankments or vertical side walls result in restricted cross sections.

Elevated Highway Segments Constructed on Embankments. Roadways built on earthen fill material creating embankments with slopes between 3:1 and 6:1. Common in suburban areas where surface streets are widely spaced, and grading designs provide adequate fill material.

Elevated Highway Segments Constructed on Viaducts. Aerial highway areas found primarily in dense urban areas where the space under the roadway is used for a variety of urban needs.

Diamond Interchanges. Linear roadway connections resulting in long narrow wedges of open space.

Looped Interchanges. Roadways are connected using arcs and loops (cloverleaf configuration) of various sizes resulting in circular areas of open space.

Table 6 provides a summary of infiltration opportunities and constraints based on highway type. Multiple highway types may be present within a single project. Additionally, future planned projects can effectively change the highway type. For example, a ground-level highway could evolve over time to have a more restricted cross section as lanes are added.

Project Type

Project types include new roadways, enhancement of an existing roadway through the addition of lanes or other improvements, and projects solely to retrofit the highway with BMPs. The project type has important ramifications for infiltration opportunities summarized as follows.

Table 6. Infiltration opportunities and constraints based on highway type.

Highway Type	Opportunities for Infiltration	Constraints on Infiltration
Ground-level highways	• Infiltration BMPs can be integrated into vegetated conveyances present in the typical cross section. • Wide shoulders and long stretches allow for flexibility in practice selection and siting.	• BMPs located in the median and shoulder must allow for errant vehicle recovery. • Future lane expansion or other widening into available space may impact BMP siting. Where lane additions are anticipated, BMP placement in these areas should be avoided. • Shallow slopes may limit routing flexibility.
Ground-level highways with restricted cross sections	• Narrow vegetated BMPs or permeable shoulders can be integrated into the right of way (ROW). • Piped conveyance may allow for regional scale BMPs at interchange locations.	• Limited space due to adjacent structures. • Construction and maintenance activities may require lane closures. • Geotechnical considerations may be amplified due to proximity to urban structures.
Highways on steep transverse slopes	• Infiltration practices can be integrated into areas with shallow slopes or routed to downslope areas. • Piped conveyance may allow for regional scale BMPs at interchange locations.	• Creating space for flat-bottomed or level pool basins would tend to increase earthwork requirements. • Construction and maintenance activities may require lane closures. • Underlying soil likely includes compacted fill in some parts of the section. • Stability and erosion concerns are amplified when using surface conveyances on steep slopes.
Highways with steep longitudinal slopes	• Piped conveyance may allow for regional scale BMPs at interchange locations.	• Creating flat-bottomed or level pool areas for infiltration can require the BMP to be segmented by cutoff walls or berms, increasing cost. This applies to linear systems such as permeable pavement shoulders, vegetated swales, and linear bioretention or infiltration trenches. • Stability and erosion concerns are amplified when using surface conveyances on steep slopes.
Depressed highways	• Geotechnical concerns about adjacent infrastructure are lessened because infiltrating surface is at a lower elevation than adjacent slopes and structures.	• Limited space due to adjacent urban areas. • Opportunities for vegetated conveyance and dispersion may be limited because of topography. • Groundwater and highway geotechnical concerns are amplified because of installation in low lying areas. • Construction and maintenance activities may require lane closures.
Elevated highways on embankments	• Space for infiltration may be available at toe of slope or footing of retaining wall. • Infiltration practices can be integrated into areas with shallow slopes or routed to downslope areas. • Interchange locations likely at lower elevations allowing for routing.	• Limited space due to steep slopes. • Geotechnical concerns amplified because of erosion on steep slopes and stability of retaining walls. • Construction and maintenance activities may require lane closures.
Elevated highways on viaducts	• Installations may not increase net imperviousness allowing for coordination with existing controls. • Available space possible at ground level. • Interchange locations likely at lower elevations allowing for routing.	• No infiltration opportunities on aerial segment. • Geotechnical stability concerns amplified when infiltrating below viaduct columns. • Land ownership may limit areas in which runoff can be managed.

Table 6. (Continued).

Highway Type	Opportunities for Infiltration	Constraints on Infiltration
Diamond Interchanges	• Wedge areas provide substantial open space that can be used as an infiltration surface or provide temporary storage upstream of an infiltration system. • Flexibility in vegetation if adequate setbacks from roadway are provided. • Geotechnical concerns lessened if adequate setbacks from roadway are provided.	• Constraints dependent on highway type. • Steep slopes may be required when interchanges connect roadways at very different grades. • Construction and maintenance lane closures have added traffic management costs.
Looped Interchanges	• Central loops provide substantial open space that can be used as an infiltration surface or provide temporary storage upstream of an infiltration system. • Topography, geotechnical, and safety considerations are reduced compared with diamond interchanges because of large space and even grade.	• Constraints dependent on highway type. • Steep slopes may be required when interchanges connect roadways at very different grades. • Construction and maintenance lane closures have added traffic management costs.

New Projects. These types of projects include construction of new roadways. When infiltration is considered early in the project design, the project team can identify opportunities to allow space for infiltration practices, integrate BMPs into the drainage and grading design resulting in cost savings, and protect soils in infiltration areas from compaction during construction.

Lane Addition or Redevelopment Projects. These types of projects involve the addition of lanes within an existing ROW. These projects tend to have less flexibility in their site design for improving infiltration opportunities. There tend to be existing utilities and structures as part of the projects that cannot be relocated; however, because these projects typically include grading and drainage modifications, project teams may have the flexibility to accommodate stormwater infiltration if this is considered early in project's planning.

BMP Retrofit Projects. These types of projects involve retrofitting BMPs into an existing roadway. Infiltration opportunities will depend on opportunities within the existing drainage configuration, including location of existing stormwater controls or feasible modifications to this drainage configuration. Impacts of grading and construction activities on infiltration feasibility will tend to be simpler; however, the project team may not be able to avoid impacts to existing utilities, structures, and other infrastructure.

Topography, Drainage Patterns, and Infrastructure

Topography and drainage patterns are key factors in identifying potential locations for infiltration BMPs. The project team can assess surface constraints relative to infiltration planning via review of the topographic survey conducted at the outset of the project or the existing infrastructure data. At early planning stages, prior to the completion of a site survey, the team can consult desktop-based methods such as digital elevation models, topographic maps, land cover or land use datasets, and local parcel datasets. The project team can obtain these datasets from national databases such as The National Map or local planning departments. The following information is recommended to support infiltration planning:

- Elevation contours showing topography and slope
- Surface drainage patterns and points of concentrated flow onto and off the site
- Location of steep slopes (greater than 10%)
- Existing impervious surfaces and structure
- On-site or adjacent utilities (within 100 ft)
- Existing storm drain infrastructure and points of connection

While infiltration capacity, groundwater quality, and geotechnical issues are addressed in separate sections, the following information may be useful to include on a topographic map:

- Known soil and groundwater contamination from state environmental agency or other applicable data source
- Known areas of sanitary sewer inflow and infiltration issues from local sewerage agency
- Groundwater elevation data (either available contour maps or well data), potentially available from a local government or groundwater management agency
- Soil type(s) such as from the Web Soil Survey (https://websoilsurvey.sc.egov.usda.gov)

The team can use conceptual design schematics to assess proposed conditions, including estimated locations of proposed structures, topography, and drainage pathways. This includes proposed changes to the roadway and adjacent land uses. As the project develops, assessments of drainage areas and catchment hydrology will impact sizing and selection of infiltration practices.

Off-Site Drainage Through the Site and Treatment of Off-Site Areas

The project team should identify off-site drainage areas that enter the ROW, characterize the relative magnitude of the flow from these areas, and identify the land uses and potential pollutant sources associated with these areas.

Off-site flows that enter or cross the project area may pose challenges for implementing infiltration practices because of excessive flowrates, high sediment loading (either chronic or episodic events), or high land use pollutant loading (posing a possible liability related to pollutant accumulation in the BMP and groundwater quality protection). In general, it is preferred to keep off-site flows separate from on-site flows.

There can be overall environmental benefits and potential additional funding sources if a DOT elects to design a BMP to treat off-site runoff. Some DOT policies and state regulations may encourage treatment of off-site flows where feasible. If a BMP will treat off-site flows, the project team should characterize pollutant levels from the tributary area and potential hot spots that could contribute to elevated groundwater quality or sediment loading issues. Additionally, the DOT should develop appropriate agreements with the owner of adjacent land to (1) ensure upkeep of source controls within the watershed, (2) define responsibility for O&M of the facility and associated cost sharing, and (3) allocate liability for potential cleanup or remediation in the event of contamination of the BMP.

If a framework exists for water quality trading or watershed-based compliance, off-site flows could also present opportunities for a project to provide additional water quality and flow control benefits to achieve watershed planning goals, possibly as part of a credit program. For example, a project could choose to manage flows from off-site and show a net benefit with respect to the hydrologic and water quality impact of the project. The project could also consider addressing off-site flows in one portion of the project to compensate for lack of opportunities to treat project runoff from other portions of the project. The existence and structure of water quality trading and watershed-based compliance options vary greatly among states and jurisdictions.

Safety Considerations

Highway safety laws, which vary between states, are a top priority when considering feasible siting opportunities for infiltration BMPs. The following safety considerations that are relevant to infiltration approaches.

Highway Geometric Design Standards. Highway geometric design refers to the layout of highways, both horizontally and vertically. Geometric design standards vary by state and are typically derived from AASHTO's *Green Book* (AASHTO 2011a). The key requirements for minimum geometric design standards are related to safety (e.g., site distance, stopping distance, design speed, etc.) and serviceability (e.g., land widths, overpass heights, etc.). Geometric design standards can influence infiltration BMP placement including the following:

- Limit the flexibility of the designer to adjust site designs to accommodate infiltration BMPs.
- Limit the features that can be located within the portions of the roadway (e.g., shoulders and medians) that may be traversed by errant vehicles.
- Establish locations where it is acceptable to have depressions, inlet and outlet structures, soils with low structural strength, and vegetation.

Vegetation and Landscaping Standards. AASHTO's *Roadside Design Guide* (AASHTO 2011b) and the Federal Highway Administration's (FHWA's) *Vegetation Control for Safety—A Guide for Local Highway and Street Maintenance Personnel* (FHWA 2007) provide guidance for the types of vegetation that can be used in the road ROW. Vegetation and landscaping standards can influence infiltration BMP placement including the following:

- Limit BMPs with mature vegetation to areas outside of lines of site and outside of errant vehicle recovery zones.
- Ensure BMP placement allows vegetation maintenance to be performed safely.

Drainage and Flood Control. Efficient and reliable drainage of stormwater from travel lanes is a critical safety consideration in the design of roadways. State DOTs typically adopt drainage criteria that specify acceptable hydrologic and hydraulic methods and minimum levels of service for travel lanes. The design of infiltration BMPs must comply with these regulations and not interfere with the level of service needed for the drainage of travel lanes including the following:

- Analysis of BMPs to ensure that they do not increase the risk of flooding. Designers should consider cases in which infiltration rates are overwhelmed by intense rainfall, BMPs drain slowly at the end of their maintenance cycle, or both. For example, in evaluating permeable pavement shoulders, consider a case in which the permeable pavement is clogged and ensure that there is still a positive drainage pathway for water to drain from the travel lanes.
- If infiltration is used as part of a flood control strategy, then designers should apply appropriate factors of safety to ensure that the target level of operation is reliably provided, even if the BMP is near the end of its maintenance cycle.

Access for O&M. The project team should consult with O&M personnel to confirm that they can safely access BMP locations to perform O&M activities. If an area would require significant lane closure or unsafe access conditions, then it may not be feasible for BMP siting.

Land Acquisition

At this phase of the project, it may also be feasible to consider opportunities outside of the project footprint. This could include land acquisition to create more room for BMPs. It could also involve establishment of a regional treatment approach that manages runoff from an area greater than the project footprint. Potential benefits of these options are as follows:

- Expand the range of sites considered, potentially allowing more suitable areas for infiltration.
- Create more room for infiltration outside of the grading limits of the project. This can allow the project to better preserve the natural infiltration capacity and protect the area from construction-phase impacts.
- Improve stormwater management system efficiency by treating water at a more regional scale. The BMP performance calculation tools available as part of *NCHRP Report 792: Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices* and

NCHRP Report 802: Volume Reduction of Highway Runoff in Urban Areas can be used to help assess these options.
- Centralize operation and maintenance activities.

2.2.3 Infiltration Capacity Assessment

Key Resources

Appendix B: Infiltration Estimation Method Selection and Interpretation Guide

Appendix C: Roadside BMP Groundwater Mounding Assessment Guide and User Tool

An understanding of the infiltration capacity of the site is critical to determine appropriate infiltration approaches and plan the site layout. Estimation of infiltration rates and potential for groundwater mounding can also influence assessment of geotechnical groundwater quality issues. The following are objectives of preliminary planning infiltration rate estimation:

- Estimate potential reliable, long-term infiltration rates of soils (semi-quantitative) to determine the feasibility of achieving volume reduction goals.
- Evaluate the groundwater level, magnitude of potential groundwater mounding, and associated influence on geotechnical and groundwater quality issues.
- Compare relative infiltration capacity of potential installation locations.

As part of this step, the project team may use methods that are more efficient and less accurate than design-level methods. To support preliminary decision-making, the project team does not need to conclusively demonstrate feasibility of infiltration; rather it needs to understand the relative capacity at different BMP opportunity locations and classify opportunity sites into general bins (e.g., ideal, favorable, marginal, infeasible) (see Table 7). The level of effort required for preliminary planning infiltration rate assessment will depend on existing data availability, size of area considered for infiltration, and variations of soil type.

Note: If there are overriding geotechnical or groundwater quality issues that do not depend on infiltration capacity, skip to Sections 2.2.4 or 2.2.5. In these cases, it may not be necessary to estimate infiltration capacity to support decision-making.

Conduct Preliminary Assessment of Soil Infiltration Rate

Preliminary planning phase investigation methods should yield adequate information to classify infiltration capacity per the general ranges in Table 7. The project team should conduct this investigation at locations within the project boundaries, where it is reasonable to site infiltration BMPs and other feasibility factors do not preclude infiltration. Desktop methods using soil maps and available data may be adequate, particularly if soil is relatively uniform. For larger or more variable conditions, this Guidance Manual recommends some form of preliminary field verification, such as simple test pits or review of boring logs if available. Infiltration rate estimation and measurement methods are described in Appendix B, including applicability for preliminary screening, and confirmatory- and design-level investigation. Preliminary methods most appropriate at this step include the following:

- Review of available reports and data
- Review of soil maps
- Estimates based on soil texture and other properties
- Simple pit testing
- Rapid infiltrometer and permeameter methods

The project team may elect to use more rigorous tests if they are feasible and not cost-prohibitive. In this case, the results of these tests may also be suitable for subsequent feasibility confirmation as described in Step 3.

Table 7. Preliminary infiltration capacity designation based on estimated reliable infiltration rate.

Infiltration Capacity	Preliminary Infiltration Capacity (in./h)[1]	Qualitative Metrics[2]	Implications for Infiltration Feasibility	Potential BMP Retention Depth[3]	Potential Sizing Factor for Full Infiltration[4]
Ideal	> 5	HSG[5] A soils **and** no indication of shallow groundwater or confining layer within 15 ft	Ideal areas have the highest potential to achieve Full Infiltration and least potential to form a significant mound, even if there is limited space.	3 ft or greater	2% to 5% (level pool)
Favorable	1 to 5	HSG A or B soils with sandy loam or coarser texture class, **and** no indication of shallow groundwater or confining layer within 10 ft **or** HSG A soils with groundwater > 5 ft	These areas could support Full Infiltration BMPs. The feasibility may be contingent on confirmation of infiltration rate via design-level testing.	1 to 3 ft	5% to 10% (level pool)
Marginal	0.1 to 1	HSG B or C soils with loamy or silty texture class (note some HSG D soils could fit into this class if they have low clay content), **or** confining layer or shallow groundwater conditions within 5 ft	These areas can support Maximized Partial Infiltration but are unlikely to support full infiltration unless there is space to design shallow BMPs with low loading ratios.	0.2 to 1 ft (often complemented by treatment)	10% to 40%. Partial Infiltration BMPs are more likely to be suitable.
Infeasible	Less than 0.1	HSG D soils with significant clay content **or** very shallow groundwater or confining layer	These areas likely do not support appreciable levels of infiltration; incidental infiltration may occur but may be too small to reliably estimate.	Less than 0.2 ft	Not feasible

[1] The preliminary infiltration capacity is based on the raw estimate (no factor of safety) with adjustment to account for limiting groundwater conditions if present. The provided ranges are recommended values in the absence of local guidance.

[2] Quantitative metrics can be used to complement testing results or can be used in lieu of testing as part of preliminary feasibility evaluation.

[3] Potential BMP depth is based on 24- to 48-hr target drawdown time witha design infiltration factor of safety of 2 to 4.

[4] Sizing factorrefers to the ratio of BMP footprint to the tributary impervious surface. Sizing ranges are based on a 0.8- to 1.6-in.water quality storm event and arange of allowable BMP depths.

[5] HSG = Hydrologic Soil Group.

The project team should consider the following factors when selecting methods for preliminary infiltration assessments.

Results of Other Groundwater and Geotechnical Investigations. Preliminary geotechnical and groundwater data collection (Sections 2.2.4 and 2.2.5) may provide useful information to inform this assessment. Soil type, soil variability, confining layers, and groundwater depths will all impact the selection of methods for infiltration assessments. This information could be available from geotechnical investigations.

Fill Conditions. If BMPs will be installed in fill conditions, in situ measurements are not possible until grading has been completed. This can be an overriding limit on the use of Full Infiltration approaches that rely on a certain design infiltration rate.

Cut Conditions. BMPs installed significantly below current grade require careful attention to the presence of confining layers and interpretation of borehole methods as described in greater detail in Appendix B.

Spatial scope and soil variability. The level of effort placed into preliminary infiltration assessments will depend on the availability of existing data and the size of the area considered. If a relatively small area is being considered, it may be cost-effective to proceed to more detailed, confirmation-phase investigations early in the project; however, for large sites, variable soil conditions, or projects with flexible layouts, project teams could use lower-intensity methods as the first phase of investigation, allowing a greater part of the site to be assessed efficiently.

Ultimately, the selection of infiltration assessment method will require project-specific judgment. The key underlying goal at this phase is to support an initial planning-level assessment and allow comparisons between potential BMP sites.

Determine Depth to Groundwater

The depth to seasonal high groundwater table (normal high depth during the wet season) beneath a project may preclude infiltration. An elevated groundwater table can reduce the capacity of the aerobic vadose zone soil to attenuate pollutants. An elevated water table can also reduce the capacity of the soil to receive infiltrated water, which can lead to extended drawdown times and premature bypass or overflow of the system.

The water table at a site often varies over time. Variations can occur diurnally (e.g., from tidal influence), seasonally (e.g., wet versus dry season), or over a longer period (e.g., from wetter versus drier conditions over several years). Therefore, obtaining longer-term records or measurements (one to several years) can be important if groundwater depth may limit infiltration.

The project team should consider groundwater levels during preliminary site investigations to determine if groundwater limits may apply. Groundwater levels may vary across the project area, which can influence site layout considerations. Additionally, if groundwater may limit infiltration, the project team may choose to begin collecting groundwater level data early in the planning process to characterize temporal variations. Applicable methods for initial screening may include some or all of the following:

- Test pits or bore holes. Use soil borings or pit investigations to measure the depth to groundwater. This provides measurement of the water table level at a given point in time. Consider precipitation conditions (wet, normal, or dry) and season in evaluating representativeness.
- Hydric soils. Use redoximorphic indicators in test pits or boreholes to estimate seasonal high groundwater levels (U.S. Department of Agriculture 2016).
- Desktop methods. Estimate seasonal high groundwater table based on review of available well data, regional groundwater elevation maps, soil maps, and geologic reports.

For sites in which groundwater depth and hydrogeologic condition may limit infiltration, the project may require more rigorous studies to characterize the site hydrogeology and understand how groundwater levels react during wet and dry periods. The project team should initiate this investigation and monitor the project process to provide a long-term record. When long-term well measurements are available, the project team can estimate the depth to seasonal high groundwater level as the average of the shallowest measurement for all years on record (or alternative local method if applicable).

In addition to characterizing current conditions, the project team may also need to consider future rise in the groundwater table, such as from sea level rise, wider spread use of infiltration in the vicinity of the project, nearby water impoundments, or other factors. Groundwater level rise that could potentially interfere with BMP operation in the future could influence feasibility determinations.

Assess Potential Groundwater Mounding

These soil infiltration rate assessment methods introduced seek to understand the rate at which water will enter the ground surface (at the planned infiltration surface level) when unimpeded. However, the capacity of the groundwater receptor (i.e., the fate of water after it enters the surface) can also be a limiting factor in overall infiltration capacity of a site and can introduce concerns related to geotechnical hazards and groundwater quality protection.

Some degree of groundwater mounding will inherently occur below stormwater infiltration BMPs. The formation of a groundwater mound is the response to a concentrated loading of water. The mound creates a local gradient in the groundwater table that allows the infiltrated water to dissipate from below the BMP. However, the degree and frequency of mound formation relative to the vertical distance of separation to groundwater table can vary greatly by BMP type, design, and site conditions. This is important for assessing whether mounding may limit infiltration rates, introduce geotechnical concerns, or reduce pollutant attenuation capacity for groundwater quality protection.

For preliminary screening purposes, mounding will very likely **not** be an issue when **all** the following criteria are met:

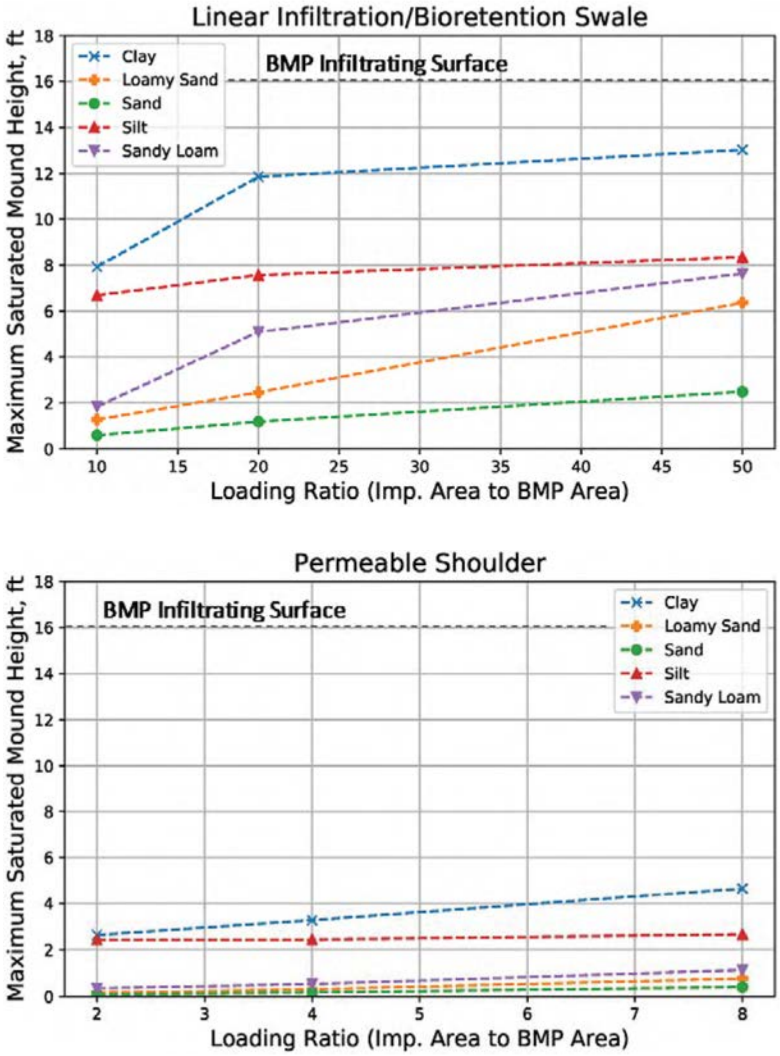
- Depth to groundwater is 15 ft or greater,
- The BMP is not located in the embankment,
- Utilities, foundations, and retaining walls are not present within 20 ft of the BMP,
- Soils above the water table are sandy loam, loamy sand, sand, or more permeable (approximately 1 in./h or greater),
- Loading ratios are less than 20:1 (tributary impervious area to BMP footprint area), **and**
- Narrow dimension of the BMP is 10 ft or less.

If these conditions are **not** met, then there is some elevated potential for mounding. Infiltration may still be feasible, but it is recommended that the project team further assess site-specific conditions and their impact on mounding.

Appendix C provides guidance for assessing groundwater mounding and describes how project planners and designers can use the User Tool (developed as part of this Guidance Manual) to support preliminary assessment. To use the Groundwater Mounding Assessment Tool, the user should collect or estimate as much of the following information as readily available:

- Soil texture and estimated infiltration rate of limiting soil layers
- Approximate depth to groundwater
- Approximate ratio of roadway tributary area to BMP area (i.e., hydraulic loading ratio)
- Proposed roadway cross section at the BMP location

Using this tool, designers and planners can perform a sensitivity analysis to evaluate the magnitude of potential mounding. Users can then rapidly screen whether the mounding would possibly impact infiltration rates or compromise the separation between the BMP and the groundwater table (see Figure 3). Prolonged saturation and reduced separation to groundwater could reduce pollutant attenuation effects in the vadose zone. Geotechnical engineers could also use the output from the tool as part of geotechnical assessments.



Imp.– Impervious.

Figure 3. Example of groundwater mounding nomographs of selected BMP for Birmingham, Alabama.

Interpret Results of Infiltration Capacity Rate Assessment

The primary objective for preliminary site investigations is to determine the semi-quantitative infiltration capacity at potential BMP locations within a project site. Table 7 provides general guidance for interpreting preliminary assessments. Designers should consult appropriate local regulations and design guidance to determine the applicability of the screening thresholds reported in Table 7 for a specific site.

Note, if there are other factors that preclude infiltration in an area (slope, landslides, contamination), it is not necessary to quantify the physical infiltration capacity. These factors could rule out infiltration in any quantity.

Prepare Infiltration Capacity Site Map

Infiltration capacity site maps can be a useful tool for site planning. Project teams can construct these maps by overlaying infiltration rate assessments with other site constraints and feasibility criteria. Maps should build on the identified preliminary infiltration opportunities map (Section 2.2.2). The infiltration capacity site map and corresponding documentation should describe the following:

- Location of BMP opportunity areas (Section 2.2.2)
- Locations of infiltration testing conducted at the project site
- Boring log locations and results relevant to infiltration feasibility determination
- Raw results and professional interpretation of infiltration test results
- Categorization of areas into infiltration feasibility classes (see Table 7): ideal, favorable, marginal, and infeasible
- Key geologic and groundwater features identified per other investigations (Section 2.2.4 and 2.2.5)

Design teams can use the infiltration capacity site map to compare the infiltration capacity across the project site to aid in site layout decision-making. For smaller projects with less opportunity for grading or design changes, the infiltration capacity site map will be of less use in comparing project areas. However, maps can still be useful in supporting selection of an infiltration feasibility designation and selecting appropriate BMPs that fit within spatial constraints.

2.2.4 Preliminary Geotechnical Feasibility Factors and Investigation Methods

Infiltration of stormwater can contribute to geotechnical issues that result in impacts to adjacent structures, utilities, or graded surfaces. Stormwater infiltration temporarily raises the soil moisture and groundwater levels below and adjacent to the infiltrating area. Geotechnical risks are greatest near the BMP and typically diminish with lateral distance. Accurate geotechnical assessments and supporting analyses are essential to prevent damage associated with infiltration in the roadway environment. Preliminary geotechnical assessments can serve an important purpose in helping to site BMPs and form appropriate infiltration goals at an early phase.

Key Resources

Appendix C: Roadside BMP Groundwater Mounding Assessment Guide and User Tool

Appendix E: Guide to Geotechnical Considerations Associated with Stormwater Infiltration Features in Urban Highway Design

The role of preliminary site geotechnical investigations is to identify geologic or geotechnical hazards that would clearly or potentially limit infiltration. Preliminary geotechnical investigations should involve review of several desktop data sources including the following:

- Available soil maps
- Geological reports
- Available site investigations (such as previous borings)
- Regionally applicable data (such as testing of similar soil units from different projects)
- Rough grading plans

The following subsections explain key aspects of the preliminary geotechnical feasibility evaluation and the associated planning-level methods and feasibility screening criteria that may be appropriate.

Evaluate Limiting Geotechnical and Geologic Factors

Relevant geological and geotechnical factors that should be reviewed at this phase.

Depth to Confining Layer and Slope of Confining Layer. Does a shallow confining layer pose a potential risk of lateral water migration and mounding-related hazards if infiltration is to be used? A depth of 15 ft or less is considered shallow and would warrant further investigation. A sloping confining layer could also indicate potential issues, because infiltrated water could travel along this face and result in a landslide or other issue.

Presence of Karst Geology. Karst can be prone to sinkhole formation. It also has groundwater quality implications, as described in Section 2.2.5. The presence of karst geology is an issue that would likely preclude infiltration.

Proposed Fill Conditions. Compacted fills have important influence on infiltration feasibility. While infiltration into fill does not inherently pose unacceptable risks, it is not possible to determine the physical properties or infiltration rates in fill soil at the preliminary planning or design phases, unless the origin and type of the fill is known and tightly specified. Even so, there would be considerable uncertainty in this estimate. As a result, these areas may be inherently unsuitable to support infiltration systems that rely on a certain minimum infiltration rate. If the depth of fill (including any remedial excavation and compaction) exceeds 5 ft, it is generally not reasonable to install a deeper profile BMP to achieve infiltration. If fill is less than 5 ft, then it is possible that the BMP could be extended into more permeable underlying soil.

Collapsible Soils. Collapsible soils are loosely deposited sediments that are separated by coatings or clay/carbonate particles. Hydrocollapse occurs when soil saturation results in the deterioration of the soil structure. Preliminary desktop assessments should evaluate the potential for hydrocollapse, especially in areas near proposed infiltration practices and potential mitigation measures. This could rule out any level of infiltration.

Expansive Soils. Expansive soil is defined as soil or rock material that has a potential for shrinking or swelling under changing moisture conditions. Expansive soils contain clay minerals that expand in volume when water is introduced and shrink upon drying. Expansive soil movement can affect nearby structures, such as foundations and roadways. Preliminary desktop assessment should evaluate whether expandable materials are present near possible infiltration facilities and potential mitigation measures. This could rule out any level of infiltration.

Potential for Liquefaction. Soil liquefaction is a phenomenon in which soil strength is lost as a result of an earthquake or other rapid loading that occurs within a saturated granular soil, resulting in the soil behaving temporarily as a liquid. This can cause lateral spreading of embankments and areas of sloping ground. If soil types and groundwater levels show the potential for liquefaction, the geotechnical engineer should consider the effect of stormwater infiltration within these areas as part of geotechnical analyses. This could rule out infiltration if it results in prolonged elevated water tables that significantly increase liquefaction risk. Shorter-term fluctuations in the groundwater table caused by episodic infiltration would pose a lower risk, because liquefaction requires that ground shaking happen concurrently with saturation.

Establish Planning-Level Setbacks from Pavement, Structures, and Utilities

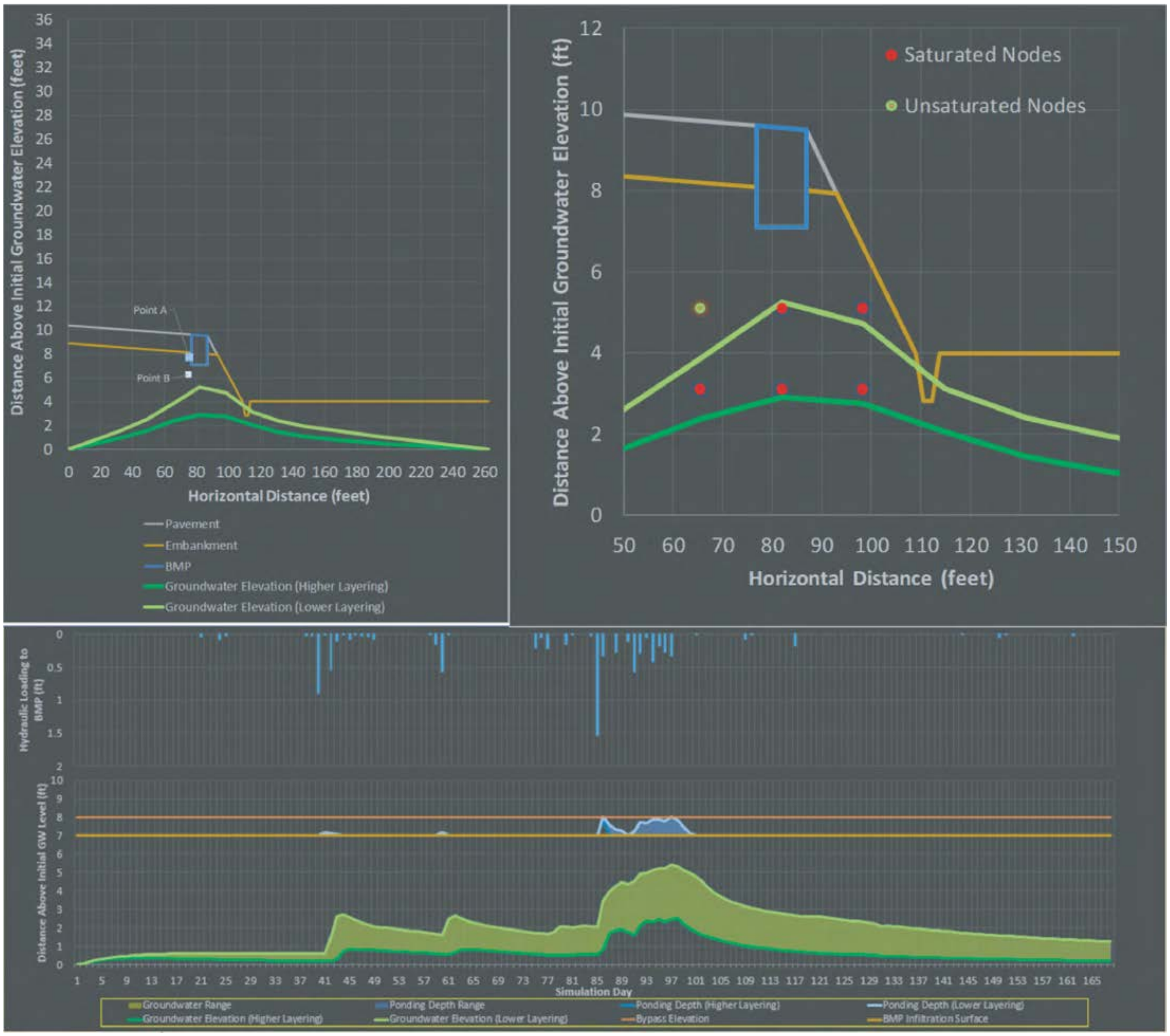
Decreased soil strength because of elevated soil moisture levels near infiltration BMPs can make foundations more susceptible to settlement and slopes more susceptible to failure. Infiltration BMPs must be set back an adequate distance from building foundations or steep slopes. At the preliminary planning stage, the project team should consult with the project geotechnical professional to determine appropriate setbacks from pavement, slopes, and structures.

Assess Risks Related to Groundwater Mounding and Near-Roadway Soil Saturation

The development of a groundwater mound could be an important factor in geotechnical risk. For example, saturation of soils or fluctuations of groundwater level near slopes could reduce soil strength and slope stability. The potential magnitude of mound formation depends on many factors but tends to be greatest in finer grained soils and for more centralized BMPs with larger dimensions and loading ratios.

Appendix C presents guidance and an Excel-based tool for estimating potential mounding response based on a preliminary understanding of site conditions and potential BMP types. The geotechnical engineer can use the output from this tool to support a preliminary evaluation of the shape and extent of the groundwater mound. The mound can be overlaid with the proposed roadway cross section and adjacent infrastructure or utilities to determine if the mound would contribute to geotechnical issues. Figure 4 shows a subset of an example output from the Groundwater Mounding Assessment Tool.

Should the results from this tool indicate that mounding or increase in soil moisture may be an issue, the project team can use the tool as a sensitivity analysis to test which parameters may have the greatest influence on mounding. This can focus the scope of subsequent site investigation efforts.



(Note: See Appendix C for tool description and documentation. Figure 4 shows select tool output for a permeable shoulder in Denver, Colorado, with a loading ratio of 8:1 and an initial groundwater depth of 4 ft. Green lines in the upper right and upper left parts of the figure depict maximum groundwater elevations during a 6-month simulation. Points A and B are model monitoring nodes beneath the edge of the pavement. Green and red colored points in the upper right indicate points that were never saturated during the 6-month simulation and points that were saturated at least once during the 6-month simulation, respectively. The bottom part of the figure depicts time-series data for precipitation as blue bars, groundwater levels as green lines, and surface ponding as blue lines.)

Figure 4. Example output visualization from Groundwater Mounding Assessment Tool.

Summarize Planning-Level Findings

Investigations of soil and geological properties at the preliminary planning stage should be only as detailed as needed to support site layout planning and initial selection of BMP strategies. Using results from these investigations, the project team can overlay soil and geological features on the physical constraints map to identify areas where (1) no issues exist, (2) potential issues exist that require further re-evaluation or may limit the amount of infiltration allowed, and (3) clear limiting conditions exist that would preclude infiltration. If, based on this evaluation and other feasibility factors, the team selects infiltration as a potential stormwater management approach, then more detailed investigations may be needed at the areas where infiltration is proposed, as described in Chapter 3.

2.2.5 Preliminary Groundwater Quality Feasibility Factors

Key Resources

Appendix C: Roadside BMP Groundwater Mounding Assessment Guide and User Tool

Appendix D: Guide for Assessing Potential Impacts of Highway Stormwater Infiltration on Water Balance and Groundwater Quality in Roadway Environments

This Guidance Manual recommends researching applicable groundwater quality standards and local groundwater protection requirements, then researching the physical setting of the project including depth to groundwater, pollutant sources, and existing soil or groundwater contamination. The following sections provide recommended steps to conduct preliminary screening. Appendix D provides additional guidance and supporting technical information related to groundwater quality considerations.

Research State and Local Standards That Apply to Stormwater Discharges to Groundwater

Applicable groundwater standards, regulatory frameworks, and groundwater protection criteria vary by state and locality, depending on the beneficial uses of the groundwater and state or local agency implementation of groundwater regulations and programs. As a result, applicable water quality criteria can vary greatly and, in some cases, can limit stormwater infiltration approaches.

Key questions for the project planners to research at a project or regional level include the following:

- Does the local groundwater management agency have a wellhead protection plan, source water protection plan, or similar plan for protecting groundwater quality? If so, does it include infiltration prohibitions, siting criteria, pretreatment criteria, water quality criteria, or other guidance?
- Is the aquifer designated an SSA (https://www.epa.gov/dwssa)?
- Are there other aquifer-specific plans that apply, such as salt and nutrient management plans, that govern discharges from the project?
- What water quality criteria apply to discharges to groundwater? This can depend on the local regulatory framework, the beneficial use of the groundwater, and the current quality of the groundwater.
- Are water quality criteria based on specified concentration limits? If so, what is the basis for these limits? Examples could include maximum contaminant levels (MCLs) derived from the Safe Drinking Water Act (SDWA) or limits based on the CWA for protection of surface waters that receive groundwater discharges.
- Are groundwater water quality protection requirements based on anti-degradation (i.e., the discharge shall not deteriorate existing water quality)? If so, what is the current water quality of the groundwater that must be preserved, and what parameters are used to evaluate this?
- Where do these limits apply (i.e., point of compliance)? This can vary including the point where infiltrated water discharges to groundwater (immediately below the BMP), a plane where groundwater leaves a site (e.g., the ROW boundary in a highway), the point of extraction (e.g., the nearest down-gradient well), or other location established by the applicable regulatory authority.

- What is the separation to private or public water wells? Do these wells draw from a shallow unconfined aquifer or a deeper confined aquifer?

This research should typically involve review of rules, guidance, and policies adopted by state environmental quality agencies and local groundwater management agencies.

Conduct Preliminary Screening of Potential Groundwater Quality Impacts

For planning-level assessment, the project team should determine whether applicable groundwater standards preclude infiltration, require specific considerations for infiltration (e.g., spill containment, pretreatment), or do not limit infiltration. Two primary categories of sites are relevant for interpreting the influence of groundwater quality limits.

Sites with Groundwater Quality Standards Based on Drinking Water MCLs. As summarized in Appendix D, infiltration of highway runoff poses limited risk to groundwater in cases in which the primary beneficial use is municipal water supply, and water quality standards are based on MCLs. The following are exceptions:

- In areas where deicing salts are applied, salt can accumulate and form plumes that exceed MCLs, particularly where points of compliance (e.g., wells) are near the highway. The Groundwater Quality Assessment Tool (found in Appendix D) can be used to evaluate acute impacts of deicing salts on nearby groundwater quality.
- Pathogenic bacteria and viruses can be mobile and persistent in groundwater. The presence of human pathogens is primarily an issue in urban areas where human waste may be present in stormwater. In these areas, groundwater is nearly always treated before being used in water supplies, mitigating this risk. In rural areas, however, the project team should consider the potential for pathogen contamination of water wells. A setback of 100 ft from drinking water wells is common, but local ordinances may prescribe much more stringent criteria to protect wells, such as 1-year or 10-year time of travel zone (i.e., the area that could enter a well within a 1-year or 10-year period, for example).
- Where groundwater is very shallow, soil is low in organic matter, or both, the vadose zone may have inadequate pollutant attenuation to prevent breakthrough of organic compounds, such as polyaromatic hydrocarbons (PAHs), to groundwater. This can be mitigated through use of organic soil amendments, observation of minimum separation from groundwater of at least 5 ft (or more if required by local regulations), and evaluation of groundwater mounding to ensure that there are not extended periods of diminished vadose zone thickness (City of Portland 2008; Brody-Heine et al. 2011).
- Water soluble pesticides such as neonicotinoid pesticides are highly mobile in soil and groundwater. These have the potential to pose risks to human health if wells are nearby; however, these parameters are infrequently detected in untreated stormwater at levels of concern to human health and can be managed via selection of pest control products in the ROW.
- In areas of karst topography, there can be limited or no attenuation, and direct stormwater inflows should be avoided.

In each case, the proximity to a public or private drinking water well and connectivity between surface infiltration and the production aquifer are important in classifying risk.

Other highway runoff contaminants are unlikely to approach MCLs or are not very mobile in soils under most conditions. Observations of metal buildup and breakthrough have been noted in some research, particularly in sandy soils that lack attenuation capacity (Pitt et al. 1999; Weiss et al. 2008). However, untreated metals concentrations in highway runoff tend to be much lower than MCLs (10 times or more), indicating relatively low risk to human health, even if no treatment occurred in the vadose zone (Table 8).

Note that aquifers used for municipal drinking water supply may have local ordinances related to aquifer or well-head protection. This may prohibit stormwater infiltration or require specific

Table 8. Typical highway runoff concentrations and filtration BMP effluent quality.

Parameter	Typical Influent Quality[1]	Typical Sand Filter Effluent Quality[1]	Drinking Water MCL	Representative Surface Water Quality Standard
E. Coli, count/100 mL	6,025	1,805	Zero (not present)	235
Fecal Coliform, count/100 mL	8,700	2,488	Zero (not present)	400
Total Copper, ug/L	42	19	1,000[a]	10 to 50[c]
Total Lead, ug/L	44	5	15[b]	20 to 130 [c]
Total Zinc, ug/L	190	26	5,000[a]	50 to 200 [c]
Nitrate-N [NO3-N], mg/L	1.06	1.06	10	Narrative [(d)]
Total Nitrogen, mg/L	3.59	2.40	N/A	Narrative[(d)]
Total Phosphorus, mg/L	0.44	0.20	N/A	Narrative[(d)]
Total Suspended Solids (TSS), mg/L	139	15	N/A (Turbidity < 1)	Narrative (50 to 100 mg/L is typical)
Chloride	Less than 20 without deicing Can exceed 1,000 with deicing	Same as influent (no removal)	250[a]	300

[1] *NCHRP Report 792* (Taylor et al. 2014)
[a] Secondary MCL
[b] Action level based on 1991 Lead and Copper Rule. MCL is zero.
[c] Metal standards are hardness dependent or based on the Biotic Ligand Model. Ranges are representative for chronic contaminant levels for illustration purposes only.
[d] Except where waterbody specific criteria exist, water quality standards for nutrients are typically narrative, based on biostimulatory effect. Limits can vary greatly based on water body sensitivity and limiting nutrients.

approaches to protect groundwater quality, including pretreatment, spill containment, separation distance, or other approaches. In general, accidental contaminant spills, such as solvents or petroleum products, are the principal concern for groundwater quality protection in these areas.

Sites with Groundwater Quality Criteria Based on Anti-Degradation Policy or Surface Water Standards. Groundwater quality criteria based on anti-degradation policy or surface water standards can be much more stringent than drinking-water-based limits for some contaminants. If this regulatory framework applies, the applicable water quality criteria depend on the existing quality of the groundwater, the beneficial uses of the groundwater, the existing water quality, and beneficial uses of the surface waters that receive groundwater discharges.

If groundwaters are degraded, stormwater infiltration can improve groundwater quality. For example, monitoring in Fresno, California, has shown that widespread use of stormwater infiltration over more than 40 years has had the effect of reducing nitrate concentrations in their SSA, which has also experienced impacts from agriculture (http://www.rechargefresno.com/groundwater/).

If groundwater is relatively clean and stormwater is discharged to groundwater on a long-term basis, it may be impossible to avoid groundwater quality deterioration. Certain soluble contaminants in stormwater, such as nitrate, could exceed background levels if the groundwater is especially clean. Additionally, over time, metals, PAHs, soluble pesticides, and other partially mobile contaminants could break through soil layers and cause detectible increases in groundwater concentrations. Breakthrough can be mitigated with soil amendments and periodic removal of surface soils; however, this risk cannot be eliminated over long periods of operation. Periodic removal of surface soils/media may also be part of an operations plan to dispose of materials before they build up contaminates such that they become classified as hazardous wastes.

Sensitive surface waters may have water quality standards considerably lower than drinking water standards. For example, the drinking water MCL for copper is 1 mg/L, but toxicity-based standards (for fish and other aquatic biota) for copper in receiving waters can be less than 0.02 mg/L.

Where anti-degradation or a direct connection to a sensitive surface water is present, a specific evaluation of the local regulatory framework, applicable standards, existing groundwater quality, and highway runoff quality is warranted to determine if any level of infiltration is allowable. This Guidance Manual does not contain categorical conclusions about these conditions.

Determine Depth to Groundwater and Assess Vadose Zone Thickness for Pollutant Attenuation

In addition to posing a physical limitation, an elevated groundwater table can reduce the capacity of the aerobic vadose zone soil to attenuate pollutants. Groundwater mounding can further reduce the thickness of the aerobic vadose zone. Section 2.2.3 provides guidance for assessing the depth to groundwater and the potential for mound formation.

Project teams should refer to local criteria for minimum separation to seasonal high, mounded groundwater to protect groundwater quality. Minimum separation may be specified in groundwater protection ordinances, Municipal Separate Storm Sewer System (MS4) permits, or other local criteria. In the absence of local criteria, planners and designers should observe a minimum separation of 2 to 4 ft from the seasonally high, mounded groundwater table to the infiltrating surface. This is intended to maintain an unsaturated aerobic vadose zone to support pollutant attenuation and retention.

Investigate Pollutant Attenuation Properties of Soil

Soil properties can influence the ability of soils to attenuate pollutant loads to protect groundwater quality. Sandy soils with high permeability and low organic content can have limited pollutant attenuation capacity, especially for dissolved constituents and those bound to very small particles. At the preliminary assessment phase, this is not typically a controlling factor in decision-making because pretreatment and soil amendments can be used to augment treatment capacity if soils are too coarse or inert; however, if the project team collects available information about soil texture and organic content at this phase, this information can be used later to assess whether amendments are needed. This information could be available from soil maps, bore logs, soil studies from nearby projects, or other sources.

Investigate Existing Soil and Groundwater Contamination

In areas with known or potential groundwater or soil contamination, the project team may need to avoid infiltration if it would contribute to the movement or dispersion of soil or groundwater contamination or adversely affect ongoing clean-up efforts. The presence of groundwater or soil contamination can preclude any level of infiltration. Pollutant mobilization can occur on-site or down-gradient of the project. Mobilization of groundwater contaminants may also be of concern where contamination from natural sources (e.g., marine sediments, groundwater naturally high in phosphorus, selenium rich groundwater, etc.) is present. In some situations, infiltration BMPs may positively impact existing contamination issues because of dilution effects. For example, if groundwater is high in total dissolved solids, infiltrating stormwater might benefit groundwater quality.

As part of preliminary site investigations, the project team should review available site data, state databases of contaminated sites, regional guidance, and other sources to determine if existing soil or groundwater contamination is a concern. If the team is considering infiltration in areas where soil or groundwater pollutant mobilization is a concern, then decisions should be supported by a site-specific analysis to determine where infiltration-based BMPs can be used without causing or contributing to adverse impacts. Appendix D provides specific guidance on assessing groundwater and soil contamination to ensure that project drainage plans do not contribute to movement or dispersion of groundwater contamination.

2.3 Selection of Preliminary Infiltration Approach

2.3.1 Overview

This step guides users in selecting a preliminary infiltration approach that aligns with the established infiltration objectives (Section 2.1) and the preliminary infiltration feasibility (Section 2.2). The primary elements of this step include the following (see also Figure 5):

1. Compile site assessment data to determine preliminary feasibility and desirability of infiltration.
2. Interpret preliminary site assessment data in the context of infiltration objectives.
3. Tentatively select an infiltration strategy: (1) Full Infiltration, (2) Maximized Partial Infiltration, (3) Incidental Infiltration, or (4) an alternative non-infiltration approach.

The following sections provide guidance for each of these steps. There are two key concepts to consider at the outset of this process:

- Infiltration should not be a "Yes" or "No" decision. While some conditions exist that can limit any amount of infiltration, this decision is not often a simple "Yes" or "No." More often, the practical decision facing project proponents is whether to attempt to rely fully on infiltration to meet applicable BMP sizing requirements (e.g., Full Infiltration) or use practices that promote partial or incidental infiltration while also providing supplemental non-infiltration processes to meet sizing requirements.
- The tentative selection may not be final. This is particularly true if rapid or coarse methods were used to determine that infiltration appears viable. The project team will often need to confirm preliminary findings with testing at specific BMP locations. Tentative selection of BMP types can and should change if more refined methods yield different findings about feasibility.

2.3.2 Integrated Assessment of Planning-Level Feasibility

The outcome of this step is a determination of the level of infiltration feasibility and desirability at the locations where BMPs can be reasonably located.

Project teams can use Table 9 to organize preliminary site assessment information and document the preliminary level of infiltration feasibility. This table is intended to be used for each BMP location or for relatively uniform segments of the project. If **all** conditions in Section 1 apply, then the rating is "favorable." If one or more conditions in Section 1 do not

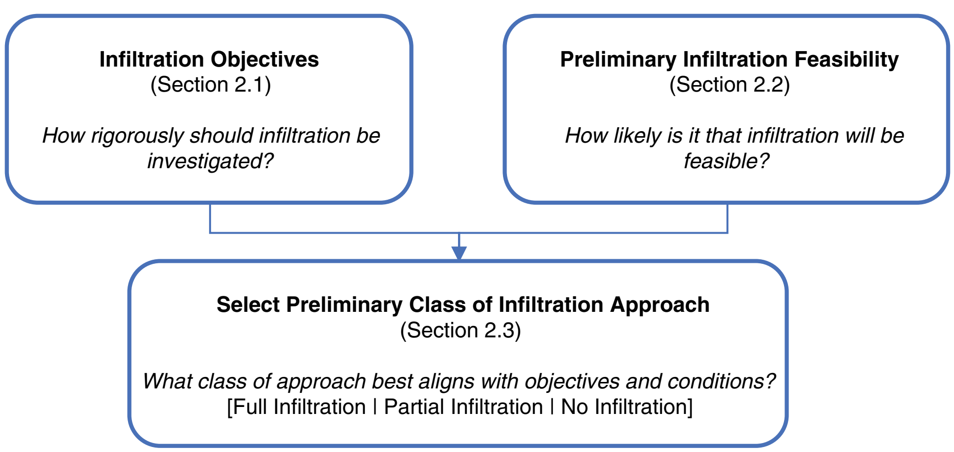


Figure 5. Overview of methodology for preliminary selection of infiltration class.

Table 9. Worksheet for rating preliminary feasibility conditions.

	Applicable?
Section 1: Favorable Conditions (check all that apply)	
Infiltration capacity is rated as favorable or ideal (see Table 7).	
The BMP location can be tested prior to construction and can be protected from construction impacts (Section 2.2.2).	
The depth to groundwater table including temporal variations can be reasonably assessed (Section 2.2.3).	
Groundwater mounding does not limit infiltration rates or come within 2 ft of the bottom of the BMP (Section 2.2.3).	
Geotechnical hazards to structures, slopes, pavement, or other infrastructure that preclude infiltration are not identified (Section 2.2.4).	
Applicable groundwater protection criteria do not preclude stormwater infiltration and infiltration is considered to pose a low risk to groundwater quality (Section 2.2.5).	
Soil and groundwater contamination are not present (Section 2.2.5).	
There is adequate space that can be used for a level-bottomed BMP (see ranges of potential space requirements in Table 7).	
Section 2: Marginal Conditions (check all that apply)	
One or more conditions in Section 1 are not met or could not be adequately assessed at the time of preliminary decision-making.	
Infiltration capacity is rated as marginal or better (Section 2.2.3).	
Infiltration does not pose unavoidable geotechnical or groundwater quality issues that preclude infiltration (Section 2.2.4 and 2.2.5).	
Applicable groundwater protection criteria include limitations on infiltration or potential groundwater quality impacts may be present and require further assessment (Section 2.2.5).	
The project has some amount of space available for infiltration but may not meet the required space for Full Infiltration (see ranges in Table 7).	
Section 3: Infeasibility Factors (check any that apply)	
Any condition is identified that poses an unavoidable geotechnical risk that limits any level of infiltration.	
Applicable groundwater protection criteria prohibit infiltration, or any condition is identified that poses an unavoidable risk to groundwater quality or sensitive receptors.	
Soil infiltration rates are rated as infeasible and do not support an appreciable level of intentional infiltration.	
Section 4: Integrated Summary (identify category that applies)	
Favorable: All conditions in Section 1 are met.	
Marginal: All conditions in Section 2 are met, but one or more conditions in Section 1 are not met.	
Infeasible: Any condition in Section 3 is met.	

apply, but **all** conditions in Section 2 apply, then the rating is "marginal." If **any** criteria in Section 3 apply, then the rating is "infeasible."

2.3.3 Identification of Tentative Infiltration Approach

To support tentative decision-making, the project team should review the feasibility findings summarized with the infiltration objectives established in Section 2.1:

- Where conditions are clearly favorable for infiltration, the decision to proceed with an infiltration approach may be obvious, regardless of infiltration objectives.

Table 10. Tentative infiltration approach selection matrix.

Tentative Infiltration Condition (Section 2.2 and 2.3)	Infiltration Objective Category (Section 2.1)		
	Opportunistic	Maximized	Specified Performance Level
Favorable	Track 1a Full Infiltration	Track 1a Full Infiltration	Track 1a Full Infiltration
Marginal	Track 2a Maximized Partial Infiltration	Track 2a Maximized Partial Infiltration	Track 1b Full Infiltration or Partial Infiltration (additional data required to support decision)
Infeasible	Track 3a Incidental/No Infiltration	Track 3b Incidental/No Infiltration with additional supporting documentation (if needed)	Track 3b Incidental/No Infiltration with additional supporting documentation

- If infiltration is clearly infeasible, then the stringency of infiltration objectives may not be relevant for making decisions about infiltration. Regardless of the level of stringency, infiltration should not be used. However, the stringency of requirements may be relevant for documenting these decisions and identifying an acceptable alternative.
- Infiltration objectives have the most relevance when sites have marginal feasibility conditions. In this "middle ground," it is possible that a range of infiltration approaches could be used but each would have different tradeoffs regarding effectiveness, the need for additional assessment, space requirements, and risk of failure. The stringency of infiltration objectives can be an important deciding factor in selecting a tentative infiltration approach and identifying the need for additional site investigations and analyses. When conditions are marginal, the project team should avoid Full Infiltration BMPs unless further consideration is mandated by project objectives.

Table 10 provides a matrix to help project teams select tentative infiltration approaches based on the infiltration objective category and tentative infiltration condition. Each of these approaches has different implications for BMP selection, which are described in Section 2.4. The remaining efforts needed to confirm the selected approach also vary by track (see Chapter 3).

2.4 Tentative BMP Selection

2.4.1 Overview

This section supports Step 2 in the decision-making process (see Figure 6). This step involves tentatively selecting the BMP types and locations for the project. This should be based on the preliminary findings from Sections 2.2 and 2.3 (collectively Step 1 in the decision-making process). The purpose of this step is to narrow down the potential BMP locations and types of BMPs so that appropriate confirmatory investigations and analyses can be scoped if needed. The results of this step may be tentative.

Key questions include the following:

- Which BMPs are most appropriate given the overlay of preliminary infiltration feasibility category and infiltration objectives? (Section 2.4.2)

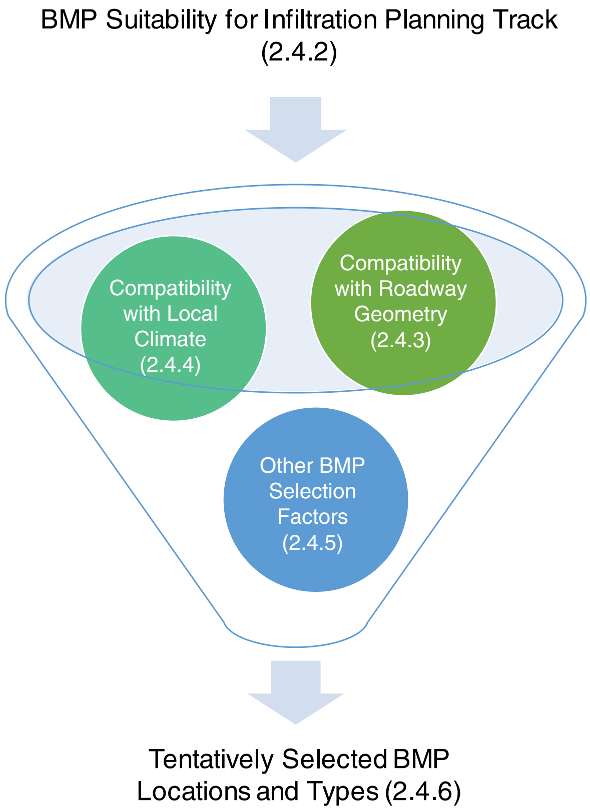


Figure 6. Overview of BMP selection approach (Step 2).

- For the site areas where infiltration could be implemented, which BMPs are applicable or suitable (considering location, geometry, and size of available space)? (Section 2.4.3)
- Which BMPs are compatible with local climate? (Section 2.4.4)
- If multiple BMPs are available, how do they compare in relation to other decision factors? (Section 2.4.5)
  - Relative level of geotechnical risks
  - Relative level of groundwater quality risk
  - Relative safety
  - Relative whole lifecycle costs
  - Relative O&M requirements

2.4.2 BMP Suitability for Infiltration Planning Track

The overlay of infiltration objectives and infiltration feasibility categories has a strong influence on the BMP types that may be suitable for the project. Table 11 identifies a narrower menu of potential BMPs based on the categorization conducted in Section 2.3.3.

2.4.3 BMP Suitability by Roadway Project Type and Site Features

The roadway project type and site features strongly influence what types of BMPs could be reasonably sited to receive roadway runoff. Table 12 provides a summary of the relative suitability of various BMPs for different highway opportunities considering the typical space and inherent shape associated with each opportunity. Figure 7 provides an example illustration of common geometric siting opportunities that may be present in the highway environment.

Table 11. Summary of infiltration BMPs potentially suitable for each planning track.

Screening Condition	Potential BMPs and BMP Adaptations Best Suited to Infiltration Screening Conditions[1]
Track 1a – Favorable Infiltration Conditions • Select BMPs to provide Full Infiltration. • Confirm planning-level feasibility findings. • Include adaptable features if desired.	☐ BMP 02 Dispersion/Filter Strips (where soils are permeable, and enough dispersion area can be provided to reliably infiltrate the full sizing criteria) ☐ BMP 03 Media Filter Drain (without underdrain) ☐ BMP 04 Permeable Shoulders (optionally with capped underdrain) ☐ BMP 05 Bioretention without Underdrains (optionally with capped underdrain) ☐ BMP 07 Infiltration Trench ☐ BMP 08 Infiltration Basin ☐ BMP 09 Infiltration Gallery
Track 1b – Stringent Infiltration Objectives in Marginal Conditions • Conduct further investigation to support BMP selection. • Select BMPs with emphasis on adaptability and resiliency.	If infiltration feasibility improves with further investigation, the BMPs described for Track 1a may be feasible. If Full Infiltration cannot be supported based on the results of further investigation, then refer to Track 2a for available BMPs. If it is not possible to achieve adequate confidence in the infiltration assessment, but infiltration must still be attempted, then select BMPs that can be readily adapted as part of the construction and post-construction process, such as the following: ☐ BMP 03 Media Filter Drain (typical design with underdrain but with the ability to cap or uncap the underdrain depending on actual in-situ conditions) ☐ BMP 05 and BMP 06 Bioretention without and with Capped Underdrains, respectively,(can be uncapped if rates do not support Full Infiltration)
Track 2a – Maximized Infiltration Objectives in Marginal Conditions • Select BMPs to maximize level of infiltration and ET within site constraints. • Design BMPs such that they do not rely on a certain minimum infiltration rate to remain operable.	☐ BMP 01 Vegetated Conveyance (including shallow sump or check dams) if possible ☐ BMP 02 Dispersion/Filter Strips (with amended soil) ☐ BMP 03 Media Filter Drain (typical design with underdrain) ☐ BMP 04 Permeable Shoulders (with elevated underdrains, creating a gravel reservoir for Partial Infiltration) ☐ BMP 06 Bioretention with Underdrains (with elevated underdrains, creating a gravel reservoir for Partial Infiltration)
Track 3a and 3b – Limited or No Infiltration Feasible • Select BMPs to limit infiltration and provide ET and supplemental treatment processes. • Collect additional information to support decision, as necessary.	☐ BMP 01 Vegetated Conveyance (with amended soil and positive drainage) ☐ BMP 02 Dispersion/Filter Strips (with amended soil) ☐ BMP 03 Media Filter Drain (underlain by low permeability soil) ☐ BMP 06 Bioretention with Underdrains (lined or with underdrains at bottom of facility) ☐ Non-infiltration approaches

[1] See Appendix A for BMP Fact Sheets.

Table 13 provides a checklist for organizing findings about the applicability of BMPs to a given site:

- Part 1 summarizes screening of project geometric design features and BMP siting opportunities.
- Part 2 summarizes screening of overall project attributes such as available space and presence of storm drains.
- Part 3 summarizes how other project-specific factors can influence BMP selection.
- Page 4 summarizes the applicability and suitability screening.

Table 12. Summary of geometric siting opportunities by BMP type.

Geometric Siting Opportunity	BMP 01 Vegetated Conveyance	BMP 02 Dispersion	BMP 03 Media Filter Drain	BMP 04 Permeable Shoulders	BMP 05 Bioretention w/o Underdrains	BMP 06 Bioretention with Underdrains	BMP 07 Infiltration Trenches	BMP 08 Infiltration Basins	BMP 09 Infiltration Galleries
Narrow Medians	X		X	X	X	X	X		
Wide Medians	X	X	X	X	X	X	X	X	X
Shoulders including breakdown lane and area within the clear zone (less than approx.15% or 6H:1V)	X	X	X	X			X		X
Shoulders outside of the clear zone (less than approx.15% or 6H:1V)	X	X	X		X	X	X		X
Moderately Steeper Shoulders (steeper than approx.15% or 6H:1V but less than approximately 25% or 4:1)			X						
ROW Locations with Limited Uses (e.g., wide spots, irregular geometries)	X	X	X		X	X	X	X	X
Adjacent Natural Areas		X							
Looped Interchange Medians	X	X	X		X	X	X	X	X
Diamond Interchange Medians	X	X	X		X	X	X	X	X
Low Traffic Areas, Maintenance Yards, etc.	X	X		X[1]	X	X	X	X	X

[1] Permeable pavement in general; shoulders not present.

Figure 7. Key to common geometric opportunities within urban highway environment (hypothetical opportunities shown).

Table 13. Checklist of site applicability.

Part 1: Screening of Project Geometric Design Features and BMP Siting Opportunities

Instructions:

1. *Enter Y (for Yes) or N (for No) in the "Project Attribute" row to indicate project attribute that is present in the project.*
2. *Match opportunity to BMPs that are potentially applicable in that location.*
3. *Enter result: Is there potentially a location where each BMP could be sited?*

BMP	Medians	Shoulders, including breakdown lane and area within clear zone	Shoulders, outside of clear zone	Steeper Shoulders	ROW Locations with Limited Uses (e.g., wide spots, irregular geometries)	Adjacent Natural Areas	Looped Interchange Medians	Diamond Interchange Medians	Low Traffic Areas, Maintenance Yards, etc.	Result: Opportunity to Site BMP?
Project Attribute:										
BMP 01 Vegetated Conveyance	**X**	**X**	**X**		**X**		**X**	**X**	**X**	
BMP 02 Dispersion (within ROW)	**(if wide)**	**X**	**X**		**X**		**X**	**X**	**X**	
BMP 02 Dispersion (outside of ROW)						**X**				
BMP 03 Media Filter Drain	**X**	**X**	**X**	**X**	**X**		**X**	**X**		
BMP 04 Permeable Shoulders	**(if paved)**	**X**							**X**[1]	
BMP 05 Bioretention w/o Underdrains	**X**		**X**		**X**		**X**	**X**	**X**	
BMP 06 Bioretention w Underdrains	**X**		**X**		**X**		**X**	**X**	**X**	
BMP 07 Infiltration Trench	**(if wide)**				**X**		**X**	**X**	**X**	
BMP 08 Infiltration Basin	**(if wide)**				**X**		**X**	**X**	**X**	
BMP 09 Infiltration Gallery	**(if wide)**									

X – Potential BMP opportunity when geometric project feature is present.

[1] Permeable pavement in general; shoulders not typically present.

Key for Table 13 (Part 1)

Headings
User Input
Guidance
No Meaningful Nexus with Site Geometric Design Features

Table 13. (Continued).

Part 2: Screening of Overall Project Attributes				
Instructions:	*1. Enter project information in the "Project Value" row to indicate project attribute that is present* *2. Determine if BMP is compatible project-entered value.* *3. Enter result in last column: Is the overall project compatible with the BMP? Y (for Yes) or N (for No)*			
Overall Project Attributes	**Typical Ratio of BMP Infiltration Surface Area to Impervious Area Needed**	**Presence of Storm Drain System**	**Undeveloped Adjacent Land Use Acceptable for Dispersion or Land Application?**	**Result: Potential for BMP Based on Project Attributes?**
Project Value:				
Vegetated Conveyance	0.01 to 0.10			
Dispersion (within ROW)	0.10 to 0.50			
Dispersion (outside of ROW)	0.10 to 0.50		Critical criteria for dispersion outside of the ROW	
Media Filter Drain	0.10 to 0.25			
Permeable Shoulders	0.10 to 0.25*			
Bioretention with Underdrains	0.02 to 0.10	Important unless grades allow underdrains to daylight		
Bioretention w/o Underdrains	0.02 to 0.10			
Infiltration Basin	0.02 to 0.10			
Infiltration Trench	0.02 to 0.10			
Infiltration Gallery	0 (BMP within impervious footprint)	Important to enable pretreatment and discharge		
Guidance	*Values shown indicate approximate minimum value to achieve meaningful volume reduction performance.*	*Underground systems and systems with underdrains must generally discharge to a storm drain system; additionally, storm drain systems allow pretreatment upstream of underground facilities.*	*Applicable to determining if dispersion is possible in the event that space is not available in the ROW*	

See Part 1e for Geometric Opportunity Screening.

* Note, constructed within pavement footprint.

Key for Table 13 (Part 2)

Headings
User Input
Guidance
No Meaningful Nexus

(continued on next page)

Table 13. (Continued).

Part 3: Other Project-Specific Factors		
Instructions:	*1. Review guidance relative to project attributes.* *2. Enter screening results (i.e., which BMPs are not applicable based on the respective factor) and supporting rationales in last column.*	
Screening Factor	**Guidance**	**Screening Result**
Planting requirements and irrigation needs	Plants are a critical element of the performance of the following: BMP 01 – Vegetated Conveyance BMP 02 – Dispersion BMP 03 – Media Filter Drain BMP 05 and 06 – Bioretention Vegetated BMPs may require irrigation of some sort during establishment or over long-term operations in some climates. **If plants cannot be identified that are compatible with irrigation that can be practically applied, then these BMPs may not be applicable.**	
Locally available materials	Does the BMP require materials that are not available locally? This will be uncommon but, for example, could include specialized binders required for permeable pavement designed for heavy traffic loadings.	
Local jurisdiction acceptance	Do the local jurisdictions with responsibility for approving plans accept the BMP type? Can barriers to approval be overcome?	
Local contractor experience	For specialized installations, such as permeable pavements, do local contractors have the experience needed to ensure successful installation? Do local contractors or the agency have experience maintaining these systems?	

Key for Table 13 (Part 3)

Headings
User Input
Guidance

Table 13. (Continued).

Part 4: Summary of Applicability and Suitability Screening		
Instructions:		1. *Review results of Parts 1 through 3.* 2. *Enter screening results: Y (for Yes) or N (for No).* 3. *Provide summary of rationale for screening result*
BMP	**Screening Results: Applicability**	**Summary of Rationales**
Vegetated Conveyance		
Dispersion (within ROW)		
Dispersion (outside of ROW)		
Media Filter Drain		
Permeable Shoulders		
Bioretention with Underdrains		
Bioretention w/o Underdrains		
Infiltration Trench		
Infiltration Basin		
Infiltration Gallery		

Key for Table 13 (Part 4)

Headings
User Input
Guidance

2.4.4 Compatibility with Local Climate

Cold and arid climates pose specific issues for BMP design and may require design adaptations (see Appendix I). The purpose of this step is to identify overriding issues related to climate that could limit the menu of applicable BMPs.

Potential Overriding Arid Climate Issues

Vegetation Establishment and Maintenance. It can be impractical to supply irrigation in the highway environment, particularly for more distributed BMPs such as vegetated swales and filter strips. The effectiveness of these BMPs relies on establishing grasses with adequate cover to stabilize soils, prevent rill erosion, and facilitate filtering and infiltration. In the arid southwest United States, it may be impractical to use these BMPs, particularly if soils are erosive. Bioretention BMPs may also have limited applicability in arid climates without irrigation (see Figure 8).

Erosive Soils in Tributary Area. Arid climates can experience high rates of erosion from open space areas. If open space areas cannot be adequately stabilized and hydraulically

Figure 8. Example Phoenix, Arizona, freeway with sparsely vegetated shoulders.

isolated from the BMP, this can be a fatal flaw for the use of infiltration and filtration-based BMPs. The BMP Clogging Risk Assessment Tool (Appendix F) can be used to evaluate potential risks. Project teams can also make use of site-specific knowledge of soil types and potential erosive loads.

Potential Overriding Cold Climate Issues

Clayey Soils and Sodium Effects. Sodium in road salts can change the ratio of sodium to calcium and magnesium, which can result in the dispersion of soil clays. This can greatly impair infiltration rate. If soils have measurable clay content and sodium-based deicers are used, then this may preclude infiltration. Similarly, if bioretention is used, then the amended media should be free of clay.

Permeable Pavements and Studded Tires. Permeable pavement can be damaged by studded tires, resulting in premature failure. *NCHRP Report 802* concluded that this was an overriding factor in determining the feasibility of permeable pavement.

Permeable Pavement and Deicing Salts. Permeable pavement can also be damaged by deicing salts. *NCHRP Report 802* concluded that design and construction approaches could limit these issues, but there was still limited experience with these approaches.

Permeable Pavements in Shady Wet Areas. Permeable pavement shoulders (e.g., in low traffic areas) could become occluded by moss in shady areas in some wet climates. This has been observed by the research team in Portland, Oregon, in shady locations with low traffic. The project team should review the exposure of the project and consult local practitioners to determine whether this has been observed in the project region.

Permeable Pavement and Frost Heave. Frost heave within pavement structures can be particularly damaging. If it is not possible to maintain the water storage reservoir below the frost line, then this can render permeable pavement infeasible.

Salt-Induced Corrosion of Steel and Reinforced Concrete Culverts and Structures. Salt can induce or enhance corrosion, which can deteriorate steel structures and steel rebar within reinforced concrete features. For infiltration in cold climates, project teams should consider whether infiltrated water would pose elevated corrosion risks to steel culverts, steel structures, or other intrastate containing steel (either external or as internal reinforcement). Note that this issue is not limited to infiltration BMPs.

2.4.5 Comparison of Other Decision Factors by BMP Type

The following sections provide guidance to help project teams compare different BMP types that may be feasible for a site. All ratings are relative and are not intended to be confirmatory. They are intended to help support BMP selection in cases were multiple BMP types may be suitable and compatible with infiltration objectives and site conditions.

Geotechnical Risk Factors

Project teams can conduct a relative assessment of geotechnical feasibility based on the unit treatment processes and typical installation geometry for different BMPs (see Table 14). This is not a replacement for geotechnical feasibility analyses described in Chapter 3 but can be used to evaluate how BMPs compare with one another.

Groundwater Quality

Table 15 presents factors related to BMP design that can influence potential for groundwater quality impacts. Pretreatment is a general term that refers to providing an initial level of treatment provided to stormwater before it enters a BMP, such as filtering through grass, settling, centrifugal separators, media filters, or other devices.

Table 16 provides a synthesis of relative risk posed by each of the nine primary BMPs based on the information provided in Table 15. Note that a higher-risk ranking in Table 15 does not necessarily imply that the BMP should not be used; however, the BMP may be less favorable than lower-risk BMPs when site conditions indicate a higher potential for groundwater quality issues.

Roadway and Maintenance Safety

Several key safety considerations may relate to the siting and design of BMPs including the following:

- Limitations on grading and structures within the clear zone along the road shoulders to allow errant vehicle recovery and reduce collision hazards
- Vegetation management to maintain line-of-site requirements as well as to eliminate collision hazards within the clear zone
- Adequate supplemental drainage as needed to avoid flooding of travel lanes
- Lane closures to allow maintenance activities within the ROW
- Other potential issues

Based on their respective locations within the highway environment and their inherent design attributes, each BMP has a different suite of applicable factors. Safety considerations that may apply to specific BMPs are described in the respective BMP Fact Sheets and are summarized in Table 17. These factors do not necessarily result in BMPs being considered infeasible but should be a factor in selection, siting, and design.

Maintenance Activities and Requirements

Maintenance of BMPs ranges from regular highway maintenance activities (e.g., trash control or vegetation management) that may be done whether or not a BMP is in place, to more

Table 14. Summary of relative geotechnical opportunities and constraints for specific categories of BMPs.

Category of BMP	Characteristic Properties	Example Opportunities and Constraints Related to Geotechnical Issues[1]	
		Opportunities	**Constraints**
Direct infiltration into roadway subgrade *Example:* ☐ *BMP 04 Permeable Pavement*	☐ Relatively low loading ratio[2] ☐ Road subgrade has important structural considerations, particularly for flexible pavement design.	☐ Broad footprint of permeable pavement may allow infiltration in relatively impermeable and compacted soils. ☐ Standard roadway designs typically account for wetting of subgrade. ☐ Rigid pavement design (e.g., concrete) is less sensitive to subgrade strength.	☐ Utilities and infrastructure in the ROW ☐ Settlement and volume change processes (e.g., consolidation, frost heave, swelling, liquefaction) ☐ Reduction in strength of subgrade material from increase in moisture content ☐ Mounding and effects on nearby infrastructure
Infiltration in breakdown lane and near shoulders *Example:* ☐ *BMP 03 Media Filter Drain* ☐ *BMP 04 Permeable Shoulders*	☐ Outside of main travel lanes; significantly less traffic loading ☐ Relatively low loading ratio[2]	☐ Shoulders designed to accommodate less traffic loading than travel lanes ☐ Well-distributed inflow ☐ Linear configuration less susceptible to groundwater mounding than basin configurations ☐ An underdrain can control the amount of water infiltrated and limit the maximum water level in the reservoir.	☐ Typically, shoulder must be compacted to same degree as mainline roadway. ☐ Potential for water to migrate laterally into mainline subgrade rock or nearby development ☐ Settlement or volume change ☐ Potential reduction in slope stability for embankment or depressed sections ☐ Mounding and effects on nearby infrastructure
Infiltration and surface dispersion in the clear zone *Example:* ☐ *BMP 02 Dispersion* ☐ *BMP 03 Media Filter Drain*	☐ Allows incidental infiltration over relatively broad area; also provides ET ☐ Typically coupled with vegetated conveyance at toe of filter strip	☐ Drainage over shoulder is a typical design feature. ☐ Higher proportion of losses to ET than other BMPs ☐ Relatively little mounding expected	☐ May lead to erosion issues if applied on slopes that are too steep or lack stabilizing vegetation. ☐ Slopes may need to be compacted to same degree as mainline roadway; surficial soils need to be strong enough for errant vehicle recovery. ☐ In some cases, settling or volume change could damage roadway. ☐ Subject to frozen ground issues
Channels, trenches, and other linear depressions offset parallel to roadway *Example:* ☐ *BMP 01 Vegetated Conveyance* ☐ *BMP 05 and 06 Linear Bioretention Variation* ☐ *BMP 07 Infiltration Trenches*	☐ Tends to be located 10 or more ft from travel lanes ☐ Typically, effective water storage depth is between 6 in. and 36 in. ☐ Typically have a relatively high loading ratio ☐ May be fully or partially infiltrated	☐ Channels with positive grade are common drainage features; have relatively limited increase in risk. ☐ Due to horizontal separation, features have less potential to damage roadway. ☐ Some settlement may be tolerable. ☐ Deeper designs may avoid frost impacts.	☐ Greater potential for impacts out of the ROW due to proximity to the ROW line. ☐ Greater potential for mounding due to concentration of infiltrating footprint. ☐ May reduce stability of slopes if located near top or toe.

Table 14. (Continued).

Category of BMP	Characteristic Properties	Example Opportunities and Constraints Related to Geotechnical Issues[1]	
		Opportunities	Constraints
Basins *Example:* ☐ *BMP 05 and 06 Bioretention (more centralized variation)* ☐ *BMP 08 Infiltration Basins* ☐ *BMP 09 Infiltration Galleries*	☐ Typically located in more centralized locations ☐ Typically have a relatively high loading ratio ☐ Typically, effective water storage depth is between 12 in. and 60 in.	☐ Centralized areas, such as wide spots in ROW or interchanges, may allow ample setbacks from foundations, slopes, and structural fill. ☐ May be possible to preserve natural soil infiltration rates through construction ☐ Impacts of potential settlement may be minor.	☐ Deeper ponding depths may result in substantial groundwater mounding and lateral water migration; greater setbacks may be needed than would be applied for more distributed systems. ☐ Surface systems subject to frozen ground issues

[1] Examples provided to identify typical opportunities and constraints of the infiltration design feature. Additional opportunities and constraints may be present at a given site.

[2] "Loading ratio" refers to is the ratio of the impervious tributary area to the footprint of the infiltrating surface. A high loading ratio indicates that the infiltrating footprint is relatively small compared with the impervious tributary area and vice versa. This Guidance Manual defines the following general categories for loading ratios: high: > 20:1; medium: 5:1 to 20:1; low: < 5:1.

Table 15. Summary of relative BMP-related risk factors for groundwater quality impacts.

Risk Factor	Discussion	Lower-Risk Indicators ⟷	Higher-Risk Indicators
Hydraulic loading ratio	The relative footprint of the system influences the pollutant loading per unit area and the potential for natural assimilative capacity to be overwhelmed.	Systems with broader, shallower footprint such as dispersion	Systems with deeper profiles and smaller footprints such as infiltration trenches
Layer at which infiltration occurs	When infiltration occurs below organic soil and/or closer to the groundwater table, there tends to be less pollutant attenuation capacity.	Systems infiltrating near the surface where soils have higher organic content and biologic activity (or are amended to provide this)	Systems infiltrating below the organic strata and not providing a treatment layer such as imported amended soil (or other pretreatment)
Amount of infiltration occurring	Potential for groundwater impacts tends to be higher when there is more infiltration.	Systems with less infiltration, such as vegetated conveyance	Systems with more infiltration, such as infiltration galleries
Potential for pretreatment or treatment within the BMP	Pretreatment is important to reduce potential for clogging as well as to address groundwater quality.	Systems providing a treatment layer such as an engineered soil media layer or an amended soil layer	Systems where pretreatment cannot be practically provided and treatment processes within and below the BMP are limited such as permeable pavement
Spill risk and spill containment options	Spills are infrequent events but have the potential to cause major groundwater quality issues. The most problematic pollutants are solvents and other phase non-aqueous dense liquids.	Systems that have a pretreatment/ containment system Systems that drain lower traffic roadways Systems with lower hydraulic loading ratio	Systems where it is not possible to provide pretreatment or containment Systems that drain higher traffic roadways Systems with higher hydraulic loading ratio

Table 16. Relative ranking of potential groundwater quality risk by BMP type.

BMP	Relative Risk of Groundwater Quality Impacts[1]	Key Characteristics Influencing Ranking
BMP 01 Vegetated Conveyance	L	More limited infiltration, shallower ponding, and soil filtration of infiltrating runoff
BMP 02 Dispersion	L	Shallower ponding, high soil contact ratio, amended/organic/biologically active soils
BMP 03 Media Filter Drain	L	Shallow ponding, specialized media with high treatment capacity
BMP 04 Permeable Shoulders	M	Can have a relatively small footprint area, some pretreatment provided in base material but additional pretreatment not practical, can infiltrate water below organic soil strata
BMP 05 Bioretention without Underdrains	L to M	Provide treatment for most constituents within media, can have relatively small footprint and deeper infiltrating surface
BMP 06 Bioretention with Underdrains	L	Provide treatment for most constituents within media, infiltrate less water than bioretention w/o underdrain
BMP 07 Infiltration Trenches	M to H	Deeper profile typically below surface soil strata, pretreatment options may be limited
BMP 08 Infiltration Basins	M	Deeper profile and typically smaller tributary area ratio but soil can be amended to improve water quality.
BMP 09 Infiltration Galleries	M to H	Deeper profile typically below surface soil strata, pretreatment may not address all pollutants of concern.

[1] Rankings are relative to other BMPs. This is not a ranking of total risk because that would also be a function of pollutant sources, site conditions, and applicable groundwater quality criteria.

L, M, and H – Low, Medium, and High, respectively.

BMP-specific maintenance activities that are needed to maintain the intended function of the systems. These activities can be categorized into routine maintenance, which includes normally scheduled inspections and activities needed on a regular basis, and corrective maintenance, which includes as-needed activities triggered by observations of damage, failure, pending issues, or other factors that require action to return the facility to its intended function. Table 18 and Table 19 provide an inventory of routine maintenance activities and corrective maintenance activities, respectively, that may apply to each of the primary BMPs. These tables were developed based on review of guidance manuals and interviews with DOT maintenance staff; however, it is important to note that information on maintenance requirements of BMPs in the highway environment is still limited to informing decision-making. *NCHRP Report 792* included assessments of maintenance needs and developed whole lifecycle cost estimating tools for a variety of stormwater control measures, including common infiltration BMPs.

Whole Lifecycle Costs

Whole lifecycle cost estimation is not the focus of this Guidance Manual; however, tools are available from *NCHRP Report 792* to support this assessment for multiple infiltration BMPs, and

Table 17. Summary of potential safety considerations by BMP.

Potential Safety Consideration	BMP 01 Vegetated Conveyance	BMP 02 Dispersion	BMP 03 Media Filter Drain	BMP 04 Permeable Shoulders	BMP 05 Bioretention w/o Underdrains	BMP 06 Bioretention with Underdrains	BMP 07 Infiltration Trench	BMP 08 Infiltration Basin	BMP 09 Infiltration Galleries
Limitations on side slopes and berms within the clear zone, including check dams, etc.	X	X	X		X	X	X	X	
Limitations on drainage structure design within the clear zone (e.g., pipe inlets and outlets flush to slope)	X	X	X		X	X	X		
Stability of soil within the clear zone, particularly if compost amended	X	X	X		X	X			
Vegetation management to remove collision hazards		X			X	X			
Vegetation management to maintain line of site	X	X			X	X		X	
Supplemental drainage to ensure free drainage of travel lanes in the event of clogging				X					
Low speed vehicle maintenance activities and lane closures	X	X	X	X					X

X = indicates that the safety consideration may apply to the BMP.

Table 18. Summary of potential routine maintenance activities by BMP.

Routine Maintenance Activities	BMP 01 Vegetated Conveyance	BMP 02 Dispersion	BMP 03 Media Filter Drain	BMP 04 Permeable Shoulders	BMP 05 Bioretention w/o Underdrains	BMP 06 Bioretention with Underdrains	BMP 07 Infiltration Trenches	BMP 08 Infiltration Basins	BMP 09 Infiltration Galleries
Mowing	●	●	●	○	⦿	⦿	●	●	○
Maintain-Level Spreading Functions	⦿	⦿	⦿	○	○	○	⦿	⦿	○
Landscaping and Weeding	⦿	⦿	○	○	●	●	⦿	⦿	○
Routine Woody Vegetation Management	○	○	○	○	⦿	⦿	⦿	●	○
Sediment Removal and Management	⦿	○	⦿	⦿	⦿	⦿	●	●	●
Vacuum Sweeping	○	○	○	⦿	○	○	○	○	○
Trash and Debris Removal	●	●	●	●	●	●	●	●	●
Erosion Repair	⦿	⦿	⦿	○	⦿	⦿	⦿	⦿	○
Rodent Hole or Beaver Dam Repair	○	○	○	○	○	○	○	⦿	○
Fence or Access Repair	○	○	○	○	⦿	⦿	⦿	⦿	○

Key: ● Primary maintenance activity; ⦿ Minor maintenance activity (may not apply in some cases or may be limited); ○ Not usually applicable.

Table 19. Summary of potential corrective maintenance activities by BMP.

Corrective Maintenance Activities	BMP 01 Vegetated Conveyance	BMP 02 Dispersion	BMP 03 Media Filter Drain	BMP 04 Permeable Shoulders	BMP 05 Bioretention w/o Underdrains	BMP 06 Bioretention with Underdrains	BMP 07 Infiltration Trenches	BMP 08 Infiltration Basins	BMP 09 Infiltration Galleries
Re-grading to maintain level spread function		X	X						
Re-grade to remove sediment or fix erosion	X				X	X		X	
Repair berms, inlets, outlets, or other structures	X	X	X		X	X	X	X	X
Cleaning of underdrain pipes			X	X		X			
Decompaction/re-amendment	X	X	X					X	
Partial removal of surface material to remediate clogging or pollutant buildup				X	X	X	X	X	X
Complete replacement of system components				X	X	X	X	X	X
Re-seeding to provide needed coverage	X	X	X					X	
Significant re-vegetation to provide needed coverage	X	X			X	X		X	
Remediate contamination from acute or chronic loadings (oil, gas, or other contaminants)	X	X	X	X	X	X	X	X	X

X = Potentially applicable.

local cost estimation frameworks can be used. It is challenging to assign an average or typical whole lifecycle cost to an entire category of BMPs because of variability in design and construction as a result of site-specific factors. Additionally, information on whole lifecycle costs and lifespan is still limited to informing decision-making. For purposes of initial decision-making about BMP selection, Table 20 represents the relative costs of selected BMPs based on a typical application, with notes to identify key site-specific factors that may influence these rankings. Because relative capital costs can be significantly different in new roadway projects and lane additions as opposed to retrofit projects, a separate column is provided for these two categories of projects.

2.4.6 Step 2 Results: Selection of BMP Locations and Types

Step 2 should yield three primary outcomes:

- Tentative selection of BMP type and variation if applicable (e.g., presence of underdrains)
- Determination of available space and tentative feasibility conditions at the BMP location
- Delineation of the tentative tributary area to the tentative BMP locations

These key parameters are needed to support the confirmation of BMP feasibility described in Chapter 3. Table 21 is an example of a template that can be used to summarize these parameters. The process for BMP selection may vary based on local criteria, the preferences of the design team, and other factors.

Table 20. Typical BMP costs per volume of stormwater managed [adapted from Washington State Department of Transportation (WSDOT) (2014)].

BMP	Capital Costs – New Roadway or Major Redevelopment	Capital Costs – Retrofit Projects or Minor Redevelopment	O&M and Replacement/ Reconstruction Costs	Effective Life Span
BMP 01 Vegetated Conveyance	**Low to Moderate** ☐ Can typically be easily incorporated into grading plans for non-ultra-urban settings. ☐ Provides conveyance function that can offset need for pipes and structures.	**Low to Moderate** ☐ Modifications to existing swales to improve volume reduction may be inexpensive. ☐ Can add significant cost if regrading and rerouting must be done to accommodate BMP.	**Low to Moderate** ☐ Requires more frequent maintenance than a typical vegetated or concrete ditch without water quality functions. ☐ Erosion/scour must be addressed.	**20 to 50 years** ☐ Regrading of conveyance. ☐ Decompact underlying soils, potentially add new amendments. ☐ Correct major erosion.
BMP 02 Dispersion	**Low** ☐ Assuming no acquisition costs for the ROW; land acquisition can render this option cost prohibitive. ☐ Provides conveyance function that can offset pipes and structures.	**Low to Moderate** ☐ Assuming no acquisition costs for the ROW; land acquisition can render this option cost prohibitive. ☐ Depends on extent of routing and grading improvements needed to utilize dispersion area.	**Low** ☐ Requires minimal maintenance of vegetation that would be similar to vegetated ROW. ☐ Reconstruction costs are typically lower than original construction.	**20 to 50 years** ☐ Regrade level spreader. ☐ Decompact underlying soils, potentially add new amendments. ☐ Correct major erosion.
BMP 03 Media Filter Drain	**Low to Moderate** ☐ Assumes no acquisition costs for land needed for conveyance or storage system. ☐ Shared grading/excavation costs with project.	**Moderate** ☐ Requires minor excavation and removal of soil. ☐ May require modifications to drainage patterns. ☐ Can fit on existing shoulders.	**Low to Moderate** ☐ Requires infrequent maintenance to remove sediment and maintain conveyance if tributary watershed is stabilized. ☐ Periodic maintenance possibly needed to replace media.	**5 to 20 years*** ☐ Regrade level spreader. ☐ Replace media if exhausted. ☐ Shorter than BMP 01 and 02 because footprint tends to be smaller and more specialized media is used.

(continued on next page)

Table 20. (Continued).

BMP	Capital Costs – New Roadway or Major Redevelopment	Capital Costs – Retrofit Projects or Minor Redevelopment	O&M and Replacement/ Reconstruction Costs	Effective Life Span
BMP 04 Permeable Shoulders with Stone Reservoirs	**Low to Moderate** ☐ Assumes new development or lane additions in which the cost of permeable pavement offsets traditional pavement costs that would have been used.	**High** ☐ Cost to add permeable shoulders to an existing roadway are much greater than building these as part of a new roadway. ☐ Requires excavation and hauling of previous roadway; import of new material. ☐ Equipment, labor, and installation costs are directly associated with BMP.	**Moderate to High** ☐ Requires regular vacuum sweeping. ☐ Surface replacement may be required more frequently than traditional pavement. ☐ Full depth replacement may cost more than initial construction. ☐ If water routed directly to subbase via inlets, sweeping not needed, but earlier clogging of the subbase layer may occur.	**15 to 25 years**** ☐ Replace top course of permeable pavement because of structural wear. ☐ Fully excavate to restore infiltration capacity of subgrade. ☐ Dependent on sediment loading, traffic loading, and other factors. Not well established.
BMP 05 and 06 Bioretention	**Moderate** ☐ Specialized planting and soil, so net cost increase should be considered over areas that would have been planted. ☐ Assumes grading and conveyance in conjunction with overall project. ☐ Use of an underdrain results in greater cost and less volume reduction; however, it can reduce the risk of failure.	**Moderate to High** ☐ Cost of rerouting flows to specific areas. ☐ Some aspects of site investigation and construction not shared with overall project. ☐ Possibility of additional land acquisition.	**Moderate** ☐ Regular maintenance of vegetation and trash similar to baseline landscape maintenance. ☐ May require restoration of surface infiltration capacity and replanting at regular intervals. ☐ Periodic removal of top layer to prevent contamination build-up and maintain infiltration.	**5 to 12 years (partial)** ☐ Dependent on effectiveness of pretreatment. ☐ Restoration of surface infiltration capacity and replanting. ☐ Intervals may be longer if vegetation is robust. **25 to 50 years (complete)** ☐ Replacement of media/ structures/piping at less frequent intervals.
BMP 07 Infiltration Trench	**Moderate to High** ☐ Requires several additional construction materials. ☐ Volume is based on porosity of gravel, so bulk volume is greater than effective volume. ☐ Assumes no land acquisition. ☐ Can be incorporated into excavation plans. ☐ May also need to construct a swale for pretreatment.	**High** ☐ Increased equipment, construction, and labor costs. ☐ Additional excavation costs.	**High** ☐ Requires maintenance of debris and sediment removal to maintain infiltration. ☐ Failures have been common. ☐ Replacement cost similar to new construction, because infiltration surface is not exposed.	**5 to 15 years** ☐ Dependent on effectiveness of pretreatment. ☐ Excavate rock and rework trench to maintain infiltration rates; backfill with existing rock after removing fines. ☐ May only be able to restore capacity a limited number of times before moving the facility location.

BMP 08 Infiltration Basin	**Moderate** ☐ Assumes no acquisition costs for land. ☐ Assumes potential additional excavation and infrastructure to convey water to centralized location. ☐ Basins can offset pipes or reduce size of downstream conveyance.	**High** ☐ Cost of rerouting flows to specific areas. ☐ Aspects of site investigation and construction not shared with overall project. ☐ Possibility of additional land acquisition. ☐ Costs can be lower if existing detention basin can be converted to infiltration.	**Moderate** ☐ Requires maintenance of debris removal to maintain infiltration. ☐ Maintenance of any conveyance systems. ☐ Periodic removal of top layer to prevent contamination build-up and maintain infiltration.	**5 to 10 years (partial)** ☐ Dependent on effectiveness of pretreatment. ☐ Restoration of surface infiltration capacity can be longer if deep rooted plants are used. ☐ May only be able to restore capacity a limited number of times before moving the facility location. **25 to 50 years (complete)** ☐ Replacement of structures/piping and deep restoration of subgrade at less frequent intervals (25 to 50 years). Eventually may need to move facility location if possible.
BMP 09 Infiltration Gallery	**Moderate to High** ☐ Excavation and piping can be incorporated into construction plans. ☐ Assumes robust pretreatment system	**High** ☐ Cost of rerouting flows to specific areas ☐ Aspects of site investigation and construction not shared with overall project ☐ Assumes robust pretreatment system	**High** ☐ Below grade is difficult to maintain ☐ Requires maintenance of debris and sediment removal to maintain infiltration ☐ Requires regular maintenance of pretreatment system	**10 to 25 year***** ☐ Rough estimate, assuming robust pretreatment; could be much less without pretreatment. ☐ If gallery is accessible, may be possible to restore capacity a limited number of times before reconstruction.
	*Based on WSDOT best professional judgment; systems have not been in place for full lifecycle. **Not provided by WSDOT; estimated from Houle et. al. 2013. *** Best professional judgment; highly site specific and dependent on pretreatment methods used.			

Table 21. Example table to summarize outcome of BMP selection.

BMP ID	BMP Type and Variation	Tentative Feasibility Condition at BMP Location	Available BMP Footprint Area	Anticipated BMP Depth	Tributary Area	% Impervious

An infiltration feasibility exhibit can also be useful to document preliminary BMP selection and siting. Potential content of this exhibit includes the following:

- Topographic and drainage feature elements (Section 2.2.2)
- Proposed project elements (e.g., roadway alignments, embankments, structures)
- Infiltration feasibility constraints and tentative categorization
- Tentative BMP locations, footprints, and types
- Tributary areas to BMP
- Locations of field soil sampling, infiltration testing, and groundwater monitoring if applicable.

The content of this exhibit may vary by project.

CHAPTER 3

Confirmation of BMP Selection Through Prioritized Analyses and Investigations

This chapter provides guidance on prioritized analyses and site investigations that may be necessary to confirm or revise preliminary selection of infiltration approach, BMP types, and locations. This is Step 3 in the overall decision-making process.

3.1 BMP Confirmation Process by Planning Track

The following sections describe the recommended next steps to confirm or revise the selected infiltration BMP types at the tentative locations determined in Step 2. An overview of this process is provided in Figure 9. These track numbers align with the matrix presented in Table 10. Tracks are further described in the subsections that follow.

To use Figure 9, find the track number in the left column that best fits the tentatively selected BMPs types and locations. Read across to determine the analyses and investigations necessary to confirm that the tentatively selected BMPs are appropriate. The following subsections provide further explanation.

3.1.1 Track 1a: Favorable Infiltration Conditions—Infiltration BMP Selected

Unless the preliminary determination of infiltration feasibility was supported by methods appropriate for BMP design, the project team should conduct additional investigations and analyses to confirm feasibility including the following:

- Confirm soil infiltration rates and develop a reliable factor of safety based on appropriate methods (see Section 3.2 and Appendix B).
- Evaluate sizing and performance based on the design infiltration rate determined from design-level methods (see Section 3.3).
- Conduct additional characterization of soil properties and geologic conditions as needed to confirm absence of geotechnical issues and verify assumptions used in groundwater mounding evaluations (see Section 3.4).
- Conduct more thorough or longer-term characterization of groundwater depth, seasonality, pretreatment requirements, and regional- or watershed-scale issues to verify assumptions (see Section 3.5).

To reduce the risk of infiltration failures, the project team should address each of these factors to confirm the selection of this approach based on the criteria presented in Sections 3.2 through 3.5 (or applicable local criteria).

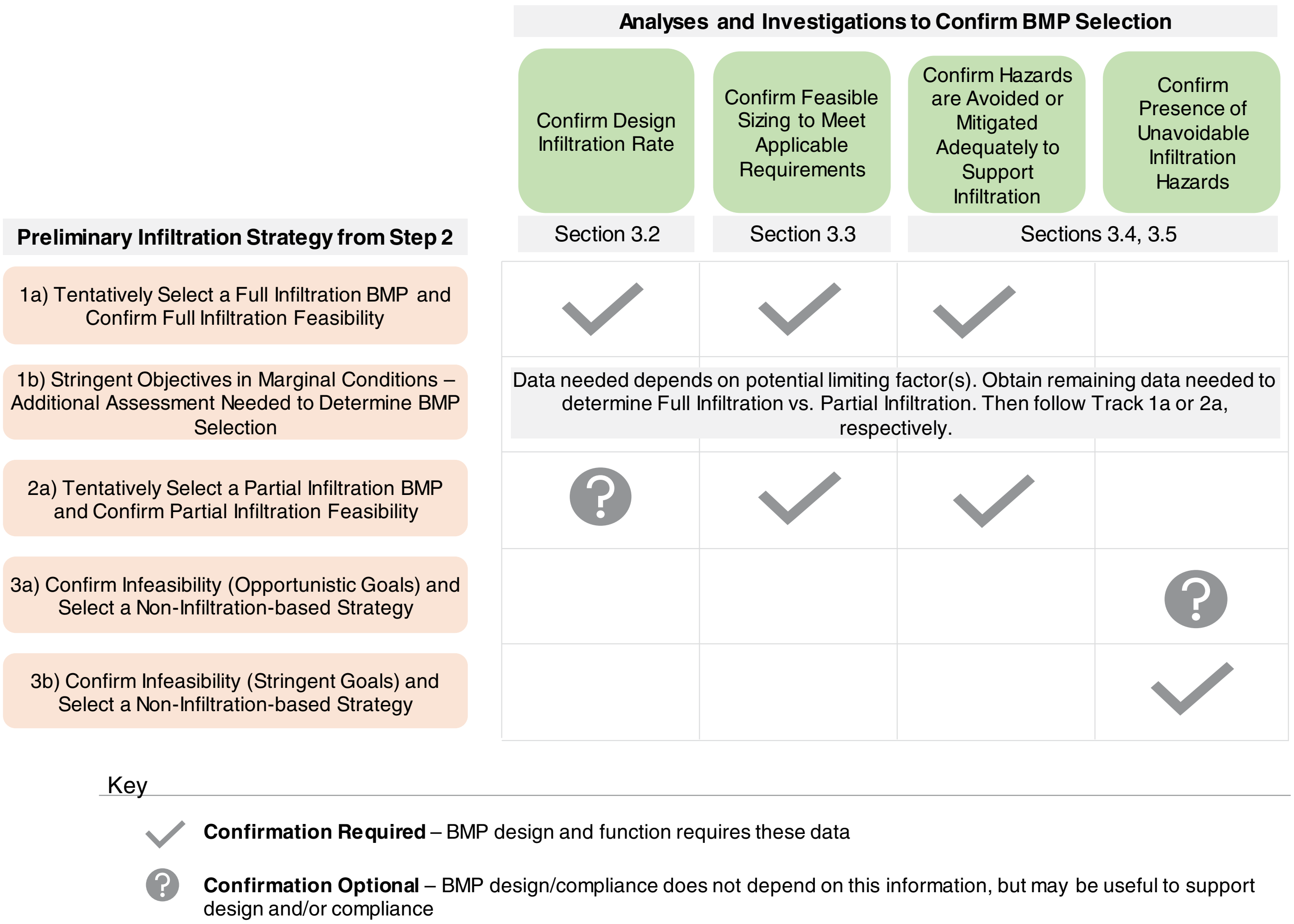


Figure 9. Overview of analyses and investigations to confirm BMP selection.

3.1.2 Track 1b: Stringent Infiltration Objectives in Marginal Conditions

In marginal conditions, the feasibility of infiltration can depend on a range of factors that may not have been present at the time of project design (e.g., soil conditions after grading has occurred) or may be costly to investigate (e.g., site-specific groundwater mounding in complex hydrogeologic conditions). When infiltration objectives are stringent, project teams may face a mandate to conduct these assessments and/or determine whether there are design alternatives that could result in adequate confidence to move forward with infiltration. **This is likely to be the most costly and time-consuming planning track.** Project teams should undertake this track only if mandated by the project infiltration objectives (either regulatory driven or project driven).

Key elements needed to confirm selection of an infiltration approach include the following:

- Confirm soil infiltration rates and develop a reliable factor of safety based on appropriate methods (see Section 3.2 and Appendix B).
  - Potential issues. The site was classified as marginal because of the inability to conduct field-scale tests or the use of rapid and less reliable tests.
  - Potential resolutions. Conduct more reliable field tests if feasible.

- Evaluate ability to better control infiltration properties through the construction phase of the project.
  - Potential issues. Infiltration conditions were rated as marginal because of the inability to predict infiltration properties in the post-constructed conditions (e.g., significant cut and fill operations or construction traffic that affects infiltration rates).
  - Potential resolutions. Consider special specifications for fill material and construction site management. Consider modifications to the project delivery process, as described in Section 3.6.
- Analyze selected BMP profile and footprint to verify sizing and performance analysis (see Section 3.3).
  - Potential issue. The combination of space constraints and marginal soil infiltration capacity make it uncertain whether BMPs will be able to meet performance goals (e.g., long-term capture efficiency) and drawdown time limits.
  - Potential resolutions. Analyze potential BMP footprints, depths, performance, and groundwater mounding impacts. Depending on results, consider different design alternatives, such as BMPs that are shallower and more distributed (e.g., permeable shoulders or infiltration swales) that provide a larger infiltration surface total.
- Evaluation of other issues needed to confirm feasibility. If evaluation of these issues indicates that Full Infiltration may be feasible, then the remaining feasibility criteria should be assessed:
  - Potential issues. Feasibility determinations relative to geotechnical and groundwater issues are preliminary and need to be finalized based on actual BMP locations and types.
  - Potential resolutions:
    - Conduct more thorough characterization of soil properties and geologic conditions to confirm absence of geotechnical issues and verify assumptions used in groundwater mounding evaluations (see Section 3.4).
    - Conduct more thorough or longer-term evaluation of groundwater depth, seasonality, pretreatment requirements, and regional- or watershed-scale issues to verify assumptions (see Section 3.5).

A flowchart is provided in Figure 10 to support decision-making. Upon completion of the applicable investigations, the project team should apply the final decision-making criteria (see Section 3.7 or locally applicable criteria) to determine whether the project should proceed with Full Infiltration or pursue a reduced level of infiltration complemented by alternative non-infiltration approaches.

3.1.3 Track 2a: Maximized Infiltration Objectives in Marginal Conditions

When a project has maximized objectives for stormwater infiltration and is in marginal (but at least partially feasible) infiltration conditions, the project team has two alternative approaches. These are at the discretion of the project designers. Decision guidance is provided as follows.

1. Select and design BMPs to achieve Maximized Partial Infiltration. Examples of BMPs that can provide this level of treatment include the following:
   a. Bioretention basins or bioretention swales with underdrains can include a gravel sump below the discharge elevation of the underdrain. This type of BMP requires the gravel sump to fill before treated discharge can occur. If soils are more permeable than expected, this type of system can achieve performance similar to Full Infiltration; the underdrain would be infrequently utilized. If infiltration rates are less than expected, then greater treated discharge would occur, but the overall the system would still provide water quality functions and be able to meet applicable treatment standards.

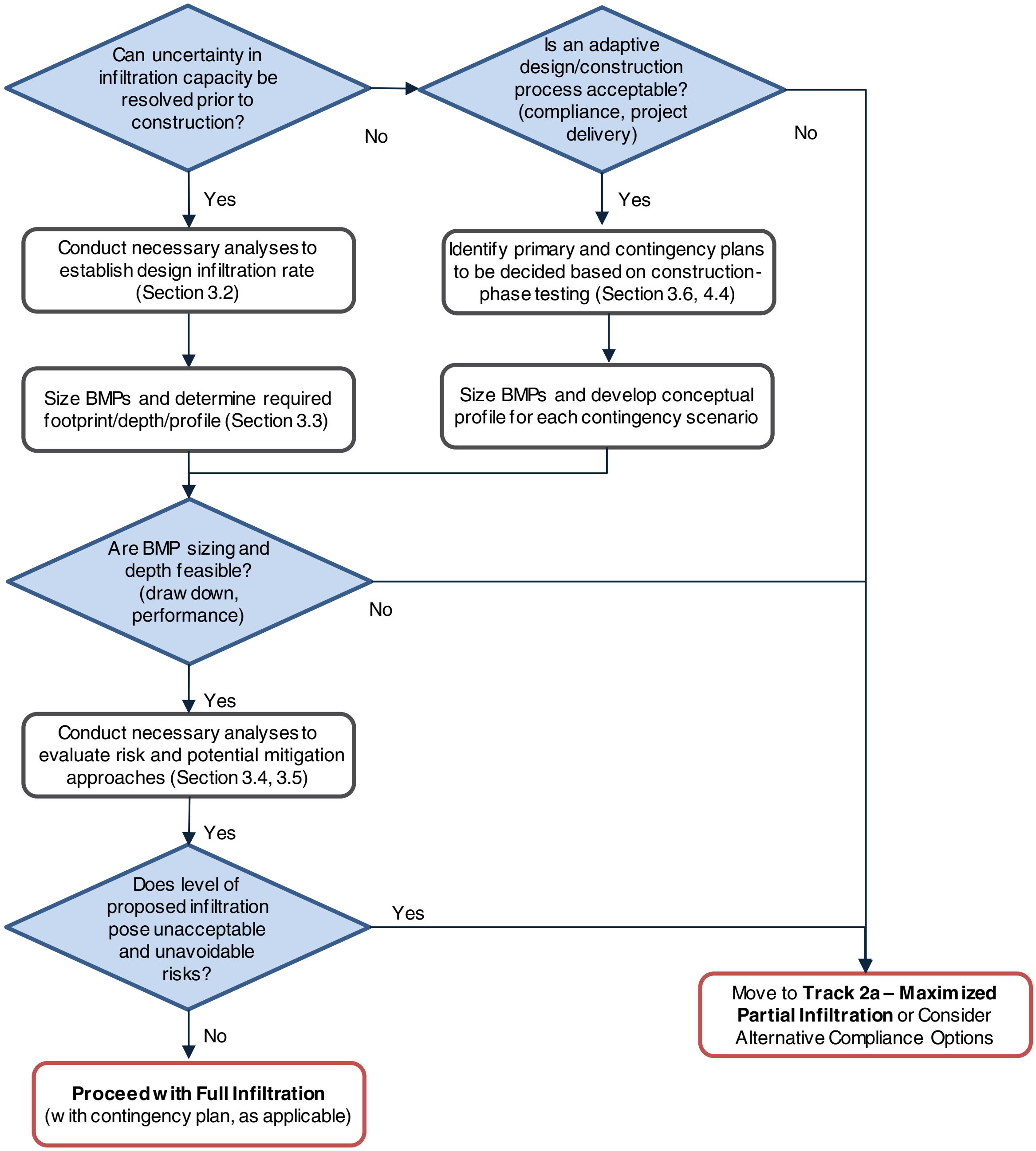


Figure 10. Flow Chart Track 1b: stringent objectives in marginal conditions.

b. Filter strips and other dispersion approaches provide treatment and positive overland flow paths for water that is not infiltrated. Therefore, the level of infiltration depends on the actual soil properties, but the operability of the BMP to manage and treat stormwater does not rely on a certain level of infiltration.

Because these approaches include supplemental treatment pathways and do not rely on a certain minimum infiltration rate, additional infiltration testing is not critical. **If this option is selected, then the project can typically proceed without further infiltration rate investigations.** The project team should still determine that partial level of infiltration would not pose geotechnical or groundwater quality risks.

2. Refine site investigations to attempt to support Full Infiltration BMPs. In cases in which the marginal categorization is based on the preliminary nature of the investigation or in which there are data gaps, the project team should consider additional analyses to refine infiltration investigations. The project would follow the guidance presented for Track 1b. Key reasons why projects may seek this option include the following:
   a. The types of Maximized Partial Infiltration BMPs described above are not feasible or are cost prohibitive. Perhaps these BMPs do not fit within the project constraints, or there are not storm drains available to receive the underdrain flow.
   b. The use of Full Infiltration BMPs (i.e., systems that infiltrate the full water quality volume) could save money overall, even if these BMPs are costly to investigate and confirm.
   c. Local guidelines or policies require greater rigor to be applied in rejecting the use of Full Infiltration. For example, if soil maps were used to make initial assessments, these may not be adequate as the sole basis for rejecting Full Infiltration. Using maps to make decisions about infiltration feasibility can be subject to local discretion and requirements.

If additional data collected clearly support Full Infiltration, then the project could shift to planning Track 1a and demonstrate the feasibility of Full Infiltration. If additional data confirm that site conditions do not support Full Infiltration, then the project could shift to using a Maximized Partial Infiltration approach if feasible.

3.1.4 Track 3a: Limited or No Infiltration Feasible—Opportunistic Objectives

In this case, nothing further is typically needed to justify decision-making. If there are not regulatory drivers to pursue infiltration and conditions appear infeasible, then additional effort to investigate or confirm this finding is not needed.

3.1.5 Track 3b: Limited or No Infiltration Feasible—Maximized or More Stringent Objectives

The primary strategies in this case should focus on one or both of the following. The specific approach will depend on the degree of certainty in the preliminary finding of infeasibility and whether local regulations establish a minimum burden of proof for rejecting infiltration.

1. Conduct analyses to confirm or revise tentative infeasibility findings. If preliminary findings were based on limited information or a rapid analysis, then supplemental investigations may be warranted to verify these findings. If the refined findings allow the project to transition to a Maximized Partial Infiltration BMP approach, then this could help the project team accrue benefits toward compliance and other infiltration objectives.
2. Conduct analyses to present an adequate regulatory case for rejecting the use of infiltration. If local requirements or guidance prescribe the use of specific methods to determine infiltration feasibility, then it may be necessary to apply these methods to justify the decision to not infiltrate.

In these cases, the final infiltration feasibility criteria presented in Section 3.7 can be used to refine or confirm initial findings.

3.1.6 Summary

Table 22 summarizes additional efforts that may be needed to confirm feasibility.

Table 22. Prioritized site investigations to confirm or revise infiltration approach.

Prioritized Investigation	Supporting Resources	Applicability and Purpose
Develop design infiltration rate	Section 3.2 and Appendix B	Track 1a, 1b: verification of Full Infiltration feasibility
Verify sizing and performance feasibility	Section 3.3, Appendix B, and Appendix C	Track 1a, 1b: verification of Full Infiltration feasibility
Confirm geotechnical findings and recommendations	Section 3.4 and Appendix E	Track 1a, 1b, 2a, 3b: confirm or revise findings as needed
Confirm groundwater findings and recommendations	Section 3.5 and Appendix D	Track 1a, 1b, 2a, 3b: confirm or revise findings as needed
Evaluate alternative project delivery options and needs	Section 3.6	Primarily 1b where construction-phase control and decision-making are critical for success
Finalize infiltration feasibility findings	Section 3.7	All except Track 3a

3.2 Design Infiltration Rate

Design-level infiltration testing is required for all Full Infiltration BMPs and for Partial Infiltration BMPs that are being designed to meet a specified infiltration performance. Design-level infiltration testing is used to confirm preliminary planning infiltration thresholds and develop design infiltration rates. Design-phase testing may not be required for Partial Infiltration BMPs that do not rely on a specific infiltration rate and do not need to be designed to achieve a specific quantify of infiltration.

3.2.1 Refinements from Preliminary Assessment

The scope of the investigation should include the following activities as explained further in Appendix B:

- Conduct infiltration testing at the location and elevation of the proposed infiltrating surface consistent with an acceptable design-phase testing method for the anticipated BMP type.
- Complete necessary infiltration tests, corresponding with method type selection, to adequately characterize infiltration surface spatial variability.
- Interpret infiltration testing results based on site conditions and other available data (e.g., groundwater levels and bore logs).
- Develop a design infiltration rate using an appropriate factor of safety to account for uncertainty and clogging.

Appendix B provides guidance on method selection and interpretation.

If groundwater mounding has been identified as a potential issue, the project team or hydrogeologic professional should further evaluate mounding. This analysis could potentially be performed using Appendix C: Roadside BMP Groundwater Mounding Assessment Guide and User Tool. At this phase, data should be site specific wherever feasible, particularly for parameters found to have an appreciable influence on results. Additionally, the project team or hydrogeologic professional should review the simplifying assumptions in this tool and verify them to be acceptable for the project site. If these simplifications are not applicable to the site, and groundwater mounding is potentially an issue, then a site-specific groundwater mounding assessment (potentially including modeling) may be needed.

If the capacity of the infiltration receptor may limit reliable infiltration, the project team should consider reasonable mitigation approaches. Example mitigation approaches are as follows:

- Adapt site design to locate BMPs in areas with fewer limitations (e.g., more permeable soils, greater separation to groundwater).
- Reduce the loading rate to the BMP.
- Reduce the width and depth of the BMP (i.e., narrower and shallower BMPs tend to result in less mounding for a given set of loading, soil, and groundwater conditions).

These cases may also warrant further evaluation of groundwater conditions to verify or improve assumptions used in these analyses.

3.2.2 Underlying Criteria

A reliable, long-term design infiltration rate is required for design of Full Infiltration BMPs. This should be used as part of sizing and performance feasibility analyses (Section 3.3) to verify that this design infiltration rate is adequate to support the selected BMP type and profile. There is not a fixed threshold that applies to all BMP types. The design infiltration rate should be adequate to drain the BMP in an acceptable amount of time and meet performance goals.

3.2.3 Example Criteria

Manuals often establish certain minimum infiltration rate thresholds, such 0.3 in./h or 1 in./h, to determine the potential feasibility (or infeasibility) of infiltration BMPs. Unless this is necessary to satisfy local regulations, this Guidance Manual recommends avoiding the use of specific thresholds. As illustrated in Section 3.3, the threshold needed to support infiltration varies depending on the available space and the selected BMP. This Guidance Manual recommends that the reliable infiltration rate, the available space, and the applicable BMP types be considered to determine if infiltration is feasible; however, if there are local requirements, these should be followed, or permission should be obtained to deviate from them.

3.3 Sizing and Performance Feasibility

Design infiltration rates have an important influence on the types of BMPs that can be supported on a site, the allowable ponding depth for these BMPs, and the resulting footprint required to capture a certain design stormwater runoff volume (e.g., the 85th percentile storm) or achieve long-term performance criteria (e.g., infiltrate or treat 80% of long-term runoff volume). As the available space for BMPs becomes more limited, the ponding depth of the BMP must typically increase to provide similar volumes of stormwater storage. This can increase the loading ratio, which in turn can increase drawdown time and increase the risk of groundwater mounding and clogging. As a result, in sites with both limited space and moderate infiltration rates, it can be infeasible to rely solely on infiltration to meet sizing and performance goals.

Table 23 summarizes the range of minimum design infiltration rates typically needed to support various types of Full Infiltration BMPs and the associated loading ratios needed to capture and store the runoff from a representative 1-in. storm.

3.3.1 Refinements from Preliminary Assessment

As part of the preliminary feasibility assessment described in Step 2, site conditions were considered independently from available space, sizing requirements, and selected BMP. Integration

Table 23. Infiltration screening thresholds by BMP type.

Infiltration BMP Type	Typical Effective Ponding Depth	Typical Design Target Drawdown Time and Controlling Factor	Minimum Design Infiltration Rate for Full Infiltration	Maximum Loading Ratio to Store of 1-in. Storm Runoff (% of Impervious Area)	Mounding Potential
Shallow Flow Infiltration BMPs					
• Shallow Infiltration Swale • Filter Strip/Dispersion • Media Filter Drain	0.2 to 0.5 ft	12 to 24 hours (plant survival; aesthetics)	0.1 to 0.5 in./h	2:1 to 5:1 (20% to 50%)	Low
Subsurface Infiltration BMPs with Shallow Storage					
• Permeable Shoulders	0.4 to 0.8 ft	24 to 48 hours (long-term performance in sequential events)	0.1 to 0.4 in./h	4:1 to 8:1 (13% to 25%)	Low
Surface Ponding Infiltration BMPs with Shallow Storage					
• Distributed Bioretention without Underdrains • Infiltration swales	0.5 to 1.5 ft	12 to 24 hours (plant survival)	0.5 to 2.0 in./h	10:1 to 16:1 (6% to 10%)	Moderate
Surface Ponding Infiltration BMPs with Deep Storage					
• Infiltration Trenches • Infiltration Basins/ Centralized Bioretention Basins • Infiltration Galleries	3.0 to 6.0 ft	24 to 72 hours (vector issues; long-term performance in sequential event)	0.75 to 3.0 in./h	20:1 to 50:1 (2% to 5%)	Moderate to High

of these factors is critical to confirm feasibility. Where it appears that the combination of available space and infiltration rate could be marginal, then Full Infiltration may not be feasible even if preliminary feasibility criteria are met. The following sections introduce key questions associated with this analysis and supporting resources.

Key Questions

The following questions may apply at this stage:

How long will BMPs take to drain? This fundamental question is of critical importance. It can affect the long-term performance (e.g., accounting for back-to-back storms), the viability of the BMP (e.g., plant mortality), and nuisance issues (e.g., vectors, odors, wildlife usage, etc.).

Do the proposed BMPs achieve the project objectives? When project objectives are expressed in terms of the performance of BMPs, designers can use models (or modeling-derived tools) to evaluate whether a proposed suite of BMPs achieves these objectives. Project objectives could take the form of the following examples:

- Example 1: Capture runoff from a design event and subsequently recovery (via infiltration) of the storage volume within a specific time (e.g., retain the 1.2-in. storm event, and recover storage within 48 hours following the end of rainfall; note that many MS4 permits do not address storage recovery, which is crucial for BMP performance as well as nuisance issues).
- Example 2: Reduce the long-term runoff volume by a certain percent (e.g., 80% long-term volume reduction) compared with the developed condition without BMPs.
- Example 3: Limit discharge volume to a certain long-term runoff coefficient (e.g., reduce runoff volume to 10% of long-term rainfall volume).

- Example 4: Match the long-term volume of surface runoff that is estimated to have occurred in the pre-project condition.
- Example 5: Reduce the frequency of discharge from the site by a certain percentage compared with the developed condition without BMPs.

How do different BMPs compare in terms of relative performance? When multiple BMPs are under consideration, designers can compare the relative performance, costs, and associated cost–benefit ratio of these BMPs.

How do sizing and design parameters influence volume reduction and capture performance? This can be a critical question when some parameters remain uncertain, such as infiltration rate. Designers can conduct an evaluation of the sensitivity of BMP performance to uncertain parameters to evaluate the range of BMP performance uncertainty that could be expected.

Tools Available to Support Analysis

In addition to local modeling and analysis tools that may be applicable to a project, several tools with nationwide coverage are available to support this evaluation.

Whole Lifecycle Cost and Performance Tools (*NCHRP Report 792*). Supports bioretention (with and without underdrains), infiltration basins (as a variation of bioretention), swales, and filter strips including long-term volume reduction performance, pollutant load reduction, and lifecycle costing. Wet ponds and sand filters are also supported by this report and tool, which provides comparison with non-infiltrating systems. Estimates are based on long-term continuous simulation modeling at 344 long-term precipitation stations (one for each climate division).

Volume Reduction Tool (*NCHRP Report 802*). Supports dispersion/filter strips, vegetated conveyance/swales, media filter drains, bioretention (with and without underdrains), permeable shoulders, infiltration trenches, infiltration basins, and infiltration galleries, including long-term volume reduction for individual BMPs and BMPs in series. Estimates are based on long-term continuous simulation modeling at 344 long-term precipitation stations (one for each climate division). This tool was based on the same hydrologic modeling as the *NCHRP Report 792* tool.

Roadside BMP Groundwater Mounding Assessment Guide and User Tool (Appendix C). Returns estimates of the magnitude and duration of mounding and accounts for reduction in effective infiltration rate as a function of groundwater mounding. This tool can be used to prorate the findings of the tools listed previously for cases in which mounding appears to influence long-term performance.

BMP Clogging Risk Assessment Tool (Appendix F). While this Guidance Manual addresses clogging as a design decision in Chapter 4, it may be advantageous to assess clogging risk as part of developing design infiltration rates and assessing how loading ratios influence BMP feasibility.

Appropriate Level of Detail

The analysis of sizing and performance to confirm feasibility is not intended to be based on detailed designs. It should be rapid enough to be useful in alternatives evaluation, but also representative in macro-level design parameters, such as footprint and ponding depth.

Figure 11 shows an example of the schematic design exhibits contained in the BMP fact sheets. Figure 12 provides an example of a preliminary conceptual site plan for a hypothetical BMP retrofit, illustrating that several options can be efficiently considered as part of a single conceptual design development process.

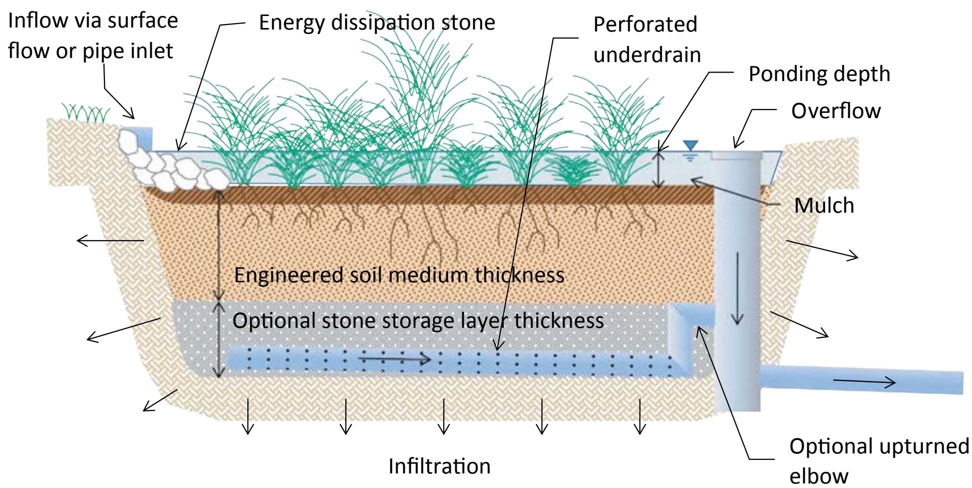


Figure 11. Example schematic design profile appropriate for use in feasibility analysis.

3.3.2 Underlying Criteria

A Full Infiltration BMP needs to be able to meet the applicable stormwater management objectives solely through infiltration. Sizing and performance analyses must be based on the reliable design infiltration rate and must demonstrate the following three underlying criteria:

- The BMP will drain in an amount of time that does not compromise the integrity of the system.
- The BMP will not pose hazards to public health related to mosquitos or other vectors.
- The BMP will meet applicable sizing and performance requirements.

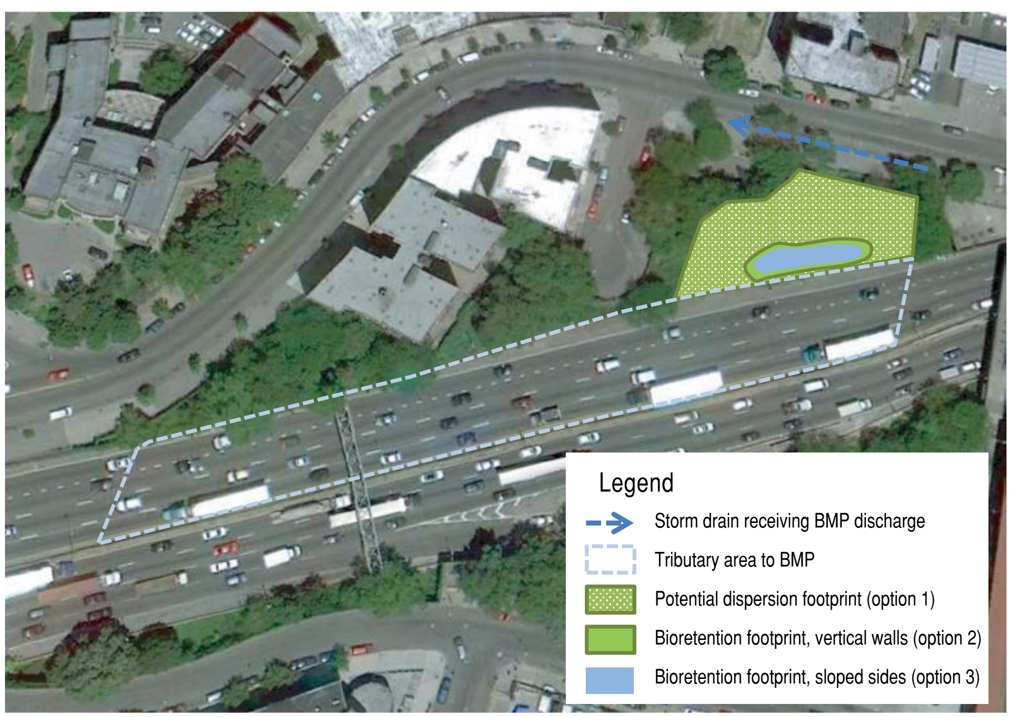


Figure 12. Example conceptual site plan appropriate for use in feasibility analysis.

3.3.3 Example Criteria

Sizing and performance criteria should typically be derived from local requirements or guidance. Example criteria include the following:

- The storage volume should be recovered via drawdown in not less than 48 hours or a locally acceptable alternative to ensure adequate long-term performance.
- If the BMP is vegetated, water should drain below the root zone of plants in 24 hours or a locally acceptable alternative to support plant survival.
- BMP should provide storage for the applicable design storm and long-term performance adequate to meet local standards.

3.4 Geotechnical Findings and Recommendations

When infiltration of stormwater is near or within the highway environments, a geotechnical report that evaluates infiltration is typically a standard practice. Appendix E provides guidance on factors to assess and recommended contents of the geotechnical report on infiltration.

3.4.1 Refinements from Preliminary Assessment

After other factors have been considered as part of the preliminary infiltration feasibility assessment, the locations of potential BMPs and the characteristics of these BMPs (size, depth, loading ratios) can be better defined. This supports more site-specific assessment of conditions and potential hazards.

The scope of the refined geotechnical evaluation should be commensurate with the level of risk posed by the BMP and the applicable burden of proof to reject the use of infiltration. For example, for shallow distributed infiltration BMPs located outside and especially downgradient of the highway prism, the level of risk may be limited and could be addressed with a brief report in the form of a letter to confirm that risks have been assessed but found to be negligible. This may require limited additional effort compared with the preliminary screening step.

For more complex conditions, such as infiltration within the roadway embankment, adjacent to structures, or in more centralized locations (e.g., highway median), the geotechnical report should be more detailed and may need to include supporting analyses, such as slope stability, buoyancy, and groundwater mounding. The initial findings and assessments from the preliminary screening step should be used to establish the necessary scope of this evaluation.

In marginal cases with stringent infiltration objectives (Track 1b), the geotechnical report may need to consider and assess the practicality of mitigation measures to improve the feasibility of infiltration (e.g., underdrains in the base layer to protect the pavement). A range of potential mitigation measures are described in Appendix E.

3.4.2 Underlying Criteria

At a minimum, the geotechnical analysis and recommendations should be adequate to address the following feasibility criteria:

- Recommendations must be pertinent to the actual locations and types of BMPs proposed.
- Recommendations must establish the maximum level of infiltration that allowed in each BMP location without posing risks (this could range from zero to unrestricted).
- If infrastructure or structures exist near BMP locations, recommendations must establish the minimum setbacks from these features.

- Recommendations must be supported by and include documentation of soil investigations and infiltration testing if performed by the geotechnical engineer.
- Recommendations must identify any construction-phase oversight or monitoring required.

3.4.3 Example Criteria

The following sections identify example criteria that could be applicable as the basis for geotechnical recommendations.

*Geotechnical Risk Factors Preventing **Any** Infiltration (Result = Infeasible)*

- Soils with potential for volume change from wetting (e.g., expansive soils) or freeze/thaw, in which volume change (soil moisture) could result in impacts to pavement or structures
- Slopes in which stability is sensitive to soil water content that cannot be reasonably designed to allow for any amount of soil wetting
- Soils that exhibit a significant loss of strength when wetted, in cases where loss of strength cannot be reasonably accommodated in design
- Utilities or existing infrastructure that cannot be designed to avoid or accommodate some intrusion of infiltrated water
- Other factors as determined by a geotechnical professional

*Geotechnical Risk Factors Preventing **Some** Infiltration (Result = Some Limitations)*

- Soils that require a high degree of compaction to serve structural functions (e.g., compacted fill, roadbed), thereby reducing infiltration rates
- Slopes or fill structures that can allow some soil wetting but cannot be reasonably designed to allow for Full Infiltration
- Utilities that would potentially be susceptible to impacts in the case of Full Infiltration
- Potential for significant mounding or lateral dispersion if infiltration exceeds allowable amount
- Other factors as determined by a geotechnical professional

Geotechnical Mitigation Approaches

If a geotechnical risk factor is identified, the geotechnical analysis should document consideration of reasonable mitigation approaches. Example geotechnical mitigation approaches are as follows:

- Attempt to locate BMPs in areas where they are outside applicable setbacks and in areas without fill or with lower depths of fill.
- Over-excavate and backfill with more permeable materials in cases where the depth of fill is relatively shallow (less than approximately 5 ft below the invert of the BMP).
- Use a more robust foundation or retaining wall design of the same type as otherwise proposed such that some infiltration can be allowed; it would be unreasonable to require a project to utilize a different type of foundation or retaining wall design solely to accommodate infiltration.
- Use underdrains or drain tiles to limit groundwater levels below infrastructure.

3.5 Groundwater Quality Findings and Recommendations

3.5.1 Refinements from Preliminary Assessment

Depending on the complexity of local groundwater and the applicable groundwater water quality standards, refinements could range from relatively little effort to considerable effort. As part of preliminary screening (Section 2.2.5), project teams should identify the need for additional assessment.

The following topics **may** need to be assessed further to determine feasibility.

Hydrogeologic Conditions. This includes depth to groundwater, groundwater properties (thickness, gradient, and direction of flow). Long-term monitoring to inform the project design may be needed in some cases, particularly where natural fluctuations are considerable. For example, the thickness of the unconfined aquifer and gradient of the water table are particularly important for assessing acute salt impacts in cold climates.

Acute Salt Contamination. If the project is in a cold climate that utilizes salts, the potential for acute contamination of nearby wells should be evaluated (if not previously assessed). The Groundwater Quality Assessment Tool (found in Appendix D) can support this evaluation. This tool performs a relatively simply evaluation of advection and dispersion of salt, accounting for user-defined salt loading, BMP dimensions, and groundwater flow properties.

Soil Properties and Pollutant Attenuation. If stormwater pollutants are identified as a potential risk to groundwater quality (as part of Step 2), then the project team may need to investigate soil properties and pollutant attenuation effects. Very sandy soils can lack the attenuation capacity to protect groundwater from stormwater pollutants at ordinary levels. The project team can analyze samples for cation-exchange capacity (CEC) and organic content to assess the pollutant attenuation capacity of soils and determine the need for soil amendments and pretreatment to protect groundwater quality.

Soil and Groundwater Contamination. If present, the limits of contamination and groundwater flow direction should be determined. The hydrogeologic investigation should evaluate whether infiltration would pose a risk of exacerbating contamination or complicating cleanup of contamination.

Consultation with Applicable Groundwater Management Agencies. In general, it is a best practice for DOTs to coordinate with agencies responsible for local groundwater management whenever infiltration is considered for a project. These agencies have a vested interest in protecting groundwater supplies and underground infrastructure and usually have extensive knowledge about these resources. This consultation should ideally start as part of establishing infiltration objectives and preliminary constraints.

Consultation with Sanitary Sewer Collection System Operators. It may be appropriate to consult with sewerage agencies to determine if inflow and infiltration (I&I) has been identified as a concern in the area. Stormwater infiltration has the potential to raise groundwater levels and increase I&I.

Spill Containment. Local groundwater quality protection policies or wellhead protection ordinances may specify the need for spill containment. Spill containment can require space and may not be compatible with all BMP types. Project teams should confirm that selected BMP types and locations can be designed to feasibly provide adequate spill containment. Where spill containment is mandated, this may be an overriding consideration in BMP selection.

Pollutant Fate and Transport Modeling and Calculations. While most projects should not require project-specific modeling of pollutant fate and transport modeling, this could be needed to support large-scale or highly constrained cases.

Groundwater Monitoring. Depending on the severity of potential issues and the stringency of infiltration requirements, there could be cases where the use of infiltration must be accompanied by monitoring to confirm absence of impacts and the need to alter operation of the BMP (e.g., uncap underdrains).

3.5.2 Underlying Criteria

At a minimum, the groundwater quality analyses and recommendations should address the following feasibility criteria at the BMP locations:

- The selected infiltration BMPs (including the use of pretreatment and soil amendments) provide adequate pollutant attenuation to avoid unacceptable impacts to groundwater quality.
- Infiltration does not mobilize existing soil or contaminate groundwater.
- Infiltration BMPs incorporate features to comply with any applicable spill containment requirements.
- Infiltration BMPs are used in a manner that complies with local criteria for groundwater resource management.
- The level of infiltration proposed does not violate water rights.
- The level of infiltration proposed does not create potential water balance modifications that could impair natural streamflow regimes (e.g., ephemeral streams) or elevate groundwater levels that impact other infrastructure.

3.5.3 Example Detailed Criteria

The following sections identify example criteria that could be applicable as the basis for groundwater-related recommendations.

*Groundwater Quality Risk Factors That Prevent **Any** Infiltration (Result = Infeasible)*

- The infiltration facility is within 100 ft of a public or private water supply well, non-potable well, drain field, or spring (or is prohibited by locally applicable guidance or requirements).
- Groundwater standards are determined to be very stringent (perhaps based on anti-degradation of high-quality groundwater or connectivity to a sensitive receiving water), such that impacts cannot be avoided.
- The infiltration facility is on or adjacent to a brownfield site where infiltration of any appreciable amount would result in a significant risk of mobilizing or moving contamination that cannot be reasonably avoided.
- A groundwater pollutant plume (constructed or natural) is under or near the site and any level of stormwater infiltration would contribute to plume movement that cannot be reasonably avoided.
- Other critical factors have been identified as part of site assessment activities.

*Groundwater Quality Factors That Prevent **Some** Infiltration (Result = Some Limitations)*

- There are soils with limited attenuation capacity and shallow groundwater, but groundwater quality standards can be reasonably protected via the use of pretreatment or soil amendments.
- There is soil or groundwater contamination in the vicinity of the project, in which a potential rise in groundwater table associated with Full Infiltration could exacerbate contaminant mobilization, migration, and cleanup efforts, but where Partial Infiltration would have acceptable effects.
- Other factors have been identified as part of site assessment activities.

Groundwater Quality Mitigation Approaches

If a groundwater quality risk factor is identified, the documentation of infiltration infeasibility should consider reasonable mitigation approaches. Example groundwater quality mitigation approaches are as follows:

- Remediate minor areas of contaminated soil on a site.
- Design infiltration BMPs with spill containment, pretreatment, and soil augmentation.

- Hydrologically isolate areas of the site that have higher risk of stormwater contaminants so that infiltration can be more feasibly applied to a lower-risk area.
- Consider pretreatment or soil amendment if the following criteria are not met [adapted from (Washington State Department of Ecology 2012)]:
  - CEC of the treatment soil is least 5 milliequivalents CEC/100 g dry soil.
  - Organic content is at least 1.0% dry weight.
  - CEC and organic content encompass all distinct layers below the base of the facility to a depth of at least 2.5 times the maximum design water depth, but not less than 6 ft.
  - Other locally applicable guidance at the discretion of the project engineer.
- Use BMP types that have lower risk of groundwater contamination or are more compatible with available groundwater separation (e.g., using shallower bioretention rather than deeper infiltration trenches).

Water Balance and Water Rights Criteria

While less common, infiltration of stormwater could change the existing flow regime of ephemeral streams or violate downstream water rights. If concerns are identified, the project team should perform a site-specific evaluation to determine whether water balance impacts or water rights violations would occur as a result of infiltration, including the following factors:

- Infiltration levels exceeding pre-developed conditions could cause impairments to downstream beneficial uses because of discharge of contaminated groundwater or changes in baseflow regimes to ephemeral streams. This is generally only a concern when infiltration rates are high (observed infiltration rates above 1 in./h), surface waters are proximate to the infiltration BMP, and groundwater depths are relatively shallow. The level of allowable increase in infiltration should be documented in a site-specific study. This could also be the case in areas experiencing widespread conversion to urban development in which infiltration is being increased on a large scale.
- Infiltration of runoff from the project would violate downstream water rights. Site-specific evaluation of water rights laws should be conducted if this is believed to be a potential issue in the project location.
- ET from vegetated infiltration BMPs would violate downstream water rights. Site-specific valuation of water rights law should be conducted if this is believed to be a potential issue at the project location.

3.6 Alternative Project Delivery

Project delivery refers to the approach for designing, bidding, contracting, and constructing a project, including bonding of the contractor, construction oversight, and transfer of maintenance responsibility at the termination of the contract. The typical project delivery process (known as "design-bid-build") involves development of plans, then bidding, then construction by a contractor that does not have a formal relationship to the designer. Potential limits of this contracting process that pertain to infiltration approaches include the following:

- DOT design team is not able to receive input about BMP constructability from the contractor during the design process.
- DOT construction manager may not be able to prescribe "means and methods" unless they are specifically defined in contract documents. This may limit the ability of the DOT construction manager to prescribe construction methods and construction phasing.
- Standard bonding and warranty periods may not be long enough for vegetation establishment.
- Construction-phase design modifications may not be feasible unless specific contingencies are included in the design and bid package.

Alternate project delivery could give the DOT more control over construction-phase decisions and site management. Alternative project delivery options could include the following:

- Development of special specifications or special contract provisions within a standard design-bid-build process. Distinct specifications could dictate construction methods, construction phasing, vegetation acceptance criteria, and other issues relevant for infiltration BMPs construction.
- Development of contingency design alternatives within a standard design-bid-build approach. This could include multiple versions of a design component, including specific with triggers for when a certain version would be activated. For example, the design drawings could include a version of the BMP that would be built if at-grade infiltration rates exceed a threshold and a different version that would be built if this threshold is not met.
- Use of a design-build or construction-manager-at-risk delivery model. In these models, the contractor is responsible for developing the design or the contractor works as part of a collaborative team with the DOT and the designer. These delivery models offer greater opportunity for design-phase input on constructability and phasing. They can also be more conducive to contingency plans, because site information could be collected during early phases of construction while detailed designs are still under development.

The following are examples of cases in which some form of alternate project delivery could potentially improve the implementation of infiltration BMPs.

Stringent Infiltration Requirements in Which Feasibility Depends on Construction-Phase Measurements. Examples could include projects that will involve considerable earthwork (cut or fill) in BMP locations such that it is not possible to obtain reliable measurements before construction. In this case, the design could proceed with two alternatives: an infiltration-based approach and a back-up plan that is based on partial infiltration and partial treatment. Construction-phase testing could be used as the ultimate deciding factor to determine which approach to construct. The project delivery approach and permitting processes would need to support this contingency. See additional guidance on adaptable designs in Section 4.4.

Unavoidable Construction-Phase Compaction or Clogging in Infiltration Areas. This may compromise infiltration rates and warrant remediation of the area at the end of the construction period to support infiltration. This too, could justify construction-phase testing to confirm that infiltration rates have been adequately restored. It could also warrant specific requirements for construction-phase approaches, including directing the means and methods of construction.

Vegetation Establishment Period for Site-Stabilization. Case studies have shown that elevated sediment loads during the post-construction vegetation establishment phase can pose risks to BMPs. This suggests that alternative phasing to allow vegetation establishment prior to the finish grading of infiltration facilities would reduce risks. This type of alternative phasing may require modifications to project delivery such as specifying phasing or requiring longer bonding/warranty periods. This could apply to the use of any infiltration or filtration BMP.

For sites where these types of risks are present, the ability to use an alternative project delivery model could be an important factor in whether there is adequate confidence to proceed with infiltration.

3.7 Step 3 Results—Feasibility Findings

Table 24 provides a template for confirming the feasibility determinations of the methods and criteria described in this section. Local guidance should be consulted to determine the degree to which infiltration is supported for each metric. This may require consultation with local

Table 24. Infiltration infeasibility screening criteria worksheet.

BMP Summary	
Drainage Area ID	
BMP Type	
Infiltration Feasibility Class	
Design Infiltration Rate	
Tributary Area	
Impervious Fraction/Area	
Loading Ratio (Tributary Impervious Area: BMP Area)	
Infiltration Sizing Criteria	

Directions:

Answer each screening question below to determine the supported level of infiltration for that factor. Provide the basis for each selection by summarizing findings of site investigations and providing a narrative discussion of study and data source applicability. If applicable, describe risk mitigation approaches taken. Attach additional information as needed or provide reference to studies, calculations, maps, data sources, and so forth.

Row	Screening Question	Level of Infiltration Supported		
		Infeasible	Partial Infiltration Supported	Full Infiltration Supported
1	**Do the design infiltration rates and available space support the selected BMP without negative consequence? (Sections 3.2, 3.3 and Appendices B and C)**	☐	☐	☐
Provide basis:				
2	**Would infiltration increase risks of geotechnical hazards that cannot be mitigated to an acceptable level? (Section 3.4 and Appendix E)**	☐	☐	☐
Provide basis:				
3	**Would infiltration pose significant risks for groundwater quality that cannot be reasonably mitigated to an acceptable level? (Section 3.5 and Appendix D)**	☐	☐	☐
Provide basis:				

(continued on next page)

Table 24. (Continued).

Row	Screening Question	Level of Infiltration Supported		
		Infeasible	**Partial Infiltration Supported**	**Full Infiltration Supported**
4	**Would infiltration pose impacts to local or regional water balance that could impact infrastructure or environmental resources? (Section 3.5 and Appendix D)**	☐	☐	☐
Provide basis:				
5	**Would infiltration conflict with water rights and/or water balance? (Section 3.5 and Appendix D)**	☐	☐	☐
Provide basis:				
Result	**Based on the screening criteria, what is the infiltration risk categorization?**	**Infeasible** ☐	**Partial Infiltration Acceptable** ☐	**Full Infiltration Acceptable** ☐
If **any** answer from row 1 through 5 is infeasible, this factor limits infiltration and the overall designation is Infeasible. If one or more factors support Partial Infiltration and no factors are infeasible, the overall designation is Partial Infiltration. If all answers are Full Infiltration, then Full Infiltration BMPs are acceptable.				

regulatory authorities and technical experts to determine site-specific requirements. As a starting point, example feasibility criteria have been summarized in Section 3.2 through 3.5 and can a serve as a reference in the absence of local criteria.

In evaluating each factor, the design team should consider reasonable approaches for mitigating risks through site design, BMP design, or other project development aspects. Section 3.2 through 3.5 provide examples of reasonable mitigation approaches for improving the feasibility of infiltration.

Table 24 is intended to serve as the method for documenting decision-making for issues that do not apply to a site or cannot be addressed with simple explanation. It is intended to serve as the method for documenting decision-making. For issues that warrant more site-specific evaluation, Table 24 can be completed with reference to applicable reports or studies.

CHAPTER 4

Key Considerations for Design, Construction, and Maintenance of Infiltration BMPs

4.1 Overview

Surveys and interviews with DOTs (see Project Summary Report) have provided the research team with insights into the challenges DOTs face in design, construction, and O&M of infiltration BMPs. The following are highlights from these surveys and interviews:

- The most common causes of failure were related to (1) incomplete information about the site leading to inadequate design assumptions and (2) compaction or clogging of BMPs during the construction phase of the project.
- The most challenging design issues were (1) the remaining uncertainty in long-term, full-scale infiltration rates, even after conducting thorough investigation and (2) challenges with providing enough space for BMPs. A wide range of other factors were also identified.
- Respondents commented on the large number of factors that must be adequately considered; a single missed factor can result in premature BMP failure.
- Respondents identified challenges associated with maintenance planning and implementation, particularly where the performance and survivability of the BMP depends solely on infiltration rate. The uncertainty in maintenance requirements is a significant barrier to the use of infiltration BMPs.
- Respondents also emphasized the importance of consulting with O&M personnel during each phase of design to ensure BMPs are selected and designed in a way that can be maintained.
- Finally, respondents identified several considerations that apply to cold and arid climates (see Appendix I).

This chapter contains three key approaches for improving the design, construction, and O&M of infiltration BMPs:

- Evaluate potential failure modes of the proposed BMPs as part of design and construction plans. This can identify approaches to reduce the risk of these failures occurring or reduce the consequences if failures do occur. Appendix J presents several case studies of infiltration BMP failures.
- Conduct a realistic assessment of the uncertainty in site conditions, construction methods, and future O&M. This assessment can be used to support development of designs that are more likely to remain operable within this range of uncertainty (i.e., are more resilient).
- Evaluate O&M requirements and methods as part of the design process and seek input from O&M staff regarding system design. This can support BMP designs that can be more efficiently operated and maintained at an acceptable cost.

4.1.1 Role of BMP Selection in Managing Uncertainty and Reducing Risk

If data are not available at the time of design to ensure feasibility, then BMPs should be selected and designed so that they do not depend on uncertain design parameters (e.g., a certain infiltration rate) for the system to remain operable, or additional investigation should be undertaken during the construction phase to achieve the necessary level of confidence. The former is strongly recommended when it complies with infiltration objectives.

BMP design is an extension of the BMP selection process. New information will often become available during the design process, such as better understanding of soil or groundwater characteristics, that can influence infiltration BMP selection. Designers should assess new information as it becomes available to determine if it justifies selection of a different BMP type or design variant. In addition to better information about the site, the design phase may also yield more information about project phasing, construction methods, and project delivery method. These can influence the suitability and feasibility of BMP types, which could also require reassessment of the selected BMPs and locations. In summary, the design process should include feedback loops for confirming or revising BMP selection.

4.1.2 Using Chapter 4

The concept of the planning tracks used in Steps 2 and 3 is carried through this chapter. Table 25 identifies key design, construction, and O&M considerations that apply to each track. Track numbering refers to the planning and design tracks described in Section 3.1. Based on the track selected in Step 3, the designer should consult Table 25 to determine the considerations that apply.

This chapter supports designs of various levels of complexity. The BMP selection process described in Steps 1 through 3 ensures that BMPs are selected to be compatible with site conditions and available data. With appropriate BMP selection, the design team can typically rely on a normal level of design complexity and use standard construction methods. This requires (1) appropriate analyses to develop designs, (2) design provisions to mitigate risk and allow for O&M, (3) appropriate construction specifications to mitigate construction-phase impacts, and (4) post-construction monitoring. In some cases (specifically Track 1b), the project team may be compelled to include Full Infiltration BMPs despite the presence of marginal conditions or residual uncertainty in the as-built condition of BMPs. In these cases, it may be necessary to use more complex approaches for design and construction, such as more adaptable designs, design contingencies, and more rigorous controls on construction phasing and methods. This may also require more rigorous post-construction monitoring.

This chapter focuses on guidance for common design, construction, and O&M issues. Additional design guidelines are provided in fact sheets in Appendix A. Design details will vary by local standards, designer preference, and other factors. Designers will need to consult local design guidance in complement to this Guidance Manual to develop complete and acceptable design and construction documents.

4.2 Soil and Media Clogging and Associated Design Decisions

Clogging is an inherent process in infiltration and filtration BMPs. In most cases, the relevant question is not whether clogging will occur, but rather how frequently it will occur and what will be required to restore infiltration rates when it does occur. The rate at which an infiltration or filtration BMP is expected to clog is a function of several factors, including the following:

Table 25. Key design, construction, and O&M considerations by planning and design track.

Planning and Design Track	Example BMPs	Key Design, Construction, and O&M Considerations
1a. Full Infiltration in Favorable Conditions *BMP Selection:* BMPs have been selected to fully infiltrate a specific design volume and solely rely on infiltration. *Design and Construction Approach:* Design and construct to preserve favorable conditions. Consider the benefit of adaptable designs to provide resiliency to unexpected conditions.	BMP 04 Permeable Shoulders BMP 05 Bioretention w/o Underdrains (optionally with Capped Underdrain) BMP 07 Infiltration Trenches BMP 08 Infiltration Basins BMP 09 Infiltration Galleries	• Long-term soil clogging and maintenance cycles (pretreatment and other design approaches) (Sections 4.2, 4.3, 4.5) • Construction phasing and site management (Section 4.6) • Adaptable BMP designs (Section 4.4) (optional) • Post-construction monitoring (Section 4.9)
1b. Full Infiltration in Marginal Conditions *BMP Selection:* Project objectives require Full Infiltration to be attempted, despite limitations. Full infiltration BMPs are tentatively selected. *Design and Construction Approach:* Design and construct to preserve or improve conditions. Improve certainty in site conditions through the construction phase. Design BMPs to be adaptable or have a backup plan. Include contingencies allowing for designs to be adapted based on construction-phase information.	BMP 03 Media Filter Drain with Adaptable Underdrains BMP 05 and 06 Bioretention without and with, respectively, Capped/Adaptable Underdrains Other Full Infiltration BMPs (less preferable because of lower ability to adapt)	All the above plus the following: • Greater need for adaptable designs supported by construction or post-construction testing (Section 4.4) • Greater need for controls on construction phasing and methods (Section 4.6). • Greater need for post-construction monitoring (Section 4.9)
2a. Partial Infiltration with Supplemental Media Filtration *BMP Selection:* BMPs have been selected to provide incidental infiltration but would be operable without any infiltration. Treatment processes rely primarily on filtration. *Design and Construction Approach:* Preserve infiltration capacity using feasible construction-level controls. Design to mitigate clogging risks.	BMP 06 Bioretention with Underdrains BMP 03 Media Filter Drain with Underdrain	• Long-term media clogging and maintenance cycles (Sections 4.2, 4.3, 4.5.3) • Construction phasing and site management (Section 4.6), especially approaches to avoid sediment loading to filtration media • Post-construction monitoring (Section 4.9)
2a. Partial Infiltration with Positive Overland Drainage *BMP Selection:* BMPs have been selected to provide incidental infiltration but would be operable without any infiltration. Treatment processes rely primarily on overland flow. *Design and Construction Approach:* Preserve infiltration capacity using feasible construction-level controls. Design and construct to promote effective treatment.	BMP 01 Vegetated Conveyance/Swale BMP 02 Dispersion/Filter Strip	• Avoidance of excess compaction (Section 4.6.2) • Soil decompaction/amendment (Section 4.6.3) • BMP vegetation establishment (Section 4.6.4) • Post-construction monitoring (Section 4.9)

- Sediment loading from the drainage area
- BMP footprint relative to sediment loading
- Soil and media characteristics
- Presence of vegetation and type of vegetation
- Use of pretreatment
- Road salting and sanding

Some factors can be beyond the control of the project designer (e.g., sediment concentrations in roadway runoff, footprint available for BMPs, and soil properties), but the remaining project design decisions can have a large effect on clogging risks, including the following:

Routing of Non-Roadway Runoff. Areas with disturbed or otherwise erosive soils can contribute large sediment loads. Disturbed soils should be remediated via erosion control when within the DOT ROW. Where open space or off-site areas drain through the same drainage system as roadway runoff, a key design decision is whether to hydraulically separate these or provide a high level of pretreatment so that they do not contribute loads to infiltration or filtration BMPs. Note that stream protection criteria may require coarse sediment supply areas (e.g., naturally erosive areas that produce stream bed sediment) to be passed through to streams to help maintain natural stream processes.

Level of Pretreatment Provided. Pretreatment can include vegetated filter strips, swales, forebays, manufactured devices (with varying treatment performance), or filtration cells. Each has a different level of effectiveness for sediment removal. Generally, more effective controls will require more upfront costs as well as greater costs for O&M for the pretreatment system but will require less maintenance of the infiltration system. Designers should consider the tradeoffs between pretreatment costs and the long-term cost of O&M.

BMP Footprint and Design Depth. Sediment loading per unit area of BMP surface is a useful metric to estimate the time to clog. A shallower BMP will have greater surface area than a deeper BMP with the same volume. It will therefore have lower sediment load per unit area. In project settings with adequate space, designers should evaluate options with a shallower ponding depth and broader footprint to reduce the frequency of maintenance cycles.

Surface versus Subsurface Infiltration. Infiltration systems that are exposed to the atmosphere (surface systems) are exposed to a greater range of weathering processes (wind, rain, drying, insects, etc.) that can help break up sediment layers that may form. Similar processes may be less present in subsurface systems. Also, surface systems often support vegetation (intentional or incidental), which can reduce clogging risk. Designers should use surface systems whenever practical.

Vegetation. Vegetated systems have been found to sustain higher long-term infiltration rates than unvegetated systems (Hart 2017). This is believed to be due to root action, root swelling and shrinking, soil soaking and drying (which is enhanced via root transpiration processes), and the role of plants in a biologically viable root zone (e.g., a soil stratum that supports insects, worms, fungus, and microbes). Vegetation can also serve to prevent the formation of a less permeable crust of fine sediment on soil surface and provide more pathways for water to enter the soil surface. Designers should consider soil amendments and plantings to support vegetation as a means of improving the longevity of BMPs.

Use of Sacrificial Soil Layer Over Underlying Soil. See description in Section 4.5.1.

Outlet Control versus Media Control of Filtration BMPs. See description in Section 4.5.3.

The BMP Clogging Risk Assessment Tool (Appendix F) is designed to support rapid evaluation of these factors to support assessment of relative risks associated with different design alternatives. Figure 13 provides an overview of the inputs and outputs of this tool, and Figure 14 shows example results from the tool. Documentation of inputs, algorithms, results, and interpretation is provided as part of the notes within the tool and the supporting user guide.

4.3 Selection of Pretreatment BMPs

Pretreatment BMPs can extend BMP lifespan by reducing the rate of sediment accumulation and associated clogging (Section 4.2 and Appendix F). Use of pretreatment BMPs may also be necessary to avoid potential impacts to groundwater quality (see Appendix D and Chapter 3). Table 26 contains potential pretreatment BMPs, classifies how well these BMPs address clogging and groundwater protection, and describes appropriate uses. Designers can use this table to support selection of pretreatment options based on project-specific factors.

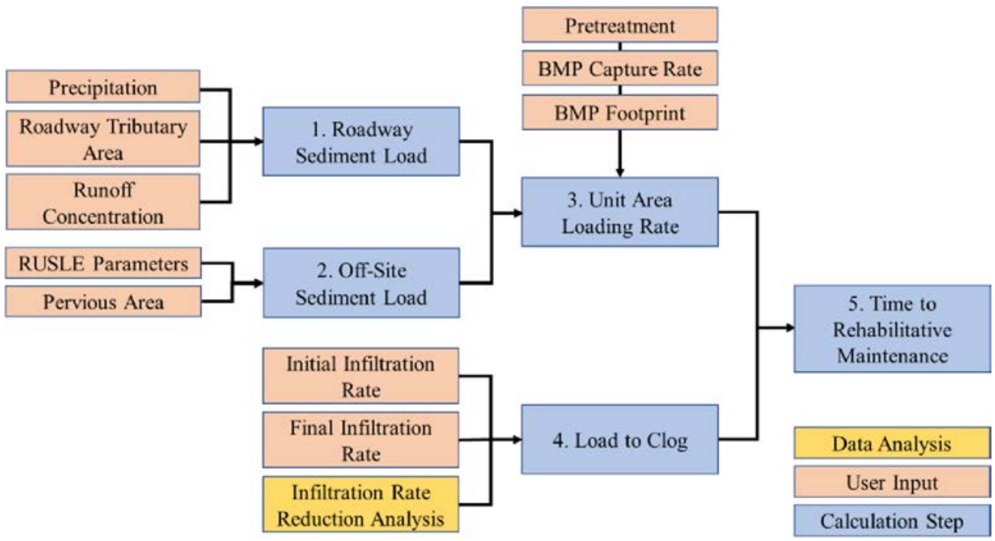


Figure 13. Overview of BMP Clogging Risk Assessment Tool (Appendix F).

4.4 Adaptable Design Approaches for Infiltration BMPs

There are cases in which adequate confidence cannot be achieved in investigation and design of infiltration BMPs, but stringent infiltration objectives create an incentive to attempt to achieve Full Infiltration. This are mostly cases for which the full-scale, reliable, long-term infiltration rate cannot be estimated with confidence prior to construction activities occurring. Examples include the following:

- Inability to reliably translate small-scale tests to full-scale operation
- Difficulty predicting post-construction bulk density and permeability of amended soils
- Inability to access the proposed BMP location infiltration surface prior to construction (e.g., permitting or excavation requirements)
- Inability to protect the infiltration area from construction impacts and uncertainty about the ability to fully remediate those impacts

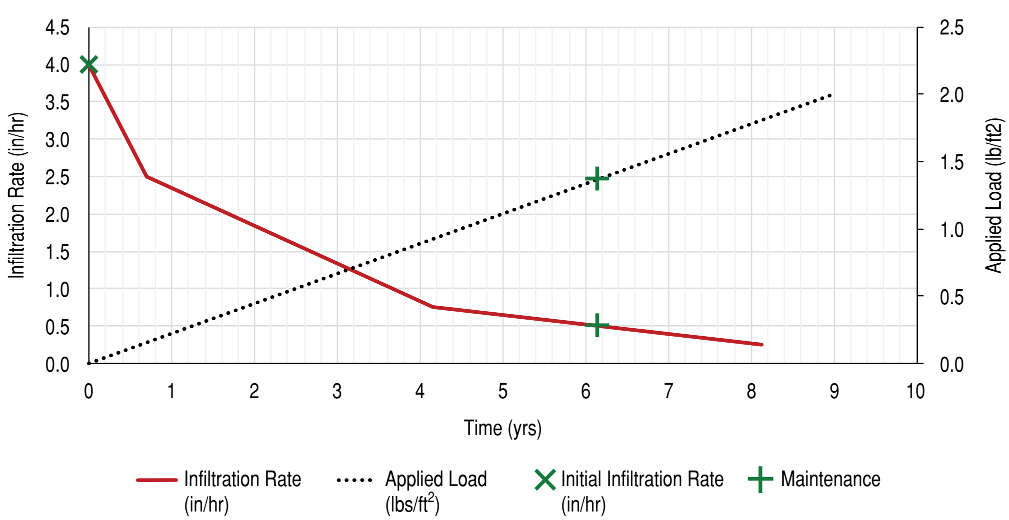


Figure 14. Example results from roadside BMP Clogging Risk Assessment Tool for infiltration rate reduction and applied load over time.

Table 26. Pretreatment options and descriptions.

Pretreatment Approach or BMP Type	Description	Sediment Removal Performance	Groundwater Protection Performance	Appropriate Uses
Settling chambers or sacrificial forebay	At least 10% (preferably 20%) additional volume beyond the required BMP size set aside for pre-settling	Moderate	Negligible	Where land use is low risk or in combination with other approaches
Catch basin insert baskets or screens	Systems intended to strain coarse solids from stormwater as it enters catch basins	Negligible	Negligible	For trash and larger debris and solids control only; no significant benefit for clogging or groundwater quality
Sacrificial mulch layer	Mulch layer provided on the surface of vegetated systems with commitments to yearly maintenance (periodic replacement of layer)	Moderate	Limited	Bioretention systems where clogging risk is low
Sacrificial sand layer	A course sand layer above the infiltrating surface with a filtration rate 5 to 10 times higher than underlying soil; ability and commitment to replacement of layer	Moderate	Negligible	Non-vegetated surface or subsurface systems where sand layer can be removed and replaced
Amended media layers	An engineered bioretention soil media layer installed in the surface of a bioretention BMP or infiltration basin to pre-filter sediment and treat other pollutants	Moderate to High	Medium to High	Bioretention or infiltration systems (see Section 4.4.2)
Proprietary pretreatment devices	A system with an approved General Use Level Designation for pretreatment by Washington State Technology Assessment Protocol—Ecology (TAPE) program or equivalent	Moderate	Limited	Underground or surface systems with adequate head for pretreatment device and low to moderate clogging risk from expected TSS levels
Non-proprietary treatment control BMPs	Treatment BMPs such as swales or media filters	High	Medium to High	Where clogging risk and groundwater risks are elevated
Proprietary treatment devices	A system with an approved General Use Level Designation for basic treatment by Washington State TAPE program or equivalent	High	Medium to High	Where clogging risk and groundwater risks are elevated

Source: Adapted from Orange County, California, Technical Guidance Document (Orange County Public Works 2017).

In these cases, the use of adaptable design approaches (e.g., infiltration BMPs with a built-in contingency plan) can have an important role. This option is recommended anytime Full Infiltration BMPs are proposed.

Adaptable designs can also allow final confirmatory testing to be conducted after the finish grade of the BMP has been reached. This allows more reliable infiltration testing methods to be used. Appendix B provides guidance on the testing methods that are applicable for confirmatory testing in BMPs.

4.4.1 Adaptable Design Options

An adaptable design approach includes predefined contingencies in the BMP design that can be made based on new information obtained from infiltration testing during or following construction. Examples of adaptable design features are described in Table 27. This table only includes Full Infiltration BMPs. BMPs that provide Partial Infiltration and have supplemental discharge pathways do not depend as much (if at all) on an understanding of underlying infiltration rate.

4.4.2 Permitting and Compliance Demonstration of Adaptable Designs

Permitting and compliance demonstrations are typically conducted before construction. Therefore, adaptive approaches can have specific considerations. Potential approaches to support permitting of adaptive designs include the following:

- Clear identification of the construction-phase testing required and the thresholds at which a contingency design element or alternative would be activated
- If the contingency plan involves changing the type of facility with respect to applicable regulations (e.g., conversion from infiltration to treatment), presentation of calculations describing how the system will still conform to applicable sizing criteria if the contingency is activated.

Table 27. Potential adaptable design features for Full Infiltration BMPs.

Infiltration BMP Type	Potential Contingency Design Elements in Marginal or Uncertain Conditions
BMP 03: Media Filter Drains	• Include elevated underdrain in design, but leave underdrain capped unless needed.
BMP 04: Permeable Pavement Shoulders	• Provide a contingency to construct a wider gravel reservoir depending on infiltration testing following construction of road base. • Provide supplemental inlets to route water into subbase in the event the surface of the permeable pavement clogs. • Provide a supplemental drainage pathway for the storage reservoir to ensure drainage if underlying infiltration rates decline. • Provide contingency for the use of supplemental downstream BMPs.
BMP 05: Bioretention without Underdrains	• Design with a capped underdrain and outlet riser such that the underdrain can be opened and converted to a bioretention BMP with underdrains. This contingency could be activated during construction or at any time after construction when need has been determined. • Design with a plugged or capped orifice at the floor of the basin that could allow conversion to a dry detention basin. (Note: the suitability of a detention basin to meet water quality treatment requirements may vary by state or project.)
BMP 07: Infiltration Trench	• Provide a contingency to construct a larger or deeper footprint, if feasible, based on construction-phase testing. • Or have plans for an alternative BMP within the footprint (e.g., media filter with underdrain).
BMP 08: Infiltration Basin	• Include an optional biofiltration media layer and underdrain system that can allow conversion to bioretention BMP with underdrains if needed. • Provide a contingency to construct a larger footprint. • Include means to switch to an extended detention basin with Partial Infiltration.
BMP 09: Infiltration Galleries	• Pretreat influent using an acceptable treatment BMP (e.g., bioretention, proprietary treatment device) to reduce clogging potential and allow any water not infiltrated to have already been treated to applicable standards. • Provide a contingency to construct a larger footprint or deeper gallery (storage).

This could potentially include changing the size of the facility. This may require primary and contingency calculations to be included in the project permitting and design documents.
- For projects requiring state or federal environmental clearance (e.g., environmental impact reports), disclosure and evaluation (in environmental documents) of both the primary and contingency plans

The ability to use adaptive approaches may also require modifications to standard project delivery processes so that changes to the compliance approach can be enacted during the construction phase of the project.

4.4.3 Whole Lifecycle Cost–Benefit Evaluation of Adaptable Designs

Contingency elements to support an adaptable design may require greater upfront cost associated with design, permitting, and construction. For example, installing underdrains and engineered media in a basin adds considerable cost, but it also provides the ability to operate the system as either an Infiltration or Partial Infiltration BMP. If site conditions clearly support Full Infiltration, then the cost of these design elements would not be justified. The decision to use these designs may depend on lifecycle cost–benefit calculations. These calculations can be supported by several NCHRP tools, including the following:

- Whole Lifecycle Cost and Performance Tools: *NCHRP Report 792*
- Volume Reduction Tool: *NCHRP Report 802*
- Roadside BMP Groundwater Mounding Assessment Guide and User Tool: Appendix C
- BMP Clogging Risk Assessment Tool: Appendix F

Appendix G provides a hypothetical case study example of how these tools can evaluate the use of contingency underdrains in a bioretention basin.

4.5 Other Design Approaches to Extend Design Life or Improve Resiliency

4.5.1 Sacrificial Soil Layers

The rate of clogging of infiltration or filtration BMPs can determine maintenance intervals. With all else being equal, a system that starts with a higher infiltration can tolerate more clogging before requiring maintenance than a system starting with a lower infiltration rate.

A sacrificial soil or media layer consists of a layer of material (sand, soil, engineered media) placed over the top of the less permeable underlying soil to serve as an embedded pretreatment layer (see Figure 15). Because of its higher permeability, more sediment can be loaded on this

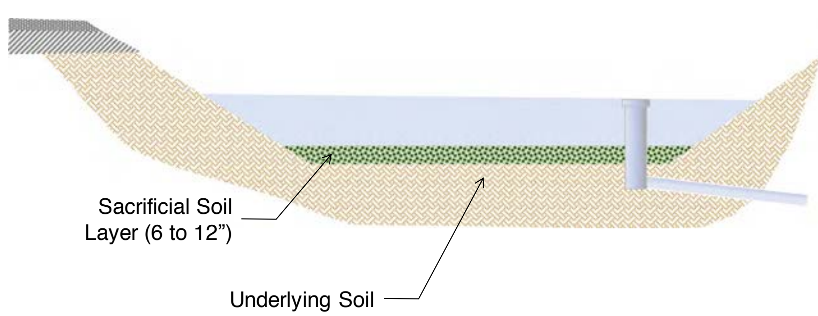


Figure 15. Schematic illustration of a sacrificial soil layer.

layer before it approaches the limiting rate of the underlying layer. Additionally, if this material is significantly coarser than incoming sediment, it is more likely that the depth filtration processes will prevail in the media rather than surface filtration (also known as cake filtration). Materials can generally accept greater loading when depth filtration prevails.

Conceptual specifications include the following:

- The permeability is 5 to 10 times higher than that of the underlying soil.
- The layer depth is 6 to 12 in.
- The coefficient of uniformity (D60/D10) is approximately 1.5 (i.e., fairly uniform material).
- The median particle size is 0.5 mm to 2 mm.
- The BMP is designed to allow for periodic raking and removal of the sacrificial layer.
- Sacrificial layers are loosely placed and lightly compacted using low ground pressure equipment. A target bulk density of approximately 80 lb per ft^3 is recommended. The design should allow for approximately 10% settlement of the sacrificial layer.

4.5.2 Compost Soil Amendments

Amending soils with compost can alter soil characteristics to allow it to absorb, infiltrate, and retain more water to help reduce runoff volume and velocity, filter pollutants, increase the quality and quantity of vegetation, and reduce erosion potential more effectively than soils without soil amendments. Compost and fertilizers are common soil amendments that must be completely mixed into the soil to function properly.

Amending soils with compost (and optionally with sand) can have similar effects as a sacrificial soil layer but can also provide other functions including the following:

- Improving the ability of soils to attenuate and retain stormwater pollutants
- Improving plant growth, which can have the effect of reducing susceptibility to clogging

Conceptual specifications include the following:

- Rototill 2 to 4 in. of compost into soil to a minimum depth of 6 in. (12 in. preferred). Sand can also be used as an amendment to improve the drainage rates of amended soils. Sand should be free of stones, stumps, roots, or other similar objects larger than 5 mm.
- Specify and source compost that is mature, stable, and weed free derived from waste materials including yard debris, wood wastes, or other organic materials (not including manure or biosolids), and meeting standards developed by the US Composting Council or equivalent.
- Design access to the BMP to allow for maintenance of the compost (and sand) layer.
- After amendment, loosely compact to approximately 80 lb per ft^3.
- Where used on slopes, revegetate promptly following amendment and apply temporary erosion and sediment control practices to minimize soil loss.

4.5.3 Passive Outlet Control for Bioretention with Underdrains

Bioretention with underdrains (BMP 06) can be an effective BMP for maximizing incidental infiltration while also providing treatment; however, filtration BMPs can be susceptible to clogging.

There are two fundamentally different ways to control filter bed hydraulics for bioretention systems with underdrains. The traditional approach has been to specify the saturated hydraulic conductivity of the bioretention soil media (BSM) to within a given range (e.g., "media control") and adjust BSM properties (e.g., fine particle content) to achieve this range. Actual infiltration rates of media are highly variable and sensitive to the degree of fines in the mix; the degree of

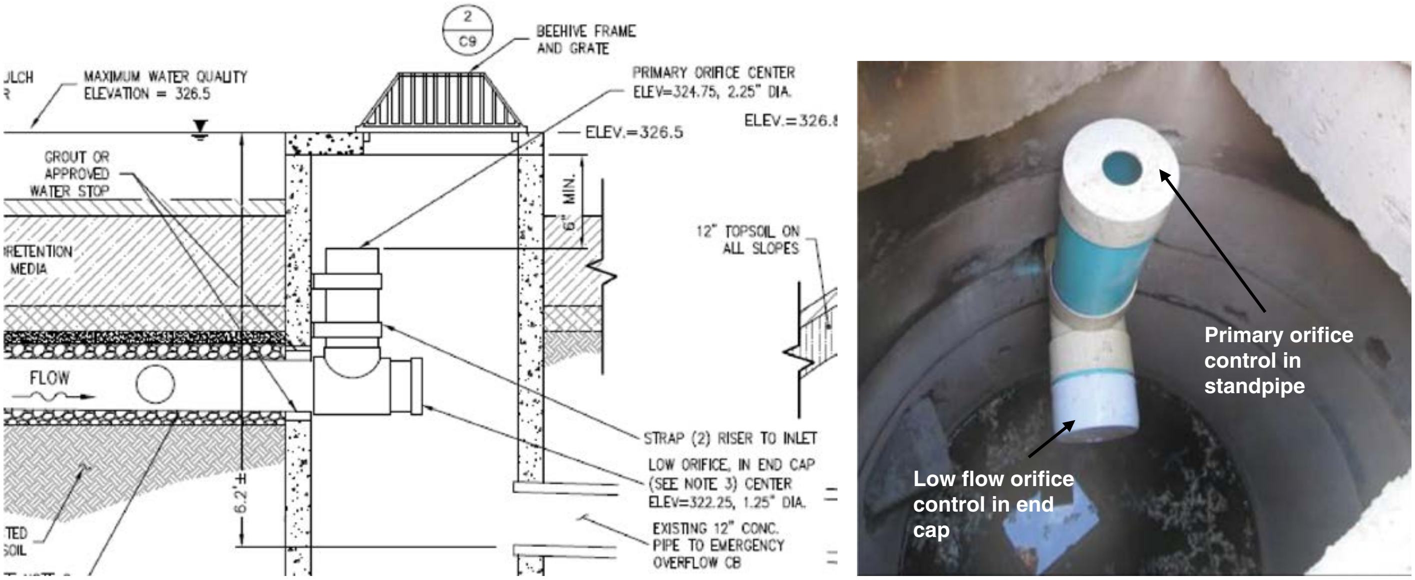


Figure 16. Example outlet control configuration for bioretention with underdrains.

mixing during blending; compaction during installation; weathering and breakdown of media materials; types and maturity of plants; amount of clogging from particulates in runoff; and other factors.

An alternative, passive, non-proprietary design approach (e.g., outlet control) involves a flow control outlet (e.g., orifice) affixed to the underdrains of the bioretention system as the primary hydraulic control in the system (see examples in Figure 16). This approach can improve performance and alleviate several vulnerabilities. Benefits of this approach include the following:

- BSM can be specified with a wider range of hydraulic conductivity. This reduces overall system sensitivity to BSM hydraulic conductivity, mixing methods, placement methods, plant growth, and other factors.
- BSM can be specified with a higher initial hydraulic conductivity, which allows the system a greater factor of safety before clogging (more void space for captured material) begins to reduce system flow rates.
- Outlet control is inherently adjustable to adapt system operations as needed.

This approach can improve the lifespan of bioretention systems. It can be compatible with an adaptable design approach (see Section 4.4).

The BMP Clogging Risk Assessment Tool (Appendix F) can be used to assess the longevity benefits of this approach. This effectively allows a higher starting flowrate to be used as Figure 17 shows schematically.

4.6 Construction Site Management and Phasing to Reduce Impacts to Infiltration and Filtration BMPs

Infiltration and filtration BMPs are susceptible to sedimentation and compaction during or immediately following construction activities. These issues are among the most common causes of failure of infiltration and filtration BMPs. Several construction-phase approaches can be used to reduce these risks or remediate them if they occur.

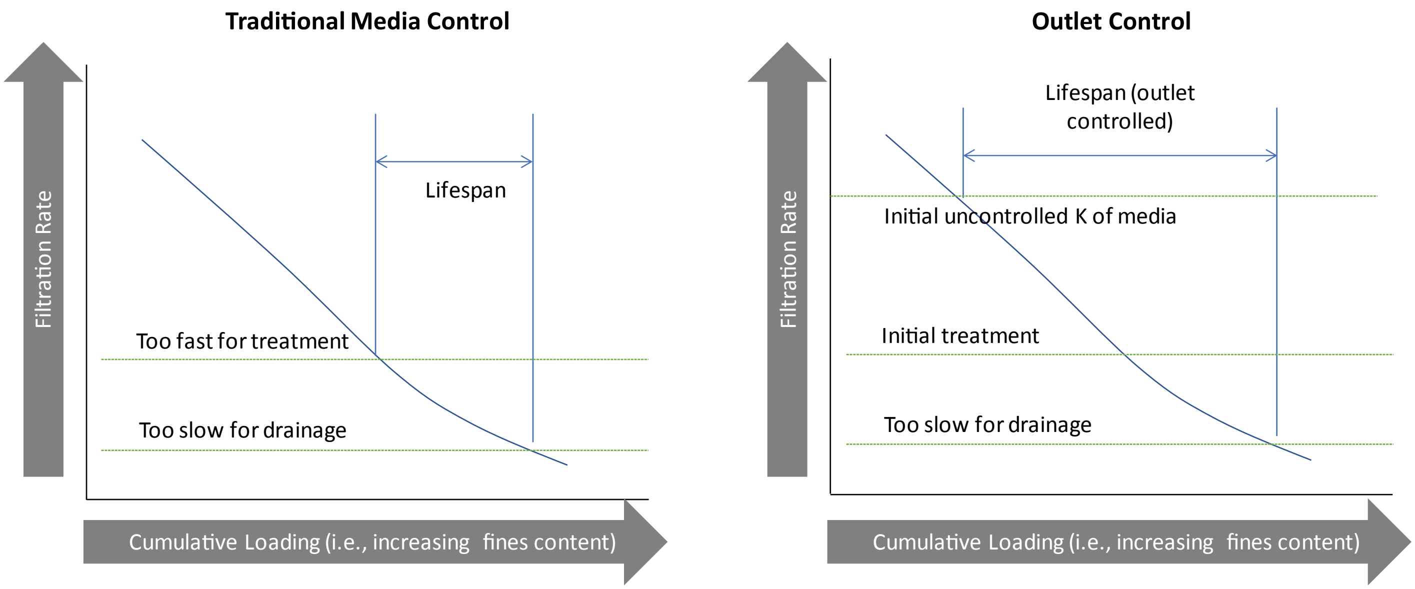


Figure 17. Schematic illustration of the lifespan benefits of outlet control.

4.6.1 Construction Phasing to Reduce Sediment Risk

In accordance with federal and state rules, construction sites must implement effective erosion and sediment control BMPs. This Guidance Manual does not cover how these should be done; however, with respect to infiltration and filtration BMPs, several common-sense approaches should be followed.

- Keep infiltration and filtration BMPs off-line (i.e., not receiving flow) during the construction phase until the site has achieved final stabilization. Temporary erosion and sediment control BMPs are not adequate to prevent loading of fine sediment that can clog infiltration facilities. Final stabilization refers to a well-established vegetation layer or local equivalent constituting full stabilization.
- Provide erosion and sediment BMPs at the top of the BMP embankment to protect the BMP from sediment-laden water. This can also delineate the BMP so that construction crews do not enter it with heavy equipment. Note, depending on sediment loading and texture, this may not be adequate to prevent clogging. See previous bullet.
- If possible, construct infiltration and filtration facilities during later phases of site construction to prevent sedimentation and damage from construction activity. After installation, prevent sediment-laden water from entering inlets and pipes draining to infiltration systems. If this is not possible, runoff from the construction site should be diverted away from the BMP to reduce clogging risk.
- Avoid using infiltration areas as construction-phase sedimentation ponds if possible. Where site constraints require infiltration areas to be used as sedimentation ponds, the initial excavation of the sedimentation pond should stop 2 ft before reaching the final grade of the infiltration BMP. Final excavation to the finished grade should then occur after all disturbed areas draining to the BMP have been stabilized or protected. A sacrificial impermeable liner can also be considered. This liner would be removed after construction is complete. As a last resort, material could be removed and decompaction techniques used to recover infiltration rates (more applicable to partial or incidental infiltration systems).
- Place filtration media after the site has been fully stabilized and most construction activities have ceased (unless applied as a sacrificial layer to be removed later).

Figure 18. Erosion of side slopes and basin floor in Pine Bend infiltration basin.

Figure 19. Sedimentation in floor of Pine Bend infiltration basin after construction.

- If local climate prevents pervious areas from being stabilized prior to commissioning of infiltration facilities, then route these areas separately so they do not pass through the infiltration BMP until they are stabilized.
- Stabilize the side slopes of BMPs so they do not contribute sediment to the infiltrating surface. As observed in a case study provided by Minnesota DOT, the side slopes and upper areas of an infiltration basin experienced erosion that led to clogging of the lower portion of the infiltration basin (Figure 18 and Figure 19). For basins with large side slopes, excavate to an intermediate grade (2 ft above finish grade) to begin stabilization of side slopes, then excavate to the final grade after side slopes have been stabilized.

4.6.2 Construction Vehicle and Traffic Management

Soil infiltration rates are affected by compaction. Several approaches can reduce the potential for compaction of infiltration areas during construction:

- Restrict heavy equipment and traffic from traveling over the proposed location of infiltration BMPs.
- Use construction fence and temporary erosion and sediment control BMPs to demarcate areas proposed for infiltration BMPs.
- Avoid routing traffic over the location of future BMPs. For example, a case study provided by Massachusetts DOT found that infiltration failure (very slow drainage) was associated with areas of the median that were used for a temporary traffic detour route (highway traffic was routed from one side of the divided highway to the other over the median to support phased bridge replacement) (see Figure 20) (Personal communication with Henry Barbaro of Massachusetts DOT 2015).
- Avoid excavation of infiltration BMPs when soils are wet or when it is raining. Soils are more sensitive to compaction when wet. Additionally, soil smearing can reduce infiltration rate and inhibit vegetation growth, which can jeopardize establishment and operation.

A best practice to help recognize these conflicts would be to include outlines of infiltration BMPs as part of the underlying base map that is used for all sheets in the design and construction-phasing sheet set. This could help make designers aware of construction-phase conflicts.

4.6.3 Remediation of Construction Impacts

Where construction-phase sedimentation or compaction cannot be avoided, soils should be remediated to restore infiltration properties to the extent possible.

- In the case of compaction, remediation could include tilling or other forms of decompaction. A decompaction depth of 6 to 18 in. is recommended depending on the severity of impacts.
- For siltation, remediation should include over excavation and removal of soils. A depth of 6 to 18 in. is recommended.
- If smearing has occurred, this can be remediated by scarifying and regrading when soils have lower moisture content.
- A sacrificial soil layer or compost amendment could also be integrated with these strategies. A sacrificial impermeable liner is another option.
- Construction-phase infiltration testing should be used to demonstrate that infiltration rates have been adequately restored. Methods appropriate for confirmatory testing are described in Appendix B.

Figure 20. Photos from site visit during construction of I-195 infiltration swales, Swansea, Massachusetts.

4.6.4 BMP Vegetation Establishment

Vegetated systems are most susceptible to declines in permeability during the period immediately after construction and before plants have been able to establish root structures. Several practices can be used to help mitigate these risks:

- Where possible, develop construction phasing to allow time for plant establishment before BMPs are brought on-line to receive stormwater inflow. This also allows time to grow plants from seed or start with smaller plantings to reduce cost and improve plant survival. Note that early construction of the facility may also require special provisions to limit construction-phase impacts.
- Consider temporary irrigation to improve the rate of vegetation establishment.
- Include contract provisions related to percentage of vegetative cover.

4.6.5 Role of Project Delivery Model in Construction Site Management and Phasing

Construction-phasing and construction methods can influence the success or failure of infiltration and filtration BMPs. DOT project managers should review this guidance and determine whether applicable approaches and project controls can be implemented with one of the DOT's standard project delivery approaches. Key questions include the following:

- Does the delivery method allow the DOT to specify phasing? For example, can the DOT specify the timing and order of BMP construction?
- Is construction-phase testing required and are design contingencies needed? If so, does the delivery method support this?
- What is the maximum bonding period allowed by the delivery method? Is this enough to ensure that full vegetation and stabilization of the site have occurred?
- Does the delivery method allow for performance-based standards? For example, if impacts are unavoidable, does the delivery method allow the DOT to specify the minimum permeability of the restored soil? Does the delivery method allow for the DOT to require a certain minimum vegetative cover of graded slopes before constructing BMPs?

If these answers are "no," then the project team may justify consideration of alternative project delivery methods or special specifications.

4.7 Design to Facilitate BMP O&M

Infiltration BMPs, like all structural stormwater BMPs, will require regular maintenance and inspection to remain operable. As a best practice, the designer should consult with O&M staff beginning in the design phase. This can result in designs that are simpler to maintain. In some cases, additional design complexity and cost can simplify maintenance. These can also make BMPs less susceptible to performance declines or nuisance conditions if there are lapses in maintenance. The measures in this section result in BMP designs that control O&M costs.

4.7.1 Design Approaches to Control Maintenance Costs

There are two primary ways to reduce maintenance costs and complexity. Both are strongly recommended.

First, using the approaches described in Sections 4.2 through 4.5, develop BMP designs to increase BMP lifespan and allow BMPs to be adapted to remain operable in adverse conditions.

This tends to result in BMPs that require less maintenance or simpler maintenance. Approaches include following:

- Utilize design approaches that limit clogging risk (Section 4.2).
- Select effective pretreatment BMPs (Section 4.3).
- Develop adaptable designs (Section 4.4).
- Use other design approaches to extended BMP life (Section 4.5).

Second, BMPs should be located and designed so that they can be readily accessed, evaluated, and maintained by means of the following:

- Provide access roads, as applicable, such that portions of the BMP requiring maintenance can be accessed with appropriate equipment without damaging other parts.
- Provide pretreatment systems or sacrificial areas (e.g., the initial cell in a multi-cell system) that are intended to concentrate the spatial extent of pollutant accumulation and maintenance activities. Design these areas to be readily accessible for maintenance.
- Locate systems in areas accessible for maintenance (e.g., not underneath a structure or other site feature).
- Locate systems where maintenance access does not require lane or ramp closures whenever possible.
- Design systems that can be maintained using readily available maintenance equipment whenever possible.
- Locate systems in areas that will not require permits and costly mitigation to perform maintenance activities.
- Develop maintenance protocols that establish the system as a treatment system and limit any future interpretations as a jurisdictional area (e.g., habitat).

Developing an O&M Plan (see Section 4.8) for the facility and consulting with O&M personnel during the design phase can ensure that these factors are considered.

4.7.2 Design Approaches to Allow for Inspection and Verification

BMPs will require regular inspection to verify that they are working properly. Designers can include the following design elements to better accommodate inspection and verification:

- Provide inspection ports for observing underground components that require inspection and maintenance; a diameter of at least 6 in. is recommended to accommodate a range of water level measurement equipment.
- Install level measurement posts in BMP components that trap and store sediment, trash, and debris so that inspectors can determine how much of the BMP capacity is utilized.
- Include a drain plug or valve at the bottom of the surface pool to allow dewatering for inspection and O&M. This can avoid the need to dewater a basin by pump prior to maintenance. Ideally, allow the drain plug or valve to be activated without requiring personnel to enter the ponded water.
- Provide a landscape plan sheet in the O&M plan that clearly identifies expectations for vegetation coverage, size, and type. This supports inspectors who assess conditions and determine the need for maintenance.
- Provide signage indicating the location and boundary of the BMP.

In general, the designer should assume that the BMP will be in a failed or clogged condition when O&M needs occur. If the system is clogged, consider how it will be accessed for maintenance and whether it can be drained without a pump. Consider whether there would be any safety issues associated with inspecting or remediating the failed BMP.

4.8 O&M Manual

The development of a facility-specific O&M manual may be beneficial for communicating maintenance needs to the entity that will be responsible for maintaining the facility.

4.8.1 O&M Manual Contents

Table 28 provides suggestions for the contents of a facility-specific O&M manual. An O&M manual should document the specific aspects of the facility that should be consulted when performing inspections and maintenance. If an agency has standard guidelines available for maintenance of certain elements, these can be incorporated as attachments or references to complement the facility-specific details and support consistency across facilities.

4.8.2 O&M Activities

O&M activities vary in their frequency and intensity through the lifecycle of the BMP. For a consistent description of activities, the following definitions can be used in the development of O&M manuals.

Table 28. Suggested O&M manual content, rationale, and guidance.

Suggestions for O&M Manual Content	Rationale and Guidance
Description of the final constructed BMPs and key design sheets	In preparing the O&M manual, it should be assumed that the full set of design drawings may not be available to O&M crews. The O&M manual should serve a stand-alone purpose.
O&M exhibit—adapted design sheet(s) showing only the features and callouts relevant for field crews performing O&M	
Identification and contact information of the responsible party(ies) for inspection and maintenance	A responsible party should be identified, and contact information must be included.
Identification of the required qualifications and any training required for personnel who will perform inspections and maintenance	Where certain activities require specific training or qualifications, the required qualifications must be clearly identified.
Identification of the funding mechanism and associated supporting information to demonstrate adequacy of funding to cover anticipated and potential expenses	The O&M manual should demonstrate adequate funding and the source of funding.
Description of any unusual, excessively costly, or hazardous O&M activities required for the proposed BMPs	Such activities need to be fully disclosed so that the acceptability of these activities can be evaluated by the entity accepting maintenance responsibility.
Regular inspection activities, frequency, and documentation requirements	These are core elements of an effective and complete O&M manual.
Description of routine and planned maintenance activities, frequency (if scheduled) or triggers (if initiated based on inspection findings), and documentation requirements	
Description of foreseen rehabilitation activities; anticipated frequency; triggers for conducting activities; and the planning, approval, and documentation process required to conduct rehabilitation	
Process for identifying, diagnosing, and correcting issues resulting from damage, unusual wear, unforeseen conditions, etc.	
Spill response; notification requirements; and plans, materials, and responsibilities	

Routine O&M Activities. These are activities conducted at regularly scheduled intervals to sustain long-term performance of each BMP, including inspections and normal upkeep. This category also includes activities conducted on an as-needed basis, prompted by inspections, to correct conditions that are anticipated to occur with normal operation of a BMP.

Rehabilitation Activities. These are activities conducted to replace or rehabilitate system components at the end of their usable life. The O&M manual should seek to estimate the expected design life and the triggers for when a system has reached the end of its usable life.

Corrective Activities. These activities are conducted to resolve major issues that were not anticipated. Because these were not anticipated, it is not possible for an O&M manual to have pre-defined remedies. Rather, the O&M manual should establish a process for identifying a major issue that requires correction, diagnosing the issue and its underlying causes, determining the appropriate corrections, obtaining applicable permits, and appropriately documenting any changes to the design as a result of its correction.

Emergency Response Activities. These activities include the DOT's response to emergencies, including spills. For DOTs, these emergencies responses often require specialized materials and equipment and applicable notifications.

4.8.3 Phases of Maintenance

Maintenance needs can change over time commensurate with plant establishment, media conditioning, and stabilization of the watershed. It may be appropriate to define one or more of the following periods.

Immediate Post-Construction (2 months to 1 year after construction or major rehabilitation). During this phase, the system is stabilizing and there may be limitations to placing the system into full service. After initial construction, the contractor may still be under warranty to maintain the system.

Short Term (2 to 3 years after construction or major rehabilitation). This is a period when plants are establishing and initial system conditioning processes (e.g., media settling, soil structure development) are occurring. During this period, more frequent inspections may be needed. Additionally, maintenance activities can be more frequent and intensive, depending on the needs of the BMP. This regime may also need to be reinstated if major replanting occurs at any point in the facility lifespan.

Long Term (after end of **short-term** phase). This period begins after vegetation has been fully established and typical functions have been adequately observed. The intention of the long-term maintenance period is to provide sufficient and sustained maintenance to keep the BMP operating within acceptable ranges while avoiding unnecessary costs. Observations during the short-term period may result in updates to frequencies or activities associated with long-term maintenance.

Applicable phases should be explicitly defined in O&M manuals especially when maintenance needs are initially uncertain or are expected to evolve over the life of the facility.

4.8.4 Example Outline of O&M Manual

This section provides an annotated outline of an example O&M manual. This outline generally follows Oregon DOT guidelines, and it could serve as a reference for developing an appropriate local outline. Oregon DOT policies call for a draft O&M manual to be prepared as part of the design phase and finalized after construction.

- Cover Content is intended to provide a quick orientation to the facility
  - Facility ID number
  - Brief description of facility
  - Ground-level picture of facility
  - Vicinity map
  - Watershed map
- Identification
  - Provides more detail to accurately identify the facility
- Facility Contact Information
  - Identifies the DOT maintenance contact
- Construction
  - Identifies the dates of original construction and subsequent modification of the facility
  - Identifies the designer of record and contractor who performed each phase of construction
- Storm Drain System and Facility Overview provides a summary of the facility and the related piping connections, including the following:
  - Tributary area
  - Storm drain connections to facility
  - Facility type and design features
  - Treated discharge point
  - Bypass/overflow points
- Maintenance Equipment Access and Special Features of Facility
  - Identifies each discrete feature, the equipment access to the facility, and any special issues associated with maintaining each component
- Facility Hazardous Materials (HazMat) Spill Features and Response Protocol
  - Describes the role of facility features in HazMat spill containment
  - Identifies spill response protocols
- Maintenance Requirements summarizes inspection and maintenance requirements, including the following:
  - Inspection schedule and observations
  - Conditions that indicate need for maintenance
  - Estimated schedule of periodic maintenance
- Waste Material Handling
  - Describes special waste handling requirements
- Appendices
  - Operational Plan: This is an O&M-specific sheets set consisting of approximate 3 sheets that serve as an efficient reference for O&M crews, including the following:
    - Location (e.g., mile points, left or right side of highway), footprint, and type of facility
    - Location of facility components such as flow splitter manhole, forebay, pollution control manhole, flow spreaders, and outlet flow control structure
    - Facility component details (e.g., flow splitter manhole, flow control manhole, forebay) with notes explaining operational functions and how the stormwater drains in and out, flow arrows that illustrate stormwater drainage paths, and any other operational notes needed to assist personnel who maintain the facility
    - Location of maintenance access to facility
    - Footprint of drainage piping and stormwater flow path into and out of the facility
  - Selected plan sheets
  - Manufacturer O&M documents (if applicable)
  - Standard drainage facility guidelines (if applicable)

4.9 Post-Construction Monitoring

Monitoring of constructed infiltration BMPs can address a range of questions and current data gaps. Monitoring can serve a range of purposes:

Guidance Improvement. DOTs can use results from monitoring to assess the reliability of site investigation methods, evaluate the applicability of feasibility criteria, and assess the influence of BMP design approaches on performance and maintenance requirements. This can be used to improve guidance.

Maintenance Planning. DOTs can use results from monitoring to determine maintenance needs, forecast maintenance events, improve maintenance cost estimates, and evaluate material disposal requirements. This can improve the reliability of whole lifecycle cost estimates in the future. It can also inform BMP selection and design.

Performance Evaluation. DOTs can use results from monitoring to evaluate and demonstrate performance. This can be used for compliance and crediting purposes and to inform design improvements.

Impact Assessment. DOTs can use results to determine if designs result in impacts related to groundwater quality and geotechnical issues. This can be used to identify needed remedial activities and improve guidance and criteria for future projects.

Table 29 introduces several monitoring questions that may be relevant to infiltration BMPs and identifies the purpose or purposes these questions may serve. This table also identifies potential study elements to inform these questions.

The Urban Stormwater BMP Performance Monitoring Guide (Geosyntec Consultants and Wright Water Engineers 2009) provides guidance on monitoring BMP performance, including hydrologic monitoring; water quality, groundwater quality, and soil monitoring; statistical analysis, and other topics (http://www.bmpdatabase.org/Docs/2009%20Stormwater%20BMP%20Monitoring%20Manual.pdf). This document also includes references to numerous resources for monitoring plan development.

Table 29. Potential monitoring questions, purposes, and study elements.

	Purposes of Monitoring				
Potential Monitoring Questions	Guidance Improvement	Maintenance Planning	Performance Evaluation	Impact Assessment	Potential Study Elements
Are BMPs operating as designed?	X	X	X		• Maintenance inspections/drawdown observations • Flow monitoring • Water level monitoring
What is the long-term volume reduction and capture efficiency performance of the BMP?	X		X		• Flow monitoring • Water level monitoring
What is the treatment performance for water that is treated?	X		X		• Flow monitoring • Influent/effluent water quality monitoring
How does performance compare with design-phase analyses?	X		X		• Flow monitoring • Water level monitoring

(continued on next page)

Table 29. (Continued).

	Purposes of Monitoring				
Potential Monitoring Questions	**Guidance Improvement**	**Maintenance Planning**	**Performance Evaluation**	**Impact Assessment**	**Potential Study Elements**
How reliable were the methods used to estimate design infiltration rate? Did methods have a high or low bias compared with full-scale performance?	X				• Water level monitoring • Water temperature monitoring[1]
Does the BMP need to be maintained?		X			• Maintenance inspections • Water level monitoring
Is there a trend in performance that can be used to forecast the timing of maintenance?		X	X		• Periodic drawdown observations or long-term water level monitoring • Water temperature monitoring[1]
How often are different types of maintenance required?		X			• Maintenance tracking system
What is the cost of conducting maintenance?	X	X			• Maintenance tracking system
What is the lifespan the BMP?	X	X			• Maintenance tracking system
How do variations in BMP design influence performance?	X				• Side-by-side studies or meta-studies[2]
How do variations in BMP design influence maintenance requirements and costs?	X	X			• Side-by-side studies or meta-studies[2]
What is the response between sediment inflow and decline in permeability?	X	X			• Water level monitoring • Water quality and flow monitoring • Water temperature monitoring[1] • Drawdown observations over time
How effectively are pollutants removed from stormwater before reaching the groundwater table?	X			X	• Stormwater quality monitoring • Vadose and groundwater quality monitoring
How do pollutant concentrations change with depth from ground surface?	X			X	• Stormwater quality monitoring • Vadose and groundwater quality monitoring
Are there detectible changes in groundwater quality resulting from infiltration?	X			X	• Stormwater quality monitoring • Vadose and groundwater quality monitoring • Upstream and downstream monitoring
How does infiltration affect the local groundwater table (e.g., mounding)?	X			X	• BMP water level monitoring • Groundwater level monitoring
Is mounding associated with a decline in infiltration rate?	X		X	X	• BMP water level monitoring • Groundwater level monitoring • Water temperature monitoring[1]
What is the geotechnical zone of influence of the BMP (e.g., is there elevated moisture in response to infiltration)?	X			X	• BMP water level monitoring • Groundwater level monitoring (array) • Soil moisture monitoring (array)
What is the pollutant level in the surficial soil or media? Does this require special disposal? How often should maintenance be done?		X			• Soil quality monitoring

[1] Water temperature affects water viscosity which affects hydraulic conductivity. Water temperature monitoring is recommended as part of monitoring studies in which changes in infiltration rate are relevant to answering study questions.
[2] Meta-studies refers to analysis of compiled studies to evaluate overall relationships between study parameters and performance. These studies may not permit isolation of parameters.

CHAPTER 5

BMP Selection and Sizing Case Studies

This chapter presents case studies of how local agencies and project proponents have approached selection and design of infiltration BMPs. Each case study presents the highlights of the process that was used and the decisions that were made. Additionally, each case study includes a section that summarizes how the decision-making process described in this Guidance Manual could have been applied to these cases. Alignment of the case study with the steps in this Guidance Manual is presented in the last section of each case study.

5.1 Case Study—WSDOT Filter Strip Design Methodology

WSDOT retrofitted a portion of Interstate 5 with various forms of vegetated filter strip BMPs and conducted monitoring to evaluate BMP performance. This installation also helped WSDOT comply with MS4 Permit requirements. The filter strips were designed in May 2010 and construction was completed by September 2011. This case study provides highlights of the site investigation and design process used for these systems. The investigation and design process used as part of this project are similar to other installations of vegetated filter strips on Washington State freeways.

5.1.1 Site Geometry

The roadway at these filter strips locations is an elevated embankment geometry with side slope of approximately 4H:1V and embankment height of approximately 14 ft. There are three travel lanes draining to the filter strips. Figure 21 shows the construction of a typical filter strip as part of this study.

5.1.2 Site Investigation

Depth to groundwater was measured using several piezometers. The groundwater was within 2 to 3 ft of the toe of embankment and approximately 12 to 14 ft below the filter strip locations.

The soils underlying the sites are composed of loose to dense silty sands with gravels and silts. The geology is consistent with glacial outwash. In contrast, glacial till soils that are present in much of Washington State would be expected to be much less permeable.

Grain size distribution data from borehole samples were used to estimate infiltration rate by applying the Massmann Method described in the WSDOT Highway Runoff Manual (HRM). The application of standard factors of safety per the HRM resulted in estimated infiltration rates of 0.2 to 2.2 in./h across different portions of the infiltration surface areas. Permeability also varied somewhat with depth.

Figure 21. Construction of I-5 Pilchuck vegetated filter strips. Photo illustrates installation of compost amended vegetated filter strips (CAVFS) and modified vegetated filter strips (VFS). (Photo provided by Fred Bergdolt, WSDOT.)

5.1.3 Sizing and Design Approach

Applicable BMP section and sizing standards for stormwater BMPs are described in the HRM. These standards require infiltration of 91% of long-term runoff volume if infiltration rates exceed 0.3 in./h. There are no other infiltration feasibility limits that apply to these sites.

In meeting the HRM criteria, WSDOT typically uses a rate of 0.3 in./h in modeling to determine the required size of the filter strips for design. While actual infiltration rates are variable, this approach is based on the following compliance narrative:

- If actual rates exceed this value, then actual performance will meet or exceed requirements to fully infiltrate 91% of long-term runoff volume.
- If actual rates are less than this value, then infiltration performance will not fully satisfy sizing requirements, but treatment through the filter strip will make up the balance of the treatment requirements. This is acceptable because Full Infiltration is only required if rates exceed 0.3 in./h.

Through this approach, the sizing of filter strips can proceed in the absence of precise knowledge about infiltration rates. Note that subsurface investigations may still be needed to confirm that infiltration would not pose slope stability or pavement integrity issues.

5.1.4 Application of This Guidance Manual

The following paragraphs summarize how the decisions associated with this case study correlate to the steps outlined in this Guidance Manual.

Step 1a. Infiltration Objectives. This condition fits the Maximized category of infiltration objectives. Infiltration needs to be prioritized to meet MS4 Permit requirements, but feasibility thresholds are defined, and other treatment processes can be used to comply with permit requirements.

Step 1b. Infiltration Feasibility Conditions. Conditions would be best categorized as Marginal for two reasons: (1) relationships between soil grain size and infiltration have residual uncertainty, and (2) there was relatively high variability between locations, including some estimates that fell below the thresholds. At any given point along the embankment, it is possible that infiltration rates would be below the 0.3 in./h threshold. However, risks associated with geotechnical and groundwater issues were not found to be limiting.

Step 1c and 2. Infiltration Approach and Planning Track. This combination of objectives would put the project in Track 2a—objectives are based on "Maximized" infiltration and conditions were marginal but not infeasible. This would justify a partial infiltration approach that maximizes but does not rely on a certain infiltration rate. According to this Guidance Manual, these are the two options:

1. Use bioretention with underdrains that maximizes infiltration and provides supplemental treatment if infiltration capacity is exceeded.
2. Use a filter strip or media filter drain that maximizes infiltration and provides positive overland flow if infiltration capacity is exceeded.

Step 3. Confirmatory Investigations and BMP Selection. No confirmatory investigations were needed beyond the characterization of geotechnical issues conducted as part of planning (which were found not to be an issue). The design does not depend on a specific infiltration rate.

Following the steps in this Guidance Manual, key deciding factors among potential BMP types are the following:

- Compatibility of BMP types with roadway geometry
- Relative infiltration feasibility of different parts of the highway section

In deciding among the BMP options, the broad vegetated embankment areas were identified as the primary opportunity for infiltration. Additionally, the depth to groundwater at the toe of slope would limit the use of infiltration swales or linear bioretention systems at the base of the embankment. Therefore, vegetated filter strips were identified as the most appropriate infiltration BMP for this site to meet the infiltration objectives.

Step 4. Design and Construction of BMPs. Sizing followed the approach described previously, including assuming the underlying soils are equal to the infiltration threshold. Design followed standard WSDOT guidelines for vegetated filter strips and compost amended vegetated filter strips. WSDOT also trialed a modified filter strip design (a standard vegetated filter strip with a 3-in. compost blanket) as part of this study. WSDOT crews performed construction, which provided control over means and methods. Irrigation was not needed for vegetation establishment. BMP installations in Western Washington State do not typically require irrigation. Most of the construction-phase considerations in this Guidance Manual did not apply to this project.

5.2 Case Study—Adaptive Design Approach for a New Project

A new planned community in the southwest United States has undergone intense regulatory scrutiny and has been required to conduct rigorous consideration of infiltration as part of environmental permitting and design. While not solely a transportation project, the takeaways from this project are applicable to DOT projects, particularly new projects that propose stormwater infiltration at centralized facilities.

5.2.1 Infiltration Objectives

As a condition of approval, the project adopted a stormwater management performance standard that established infiltration as the highest priority, unless it was demonstrated to be infeasible. Biofiltration is the second priority but can require larger facilities and be more expensive to construct. This established relatively rigorous objectives for use of infiltration.

5.2.2 Early Planning

Environmental clearance and layout of the project site required advanced planning efforts. Infiltration was considered as part of these efforts, including preliminary screening of infiltration feasibility based on readily available information. Available data for this step included the following:

- Natural Resources Conservation Service (NRCS) soil survey maps
- Geologic formation maps
- Groundwater depth contours available from the local county
- Mapped landslides obtained from an early geologic study of the site
- Preliminary bulk grading plans processed to estimate net depth of cut and fill

Based on this analysis, regional BMP locations in alluvial soils were determined to be the most suitable for infiltration BMPs. This informed the overall stormwater management strategy for the projects. An example of a preliminary infiltration feasibility screening map developed as part of this effort is shown in Figure 22.

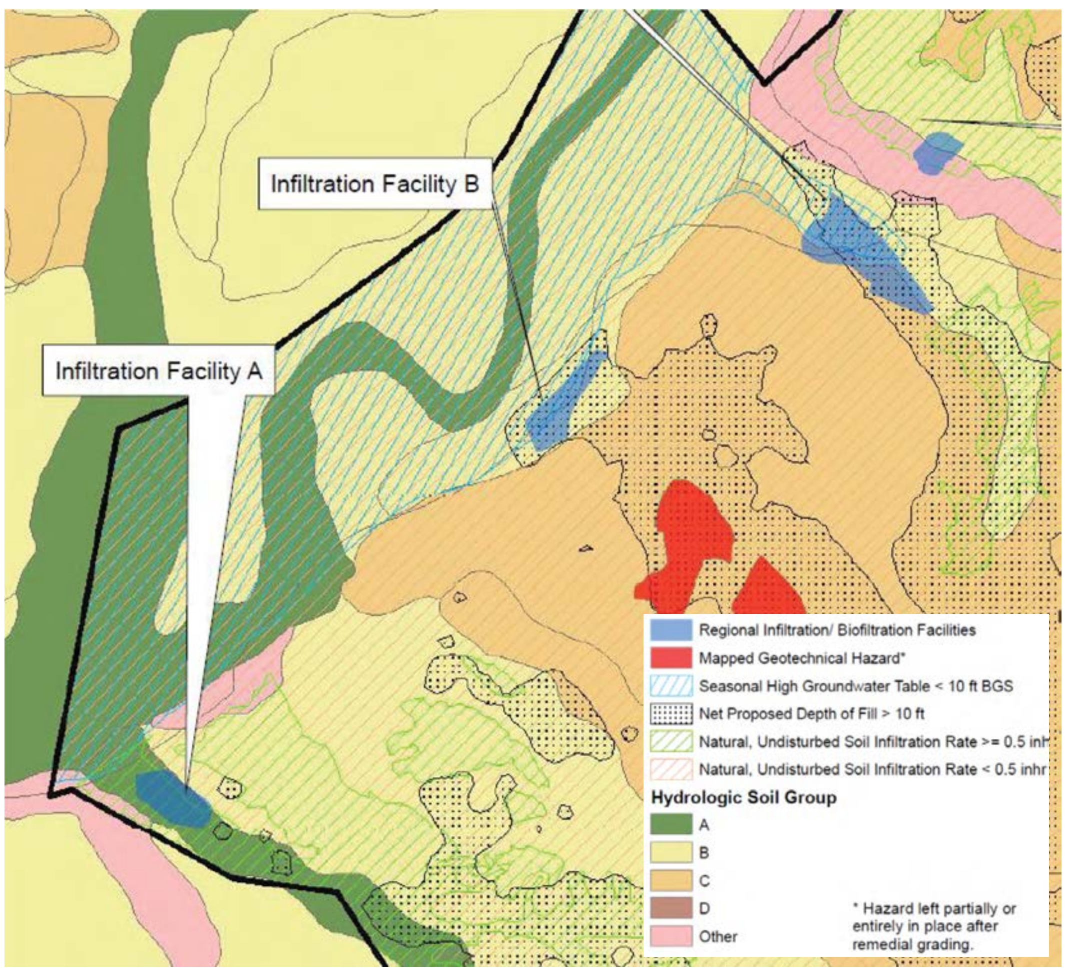


Figure 22. Example preliminary infiltration feasibility screening map.

The stormwater management approach described in project environmental documents was based on these findings. Additionally, project environmental documents identified the need for subsequent investigations to confirm or refine infiltration feasibility. Biofiltration was described as an alternative if infiltration was found to be infeasible. Therefore, the project retained flexibility to apply a range of infiltration approaches in the final design. However, biofiltration tends to be costlier and less favorable relative to project permitting, so there was a strong incentive to utilize infiltration wherever feasible.

5.2.3 Confirmatory Investigations

Following environmental clearance, more detailed design investigations were conducted to finalize the stormwater management plan. To confirm infiltration feasibility, geotechnical investigations were conducted as close to BMP locations as possible. Investigations included the following:

- Classification of soil texture and layering via borehole logs (see example borehole log in Figure 23)
- Investigation to a depth of 15 ft below the elevation of each BMP
- Borehole infiltration testing (falling head method)
- Investigation of groundwater level via local data sources (maps of seasonal high groundwater level) and site-specific piezometer records

Investigations occurred after original environmental approvals; however, access restrictions associated with environmental resource areas limited the ability to conduct drilling and infiltration testing in all BMP locations. Additionally, one of the facilities is located more than 15 ft below existing grade and substantial excavation would be required in this area to reach the proposed grade of the facility.

5.2.4 Design and Permitting Approach

Design and permitting decisions were informed by BMP-specific conditions.

Facility B was determined to have reliable infiltration rates that could be reasonably confirmed via testing at the grade of the facility at three locations within the facility footprint. However, separation to the mapped high groundwater elevation was less than 10 ft and mounding was estimated to be a limitation in this area under more intense storm events. Therefore, this facility was designed as a bioretention BMP with elevated underdrains. Under most conditions, when groundwater is not near the mapped high groundwater elevation and events are less intense, infiltration would be the dominant process in the facility. However, it was not possible to confirm the safe and reliable operation of a Full Infiltration facility at this location.

Measured infiltration rates for Facility A were found to range from 4.6 to 11 in./h at two nearby locations (approximately 50 ft away). Additionally, no geologic or groundwater conditions were identified that would impact the amount of infiltration in the proposed location; however, because of site access limitations, the boring locations used to measure the infiltration rate could not be located within the BMP footprint. Measurements were taken via borehole methods between 20 and 30 ft belowground and primarily measured horizontal infiltration rates because of the inherent geometry of borehole infiltration methods. As a result, these estimates may not be representative of the actual full-scale vertical infiltration rates encountered after the facility is excavated to the proposed grade.

Because of the uncertainty in infiltration rate and the inability to obtain a more reliable rate prior to bulk grading, an adaptable design approach was used:

1. For primary design purposes, Facility A was proposed as a bioretention BMP with elevated underdrains. This facility did not depend on infiltration but is anticipated to result in a high level of infiltration because of the inclusion of 3 ft of gravel storage below the underdrain elevation.

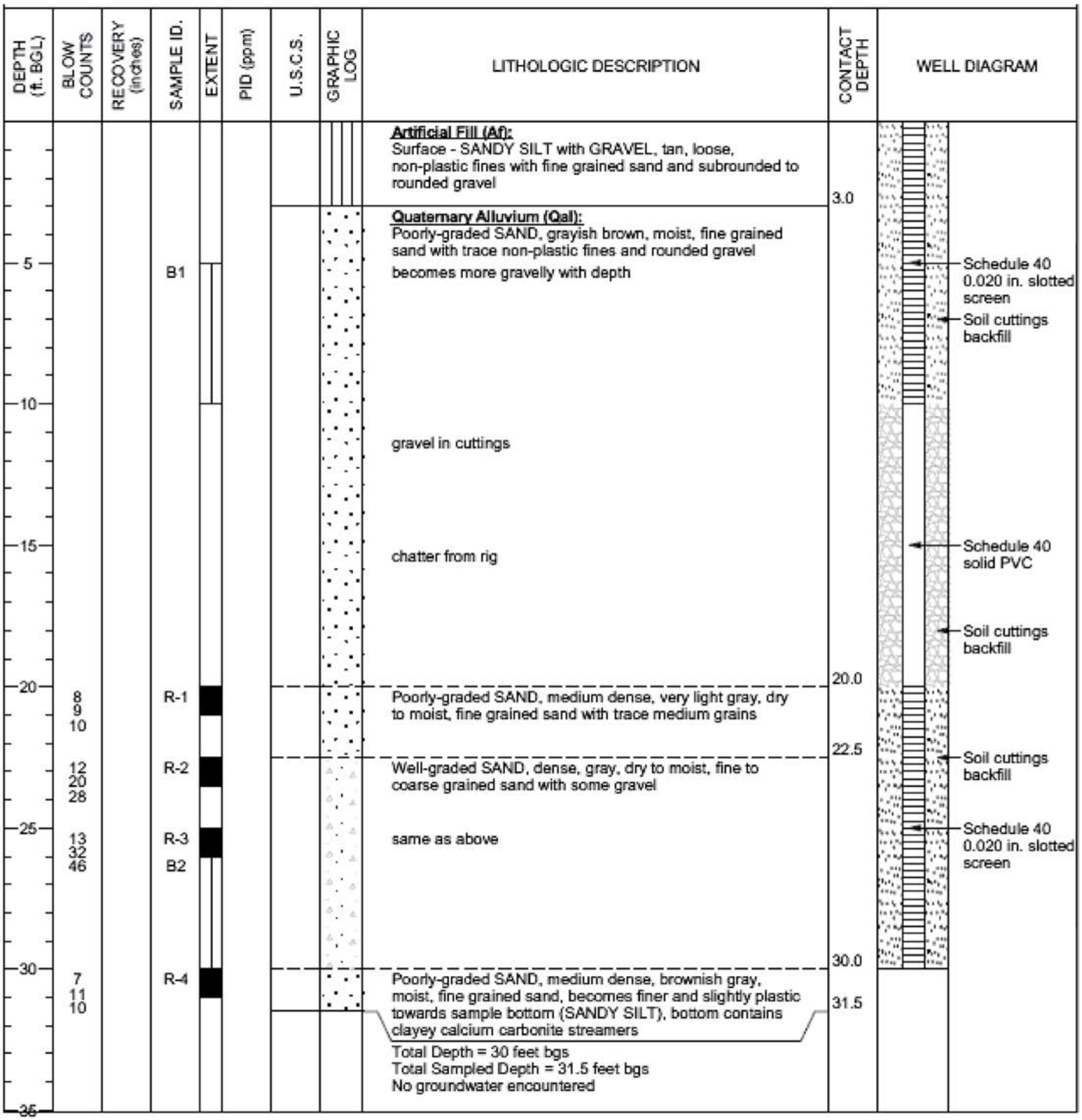


Figure 23. Example borehole log from borehole percolation test.

2. A valve was proposed to be installed at the underdrain outlet of Facility A as a means of providing adaptability for potential design or operation revisions.
3. Project conditions of approval specify that infiltration testing be conducted after grading activities in this area expose the final grade of the facility.
4. If the factored infiltration rate measured after excavation to final grade is 2.3 in./h or greater, and design of a Full Infiltration facility is determined to be acceptable to the local permitting authority, the underdrain valve can be left closed, effectively turning Facility A into an infiltration facility (preferable in this case) (see Figure 24). The threshold of 2.3 in./h was established based on the rate required to achieve the target drawdown time and achieve the target long-term performance of the facility, considering space constraints.
5. Design calculations prepared to support permit applications demonstrated that the facility would fully meet applicable sizing standards as either a Full Infiltration facility if rates are 2.3 in./h or higher or a Partial Infiltration facility with media filtration without relying on a minimum infiltration rate.

This approach preserved the option to infiltrate if it was found to be feasible. The approach provided a compliance demonstration that did not depend on actual infiltration rates to achieve the overall combined infiltration/treatment volume. If infiltration is found to be clearly favorable via construction-phase testing, project proponent could consider adapting the design to a simpler infiltration basin rather than a bioretention basin with underdrains.

5.2.5 Example Application of this Guidance Manual

The following paragraphs summarize how the decisions associated with this case study correlate to the steps outlined in this Guidance Manual.

Step 1a. Infiltration Objectives. Due to the regulatory scrutiny and benefits of infiltration, this Guidance Manual would have classified the infiltration objective as being between Stringent and Maximized. There were strong motivations to achieve infiltration, but Partial Infiltration or non-infiltration alternatives were also available if conditions were not suitable

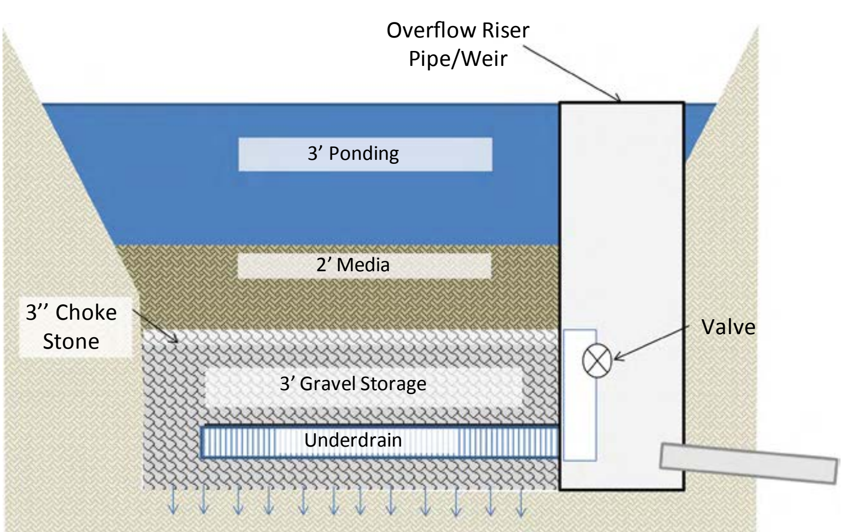


Figure 24. Conceptual cross-sectional design of Facility A showing adaptable design features.

for Full Infiltration, allowing compliance with the overall water quality requirement to be demonstrated without fully relying on infiltration.

Step 1b. Preliminary Infiltration Feasibility Conditions. Based on preliminary screening data available at the time of environmental clearance, both facilities appeared reasonably favorable for infiltration.

Step 1c and Step 2. Infiltration Approach and Planning Track. At the planning (environmental clearance) phase, infiltration was described as the priority for these areas; however, due to the relatively large uncertainty in regional maps, environmental documents described the need for site-specific investigations and feasibility criteria that must be used to determine feasibility at those steps. This correlates to Track 1a in this Guidance Manual.

Infiltration basins were identified as the tentatively selected BMP.

In retrospect, the elevated groundwater condition at Facility B could potentially have been identified with more focused investigation in this area, which would have shifted this facility to Track 2a (Partial Infiltration).

Step 3. Confirmatory Investigations and BMP Selection. Based on the track selected, this Guidance Manual would have called for confirmatory investigations of infiltration rates and geotechnical and groundwater issues. Where feasible, these analyses were done; however, because of access restrictions and the amount of bulk grading required, adequate confidence could not be obtained at Facility A to fully rely on infiltration. Facility A would require additional confirmatory investigation of design infiltration rate as part of and during the construction process. This Guidance Manual would have recommended two options for Facility A based on the information obtained:

1. Use an adaptable design approach to allow infiltration to be an option supported by construction-phase testing, OR
2. Switch to Track 2a and design only a biofiltration with Partial Infiltration design.

Based on an overall assessment of project objectives, the proponent elected to pursue Option 1.

Confirmatory investigation at Facility B revealed previously unidentified issues with high groundwater. Because high groundwater is a limiting factor that cannot be reasonably mitigated, no further investigations were required to support BMP selection and design.

Step 4. Design and Construction of BMPs. Construction of this project was in progress at the time of writing this Guidance Manual.

5.3 Case Study—Ballard Rain Gardens Lessons Learned

5.3.1 Introduction

In 2010, Seattle Public Utilities (SPU) installed bioretention facilities along eight blocks of city ROW in the Ballard neighborhood. In the winter following construction, widespread failures were noted. SPU determined that approximately a third of the cells were not draining, a third were draining too slowly, and a third were working as designed (Figure 25). The resolution of these issues involved removal of 40% of facilities and retrofit of 50% of facilities with underdrains. SPU's retrospective evaluation of the planning, design, and construction process (Tackett and Colwell n.d.) revealed lessons learned that have prompted changes in the way the city plans and designs roadside infiltration BMPs.

Source: https://www.epa.gov/sites/production/files/2015-10/documents/gi_ballardproject.pdf.

Figure 25. Examples of slowly draining rain gardens in the Ballard neighborhood of Seattle, Washington.

5.3.2 Key Lessons Learned

SPU used this project as an opportunity to learn how to improve practices and has published articles and presentations to transfer these findings to other organizations. Examples of lessons learned included the following:

- Geotechnical testing was not conducted early enough in the process. The geotechnical and groundwater investigation report was prepared concurrent with the final design. While some infiltration tests indicated relatively slow infiltration rates (0.1 to 0.3 in./h) and observed fine-grained soils, there was not a feedback loop so that these findings could be incorporated into design adjustments. This was partly due to the expedited project schedule driven by funding sources.
- Designers should more carefully distinguish short-term tested infiltration rates from long-term design infiltration rates. Short-term tested infiltration rates can over-predict infiltration, particularly in cases such as this in which some BMP locations were subject to slow draining soils and perched groundwater tables.

- The investigation period occurred during the summer, and geotechnical recommendations did not account for groundwater mounding and perched groundwater conditions that can form in the soil types present at the sites. Recommendations conducted over an abbreviated period should have been interpreted with a greater implied uncertainty.
- Geotechnical engineers needed to be integrated into all phases of the project, including initiating explorations earlier in planning phases and continued engagement through design development and construction. The city now relies primarily on the recommendation of geotechnical engineers to determine the need for underdrains (or capped underdrains) rather than relying solely on the design infiltration rates.
- Geotechnical engineers should be tasked with a more comprehensive assessment than simply infiltration rate testing. Other observations made as part of geotechnical explorations can support recommendations.
- When new information suggests that infiltration is unlikely or high risk, there should be a more methodical review of whether these data trigger a need for design adjustments. This should include new information obtained in the design and construction phases.
- Stemming from this failure, the city now puts greater emphasis on determining the need for underdrains or backup underdrains. Where measured infiltration rates are less than 0.6 in./h, the city's stormwater management manual requires the use of underdrains. However, underdrains may still be prescribed for sites above this threshold if data do not conclusively support infiltration.
- This case study also illustrated issues that can arise from constructing during the wet season. Because of schedule delays, this project was built in the middle of a relatively wet winter. This increased the risk of over-compacting the BSM (due to placement of wet BSM), increased sediment load from the tributary area, and exposed the systems to relatively heavy hydraulic loading prior to the establishment of vegetation.

Overall, this case study highlights the importance of a structured process for data collection and integration to continue to improve and revise design assumptions and BMP selection decisions. It also highlights the inherent uncertainties that may continue to exist in some parameters until full-scale facilities are built. Finally, it demonstrates the value in having a built-in backup plan (resiliency), particularly in more marginal conditions.

5.3.3 Application of this Guidance Manual

The following paragraphs summarize how the decisions associated with this case study correlate to the steps outlined in this Guidance Manual.

Step 1a. Infiltration Objectives. Infiltration was being considered to reduce the volume of runoff to the city's combined sewer system. While infiltration was not required in this specific area, the overall drivers to reduce combined sewer overflows led to a strong incentive to pursue infiltration. Other approaches would have had less benefit. This is best classified as a Stringent objective.

Step 1b. Infiltration Feasibility Conditions. Conditions were Marginal according to the classification scheme in this Guidance Manual. Soils were fine grained, and measured infiltration rates were relatively low (often less than 0.3 in./h). Additionally, the short investigation period left considerable uncertainty regarding depth to groundwater and the potential for perched groundwater tables to form. Groundwater quality and geotechnical hazards did not exist, so the issues affecting this project were primarily related to infiltration rate and groundwater mounding.

Step 1c and Step 2. Infiltration Approach and Planning Track. This combination of objectives would put the project in Track 1b. There was a strong motivation to achieve infiltration, but conditions were marginal and uncertain. According to the decision tree in this Guidance Manual, these are the three options:

1. Conduct additional investigation to confirm infiltration feasibility,
2. Utilize Partial Infiltration BMPs that are less sensitive to uncertain conditions, or
3. Pursue infiltration with a built-in backup plan to address uncertainty in infiltration rates (note, this is like Option 2 but starts with underdrains capped).

Step 3. Confirmatory Investigations and BMP Selection. Following the steps in this Guidance Manual would likely have resulted in selection of bioretention with underdrains (Partial Infiltration, partial biofiltration/detention). The city's current BMPs selection approaches (refined following these failures) would have reached this conclusion as well.

In retrospect, longer-term groundwater evaluation and groundwater mounding analyses would have rejected the viability of Full Infiltration (Option 1). Options 2 and 3 would not have required further investigations and would have been less sensitive to groundwater and soil conditions; however, they would have been less advantageous for combined sewer overflow (CSO) control.

Step 4. Design and Construction of BMPs. This Guidance Manual encourages modified project delivery such that design revisions can be made during construction if new information is encountered. SPU has identified this as a key lesson learned.

More information is available at the following website: https://www.epa.gov/sites/production/files/2015-10/documents/gi_ballardproject.pdf.

5.4 Summary

These case studies present brief overviews of decision processes and lessons learned from real-world infiltration projects. These case studies also introduce how the decision structure described in this Guidance Manual could be applied to real projects. Additional case studies of infiltration BMPs, focusing on BMP failures, are included in Appendix J.

Acronyms

AASHTO	American Association of State Highway and Transportation Officials
BMPs	Best management practices
BSM	Bioretention soil media
CEC	Cation-exchange capacity
CWA	Clean Water Act
DOT	Department of Transportation
ESA	Endangered Species Act
ET	Evapotranspiration
FHWA	Federal Highway Administration
GW	Groundwater
HRM	Highway Runoff Manual (Washington State DOT)
HSG	Hydrologic Soil Group
IWS	Internal water storage
LID	Low Impact Development
MCL	Maximum Contaminant Level
MEP	Maximum extent practicable
MS4	Municipal Separate Storm Sewer System
NEPA	National Environmental Policy Act
NPDES	Clean Water Act National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
O&M	Operations and maintenance
PAH	Polyaromatic hydrocarbon
ROW	Right of way
SDWA	Safe Drinking Water Act
SPU	Seattle Public Utilities
SSA	Sole source aquifer
TAPE Program	Technology Assessment Protocol—Ecology program
TSS	Total suspended soils
TMDLs	Total maximum daily loads
WLC	Whole lifecycle costs
WSDOT	Washington State DOT

Glossary of Key Terms

The following glossary contains definitions of the key terms as used in the context of this Guidance Manual.

Anisotropy: A soil structure property defined as the ratio between horizontal hydraulic conductivity and vertical hydraulic conductivity. As a model parameter, anisotropy is a function of inherent microscale anisotropy (particle arrangement) and macroscale anisotropy (soil layering).

Average Annual Capture Efficiency [also known as (aka) capture efficiency]: The estimated percentage of long-term average annual runoff volume that is managed or controlled by a BMP.

Baseflow: The portion of streamflow that comes from the sum of deep subsurface flow and delayed shallow subsurface flow. Baseflow tends to dominate discharge during dry weather and small storm events. In contrast, elevated flows during large storm events tend to be derived primarily from overland flow or rapid shallow subsurface flow.

Best Management Practice (BMP): A device, practice, or method for removing, reducing, retarding, or preventing targeted stormwater runoff quantity, constituents, pollutants, and contaminants from reaching receiving waters. This Guidance Manual uses the term BMP to refer to a stormwater control facility.

BMP System: A system including the BMP and any related bypass or overflow**.**

Bypass: Runoff that is routed around a BMP or passes through the BMP with minimal treatment. Bypass generally occurs when the inflow volume or flow rate has exceeded the capacity of the BMP.

Catchment (aka subcatchments, drainage area, drainage basin, subwatershed): The land area that drains to a specific point of interest. A catchment is typically a portion of a watershed.

Clean Water Act (CWA): Federal legislation (1972) that established the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters. The CWA authorized the U.S. Environmental Protection Agency (EPA) to implement pollution control programs such as the National Pollutant Discharge Elimination System (NPDES).

Coefficient of Uniformity: A soil characteristic that influences geotechnical properties. Defined as the ratio of D60/D10. **D10** is the diameter at which 10% of the sample's mass comprises particles with a diameter less than this value. **D60** is the diameter at which 60% of the sample's mass comprises particles with a diameter less than this value.

Compaction: The densification, settlement, or packing of soil in such a way that the bulk density of the soil increases. Compaction tends to result in reduction in soil permeability. Compaction may be intentional, as in the preparation of a site for construction, or incidental, as in the movement of machinery or foot traffic over an area.

Confining Layer: A layer of low permeability soil or rock that limits the vertical movement of water. Bedrock is a colloquial term for a type of confining layer. Clay layers may also behave as confining layers.

Continuous Simulation Modeling: A method of hydrological analysis in which a continuous timeseries (e.g., a period of years) of precipitation and other climatic data are used as input. Watershed processes including infiltration, evapotranspiration (ET), and runoff are calculated on a continuous basis. The outputs of continuous simulation models are typically continuous timeseries of watershed and BMP responses that can be analyzed sequentially or continuously.

Cost-Effectiveness: Defined in general as the ratio of effectiveness of a control for a given metric versus the cost of the control. A higher cost-effectiveness results when the ratio of effectiveness to cost is higher.

Depth Filtration: Refers to a process that occurs in granular media filtration in which larger particles are retained at the surface and progressively finer particles penetrate the media matrix and are retained at various depths from the surface. [Contrast with **Surface Filtration** (also Cake Filtration)].

Design Criteria: In this context, design criteria refer to the set of requirements that serve as the basis for designing a BMP to achieve its intended performance. For example, design criteria for a filter strip may include the slope, length, vegetation density, amended soil thickness, maximum flow depth, and other criteria.

Design Infiltration Rate (also Factored Infiltration Rate): An infiltration rate that has had appropriate factor of safety applied and is suitable for use in design.

Design Parameters: The qualitative and quantitative physical characteristics that are used in the design process to describe and analyze a given BMP design. Design criteria are commonly expressed in terms of allowable bounds on design parameters.

Design Storm: A prescribed precipitation distribution (hyetograph) and the total precipitation amount that is used as part of the design process of BMPs. Design storms may be statistically derived hypothetical events or real events that have been observed.

Discharge Rate: Discharge rate refers to the rate at which water is discharged from a BMP.

Disconnection: (aka dispersion, disconnected impervious area): A stormwater drainage pattern that routes flow from impervious areas across pervious surfaces prior to discharging to a storm drain or receiving water. There are various degrees of disconnection, such as disconnection that attempts to fully mitigate hydrologic impacts, and disconnection that may attempt to provide only a portion of total control needed to mitigate impacts.

Drawdown Rate: The rate at which the storage volume in a BMP is recovered as a result of water discharging from the BMP, making storage volume available for subsequent storm events.

Drawdown Time: The time required for a BMP to drain and return to its dry-weather condition. For example, the drawdown time of an infiltration basin is the time it takes for the basin to drain from brim full to empty following the end of inflow. For detention facilities, drawdown time is a function of basin volume and outlet orifice size. For infiltration facilities, drawdown time is a function of basin volume and infiltration discharge rate.

Effectiveness: A measure of how well a BMP system meets its goals for all stormwater flows reaching the BMP, including flow bypasses. For example, effectiveness is a function of capture efficiency, percentage of volume reduction, and effluent pollutant concentration. See **Performance** and **Efficiency** for complementary definitions.

Efficiency: A measure of how well a BMP or BMP system removes pollutants. See **Performance** and **Effectiveness** for complementary definitions.

Evaporation: The change of phase of a liquid into a vapor at a temperature below the boiling point, taking place at the liquid's surface.

Evapotranspiration (ET): The loss of water to the atmosphere by the combined processes of evaporation (from water, soil, and plant surfaces) and transpiration (from plant tissues).

Factor of Safety (FS): A factor applied to a specific system design parameter that is intended to make the design of the system more robust in the event conditions are different than analyzed, conditions change with time, or other factors are present that are not explicitly considered or are not foreseen in the design process.

Feasibility Criteria (aka infeasibility criteria): Specific qualitative or quantitative criteria that are used to identify conditions under which a given stormwater management approach is considered feasible or infeasible.

Flood Control Regulations: In this Guidance Manual, Flood Control Regulations are requirements meant to reduce the risk of damage to public property or hazards to public safety as a result of runoff from large storm events. For example, flood control regulations may require peak runoff flowrates be matched for pre-project versus post-project for a specific large design storm event (e.g., 25-year, 24-hour event). In contrast, water quality regulations typically focus on smaller, more frequent events that are of specific interest to protection of receiving water quality.

Full Infiltration BMP/Full Infiltration: A type of infiltration BMP that relies solely on infiltration into underlying soils. Full Infiltration does not imply that all stormwater runoff is infiltrated. The amount of water infiltrated is a function of BMP size and design goals as well as site conditions. However, these BMPs do not have a design discharge to surface waters except when the system overflows or bypasses. The key distinguishing trait of these BMPs is that they depend on a certain minimum infiltration rate to meet their intended functions.

Geotechnical Considerations: In this Guidance Manual, geotechnical considerations refer specifically to factors related to geotechnical design and performance of soil structures when considering infiltration of stormwater. Considerations include landslides, liquefaction, settlement, and other factors.

Groundwater Mounding: Refers to the development of a localized increase in the groundwater table below a BMP on a temporary basis in response to stormwater infiltration. The development of a mound is an inherent hydrogeologic phenomenon in response to point loading of stormwater infiltration.

Groundwater Mounding Assessment Tool: Refers to the spreadsheet tool developed as part of NCHRP Project 25–51 and included as Appendix C.

Groundwater Quality Criteria: Pursuant to the CWA, water quality criteria are numeric, narrative objectives, or limit used to determine when water has become unsafe for people and wildlife. The EPA developed water quality criteria as recommendations. State and tribal governments may use these criteria or use them as guidance in developing their own.

Groundwater Quality Standard: Pursuant to the CWA, water quality standards are provisions of state, territorial, authorized tribal, or federal law approved by the EPA that describe the desired condition of a water body and the means by which that condition will be protected or achieved.

Groundwater Recharge: The process by which surface water infiltrates into permeable soil and ultimately contributes additional water volume to groundwater sources.

Head: In hydraulics, energy represented as a difference in elevation. In slow-flowing open systems, the difference in water surface elevation (i.e., between an inlet and an outlet).

Hydraulic Loading: The ratio of stormwater inflow (volume/time) to a BMP divided by the surface area of the BMP that receives flow; this can be a specific value, expressed in terms of a length per unit time (e.g., ft/s) or it can be used in a more qualitative sense to make a comparison between BMP configurations.

Hydraulic Loading Ratio: In this Guidance Manual, this term refers to the ratio between the impervious area tributary to a BMP and the infiltration or filtration surface area of the BMP.

Hydrocollapse: A sudden collapse of granular soils caused by a rise in groundwater dissolving or deteriorating the inter-granular contacts between the sand particles.

Hydrograph: A timeseries of flow discharge (e.g., runoff rate, inflow rate, outflow rate) versus time.

Hydromodification: Changes in runoff and sediment yield caused by land use modifications.

Impervious Surface: Surface area that allows little or no infiltration. Impervious surfaces include pavements, roofs, and similar surfaces. Highly compacted gravel and earth can behave as impervious surfaces.

Incidental Infiltration: Infiltration that occurs within a BMP as an incidental and reasonably expected part of operation but is not a primary design goal or treatment process.

Infiltration: The movement of water from the surface into the soil. Movement from shallow surface layers to deeper surface layers is referred to as "percolation."

Infiltration Approach: Refers to classes of infiltration BMPs. For example, Full Infiltration and Maximized Partial Infiltration are infiltration approaches.

Infiltration BMP: A BMP designed to rely in whole or part on infiltration of stormwater into subsurface soils to meet stormwater management objectives. Infiltration BMPs vary in (1) the degree to which they rely on a certain minimum infiltration rate to remain operable, (2) the degree of infiltration provided, and (3) their design approach, relative to the specificity of infiltration goals. See also **Full Infiltration BMP**, **Partial Infiltration BMP**, and **Incidental Infiltration**. Classes of approach involve infiltration BMPs that rely solely on infiltration into underlying soils. Full Infiltration does not imply that all stormwater runoff is infiltrated. The amount of water infiltrated is a function of BMP size and design goals as well as site conditions. However, these BMPs do not have a design discharge to surface waters except when the system overflows or bypasses. The key distinguishing trait of these BMPs is that they depend on a certain minimum infiltration rate to meet their intended functions.

Infiltration Capacity: Refers to the overall ability of the infiltration receptor to accept infiltrated water, considering infiltration rates and soil permeability as well as hydrogeologic factors. This is a semi-quantitative metric.

Infiltration Rate: The rate at which water moves into the soil, expressed as length per unit of time. Infiltration rate is a "bulk" measurement in that it describes the overall rate not the velocity of water through pores, which would tend to be faster.

Infiltration Receptor: Refers broadly to the unsaturated soil layers, perched groundwater, or aquifer that will receive infiltrated stormwater.

Interflow (aka shallow interflow): The flow of water through the upper soil zones into a stream. In comparison with baseflow, which tends to originate from lower soil zones, interflow tends to have a shorter travel time and quicker response. However, interflow tends to have a longer, more attenuated response than sheet flow and concentrated overland flow.

Liquefaction: A seismically induced geological hazard that can result in damage to structures because of a reduction in bulk volume of saturated granular soils during shaking of the earth. Liquefaction results in the loss of a soil's ability to support a structure. It is specifically associated with saturated granular soils.

Local Groundwater Protection Criteria: Criteria established by local groundwater protection agencies to protect the quality of groundwater. These may be at a state or local level. These criteria may be based on CWA water quality standards and/or SDWA maximum contaminant levels.

Maximum Extent Practicable (MEP): Standard established by the 1987 amendments to the CWA, for the implementation of municipal stormwater pollution prevention programs. According to the Act, municipal stormwater NPDES permits "shall require controls to reduce the discharge of pollutants to the maximum extent practicable including management practices, control techniques and system, design and engineering methods, and such other provisions as the Administrator or the State determines appropriate for the control of such pollutants." MEP is not defined by the CWA.

Monitoring: Refers to observations and measurements used to assess condition, performance, maintenance needs, and impacts of an infiltration BMP.

Municipal Separate Storm Sewer System (MS4): A conveyance or system of conveyances (including roads with drainage systems, municipal streets, catch basins, curbs, gutters, ditches, constructed channels, or storm drains) designed for collecting or conveying stormwater as defined in 40 CFR 122.26(b)(8).

National Pollutant Discharge Elimination System (NPDES): A provision of the CWA that prohibits point-source discharges of pollutants into waters of the United States unless a special permit is issued and administered by states or the EPA.

New Development Project: Refers to a project involving construction of a new segment of roadway in a previously undeveloped or much less developed ROW. (Contrast with **Retrofit Project** or **Redevelopment Project**.)

Observed Infiltration Rate (also Raw Infiltration Rate): The estimated infiltration rate based on the results of field tests, prior to incorporating a factor of safety for design purposes.

Off-Line BMP: Off-line BMP systems receive flow from a flow-splitter structure of some sort such that the maximum inflow to the system is restricted and peak flows are designed to bypass the system without treatment.

On-Line BMP: On-line BMP systems receive all the stormwater runoff from a drainage area. Flows above the water quality design flow rate or volume are passed through the system, generally via an overflow device or structure.

On-Site BMPs: BMPs that are implemented within the boundary of a project site. In contrast, see **Regional BMPs**.

Operations and Maintenance (O&M): Refers to inspection of BMPs, operation of the BMPs (if actively operated), and implementation of preventative and corrective maintenance into perpetuity. O&M represents a continuing cost associated with the BMP after the initial capital cost of construction.

Outlet Control: A design approach for bioretention BMPs in which the flow through the soil media bed is primarily controlled by an outlet control structure affixed to the underdrains of the system rather than limited by the hydraulic conductivity of the bioretention soil media.

Overland Flow: Flow of water across the land surface in a downgradient direction. Sheet flow, shallow concentrated flow, and channelized flow are forms of overland flow.

Partial Infiltration BMP/Maximized Partial Infiltration: A type of infiltration BMP that is designed specifically to maximize infiltration while also providing other treatment mechanisms. These BMP types are not wholly reliant on infiltration to maintain an operable condition and meet water quality and flow control requirements but are expected to result in significant levels of infiltration.

Partially Feasible: The concept of "partial feasibility" refers to a condition in which it is feasible to achieve a portion of the established design goals, but in which it would be infeasible to achieve the entire design goal based on constraining factors. For example, if it is feasible to retain 0.3 in. of runoff, but the design goal is 1.0 in. of runoff, then it would be considered partially feasible to meet the design goal.

Performance: A measure of how well a BMP meets its goals for the stormwater that flows through or is processed by it. In comparison to **Effectiveness**, assessment of BMP performance does not account for bypass of flows, because these flows are beyond the design goal of the system. See **Effectiveness** and **Efficiency** for complementary definitions.

Performance Criteria: A specific measurable or verifiable set of requirements against which the performance of a system is compared to assess conformance with regulatory requirements. For example, reduction of a certain percentage of average annual runoff volume is a common form of a performance criterion established for volume reduction approaches.

Pervious Surface: Surface area that allows infiltration of water.

Physical Setting: The physical aspects of a project site that may impact project design and performance relative to volume reduction, including the site-specific climate, geology, soils, and vegetation.

Precipitation: Water that falls to the earth in the form of rain, snow, hail, or sleet.

Precipitation Event: A period of precipitation separated from other events by established inter-event criteria, such as a dry period of a certain length.

Pretreatment: A system used to remove pollutants from stormwater before it enters the main part of a BMP.

Project Attributes: The aspects of a project design that may impact performance relative to volume reduction, including planimetric geometry, topography, utilities, regulatory overlays, construction methods, and other factors.

Redevelopment Project: Refers to a project involving re-alignment, lane addition, or other roadway construction work within an existing developed ROW. (Contrast with **Retrofit Project** or **New Development Project**.)

Regional BMPs (aka watershed-scale BMPs): BMPs implemented within the local subwatershed, typically outside and downstream of the project boundary or treating nearby areas. In contrast, see **On-Site BMPs**.

Resiliency: In the context of stormwater BMPs, resiliency can be defined as the ability to tolerate, adapt to, or rapidly recover from adverse conditions, such as incomplete site investigations, construction impacts, elevated sediment loading, contaminant spills, extreme storm events, lack of maintenance, change in tributary area characteristics, and change in design goals.

Retrofit: A type of project that principally involves retrofitting a roadway with a stormwater BMP for the purpose of providing treatment of existing paved surfaces. This may not be associated with a roadway. (Contrast with **Redevelopment Project** or **New Development Project**.)

Right of Way (ROW): Is defined as the legal parcel within which the roadway project is constructed.

Roadside BMP Clogging Risk Assessment Tool: Refers to the spreadsheet tool developed as part of NCHRP Project 25–51 and included as Appendix F.

Roadway Design Regulations: Refers to regulations related to roadway geometrics, public safety, drainage, and other aspects of roadway design, inclusive of water quality and volume reduction as applicable.

Root Zone: The depth to which the major vegetation draws water through a root system in soil.

Runoff Volume: The volume of water that flows off a surface during a period of interest.

Sacrificial Soil Layer: A sacrificial soil or media layer consists of a layer of material (sand, soil, engineered media) placed over top of less permeable underlying soil to serve as an embedded pretreatment layer. Because of its higher permeability, more sediment can be loaded on this layer before it approaches the limiting rate of the underlying layer. Additionally, if this material is significantly coarser than incoming sediment, it is more likely that the depth filtration processes will prevail at the surface rather than cake filtration or surface filtration.

Safe Drinking Water Act (SDWA): The federal law that protects public drinking water supplies throughout the nation. Under the SDWA, EPA sets standards for drinking water quality and with its partners implements various technical and financial programs to ensure drinking water safety.

Sheet Flow: An overland flow, downslope movement of water taking the form of a thin continuous film over a generally smooth surface.

Shoulder (of a roadway): A reserved open area located at the edge of a roadway consisting of pavement or pervious surface.

Site Design: A stormwater management strategy that emphasizes conservation and use of existing site features as well as incorporation of strategic drainage patterns to reduce the amount of runoff and pollutant loading that are generated from a project site.

Sizing Criteria: Specific design criteria related to BMP sizes that serve as a presumptive basis for meeting performance criteria.

Sole Source Aquifer (SSA): EPA defines an SSA as one in which (1) the aquifer supplies at least 50% of the drinking water for its service area, and (2) there are no reasonably available alternative drinking water sources should the aquifer become contaminated.

Spill Isolation and Containment: A system to capture and contain a contaminant spill before it reaches a BMP or a stormwater outfall.

Surface Filtration (also Cake Filtration): Refers to a process that occurs in granular media filtration in which most particles are retained at the surface of the media and form a layer of material that predominantly comprises particles filtered from stormwater. (Contrast with **Depth Filtration**.)

Total Maximum Daily Load (TMDL): The calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards and an allocation of that load among the various sources of that pollutant. Pollutant sources are characterized as either point sources that receive a wasteload allocation or nonpoint sources that receive a load allocation.

Travel Lane: A portion of a road or highway that is primarily dedicated to conveying automobile travel.

Vadose Zone (also Unsaturated Zone): Refers to soil layers that are unsaturated, extending from the ground surface to the water table.

Volume Reduction: The process by which the volume of runoff that discharges directly to receiving waters is reduced through volume reduction approaches that include infiltration, ET, and/or harvest for beneficial use.

Volume Reduction Tool: Refers to the spreadsheet tool developed as part of *NCHRP Report 802*.

Water Balance (aka Water Budget): The accounting of a system's state of water storage and flux, considering the total flow of water into and out of a system and the change in storage conditions in the system. For example, water balance can refer to the flux of water in and out of a specific BMP system, a local groundwater system, or a regional groundwater system.

Water Balance Analysis: Water balance analysis refers to the consideration of the fate of retained stormwater (e.g., percolation, interflow, ET, or beneficial use) such that potential adverse effects on local systems can be evaluated.

Water Table: Refers to the interface between saturated subsurface soil (phreatic zone) and unsaturated soil (vadose zone).

Watershed Characteristics: Characteristics of the watershed in which a project is located that may influence goals for volume reduction or the amount of volume reduction that can be achieved (e.g., topography, regional groundwater table, regional water balance, and other factors).

Whole Lifecycle Cost and Performance Tools: Refers to the spreadsheet tools developed as part of *NCHRP Report 792*.

Whole Lifecycle Costs: An economic assessment, expressed in monetary value that considers all significant and relevant cost flows over a period of analysis (project life expectancy). Project costs include those needed to achieve defined levels of performance, including reliability, safety, and availability. Included are both capital and O&M costs.

References

Note: The information provided in this Guidance Manual is distilled from topical research documented in the appendices to this Guidance Manual and the accompanying Project Summary Report. Reference lists for the respective topics are included in each of these documents. Appendices B through J and the Project Summary Report can be found on the TRB website (www.trb.org) by searching for "*NCHRP Research Report 922*". The following references are directly cited in this Guidance Manual.

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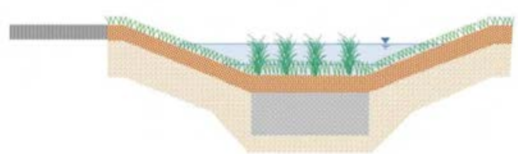
APPENDIX A

Infiltration BMP Fact Sheets

Contents

Vegetated Conveyance BMP 01

Alternative names: *dry swale, bioswale, grassed swale, retention swale, regenerative stormwater conveyance*



(Photo credit: Caltrans.)

VOLUME REDUCTION PROCESSES	
◉	Overall Volume Reduction Potential
◉	Infiltration
◉	Evapotranspiration
○	Consumptive Use
○	Baseflow-mimicking Discharge

URBAN HIGHWAY APPLICABILITY	
●	Ground level highways
◉	Ground level highways with restricted cross-sections
◉	Ground level highways on steep transverse slopes
◉	Steep longitudinal slopes
◉	Depressed highways
○	Elevated highways on embankments
○	Elevated highways on viaducts
●	Linear interchanges
●	Looped interchanges

● High ◉ Moderate ○ Low

Description

This category includes engineered vegetated swales and other vegetated drainage features that convey stormwater runoff and significantly reduce stormwater runoff volume. Some variations on this approach include an amended soil or stone storage layer to increase storage capacity and promote infiltration. A critical element of this BMP is that it must be designed to sustain robust plant growth so that infiltration rates are maintained and regenerated via root structure, and the conveyance system itself does not contribute to sediment loading from scour.

In contrast to a linear variation of bioretention, this approach is generally designed with a positive surface slope toward an outlet located at the surface grade. Where check dams or step pools provide significant ponded storage volume in the system that is infiltrated between precipitation events, it may be more appropriate to consider the system as a linear bioretention area BMP for the purpose of design and performance evaluation.

Volume Reduction Processes and Performance Factors

Volume reduction is achieved through infiltration and evapotranspiration (ET). Volume reduction can be enhanced by including a stone or amended soil storage layer, providing shallow retention in the conveyance, and using a broader, flatter cross section. Soil infiltration rates, longitudinal slopes, and the relative ratio of BMP bottom area to tributary area are believed to be the most important key factors in volume reduction effectiveness.

General DOT Experience

In many cases, vegetated conveyances may be a standard highway design feature that would be installed regardless of water quality and volume reduction benefits. Therefore, these features can be used at very low incremental costs (for example, some minor additional bottom width may be what is needed to achieve volume reduction goals). In addition to a standard conveyance feature in many highway systems, vegetated conveyances have been implemented by DOTs to achieve both water quality treatment benefits and volume reductions of highway runoff. A review of volumetric measurements from swale studies in the International BMP Database shows moderate volume reduction on average (Geosyntec and Wright Water Engineers 2011) .

Applicability and Limitations

Site and Watershed Considerations

- Vegetated conveyances are suitable for most soil types. Soil infiltration rates will determine whether the swale can be designed to achieve significant infiltration or will serve primarily as conveyance with incidental volume reduction.
- Longitudinal slopes must be positive but not too steep (typically 1% to 6%) in order to provide positive drainage but to avoid the creation of high velocity flows that result in erosion. Check dams can allow the use of swales on somewhat steeper slopes (about 4% or over).
- Vegetated conveyances are relatively narrow and linear in profile, which allows them to fit into constrained spaces. They are suitable for use on shoulders and in medians, and compatible with general highway design and maintenance.

Geotechnical Considerations

- Vegetated conveyances must be located a sufficient distance from the roadway so that infiltration will not compromise its structural integrity,
- Vegetated conveyances are a standard design feature in ground level highway types; they should not pose significant incremental geotechnical risks.
- Use of vegetated conveyances along steep transverse slopes may require enhanced protection of slope integrity.

Groundwater Quality and Water Balance Considerations

- Vegetated conveyance does not generally pose elevated risks to groundwater quality or water balance.
- In areas with very high soil infiltration rates or shallow groundwater tables, captured stormwater may not be sufficiently treated prior to contact with groundwater. In these situations, designs may need

pretreatment (e.g., addition of filtration media in the design) or adjustment to enhance treatment and prevent groundwater contamination.

- Where soils allow high rates of infiltration, the use of vegetated conveyance may shift the water balance toward excess infiltration.

Safety Considerations

- For vegetated conveyances to be located within the “clear zone” (typically in the range of 22 to 32 feet from driving lanes), vegetated conveyances should either be constructed with side slopes of 3H:1V or flatter, or a barrier should be used between the road and the conveyance (parallel to road).
- If a piped inlet is used, the pipe openings should be cut flush with the cross slope in order to reduce the potential that the pipe will be struck head-on by an errant vehicle. Pipes with diameters greater than 24 in. should be covered with traversable grates.

Regional Applicability

- Vegetated conveyances are used across a broad range of climates. As a result, plants must be selected to be compatible with the local climate.
- In cold climates, use sod-forming grasses and cold climate-tolerant vegetation adjacent to roadway shoulders.
- Salt loadings in cold climates may also influence plant selection.
- Vegetative conveyances are more susceptible to clogging, as snow plowed alongside a roadway facility carries high sediment (road sand) and pollutant (road salt mixtures) loads. Vegetation, if not salt-tolerant, can be adversely affected. Sodium-based deicers have been shown to break down soil structure and potentially decrease infiltration rates.
- Irrigation is typically required for robust plant establishment, especially in arid climates. Highly arid climates without some irrigation may be more challenging.

New Projects, Lane Additions, and Retrofits

- Vegetated conveyances are applicable and appealing retrofit options due to their low cost, effective treatment performance, and compatibility with highway design.
- Vegetated conveyances may have small incremental costs in new projects with sufficient ROW widths because grading can be balanced, and landscaping would otherwise be installed; incremental costs may be greater in lane additions and retrofits where a swale did not previously exist.
- Retrofitting an existing vegetated conveyance to improve volume reduction processes, such as by adding check dams, amending soils, or increasing plant density, can be an effective method of providing an

incremental improvement in volume reduction for relatively minimal investment.

- Vegetated conveyances are applicable for ultra-urban highway retrofits when sediments and metals are the main target constituents; there is adequate space along the highway shoulder, along ramps, between sidewalks and roadways, and other landscaped areas; drainage patterns and topography are suitable; and there is safe maintenance access.

Use in a Treatment Train

- Vegetated conveyances can be used to collect and convey water downgradient of a filter strip.
- Vegetated conveyances can be used to pretreat, achieve some volume losses and convey stormwater to centralized BMPs such as bioretention areas, infiltration trenches, or infiltration basins.

BMP-Specific Maintenance Considerations

- They typically require maintenance activities similar to those already needed for maintenance of roadside vegetation and ditches.
- Proper function requires maintaining dense plant cover to prevent scouring. Patches of thin or missing vegetation should be repaired right away.
- Vegetation may need to be mowed or cut back regularly to maintain optimal plant height.

Enhancements and Variations

Add storage below the surface outlet. Vegetated conveyances may be underlain by storage areas composed of either stone and/or amended soils in order to increase storage capacity and promote infiltration and ET. Where this storage becomes the defining feature of the system, the BMP may be more appropriately categorized and designed as a linear bioretention area.

Use check dams. In addition to helping slow and more evenly distribute flow, check dams can also prevent erosion (assuming that downstream of the check dam is protected). Check dams are used in vegetated conveyances to promote ponding and infiltration when the longitudinal slopes are large. It has also been found that retrofitting existing roadside ditches with check dams provides significant water quality benefits.

Apply a compost amendment. Compost added to the soils of vegetated filtration systems can provide many benefits, the most significant being an increase in the retention and infiltration capacity of soils, which correspondingly increases pollutant load reductions. Compost amendments also increase the sorption sites, lower the bulk density, provide conditions conducive to healthy soil microbes, and promote growth and increased density of vegetation. Peat and compost should not be used as media as they retain water and freeze during the winter, and are thereby impermeable and ineffective. A slightly higher level of permeability should be used in colder climates to prevent frost heaving and encourage snowmelt runoff.

Slow the velocity of flow. Vegetated conveyances may be planted with densely growing native/non-invasive vegetation (turf not preferred) to slow flows, promote more infiltration, and allow greater volume reduction.

Provide low flow outlet. Water can be held and released at a slow rate via a low flow outlet, such as a slotted weir, located at the downstream end of the system. This can provide detention and added volume reduction benefits.

Stabilize the surface. A stabilization approach may be included in vegetated conveyances, such as reinforcement matting, to enable higher flows to be conveyed without scour. This has the benefit of reducing scour pathways where water moves more quickly with less potential for volume reduction. It also helps prevent sediment loading from scour.

Create permanent pools for water quality improvement. Wetland-type systems, often referred to as wet swales, make use of check dams to create a series of impoundments where wetland conditions are allowed to develop. These systems can achieve high pollutant removal. However, they typically display low volume removal performance because their construction relies on impermeable soils, and thus ET is the primary mechanism for volume removal. Wetland-type systems can also provide areas for vector establishment and reproduction, resulting in the possible need for abatement measures.

Cold climate applicability. In cold climates, these may be used as snow storage/melt areas. Salt-tolerant vegetation should be used, and length of growing season should be considered during construction of the BMP. It may take longer to establish vegetation, possibly two growing seasons, to achieve significant grass cover. Erosion control measures such as mats or blankets should be used to stabilize the slopes while the vegetative cover becomes established. The depth of soil media that serves as the planting bed must extend below the frost line to minimize the effects of freezing.

Resilient Design Features

The standard design of vegetated conveyances includes resiliency. The standard system design gravity drains from inlet to outlet, allowing water that does not infiltrate to discharge to the outlet.

If check dams are included to promote infiltration, design them to allow the height to be adjusted if infiltration does not support the amount of infiltration intended.

High flow through the system can cause damage and impair function. Designing off-line systems that only receive water quality storms can improve resilience by reducing the effects of high flow events.

Seed/vegetation mixtures that will create a denser, deep-rooted vegetation mat will be more erosion resistant, enabling a more resilient surface during higher-intensity storms.

Additional References for Design Information

California Stormwater Quality Association. California Stormwater BMP Handbook: New Development and Redevelopment. TC-30, Vegetated Swale. 2003. Fact Sheet containing design guidance, construction and maintenance information for infiltration trenches, including costs. Available online at https://www.casqa.org/resources/bmp-handbooks/new-development-redevelopment-bmp-handbook.

Center for Watershed Protection's Stormwater BMP Design Supplement for Cold Climates (Caraco and Claytor 1997). Includes recommended modifications for infiltration and other stormwater BMPs in cold climates. The document is available from the Center for Watershed Protection (CWP) at http://owl.cwp.org/mdocs-posts/caracod_sw_bmp_design_cold_climates/.

New York State Stormwater Management Design Manual (2015). Chapter 6: Performance Criteria. Center for Watershed Protection, Ellicott City, Maryland. This chapter contains 66 pages on the performance criteria for five groups of structural stormwater management practices (SMPs) to meet water quality treatment goals, including feasibility and cold climate design guidance. There are highly detailed plan and profile figures for all types of BMPs under varying conditions, as well as a cold climate sizing example in Appendix I. The entire document can be downloaded from http://www.dec.ny.gov/docs/water_pdf/swdm2015entire.pdf.

Oregon State University et al. 2006. *NCHRP Report 565: Evaluation of Best Management Practices for Highway Runoff Control*. Transportation Research Board of the National Academies, Washington, D.C. Manual intended to provide the highway engineer with selection guidance toward implementation of BMPs and LID facilities for control of stormwater quality in the highway environment. Includes detailed schematics and cost tables for different items in each BMP. http://www.trb.org/Publications/Blurbs/158397.aspx.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 3: Grass Channel v.1.9. 2013. Fact sheet including design guidance, construction and feasibility. Excellent figures and schematics. http://chesapeakestormwater.net/category/publications/design-specifications/

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Key Planning Level Design Parameters for Volume Reduction

Conceptual Design Parameter	Description	Representative Range
Bottom width	The width of the level bottom of the conveyance feature.	1 to 10 feet
Side slopes	The steepness of the sides of the conveyance that connect the bottom of the swale to the ground surface.	3H:1V or flatter
Longitudinal slope	The slope of conveyance in the direction of flow.	1% to 5%
Storage layer thickness	The depth of the stone or amended soil storage reservoir.	0 to 24 inches (not required)
Effective sump storage depth	The effective depth of water retained (in media or stone pores, or behind check dams) that does not freely drain to surface drainage (if storage is in pores, the depth is the effective depth accounting for pore space).	0 to 6 inches (not required)
Water quality flow depth	The water level above the bottom of the swale during small storms that is considered to provide "treatment."	0 to 6 inches
Maximum flow depth	The maximum water level above the bottom of the swale under peak storm design conditions.	1 to 2 feet
Design infiltration rates	The rate at which water is assumed to infiltrate into the subsurface soils for design and benefits evaluation. This should be the rate of infiltration below the amended soil layer or stone reservoir.	Can be used in any soil condition
On-line versus off-line configuration	Vegetated conveyance that is on-line is designed to provide conveyance for all storm events; treatment functions are considered to cease or be minimal when the water quality flow is exceeded. However, volume reduction would be expected to continue to occur at higher rates based upon higher head values. Vegetated conveyance that is off-line receives only water quality design flows; peak storm flows are bypassed around the system while treatment and volume reduction processes continue.	Highway vegetated conveyance is typically on-line because of the challenge of providing flow splitter diversion at various diffuse locations

Example Conceptual Design Schematics

Figures 1, 2, 3, and 4 show cross-section view, longitudinal profile, plan view, and an example of swale adjacent to roadway environment, respectively.

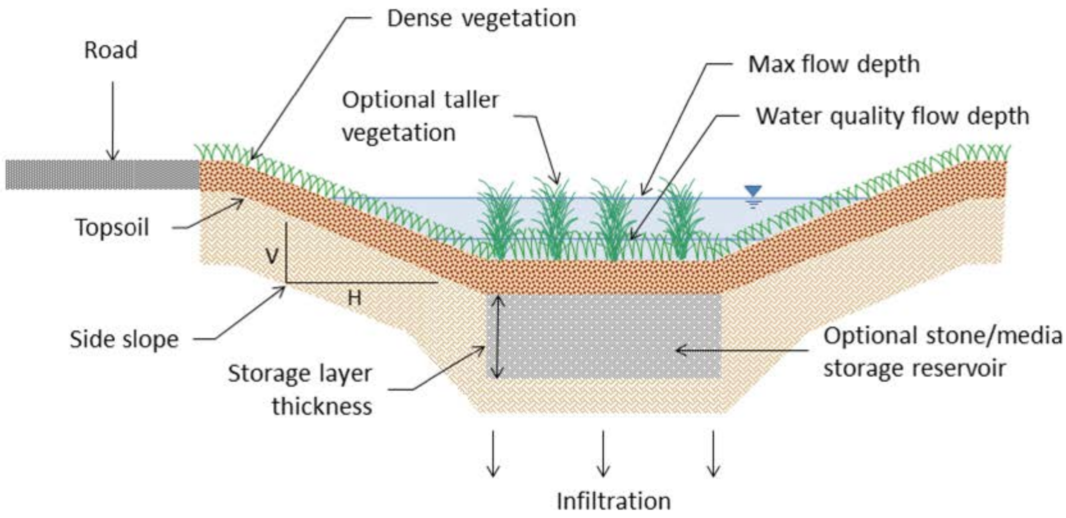


Figure 1. Cross-section view.

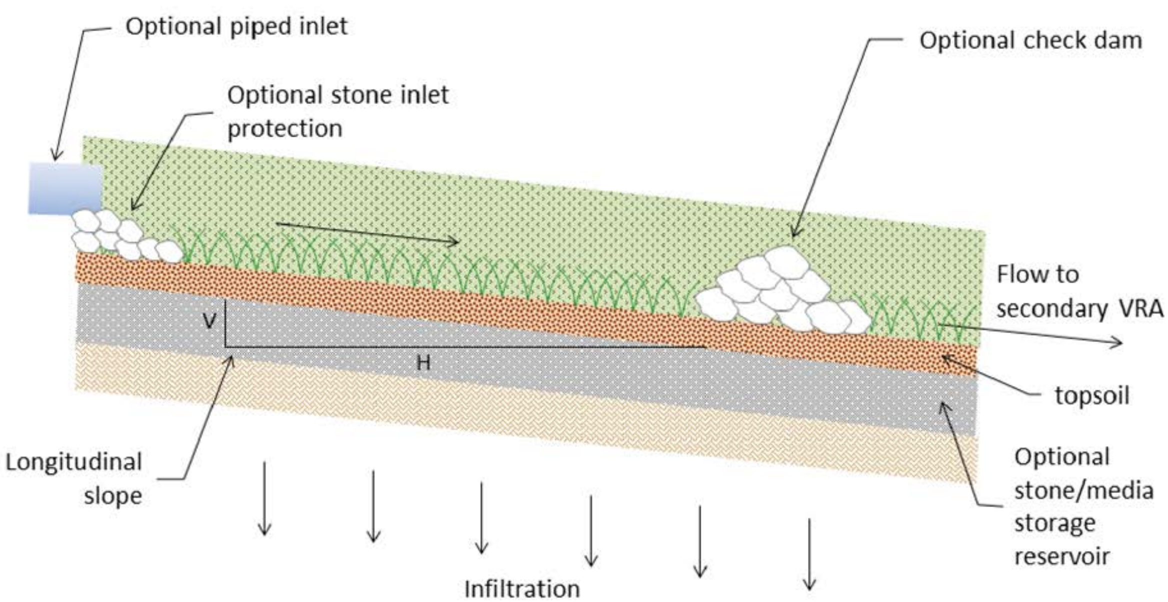


Figure 2. Longitudinal profile.

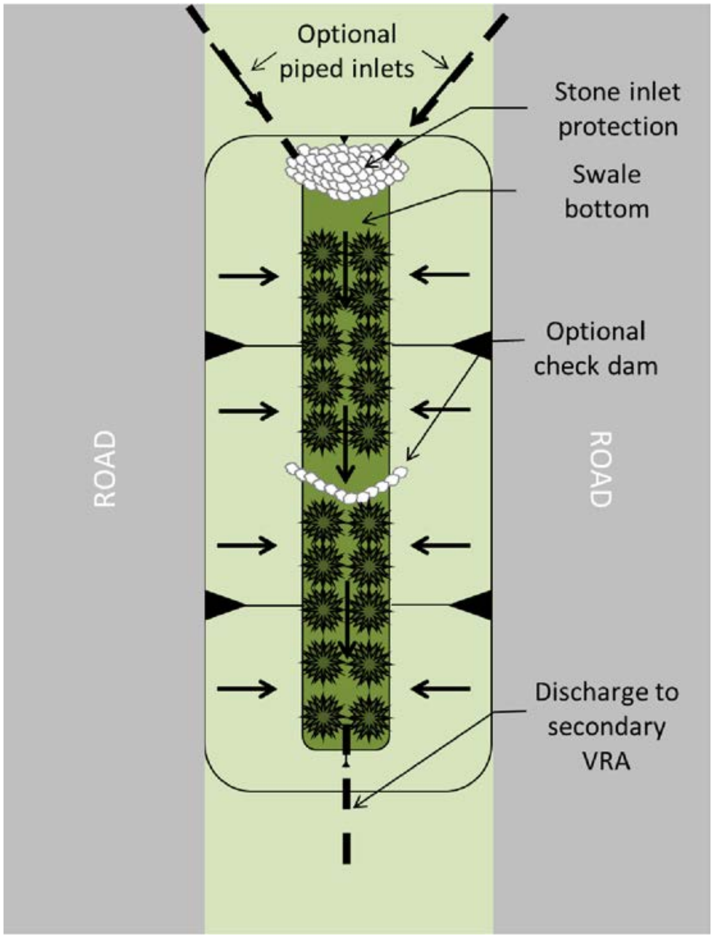


Figure 3. Plan view.

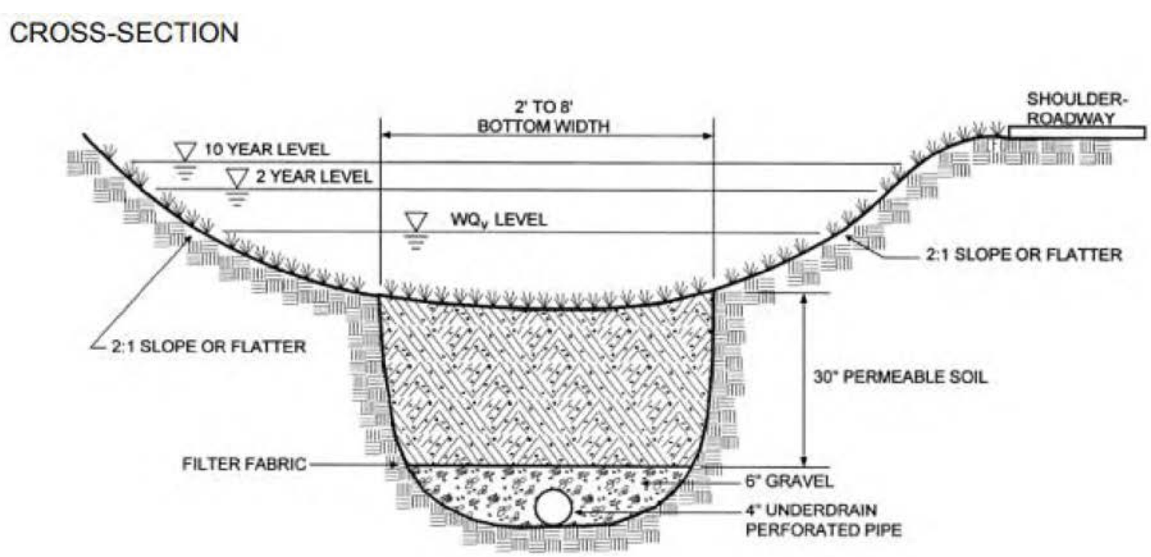


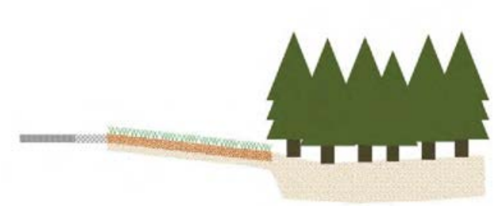
Figure 4. Example of swale adjacent to roadway environment (from NCHRP Report 565).

Example O&M Activities and Frequencies

Activity	Frequency
GENERAL INSPECTIONS	
Remove trash and debris	Two times per year including before and after wet season.
Repair eroded facility areas	
Inspect and maintain access roads	
Inspect and resolve areas of standing water	
Remove minor sediment in facility bottom	
Provide vector control if needed	
Identify any needed corrective maintenance that will require site-specific planning or design	
ROUTINE MAINTENANCE	
Vegetation	
In arid climates, irrigate as recommended by a landscape professional, typically for the first 3 years to establish vegetation	As needed
Remove undesirable vegetation	Annually
Repair areas of thin or missing vegetation	Annually
Repair areas of scour, rilling, or channelization	Annually
Inflow Outflow Structures	
Check energy dissipation function and add riprap	Annually
Inspect inlets and outlets and remove accumulated sediment if it impairs hydraulic function	Annually
CORRECTIVE (MAJOR) MAINTENANCE	
Regrade and replace top 3 to 6 inches of topsoil layer and accumulated sediment and replace vegetation	Estimated every 10 years (highly site specific)
Repair structural damage to inlets, outlets, and underdrain	As needed
Prepare documentation of issues and resolutions for review by appropriate parties	Before major maintenance
Document major maintenance activities; record modified O&M Plan and as-built plan set if needed	After major maintenance
Take photographs before and after from the same vantage point	Before and after

Dispersion **BMP 02**

Alternative names: *natural dispersion, engineered dispersion, vegetated filter strip, compost amended vegetated filter strip, vegetated buffer area*



Informal dispersion to median and shoulder, Interstate 8, San Diego, California, urban area. (Credit: Google.)

VOLUME REDUCTION PROCESSES	
●	Overall Volume Reduction Potential
●	Infiltration
◉	Evapotranspiration
○	Consumptive Use
○	Baseflow-mimicking Discharge

URBAN HIGHWAY APPLICABILITY	
●	Ground level highways
◉	Ground level highways with restricted cross-sections
○	Ground level highways on steep transverse slopes
○	Steep longitudinal slopes
○	Depressed highways
◉	Elevated highways on embankments
○	Elevated highways on viaducts
●	Linear interchanges
●	Looped interchanges

● High ◉ Moderate ○ Low

Description

This category consists of the dispersion of runoff toward existing and/or restored pervious areas for reducing stormwater runoff volumes and achieving incidental treatment. It also includes road shoulders amended with compost and additional materials such as sand (if needed), designed to convey runoff as sheet flow over the surface or as shallow subsurface flow through amended soil layers. Dispersion reduces overall runoff volume by means of infiltration and ET. Volume reduction performance can be improved with the use of flow spreaders, soil amendments, and re-vegetation. A critical element to this BMP is ensuring that dispersion areas support robust vegetative growth to stabilize the surface and maintain good infiltration rates.

Dispersion involves making use of existing design features such as vegetated medians, road shoulders, and buffers by routing water to these areas and/or improving their ability to accept water. For example, dispersion could include removing curb/gutter sections where this would enable the flow of water to a pervious area that is acceptable. Additionally, the benefits of an existing dispersion pathway can be enhanced through minor investments in modification of drainage patterns (e.g., improve uniformity of dispersion) and/or restoration of degraded areas. In many cases, the buffers and medians that would otherwise be constructed as part of standard roadway design can provide volume reduction and treatment benefits with very limited incremental cost.

Volume Reduction Processes and Performance Factors

Volume reduction is achieved through infiltration and ET. The quantity of volume reduction expected is dependent on the site's soils, topography and hydraulic characteristics (e.g., storage capacity, hydraulic retention time, etc.). Highly permeable soils have the capacity to infiltrate large volumes of stormwater and small depressions can capture and store stormwater runoff, which can then infiltrate, evaporate, or be consumed by vegetation between events. Because of the extensive nature (i.e., larger footprint) of dispersion-type approaches, it is the ET fraction of the water balance that tends to be significant.

General DOT Experience

Dispersion is commonly used for management of stormwater runoff from highways, particularly in more rural areas. The approach of allowing water to sheet flow over shoulders tends to be compatible with standard highway designs where shallow gradient medians and shoulders would otherwise be constructed.

Benefits of dispersion on reducing runoff volumes and treating stormwater are increasingly recognized by DOTs. While DOTs made these land and design investments for transportation and safety purposes, they also provide water quality and volume reduction benefits. For swales and filter strips, water quality benefits can effectively be considered free when compared with conventional drainage systems, and when the maintenance is performed by the property owner. Additionally, by amending roadway shoulders with compost and other materials, there is potential to improve the ability of existing road shoulders to reduce runoff volumes and provide treatment, thereby allowing incremental benefit to be claimed for relatively low investment.

In more constrained situations, DOTs have found that current design standards for highway construction do not always align with applicable design guidelines for filter strips and dispersion. For example, WSDOT (2014) notes that its highway runoff manual recommends a maximum side-slope of 4H:1V for dispersion practices while most roadway embankments fall between 2:1 to 6:1 where space and or topography constrain designs. For steeper slopes, specific attention should be given to effective spreading of flow and maintaining sheet flow. Alternatively, a more engineered approach, such as a Media Filter Drain (see BMP 03), may be more appropriate for steeper shoulders than simple dispersion over a naturally vegetated area.

DOTs have also found that vegetative cover and regenerative growth are critical to maintaining long-term infiltration rates. A monitoring case study on vegetated filter strips in Texas by Walsh et al. (1998) also highlights the importance of infiltration capacity to vegetative cover with more "natural" and wooded areas having greater capacity to infiltrate runoff.

Studies of filter strips reported to the International Stormwater BMP Databases, mostly in California, showed moderate levels of volume reduction (Geosyntec and Wright Water Engineers 2011). In addition, DOTs have considerable experience using compost amendment of road shoulders as an initial treatment following construction to promote stabilization and vegetation growth (U.S. EPA 2013; Connecticut DOT 1999; Black 1999; Caltrans 2010; Glanville et al. 2003).

Applicability and Limitations

Site and Watershed Considerations

- Dispersion to areas with high infiltration rates will result in higher rates of volume reduction.
- Dispersion is suitable for most soil types. Where soils are silty or clayey, a sand or compost amendment may be needed to provide adequate long-term permeability for water to flow into the soil.
- Dispersion practices rely on sheet flow over a relatively large distance (typically at least 10 to 15 feet) to achieve significant volume reduction. They may therefore not be suitable for roads with very restricted ROWs.
- Embankment slopes should provide positive drainage away from the roadway but not be steeper than approximately 6H:1V.
- Longitudinal slopes must not be too steep (typically less than 5%) in order to allow more uniform dispersion and avoid the creation of high velocity flows that may result in erosion.
- Large drainage areas (e.g., roadways wider than approximately 2 to 3 lanes) may increase the potential for flow to concentrate during high intensity storm events and produce high velocity flows with the potential to create erosive conditions. Because of the importance of maintaining sheet flow into dispersion areas, site-specific calculations are recommended to account for local precipitation intensities, design geometries, and soil conditions. Sheet flow conditions can be encouraged using a gravel area between the road shoulder and the dispersion area (see schematic design of BMP 03: Media Filter Drain).
- Urban highways are not typically surrounded by undeveloped area; however, patches of natural vegetation sometimes exist, particularly in the centers of interchanges and in wide spots in the ROW. Therefore, the opportunity for dispersion is dependent on specific site conditions and available vegetation in the vicinity of the project.
- The dispersion area should be owned by the project owner or located in a permanent easement dedicated for water quality purposes.

Geotechnical Considerations

- Generally, dispersion poses relatively limited incremental risk for slope stability and settlement, because standard design practices help mitigate risks, including (1) accounting for surficial wetting in geotechnical calculations, (2) design of near-highway areas with positive drainage away from the highway, and (3) design features to prevent surficial erosion (e.g., flow spreading, shallow slopes, vegetated cover).
- The most significant geotechnical issue is potential for rill erosion to form and progress along the roadside shoulder if soil is not stabilized and/or concentrated flow paths develop.
- Where a design modification will result in significant infiltration occurring in a concentrated area, such as ponding more than a few inches deep, analysis of slope stability and other geotechnical factors should be considered within the vicinity of this area.

- Long-term stability and reduction in erosive flow potential can be enhanced with robust plant growth, effective dispersion, and adhering to recommended upper limits on embankment slope.

Groundwater Quality and Water Balance Considerations

- Because water disperses in shallow depths over a broad area, dispersion poses relatively low risk of groundwater quality impacts and water balance impacts.
- Risks may be elevated in areas with very high soil infiltration rates or shallow groundwater tables. In these situations, soil amendments may be warranted to provide better treatment of infiltrated water and better soil water retention.

Safety Considerations

- Dispersion areas should be free from trees or other obstacles within the clear zone (typically in the range of 22 to 32 feet from driving lanes). Cross-slopes within the clear zone should not exceed 4H:1V. If maintaining these conditions is not possible, a barrier should be placed between the road and the dispersion area, parallel to vehicular travel.
- Soil amendments that are used within the clear zone to improve permeability and/or vegetation growth should be selected to provide a finished surface that is adequately stable for errant vehicle recovery.
- If a vegetated conveyance is used to convey water to dispersion areas, it should be constructed with side slopes of 3H:1V or flatter. Any piped inlets should have openings cut flush with the slope in order to reduce the potential that the pipe will snag an errant vehicle. Pipes with diameters greater than 24 inches should be covered with traversable grates.

Regional Applicability

- Dispersion can be applied across a broad range of climates but will differ in nature in terms of vegetation.
- Dispersion approaches require dense and robust vegetation for proper function. In arid regions, drought tolerant species should be selected to minimize irrigation needs and reduce the potential for seasonal die-off.
- In cold climates where salt is utilized, vegetation should be selected to be tolerant of elevated salt levels.
- Vegetative conveyances are more susceptible to clogging, as snow plowed alongside a roadway facility carries high sediment (road sand) and pollutant (road salt mixtures) loads. Vegetation, if not salt-tolerant, can be adversely affected. Sodium-based deicers have been shown to break down soil structure and potentially decrease infiltration rates.
- Regional rainfall intensities and characteristic patterns should be considered during the design process to ensure road shoulder sections will not be hydraulically overloaded and sheet flow conditions will be maintained to the extent practicable.
- Where adjacent natural land covers are highly erosive (such as arid areas), the elevated potential for rill erosion may present challenges for the application of this approach.

New Projects, Lane Additions, and Retrofits

- Dispersion may have small incremental costs in new projects because suitable areas such as vegetated shoulders are often already incorporated into the project as design features.
- Retrofit of dispersion may include modifying the current drainage pathway, such as by removing a curb and gutter to allow dispersion to occur or providing more uniform dispersion, and/or enhancing the dispersion area, such as by amending, decompaction, leveling, and/or vegetating the area. In either case, an incremental benefit in treatment and volume reduction capabilities can be claimed through this retrofit.
- The feasibility of retrofitting an existing embankment would be influenced by the amount of import/export of material that would be needed (i.e., soil amendment versus soil replacement).

Use in a Treatment Train

- Vegetated conveyance can be used to convey runoff to a dispersion area.
- Dispersion can be used to pretreat and convey stormwater to secondary BMPs.

Enhancements and Variations

Slow the velocity of flow. Areas of dispersion may be planted with densely growing native/non-invasive vegetation to slow flows and allow greater volume reduction. Minor re-grading to leveling the surface can also help slow and more evenly distribute flow. Check dams and berms may be constructed on steeper slopes to slow flows and create small ponding areas to encourage infiltration and treatment.

Spread out the flow equally. Equal distribution of flows can help ensure that all the available area is being utilized, thereby improving both volume reduction and treatment capacity. Equal dispersion can be achieved by leveling the surface and using shoulder treatments such as stone spreading trenches that promote more even inflow. Maintenance may be needed to avoid the development of concentrated flow pathways.

Landscaping/restoration. Planting and/or restoring areas of dispersion can be used to establish and promote higher and stable infiltration rates while also providing increased roughness to slow overland flows. Establishing and retaining dense/natural vegetation will help ensure that infiltration rates are maintained over the long term.

Vegetated conveyance dispersion area. Where road shoulders are not conducive to overland flow or the dispersion area is a distance from the roadway, vegetated conveyance can be used to convey flow to the dispersion area.

Improve infiltration rates. Where site soils are silty or clayey, sand may be incorporated into the soil along with compost to improve infiltration and flow through the media. Where site soils are plastic and would not sustain long-term permeability, the topsoil layer can be removed and replaced with a compost–sand mixture.

Resilient Design Features

The standard design of dispersion has resiliency included in the design because this BMP does not rely on a minimum infiltration rate to function properly.

A key cause of failure is rill erosion or channelization in the dispersion area. Emphasizing property design and maintenance of level spreader can reduce the risk of failures to the dispersion area/filter strip.

The dispersion area may be amended with compost material to increase infiltration rates, provide pretreatment, and further enhance filtration or groundwater recharge within the dispersion area. Absorption capacity can be gained by using compost-amended soils to disperse and absorb contributing flows to the dispersion area. This will help ensure the dispersion area has the capacity and ability to infiltrate surface runoff.

Natural dispersion areas may initially cost as much as other constructed BMPs (ponds or vaults), because ROW or easements often need to be purchased, but long-term maintenance costs are lower because water is able to spread and therefore has low risk of clogging or erosion.

Additional References

California Stormwater Quality Association. California Stormwater BMP Handbook: New Development and Redevelopment. TC-31, Vegetated Buffer Strip. 2003. Fact sheet containing design guidance, construction and maintenance information for infiltration trenches including costs. Available online at http://www.cabmphandbooks.com/Development.asp.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 2: Sheet Flow to a Vegetated Filter Strip or Conserved Open Space v.1.9. 2011. Fact sheet on infiltration practices including design guidance, construction and feasibility. Excellent figures and schematics. Available online at http://chesapeakestormwater.net/category/publications/design-specifications/.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 4: Soil Compost Amendment v.1.9. 2011. http://chesapeakestormwater.net/category/publications/design-specifications/.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 2: Sheet Flow to a Vegetated Filter Strip or Conserved Open Space v.1.9. 2011. http://chesapeakestormwater.net/category/publications/design-specifications/.

Washington State Department of Transportation, Highway Runoff Manual. 2014. http://www.wsdot.wa.gov/Publications/Manuals/M31-16.htm.

Washington Department of Ecology. Stormwater Manual for Western Washington. BMP FC.01: Natural Dispersion. 2012. https://fortress.wa.gov/ecy/publications/summarypages/1210030.html.

Washington Department of Ecology. Stormwater Manual for Western Washington. BMP FC.02: Engineered Dispersion. 2012. https://fortress.wa.gov/ecy/publications/summarypages/1210030.html.

Washington Department of Ecology. Stormwater Manual for Western Washington. BMP RT.02: Vegetated Filter Strip. 2012. https://fortress.wa.gov/ecy/publications/summarypages/1210030.html.

Key Planning Level Design Parameters for Volume Reduction

Conceptual Design Parameter	Description	Representative Range
Footprint area	The area that will receive stormwater.	No practical limit, larger areas will tend to provide greater volume reduction.
Contributing area	The area draining to the footprint area.	No practical limit; however, inflows should be distributed as sheet flow or multiple diffuse inflow points to avoid concentrating flows.
Infiltration rate	The infiltration rate of the underlying soils within the dispersion area.	Any. Higher infiltration rates will achieve greater volume reduction.
Width of amended shoulder	The width of the shoulder in the direction of flow (i.e., perpendicular to the roadway edge).	10 to 15 feet typical; however, there is no practical limit—larger areas will tend to provide greater volume reduction.
Cross slope	The final grade of the road shoulder surface (perpendicular to the roadway edge) as a ratio of vertical distance to horizontal distance (i.e., 12%, or 8H:1V).	4H:1V or flatter
Amendment thickness	The depth to which amendments are incorporated into the soil.	6 to 12 inches
Effective depth of depression storage	Including pore storage added through soil decompaction/amendment and/or naturally occurring depressions where ponding is expected (expressed as depth).	1 to 6 inches

Example Conceptual Design Schematics

Figures 1 and 2 show cross-section and plan views, respectively. Figures 3 and 4 show natural or engineered dispersion without a gravel level spreader and with a gravel level spreader, respectively.

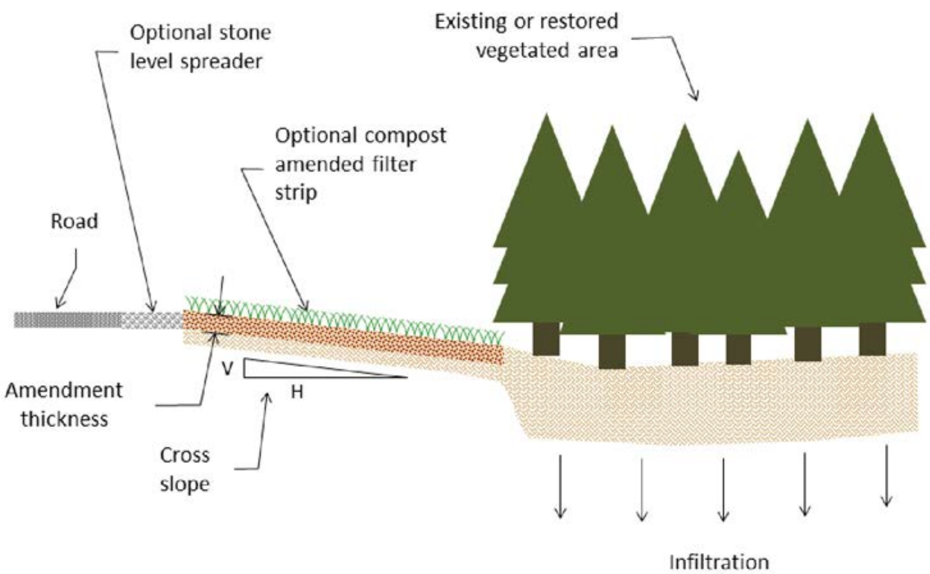


Figure 1. Cross-section view.

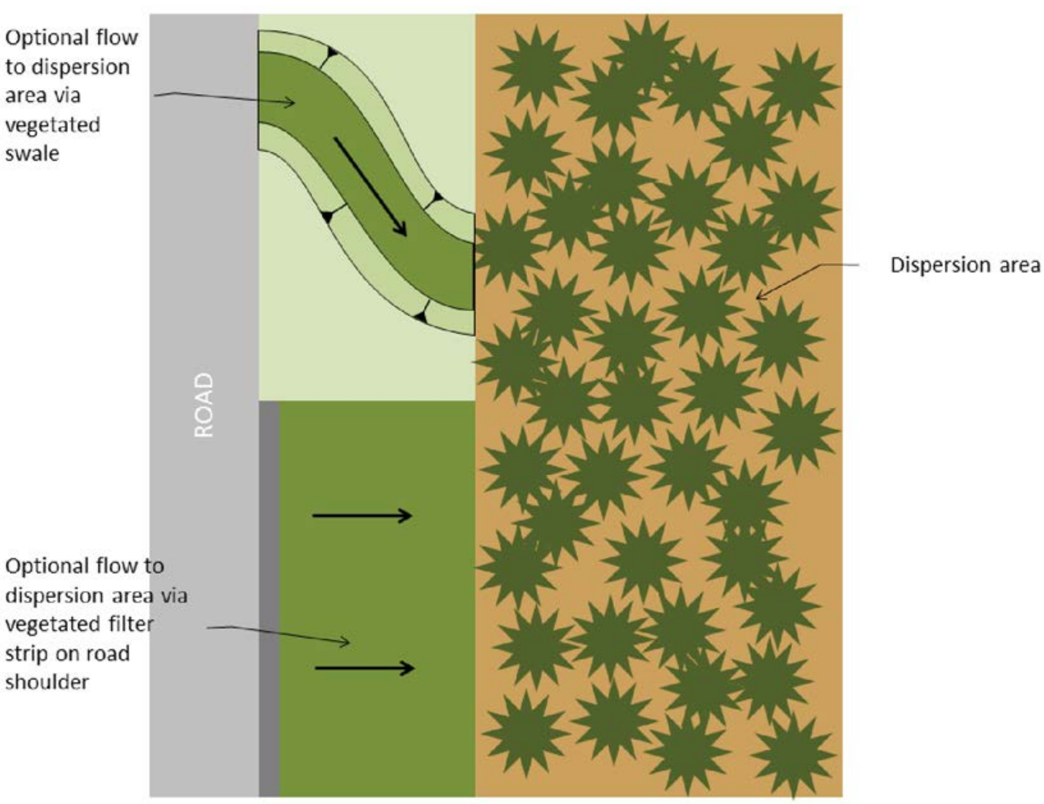


Figure 2. Plan view.

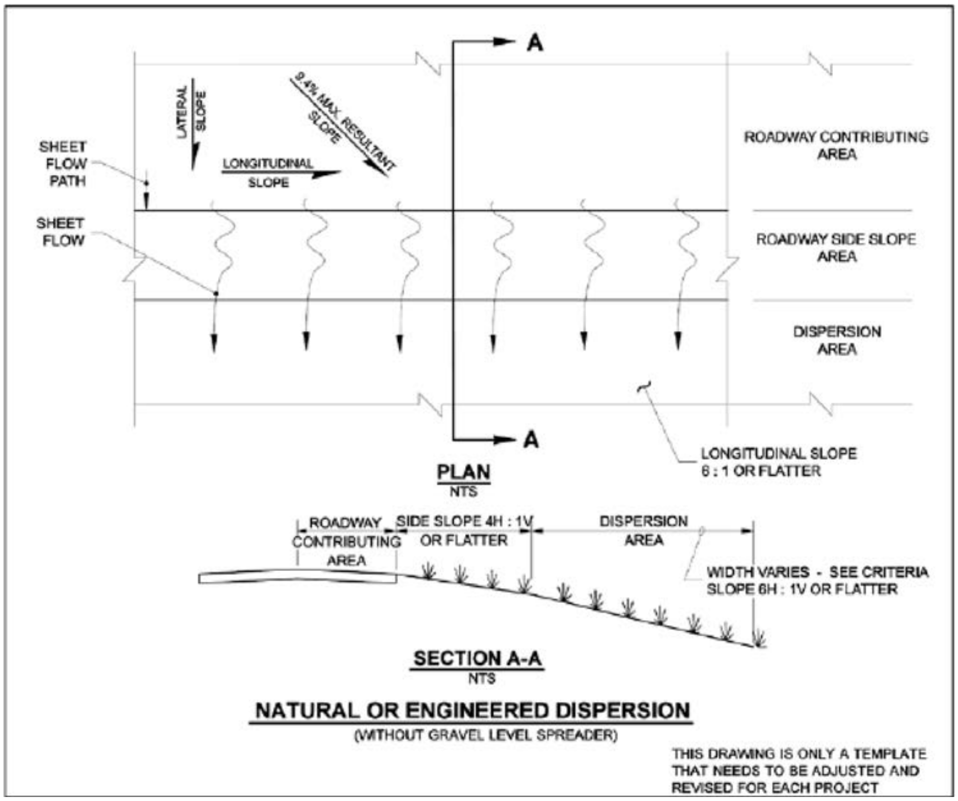


Figure 3. Natural or engineered dispersion without a gravel level spreader (WSDOT 2014).

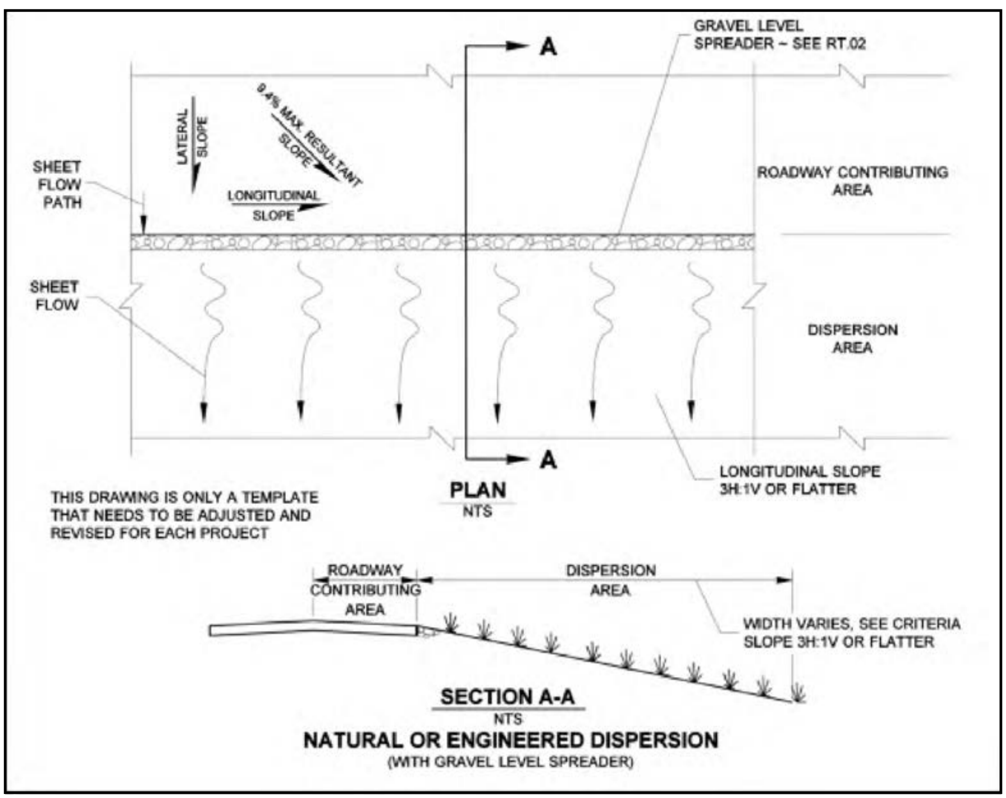


Figure 4. Natural or engineered dispersion with a gravel level spreader (WSDOT 2014).

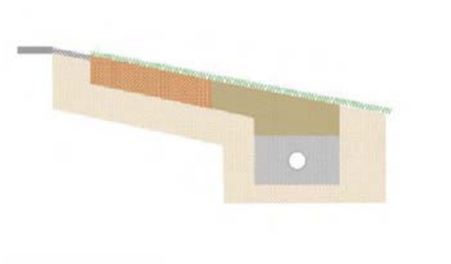
Example O&M Activities and Frequencies

Activity	Frequency
GENERAL INSPECTIONS	
Identify any needed corrective maintenance that will require site-specific planning or design	Annually
Inspect function of level spreader	
Inspect degree of degree of channelization in filter strip	
Inspect degree of undesirable vegetation (weeds)	
ROUTINE MAINTENANCE	
Vegetation	
In arid climates, irrigate as recommended by a landscape professional, typically for the first 3 years to establish vegetation	As needed
Reseed areas of thin or missing vegetation	Annually
Repair eroded areas	Annually
Level Spreader	
Fill areas of level spreader that appear to be channelized or sedimented to restore function	Annually
Regrade road shoulder and augment gravel periodically to restore level spreader	3 to 5 years
CORRECTIVE (MAJOR) MAINTENANCE	
Decompact/aerate filter strip to at least a 6-inch depth and reseed to maintain porosity and robust vegetation replace vegetation	Estimated every 10 to 15 years (highly site specific)
Regrade to correct channelization. Decompact, amend, and reseed filter strip to restore.	Estimated every 30 years (highly site specific)
Prepare documentation of issues and resolutions for review by appropriate parties	Before major maintenance
Document major maintenance activities; record modified O&M Plan and as-built plan set if needed	After major maintenance
Take photographs before and after from the same vantage point	Before and after

Media Filter Drain

BMP 03

Alternative names: *formerly known as "Ecology Embankment"*



Media Filter Drain along SR 14in Clark County, Washington. (Source: WSDOT 2011.)

VOLUME REDUCTION PROCESSES	
High	Overall Volume Reduction Potential
High	Infiltration
Moderate	Evapotranspiration
Low	Consumptive Use
Low	Baseflow-mimicking Discharge

URBAN HIGHWAY APPLICABILITY	
High	Ground level highways
High	Ground level highways with restricted cross-sections
Moderate	Ground level highways on steep transverse slopes
Moderate	Steep longitudinal slopes
Low	Depressed highways
Moderate	Elevated highways on embankments
Low	Elevated highways on viaducts
High	Linear interchanges
High	Looped interchanges

High Moderate Low

Description

This BMP consists of a stone vegetation-free zone, a grass strip, a media filter storage reservoir filled with specialized media, and a conveyance system for flows leaving the reservoir. This conveyance system usually consists of a gravel-filled underdrain trench or a layer of crushed surfacing base course. The stone vegetation-free zone produces sheet flow, which is pretreated as it flows across the grass strip, and is then captured by the storage reservoir, where it infiltrates into the subsoil or is discharged through the underdrain. This BMP is typically installed between the road surface and a ditch or other conveyance located downslope. While this approach shares many similarities to BMP 02 Dispersion, its engineering design features allow it to be sited in more constrained areas and on steeper cross slopes where dispersion would not be as viable.

Volume Reduction Processes and Performance Factors

Runoff volume is reduced through infiltration and ET. Water is treated as it moves over the grass strip and through the media within the reservoir. The relative volume reduction potential is a function of the underlying infiltration rate and the local wet-season ET rates. The primary flow pathway through the media tends to provide flow attenuation that may partially mimic baseflow in some environments.

General DOT Experience

This BMP is widely used by WSDOT and was formerly referred to as an "Ecology Embankment." A technology evaluation report prepared for "Ecology Embankments" for WSDOT shows both significant volume and load reductions in some cases up to 100% (Herrera Environmental Consultants 2006). Some design standards for filter strips employed by other DOTs include elements that resemble the media filter drain.

These are applicable for siting linearly in the median and ROWs on most shoulder slopes. Limiting their use to treatment of runoff from impervious areas only will maximize their life.

Applicability and Limitations

Site and Watershed Considerations

- Media filter drains are suitable for most soil types. Where soils are silty or clayey, an underdrain may be required to convey excess runoff.
- Media filter drains are one of the few BMPs that can be constructed directly on roadside embankments up to a 4H:1V slope and incorporated into conventional highway design. They may be quite useful in situations where roadway embankments are the only vegetated area within the ROW.
- Media filter drains work best on low to moderate longitudinal slopes (less than 5%). Greater longitudinal slopes present greater difficulties for evenly spreading water.
- Large drainage areas (e.g., wider roadways) may increase the potential for flow to concentrate during high intensity storm events and produce high velocity flows with the potential to create erosive conditions. Sheet flow conditions can be encouraged using a dispersion trench or other approach intended to spread and slow flows.
- Media filter drains can be sited in confined ROWs, on shoulders, and in narrow medians, and are suitable in many confined urban highway settings.

Geotechnical Considerations

- Generally, use of media filter drains introduces relatively limited incremental risk for slope stability and settlement because standard highway design practices help mitigate risks, including (1) accounting for surficial wetting in geotechnical calculations, (2) design of shoulder with positive drainage away from the highway, and (3) design features to prevent surficial erosion (e.g., flow spreading, shallow slopes, vegetated cover).
- Site specific infiltration rates and physical makeup of the soil (i.e., soil class) will determine what design features are needed for effective volume reduction and treatment.
- Long-term stability and reduction in erosive flow potential can be enhanced with robust plant growth, effective dispersion, and adhering to recommended upper limits on embankment slope.

Groundwater Quality and Water Balance Considerations

- Due to its extensive nature and the degree of treatment provided by the media, this BMP poses relatively low risk of groundwater quality impacts and water balance impacts.

- Risks of water balance impacts may be elevated in areas with very high soil infiltration rates and hydrogeologic conditions that are sensitive to increases in infiltration volume.

Safety Considerations

- Media filter drains are usually located within the clear zone, but their low cross-slopes and lack of fixed obstacles make them safely traversable, and no barriers are required.

Regional Applicability

- Media filter drains require dense and robust vegetation for proper function. In arid regions, drought tolerant species should be selected to minimize irrigation needs and reduce the potential for seasonal die-off. If a regionally adapted species cannot be identified to provide surface stabilization without irrigation, then this BMP may not be applicable.
- In cold climates where salt is utilized, vegetation should be selected to be tolerant of elevated salt levels.
- Regional rainfall intensities and characteristic patterns should be considered during the design process to ensure road shoulder sections will not be hydraulically overloaded and sheet flow conditions will be maintained to the extent practicable.

New Projects, Lane Additions, and Retrofits

- Media filter drains can be incorporated into conventional highway design or can be constructed on existing roadside embankments.
- Retrofitting an existing embankment would involve export of existing soils, installation of an underdrain, and import of the specialized media filter mix. As such, retrofits are expected to be more expensive than when constructed as part of a new project or lane addition.

Use in a Treatment Train

- Media filter drains can be used to pretreat and convey stormwater to secondary BMPs.

Enhancements and Variations

Apply on internal as well as external embankments. If the roadway has a median, then a dual media filter drain design can be used to capture runoff from both of the internal embankments.

Use an underdrain to improve hydraulic conveyance where infiltration rates are limited. Where site soils are silty or clayey, an underdrain may be used to improve hydraulic conveyance of stormwater through the media. Treated runoff would be conveyed to a downstream BMP or stormwater outfall.

Increase footprint area at intersections and wider portion of ROW. Drainage can be routed to media filter drains with broader footprints in the open space formed by intersections and at wider sections of the ROW to help increase the dispersion area that is provided.

Use soil amendments. Media amendments to sand filters or specially designed media mixtures can be used to improve treatment performance over sand media alone. For example, the media mix in WSDOT media filter drains includes crushed stone, dolomite and gypsum for alkalinity and ion exchange capacity to promote the precipitation and exchange of heavy metals, and perlite for moisture retention.

Apply outlet control. Use an orifice outlet to regulate flows through the gravity drainage filtration system, rather than use the media properties to control the hydraulic design. A primary discharge orifice can be placed near the top of the media bed, sized and configured to pass the design storm flows under saturated media conditions. A low flow orifice can be placed below the media bottom, sized and configured to restrict flows and encourage filling for small storm event flows and allow for complete drainage of the media bed within a specified drain time following a storm event.

Use filter fabric. If a filter is used to treat runoff from a roadway that is sanded, there is higher potential for clogging from the sand in the runoff. To prevent clogging of the underdrain, a permeable filter fabric should be placed between the gravel layer and the filter media, as shown on Figure 3. The purpose of filter fabric is to prevent sand from infiltrating into the gravel layer and the underdrain piping.

Resilient Design Features

Typical guidance calls for configuring a media filter drain with an underdrain as a protective measure to ensure free flow through the media filter drain to prevent prolonged ponding, and to discharge excess water in marginal infiltration conditions. This provides resiliency. If infiltration is more clearly feasible, a capped underdrain could be used, and only opened if infiltration rates are not adequate.

In areas where there is a narrow roadway shoulder that does not allow enough room for a vehicle to fully stop or park, place the media filter drain farther down the embankment slope, this will reduce the amount of rutting in the media filter drain and decrease overall maintenance repairs.

In cold climates, the underdrain should be extended below the frost line and oversized to prevent freezing of the underdrain itself or the filter media.

Additional References

Washington State Department of Transportation, Highway Runoff Manual. 2014. Chapter 5 includes fact sheets for Stormwater BMPs. Available online at http://www.wsdot.wa.gov/Environment/WaterQuality/Runoff/HighwayRunoffManual.htm.

Washington Department of Ecology. Stormwater Manual for Western Washington. BMP RT.07: Media Filter Drain. 2012. Available online at https://fortress.wa.gov/ecy/publications/summarypages/1210030.html.

Herrera Environmental Consultants (2006). Technology Evaluation and Engineering Report, WSDOT Ecology Embankment, Prepared for Washington State Department of Transportation. July 2006. http://www.wsdot.wa.gov/NR/rdonlyres/3D73CD62-6F99-45DD-B004-D7B7B4796C2E/0/EcologyEmbankmentTEER.pdf.

Key Planning Level Design Parameters for Volume Reduction

Conceptual Design Parameter	***Description***	***Representative Range***
Footprint area	The area covered by the surface of the media filter drain.	Any
Maximum flow path	The maximum distance runoff should travel as sheet flow to the media filter drain (i.e., maximum width of travel lanes).	Up to 150 feet
Tributary area ratio	The footprint of the media filter drain as a fraction of the total tributary area (including the media filter drain itself).	Up to 10:1 may be typical of urban roadways
Cross slope	The slope of the embankment perpendicular to the roadway.	4H:1V or flatter
Longitudinal slope	The slope running parallel to the roadway.	Typically limited to less than 5%
Stone strip width	The width of the stone strip used to create sheet flow.	1 to 3 feet
Grass strip width	The width of the grass strip used for pretreatment.	3 to 5 feet
Media filter depth	The depth of the filter media storage reservoir.	12 inches
Design soil infiltration rate	The rate at which water is assumed to infiltrate into the subsurface soils for the purpose of design and benefits evaluation. This should be the rate of infiltration below the amended soil layer or stone reservoir.	Any

Example Conceptual Design Schematic

Figures 1, 2, and 3 show cross-section view, plan view, and components of a media filter drain, respectively.

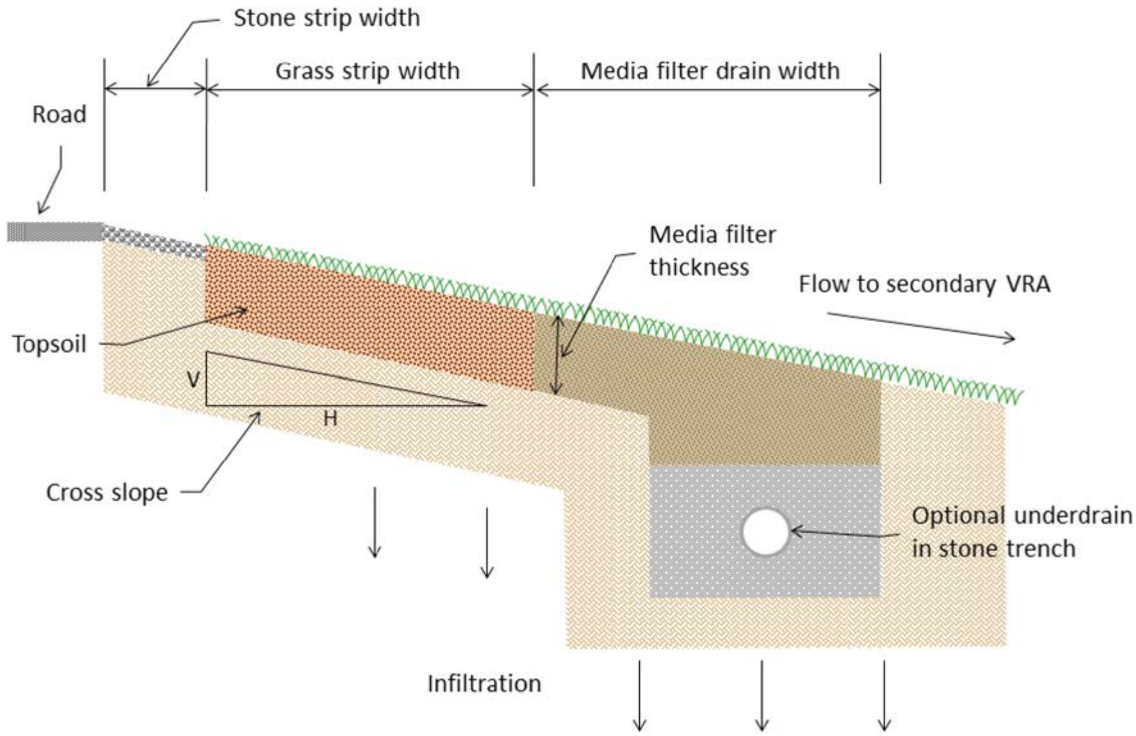


Figure 1. Cross-section view.

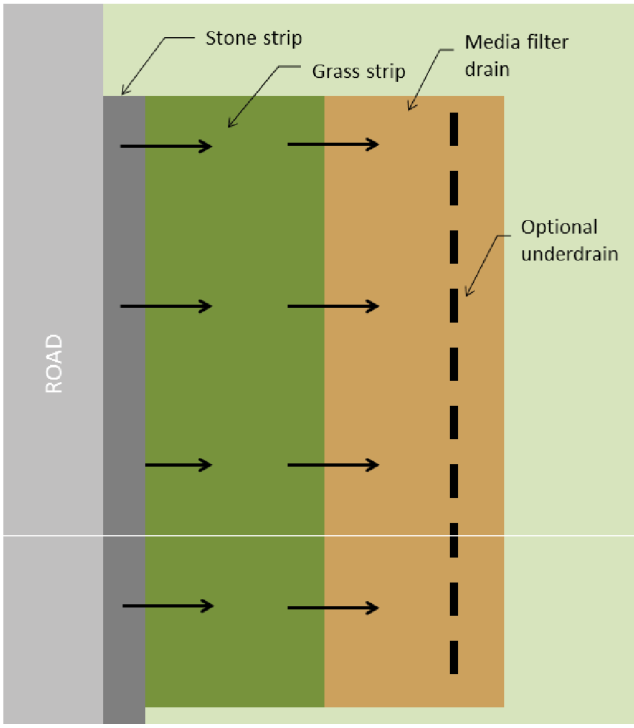


Figure 2. Plan view.

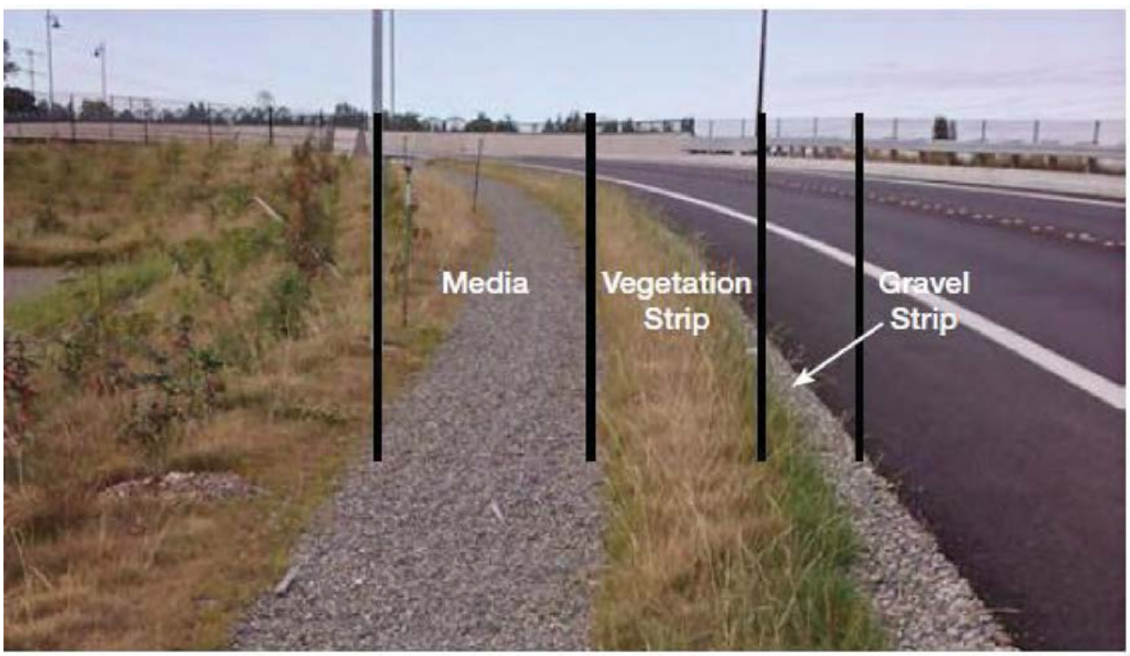


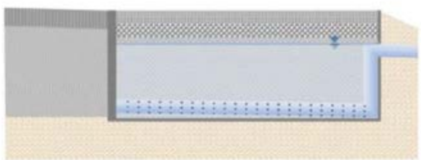
Figure 3. Components of a media filter drain.

Example O&M Activities and Frequencies

Activity	Frequency
GENERAL INSPECTIONS	
Identify any needed corrective maintenance that will require site-specific planning or design	Annually
Inspect function of level spreader	
Inspect degree of degree of channelization in filter strip or media filter drain	
Inspect degree of undesirable vegetation (weeds)	
ROUTINE MAINTENANCE	
Vegetation-Free Zone (rock level spreader)	
Level areas that are channelized and interfere with sheet flow	As needed
Remove accumulated sediment that interferes with sheet flow	
Grass Filter	
In arid climates, irrigate as recommended by a landscape professional, typically for the first 3 years to establish vegetation	As needed
Reseed areas of thin or missing vegetation	As needed
Repair eroded areas or accumulated sediment that interferes with sheet flow	As needed
Mow vegetation greater than about 10 inches	As needed
Media Filter Drain	
Repair eroded areas by leveling surface of media filter	As needed
Replenish media if spots of scour have occurred (and remedy source of scour)	As needed
CORRECTIVE (MAJOR) MAINTENANCE	
Replace filter media	Estimated every 10 years
Replace underdrain if damaged or clogged	As needed
Prepare documentation of issues and resolutions for review by appropriate parties	Before major maintenance
Document major maintenance activities; record modified O&M Plan and as-built plan set if needed	After major maintenance
Take photographs before and after from the same vantage point	Before and after

Permeable Shoulders BMP 04

Alternative names: *permeable shoulders with stone reservoirs, permeable gutters*



(Photo credit: Pike Industries.)

VOLUME REDUCTION PROCESSES	
●	Overall Volume Reduction Potential
●	Infiltration
○	Evapotranspiration
○	Consumptive Use
◉	Baseflow-mimicking Discharge

URBAN HIGHWAY APPLICABILITY	
●	Ground level highways
●	Ground level highways with restricted cross-sections
◉	Ground level highways on steep transverse slopes
○	Steep longitudinal slopes
◉	Depressed highways
◉	Elevated highways on embankments
○	Elevated highways on viaducts
○	Linear interchanges
○	Looped interchanges

● High ◉ Moderate ○ Low

Description

This BMP includes use of a permeable pavement surface course (typically permeable asphalt or concrete) along the shoulders of a roadway, underlain by a stone reservoir. Precipitation falling on the permeable pavement as well as stormwater flowing onto permeable pavement from adjacent travel lanes infiltrates through the permeable pavement top course into the stone reservoir, from which it infiltrates into the subsoil or is discharged through an underdrain and outlet control structure. Through the use of an underdrain and flow control outlet to augment infiltration capacity, permeable shoulders can be applied in a wide range of soil conditions. This BMP is most effective for volume reduction when soils are suitable for infiltration and outlet control can be provided to mimic baseflow discharge.

In contrast to permeable pavements applied in parking lots, parking strips, streets, and walkways in other land uses, permeable road shoulders tend to be characterized by a higher ratio of tributary impervious area (travel lanes) to pervious area (shoulders). Additionally, more stringent requirements may apply to the structural design and subbase drainage design than apply to permeable pavements in other land uses.

These BMPs can have extreme limitations, associated with studded tires, traction sand, longitudinal slopes, and cost to retrofit in existing roads.

Volume Reduction Processes and Performance Factors

Volume reduction is achieved primarily through infiltration. The degree of allowable infiltration is a function of soil infiltration rates (after compaction), degree of subbase wetting that is allowable in design, and the presence of other factors such as slope stability or utility issues. Where infiltration is limited due to soil conditions or other factors, permeable pavement systems can be enhanced with underdrains to provide flow control and augment infiltration discharge. When designed with adequate storage, permeable pavement systems can provide temporary detention of storm flows and controlled release, discharging flows at rates similar to natural base flows with the use of underdrains and flow controls.

General DOT Experience

Permeable pavement shoulders are increasingly being considered for implementation within the highway environment. However, their application remains very limited.

Some DOTs have found open graded friction course to be an effective method to improve roadway safety (by reducing surface flow and splash/spray effects). Permeable shoulders would have these benefits and also provide volume reduction.

Runoff reduction estimates derived from various case studies summarized by Hirschman et al. (2008) range from 45% when incorporating underdrains to 75% when not using underdrains and assuming adequate pretreatment and soil testing. In some studies volume reductions ranged from 94% to 100% (Van Seters et al. 2008; Legret and Colandini 1999; Bean et al. 2007; Collins et al. 2008; and Brattebo and Booth 2003). The University of California Pavement Research Center (UCPRC) concluded that permeable shoulders are technically feasible and economically advantageous compared with other BMPs and can be used where infiltration rates are as low as 0.014 inches per hour (Chai et al. 2012).

Permeable shoulders can have extreme limitations in cold climates as a result of studded tires and traction sand. They are also not feasible on roadways with longitudinal slope greater than about 1% and can be very expensive to retrofit into existing roadways.

Guidance on design, construction, and maintenance of permeable shoulders with stone reservoirs was conducted as part of NCHRP Project No. 25-25/Task 82 (Hein et al. 2013). A review of permeable shoulder applicability and limitations is found in *NCHRP Report 802: Volume Reduction of Highway Runoff in Urban Areas—Guidance Manual*.

Applicability and Limitations

Site and Watershed Considerations

- Permeable pavements are better suited to areas with granular soils, such that infiltration rates are relatively high and subgrade strength is not significantly diminished by wetting.
- Roadways with flat to shallow longitudinal slopes (less than 1%) are suitable for permeable shoulders, because the volume of the storage reservoir is best utilized. Steeper longitudinal slopes require cutoff walls and intermediate outlet points, and there is greater potential for water to flow below the roadway. This can greatly reduce feasibility.
- Permeable pavements can be used on road shoulders and in medians. They can be useful in constrained areas where there is insufficient space for vegetated BMPs.
- A fully-lined version of permeable pavement with an underdrain could be used on elevated highways or viaducts. Stormwater could be stored within the stone

reservoir and would then be discharged via underdrains or routed to additional BMPs.

- Current applicability of permeable pavements to main roadway sections is not well established relative to structural design requirements, top course durability, and safety. Research is ongoing.

Geotechnical and Pavement Design Considerations

- The overflow elevation from the storage reservoir should be equal to or lower than the bottom of the base course. This helps maintain positive drainage from the base material and reduces the risk of saturation of the subbase.
- Use of a permeable shoulder without a liner increases moisture content below the shoulder and may also increase moisture content below the main line road segment; this should be accounted for in subgrade strength calculations. A greater subbase depth may be required to account for reduced subgrade bearing capacity.
- The bearing strength of granular soils tends to be less sensitive to moisture content than fine grained soils. The strength of fine grained soils such as clays can be significantly reduced when the subgrade is wetted.
- Infiltration may also result in settlement, slope stability, utility issues, or other issues that may damage pavements.
- Impermeable barriers can be used between the permeable pavement installation and the roadway (e.g., a separation wall) to avoid compromising road integrity from excess infiltration and saturated conditions. However, this may require a supplemental drainage upstream of the separation wall to prevent accumulation of water below the main line road section. While flow water into traditional pavement is less than permeable pavement, water still enters the subgrade from incidental wetting through cracks, potholes, and other imperfections.

Groundwater Quality and Water Balance Considerations

- In areas with very high soil infiltration rates or shallow groundwater tables, captured stormwater may not be sufficiently treated prior to contact with groundwater. In these situations, designs may need to be adjusted to enhance treatment and prevent groundwater contamination. Examples of design adjustments include providing (a) an amended soil layer below the storage reservoir and (b) greater separation to groundwater.
- Impermeable liners between the pavement subbase and subgrade soils can be used to prevent infiltration where needed.
- Permeable shoulders can result in substantially greater groundwater recharge than pre-development conditions; the use of underdrains with adaptable outlet elevation can provide a contingency for water balance impacts.

Safety Considerations

- Permeable pavement shoulders should always have a supplemental drainage pathway if the surface is clogged. Supplemental drainage is especially important in critical cross sections, such as “sags” and depressed sections, to ensure that peak flows can be conveyed from the roadway if the permeable surface clogs.

- Permeable shoulders function in the same way as shoulders with standard pavement and do not present any added safety hazards.
- In cold weather climates, studies have found that less salt application is needed to address ice formation than is needed on traditional pavements (see Appendix F).

Regional Applicability

- Freeze/thaw cycles should be considered in cold climates, particularly when permeable pavement is designed with storage capabilities. Expansion and contraction of stored water can have implications to long-term pavement structure and stability.
- Permeable shoulders should not be used where roads are sanded during the winter or where studded tires are used.
- Permeable pavement can be effective for controlling temperature impacts associated with roadway runoff in humid areas.

New Projects, Lane Additions, and Retrofits

- Permeable shoulders tend to be more practicable and cost-effective in new construction and lane additions than as a retrofit. In new construction, the cost of the permeable shoulder can be offset in part by the avoided cost of a traditional shoulder that would otherwise be constructed. Additionally, the drainage of the main line roadway subbase can be coordinated with the drainage of the permeable shoulder.
- In contrast, retrofitting existing roadways with permeable pavement requires complete removal of the existing shoulder pavement and subbase, modification of the subbase drainage, and interfacing of the new permeable shoulder with the main roadway. If an impermeable liner is needed between the main line roadway and the permeable shoulder, a portion of the main line roadway may need to be excavated to provide secondary drainage for the upstream side of the liner.
- However, permeable shoulder retrofits may be one of the only options available in space-constrained highway segments.

Use in a Treatment Train

- Permeable pavement can be designed with an underdrain that can be used to convey stored and partially treated runoff to secondary BMPs.
- An amended soil layer below the stone reservoir can be used to improve the level of treatment of infiltrated water before it reaches groundwater.

Enhancements and Variations

Add storage. Increasing the depth and porosity of the stone subbase can be used to significantly increase the storage capacity of permeable pavement systems. Structural implications should be considered in alterations to stone properties.

Incorporate an underdrain and outlet controls. The use of underdrains in permeable pavement systems can provide a means of controlled and directed release of stored and partially treated stormwater. This variation can be used to direct effluent to secondary BMPs and/or mimic natural baseflow conditions. It can also provide adaptability of designs relative to water balance issues.

Consider various materials and thicknesses. Several different surface materials are available for permeable pavement (e.g., permeable concrete, permeable asphalt, permeable pavers). Different materials and thicknesses can be selected to improve porosity, permeability, and water quality performance for local climate and highway pavement performance standards.

Incorporate sweeping into maintenance activities. Some degree of cleaning and sweeping may reduce or delay clogging. For regular surface cleaning, regenerative air sweepers may be sufficient to improve the pavement permeability. For permeability restoration for significantly clogged pavements, a true vacuum sweeper may be required. Vacuum sweeping at regular intervals (twice per year) is recommended and should be increased in areas subject to higher loading of sediment. Mechanical sweeping is not recommended because rather than remove particles from the pavement, it will push particles farther into the pavement. At some sites, power washing used to break up surficial sediments is followed by sweeping. However, power washing has also been shown to force particles into deeper strata where they can cause clogging.

Resilient Design Features

Consider supplemental or alternative pathways for water to enter the subsurface storage if the permeable pavement clogs or a permeable wearing course is not desirable (areas with applied sanding, use of studded tires, etc.). Some designs incorporate an "overflow edge," which is a trench surrounding the edge of the pavement. The trench connects to the stone reservoir below the surface of the pavement and acts as a backup in case the surface clogs. If the surface clogs, stormwater will flow over the surface and into the trench and still reach the underlying infiltration reservoir. Use of inlets that connect to the subsurface reservoir can also be considered.

Consider adaptable outlet structures to be able to adjust the depth of water retained in the storage reservoir versus water detained and released.

Additional References

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ACPA (2012). American Concrete Paving Association, Pervious Pave—Background, Purpose, Assumptions and Equations, Washington, D.C.

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Hein, D., Strecker, E., Poresky, A., Roseen, R., Venner, M. 2013. Permeable Shoulders with Stone Reservoirs. NCHRP Project 25-25/Task 82 Final Report prepared for the AASHTO Standing Committee on the Environment, Washington, D.C. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP25-25(82)_FR.pdf.

NAPA. (2008). Design, Construction, and Maintenance Guide for Permeable Asphalt Pavements. Information Series 131, National Asphalt Pavement Association. Available from https://store.asphaltpavement.org/index.php.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 7: Permeable Pavement v.2. Fact sheet on permeable pavement including design guidance, construction and feasibility. Available online at http://chesapeakestormwater.net/wp-content/uploads/downloads/2014/04/VA-BMP-Spec-No-7-PERMEABLE-PAVEMENT-FINAL-DRAFT-EDITS-v2-0-02April2014.pdf.

Washington State Department of Transportation, Highway Runoff Manual. BMP IN.06. Permeable Pavement Surfaces. 2014. Chapter 5 includes fact sheets for Stormwater BMPs. Available online at http://www.wsdot.wa.gov/Environment/WaterQuality/Runoff/HighwayRunoffManual.htm.

Key Planning Level Design Parameters for Volume Reduction

Conceptual Design Parameter	***Description***	***Representative Range***
Footprint area	The area covered by permeable shoulder.	N/A
Tributary area ratio	The footprint of the permeable shoulder as a fraction of the total tributary area (including the permeable shoulder itself).	Typically limited to 5:1, but may be increased with effective maintenance
Stone reservoir thickness	The thickness of the stone storage layer.	Typically, 1 to 3 feet
Porosity	The effective void space within the stone storage layer.	Typically, 0.35 to 0.45
Effective reservoir storage depth	The effective depth of water stored within the permeable pavement system, function of the depth and porosity of the permeable stone storage layer, and the elevation of the overflow.	Up to about 0.4 feet (approximately 1 foot of stone) below the discharge elevation
Longitudinal slope	Slope along the axis of the road and associated slope along the bottom of the infiltration bed.	Preferably less than 1%; possible up to 3% with cutoff walls/berms
Top course permeability	The rate at which water is assumed to flow through the permeable top course above the storage layer; note permeability typically does not control volume reduction design for shoulders that are maintained.	Typically, greater than 100 in./hr, up to more than 1,000 in./hr (not typically assumed to control design)
Soil design infiltration rates	The rate at which water is assumed to infiltrate into the subsurface soils for the purpose of design and benefits evaluation. This should be the rate of infiltration below the stone reservoir.	At least 0.3 to 0.5 in./hr for full infiltration systems without underdrains; systems with partial infiltration possibly down to approx. 0.01 in./hr
Surface outlet stage	The stage at which the system begins to discharge to the surface conveyance system via the underdrain and outlet control features if provided.	Equal to or below the subbase/subgrade interface is preferred to reduce the risk of subgrade saturation
Surface outlet discharge drawdown time	The time it takes for the storage volume above the surface outlet stage to drain from brim full if extended detention is provided.	Typically, 24 to 48 hours for extended detention treatment

Example Conceptual Design Schematics

Figures 1 and 2 show two different cross-section views, Figure 3 shows the plan view, and Figures 4 and 5 show two different longitudinal profiles.

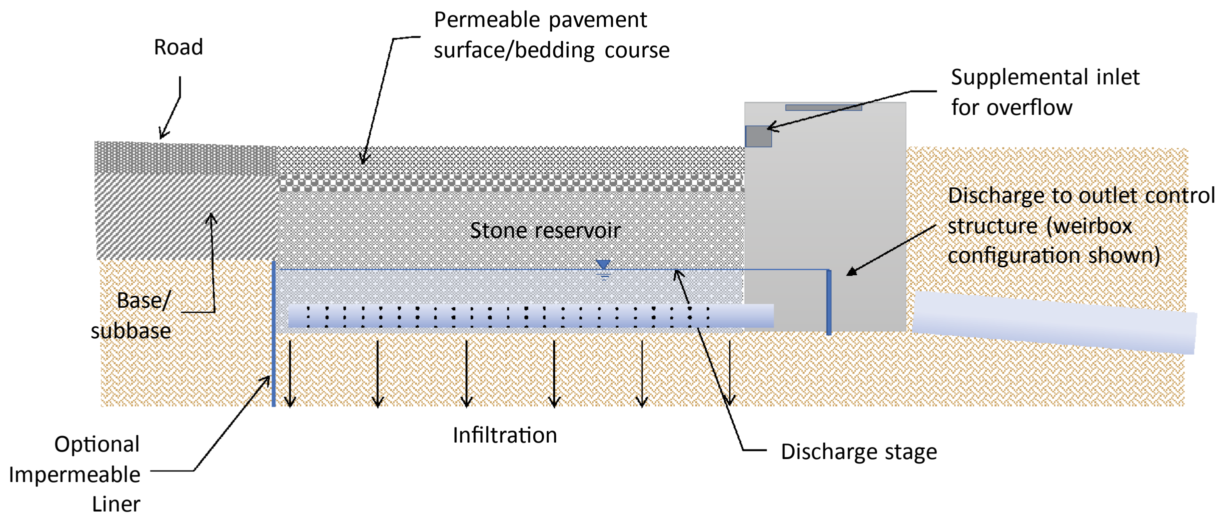


Figure 1. Cross-section view—urban setting with weir box.

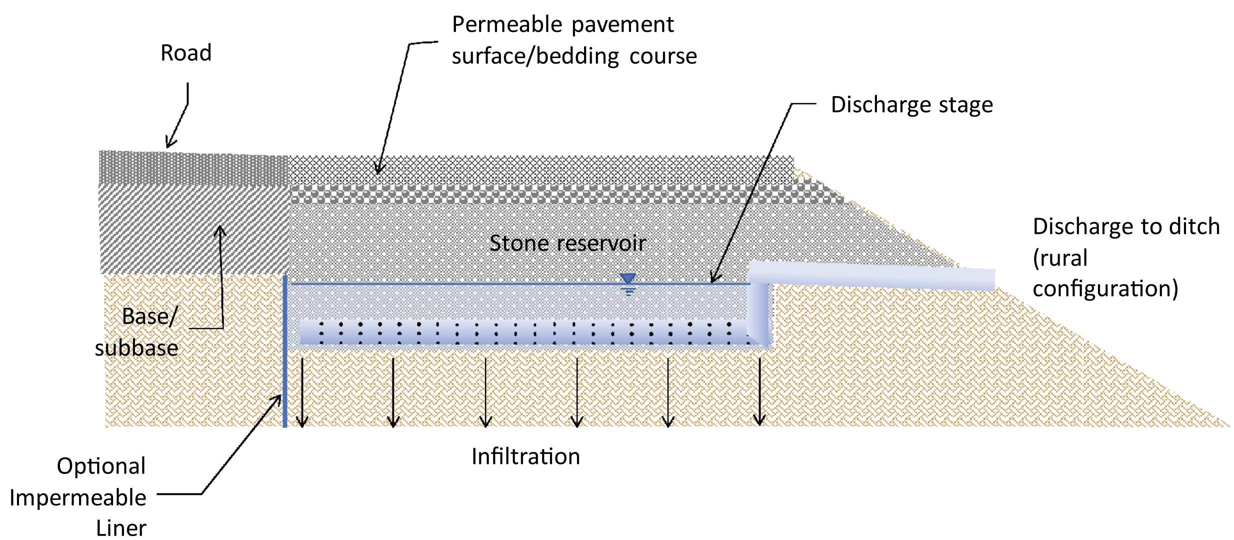


Figure 2. Cross-section view—rural setting with upturned elbow.

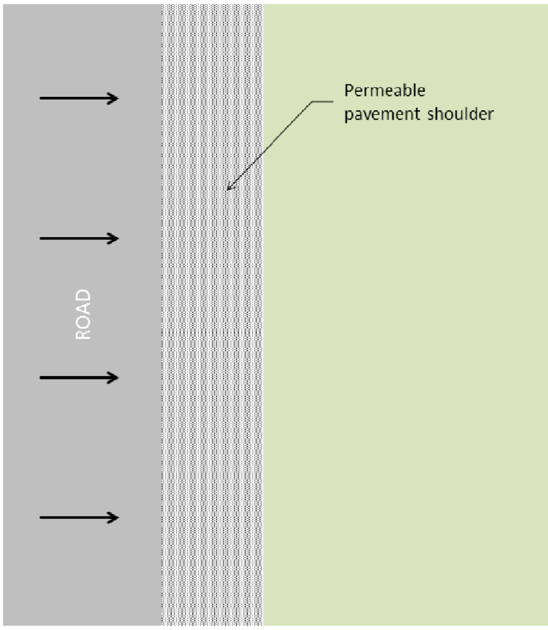


Figure 3. Plan view.

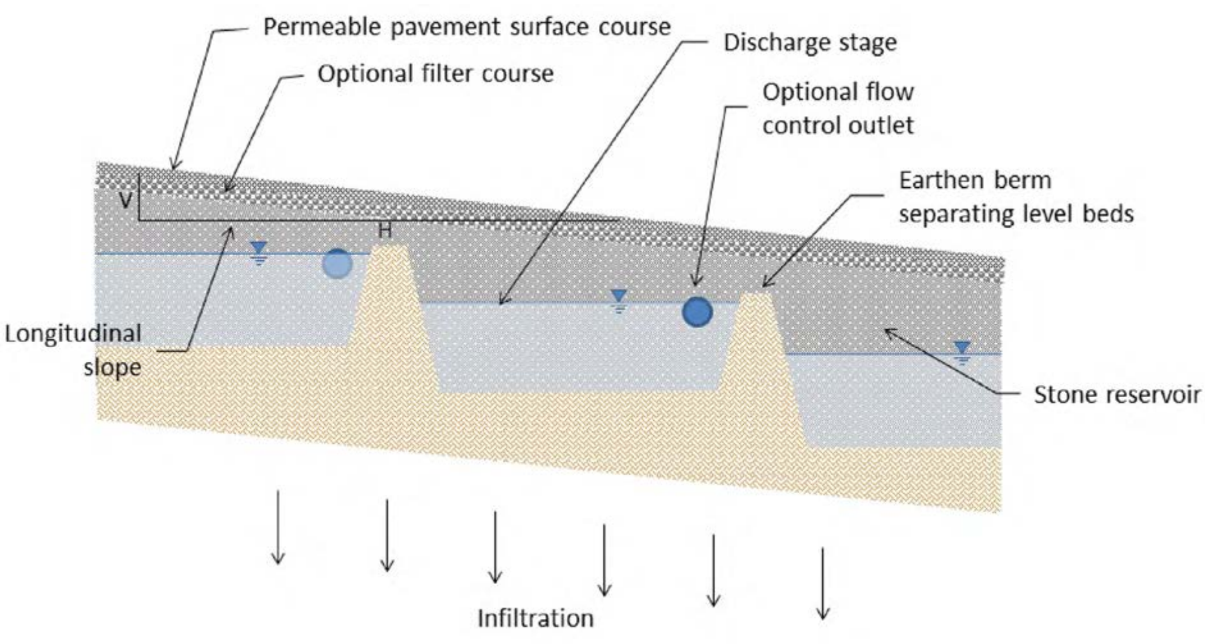


Figure 4. Longitudinal profile of an installation along a mild slope (earthen berms).

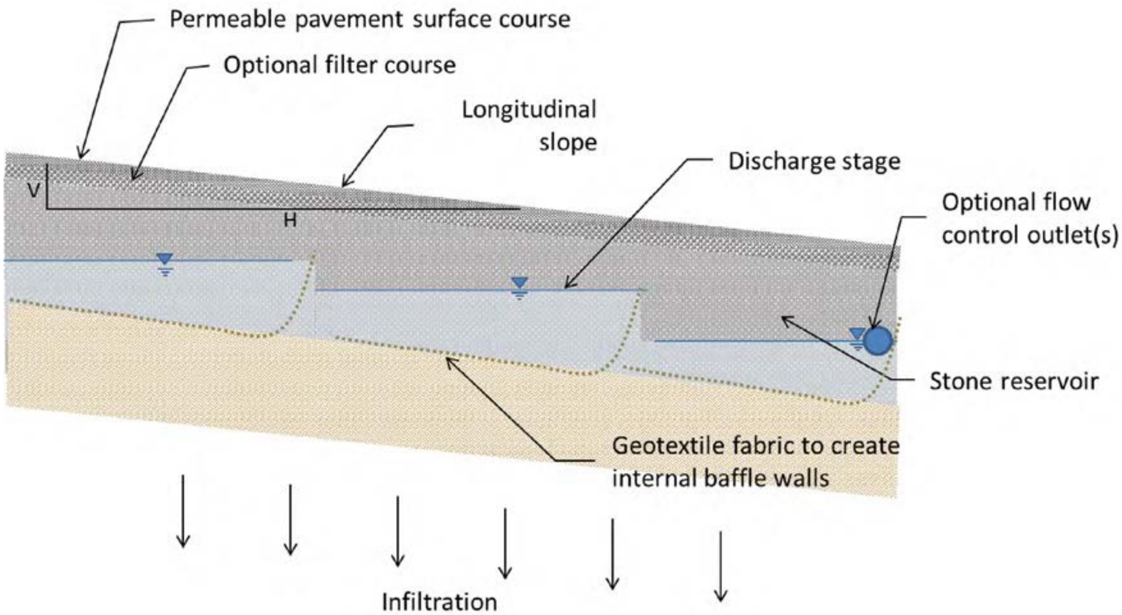


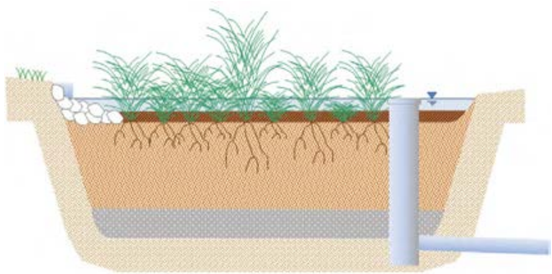
Figure 5. Longitudinal profile of an installation along a mild slope (geotextile cutoff walls).

Example Inspection and Maintenance Activities

Activity	Frequency
GENERAL INSPECTIONS	
Inspect for areas of sediment accumulation in the pavement surface	Annually or as noted
If sediment accumulation is elevated, inspect for potential sources of sediment in the tributary area and determine control approaches to reduce sediment	
Observe and record drawdown rate via observation port following storm event	
Periodically (every 2 to 5 years) measure the permeability of the surface of the permeable pavement	
Identify any damage to pavement	
Inspect outlet control and overflow structures	
Identify any needed corrective maintenance that will require site-specific planning or design	
ROUTINE MAINTENANCE	
Permeable Surface Layer	
Remove sediment and leaf litter using a mechanical sweeper (e.g., regenerative air or vacuum-assisted sweeper)	One to two times per year, depending on loading rates
Power wash surface layer (without using surfactants)	As needed
Patch pavement surface where needed	As needed
Other activities specific to pavement surface type	As needed
Coordinate with maintenance of adjacent pavement to ensure permeable pavement is protected	As needed
Underdrain and Outflow Structures	
Inspect outlets and remove accumulated sediment	Annually
Repair structural damage to outlets	As needed
CORRECTIVE (MAJOR) MAINTENANCE	
Replace surface wearing course when it becomes excessively rutted or permeability cannot be restored via other methods	Estimated 10 to 20 years
Full-depth remediation and over-excavation of underlying soil if infiltration rates decline below acceptable range	Most practical as part of roadway rebuild
Prepare documentation of issues and resolutions for review by appropriate parties; modify O&M Plan if needed.	Before major maintenance
Document major maintenance activities; record modified O&M Plan and as-built plan set if needed	After major maintenance
Take photographs before and after from the same vantage point	Before and after

Bioretention without Underdrains BMP 05

Alternative names: *rain garden, bioretention, retention swale*



Highway 99E Viaduct, Portland, Oregon. (Photo credit: Geosyntec Consultants.)

VOLUME MANAGEMENT POTENTIAL/PROCESSES	
●	Overall Volume Reduction Potential
●	Infiltration
◉	Evapotranspiration
○	Consumptive Use
○	Baseflow-mimicking Discharge

URBAN HIGHWAY APPLICABILITY	
●	Ground level highways
●	Ground level highways with restricted cross-sections
○	Ground level highways on steep transverse slopes
○	Steep longitudinal slopes
◉	Depressed highways
◉	Elevated highways on embankments
●	Elevated highways on viaducts (if space below viaduct is available for VRAs)
●	Linear interchanges
●	Looped interchanges

● High ◉ Moderate ○ Low

Description

Bioretention consists of a shallow surface ponding area underlain by porous soil media storage reservoirs and an optional porous stone storage layer. Captured runoff is directed to the bioretention area where it infiltrates into an engineered soil medium and then infiltrates into the subsoil. Engineered soil media is a central element of bioretention design and typically includes a mixture of sand, soils, and organic elements that are designed to provide permeability, promote plant growth, and provide treatment. Guidance for media design varies by region. Vegetation is also a characteristics element of bioretention design and typically includes grasses, sedges, and small woody plants and shrubs. Selection of vegetation should vary by climatic region. Storage capacity is a function of the ponding depth, media/stone porosity, and the footprint of the facility. Additional storage can be gained by adding a stone storage layer beneath the soil medium. The shape of a bioretention area is not critical to its function, and it is common for facilities to be roundish, irregular, or linear. Overall volume reduction potential relies on infiltration rates and storage capacity, with some losses to ET.

Volume Reduction Processes and Performance Factors

Volume reduction in bioretention cells is achieved through infiltration and ET. Efficient volume reduction performance is dependent on adequate medium and subsoil infiltration rates to ensure that captured runoff filters through the system between storm events. Vegetation and roots play an important role in maintaining and regenerating infiltration and ET rates as well as supporting a healthy biological community in the soil media for treatment purposes.

General DOT Experience

Bioretention facilities have seen widespread use in other land uses and are increasingly being found in DOT stormwater design manuals across the country. They have been successfully implemented within the linear highway environment in many locations. Maryland State Highway Administration (SHA) is installing 80 permanent BMPs, mostly rain gardens in one interchange. Case studies along the eastern United States have shown volumetric reductions from 47% to 69% in the urban highway environment (Davis et. al. 2012). Various studies summarized by Hirschman et al. (2008) estimate volume reduction from bioretention ranging from 40% with underdrains to 80% when using an infiltration-based design. Minnesota DOT (MnDOT), Oregon DOT (ODOT), and WSDOT also have considerable experience with bioretention (with or without underdrains) in the urban highway environment.

Applicability and Limitations

Site and Watershed Considerations

- Use of bioretention without an underdrain requires soils with infiltration rates high enough to ensure that the bioretention cell drains fully between storm events.
- Proper infiltration of captured stormwater from bioretention cells requires that the groundwater table be at least several feet below the bottom of the bioretention cell.
- Bioretention can be used in many urban applications where available space exists and site characteristics meet or can be modified to design requirements. It can be readily applied on shoulders, interchanges, and medians with low slopes.
- Bioretention can be incorporated into narrower linear spaces by using vertical side walls as barriers between the bioretention cell and the road instead of shallow slopes. Appropriate safety considerations such as guard rails are necessary.
- Steeper slopes near bioretention can render full infiltration BMPs infeasible because of geotechnical concerns. Terraced bioretention cells can be constructed in areas with moderate longitudinal slopes that do not preclude infiltration.
- In linear configurations, bioretention can serve a conveyance purpose and allow reduction in piping requirements.
- Watersheds with high sediment loads (such as from disturbed open space) may result in premature clogging of the system.

Geotechnical Considerations

- Bioretention without underdrains is primarily an infiltration measure and must be sited and designed accordingly. Wide medians, wide shoulders, and/or interchanges tend to provide the best opportunity for bioretention in the urban highway environment.

- Through the use of underdrains (see BMP 06), geotechnical considerations can be reduced while still providing some volume reduction.

Groundwater Quality and Water Balance Considerations

- The amended media layer in bioretention provides a relatively high level of treatment of particulate-bound pollutants, dissolved metals, petroleum hydrocarbons, and pesticides. There is relatively low risk of groundwater quality impacts from these constituents if separation to groundwater is observed.
- Like other infiltration BMPs, bioretention is not generally effective for controlling salts or viruses.
- Media with excessive compost and/or poor controls on sources of media elements can leach nutrients, specifically nitrate and dissolved phosphorus, as well as metals and pathogens. This can be mitigated through careful media design.
- In soils with high infiltration rates, bioretention can result in greater recharge than natural conditions. If water balance issues would potentially result from increase in groundwater recharge, this can be mitigated by including an underdrain to reduce the amount of infiltrated water (see BMP 06).

Safety Considerations

- Bioretention soils are intentionally porous and uncompacted, therefore bioretention should be located out of the clear zone, or barriers oriented parallel to traffic should be used to prevent errant vehicles from entering the bioretention cell.

Regional Applicability

- Bioretention has been applied successfully across a broad range of climates; plant and soil media must be selected to be compatible with the local climate.
- Salt loadings in cold climates may influence plant selection and may necessitate the use of an underdrain if groundwater quality issues would result from infiltration of salts.
- If roads are sanded, providing a pretreatment system to settle sands is recommended.
- Irrigation is typically required for plant establishment in most climates in North America. Vegetation should be planted as early as possible to account for a shorter growing season in colder regions. Careful planning and scheduling may be required to ensure enough time is allowed for establishment of adequate soil stabilizing vegetation. Seeding windows should be specified for different regions in Standard Specifications. Supplemental irrigation may be required depending on seeding and planting times. In arid climates, supplement irrigation may be needed to

establish plants. In both cases, native plant species are preferred, with considerations to both salt-tolerant and drought-tolerant situations.

- Peat and compost media are ineffective during the winter in cold climates. These filters retain water, freeze solid, and become completely impervious during the winter. Rather, highly permeable, well-draining coarse granual materials (void of silts and clays) decreased the duration time of soil saturation to minimize freezing and to restore soil capacity to accommodate future melt events. A well-draining soil type may be the single most important design characteristic.

New Projects, Lane Additions, and Retrofits

- For retrofit applications, existing compaction of subgrade may limit application; restoration of infiltration rates may be possible with decompaction.
- Cut and fill can typically be balanced in new construction, and drainage can be configured to account for bioretention areas. In contrast, in retrofit situations, bioretention may require additional excavation and hauling costs as well as additional piping costs.

Use in a Treatment Train

- Pretreatment of runoff to reduce particulate matter and suspended solids will increase the life of the bioretention cell and reduce required maintenance. Pretreatment can be provided prior to the bioretention cell by the use of vegetated conveyance features.
- Stormwater runoff in excess of the bioretention cell's storage capacity can be conveyed to additional BMPs by use of overflow controls, such as weirs.

Enhancements and Variations

Slow flow velocities and provide level pools. Bioretention can be used wherever there is open, fairly level space. When slopes exceed 6%, intermediate berms can be used to create level ponding areas within the bioretention area.

Adaption to narrow spaces. Bioretention cell geometry is flexible and is easily adapted to the narrow linear spaces commonly available in the urban highway ROW, such as the following:

Linear bioretention/retention swales. A bioretention area constructed in a linear configuration such that it provides retention and also serves as a conveyance feature when its capacity is exceeded. This configuration is likely well suited to linear segments of urban highway projects, whereas traditional bioretention may be better suited to interchanges.

Bioretention planters. In constrained urban areas, it may be necessary to construct bioretention with vertical concrete retaining walls, such as a typical stormwater planter used on residential and commercial streets. Additional safety considerations, such as a guard rail or barrier, may be needed to allow for vertical retaining walls.

Increase storage capacity. A variety of factors can be adjusted to increase storage capacity. A stone layer can be included beneath the bioretention medium. The depth of the bioretention medium can be adjusted. Additionally, the composition of the bioretention medium can be adjusted to increase porosity. This can be accomplished through the addition of sand, expanded shale, compost, or other soil amendments.

Add surcharge detention. Perimeter berms or site topography can be used to provide additional storage capacity above the maximum infiltrated ponding depth to provide enhanced flow control performance; it may be possible to meet flow control and volume control objectives with one facility.

Resilient Design Features

Bioretention without underdrain can include a capped underdrain that can be opened if observed infiltration rates are inadequate. The capped underdrain should be placed at the bottom of the infiltration layer and tied into an adjustable outlet structure such that the amount of retained depth can be adjusted.

Filtered runoff can be allowed to infiltrate into the surrounding soils (functioning as an infiltration basin or rain garden) or collected by an underdrain system and discharged (like a surface sand filter). The installation of an underdrain system with an accessible cap or valve at its outlet is recommended to allow the option of operating the bioretention cell as either an infiltration system (valve closed) or a filtration system (valve open). Residence time for water quality treatment can be managed by adjusting a partially open valve. Opening the subdrain valve may allow early fall drawdown in preparation for freezing weather. In cold climates, it is better to open the valve to have a functional filtration system than have a non-functional (frozen) infiltration system.

Consider using an outlet orifice to control the rate of flow through the media rather than using the hydraulic conductivity of the media. This allows a higher permeability fill media (more space for fine sediment accumulation) with a greater margin of safety on media (soil) clogging without diminishing treatment performance.

Selection of vegetation has an effect on the resiliency of the BMP; plant materials should be deep rooted native species. The dense matrix of deep roots provided by native vegetation creates long downward flow paths as roots decay. Plants should be salt tolerant because of the likelihood of road runoff having high salt concentrations in cold climates. Plants should also be tolerant to wide fluctuations in soil moisture content.

A bioretention cell can be off-line or in-line, depending on site constraints and the configuration of the existing drainage system. Off-line systems are preferable, because they tend to minimize the transport of pollutants and debris downstream. (Both types of systems may use underdrains.) The difference between off-line and in-line cells is how the cell handles excess runoff when the maximum ponding depth has been reached.

Pretreatment by capture of coarser sediments can be accomplished by a vegetative filter, forebay, or manufactured treatment device, and can extend the functional life and increase the pollutant removal capability of a bioretention system.

Additional References for Design Information

Massachusetts Stormwater Handbook, Volume 2, Chapter. 2. Stormwater Best Management Practices (MassDEP). Contains detailed BMP Fact Sheets, with figures, design considerations, construction and maintenance guidance. http://www.mass.gov/eea/docs/dep/water/laws/i-thru-z/v2c2.pdf.

North Carolina State University. Bioretention at North Carolina State University Fact Sheet C-2, Bioretention Cell. 2017. NCSU-BAE Assisted Design Chapters of NCDEQ Stormwater Design Manual. Fact sheet includes detailed schematics, design, media, planting plan recommendations, and suggested plant species. Available online at https://ncdenr.s3.amazonaws.com/s3fs-public/Energy%20Mineral%20and%20Land%20Resources/Stormwater/BMP%20Manual/C-2%20%20Bioretention.pdf.

Oregon State University et al. 2006. *NCHRP Report 565: Evaluation of Best Management Practices for Highway Runoff Control*. Transportation Research Board of the National Academies, Washington, D.C. Manual intended to provide the highway engineer with selection guidance toward implementation of BMPs and LID facilities for control of stormwater quality in the highway environment. Includes detailed schematics, cost tables for different items in each BMP. http://www.trb.org/Publications/Blurbs/158397.aspx.

Prince George's County Bioretention Manual. 2007. Environmental Services Division, Department of Environment Resources. Available online at http://www.ct.gov/deep/lib/deep/p2/raingardens/bioretention_manual_2009_version.pdf.

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Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 9: Bioretention v.1.9. Available online at http://chesapeakestormwater.net/2012/03/design-specification-no-9-bioretention/.

Washington Department of Ecology. Stormwater Manual for Western Washington. BMP T7.30: Bioretention Cells, Swales, and Planter Boxes. 2012. Available online at https://fortress.wa.gov/ecy/publications/summarypages/1210030.html.

New Jersey Stormwater Best Management Practices Manual. Fact Sheet 9.1 – Bioretention Systems. Chapter 9 contains detailed design, construction, maintenance; sizing and applicability of bioretention systems, including with and without underdrain. Available online at http://www.njstormwater.org/bmp_manual/NJ_SWBMP_9.1.pdf.

Key Planning Level Design Parameters for Volume Reduction

Conceptual Design Parameter	***Description***	***Representative Range***
Footprint area	The area covered by the surface of the bioretention cell.	Typically, 100 to 2,000 sq-ft; can potentially be much larger
Effective footprint area	The portion of the total facility footprint area that provides storage and infiltration during typical operations. For planning level design efforts, the effective footprint can be considered to be the ponded water area when the system is at half of its design ponding depth.	Slightly smaller than total footprint area
Ponding depth	The maximum water depth above the surface of the bioretention medium prior to overflow.	Typically, 0.5 to 1.5 feet; can potentially be increased if plant selection and soil infiltration rates are suitable.
Engineered soil medium thickness	The thickness of the engineered soil medium layer.	Typically, 1 to 4 feet
Stone storage layer thickness	The thickness of the optional stone storage layer if provided.	Not typically provided in bioretention design; may be any depth if used for supplemental storage
Total storage depth	The effective depth of water stored within the bioretention cell. Total storage depth is a function of ponding depth, bioretention medium depth and porosity, and the depth and porosity of the optional stone storage layer.	Typically, 0.5 to 3 feet
Available pore storage capacity	The effective void space of engineered soil media or stone reservoirs that is available for water storage.	0.2 to 0.35
Media filtration rate	The rate at which water filters into the media layer from the surface storage area.	Typically designed to be greater than 1 in./hr
Design infiltration rate	The rate at which water infiltrates into the subsurface soils for the purpose of design and benefits evaluation. This should be the rate of infiltration below the amended soil layer or stone reservoir.	Typically limited to underlying soils with greater than 0.3 to 0.5 in./hr for full infiltration design

Example Conceptual Design Schematic

Figures 1 and 2 show cross-section and plan views, respectively.

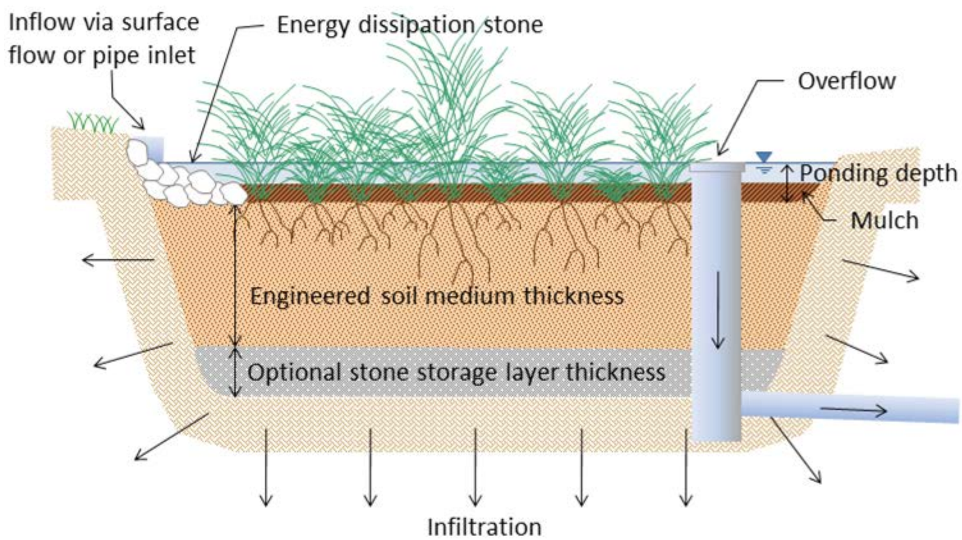


Figure 1. Cross-section view.

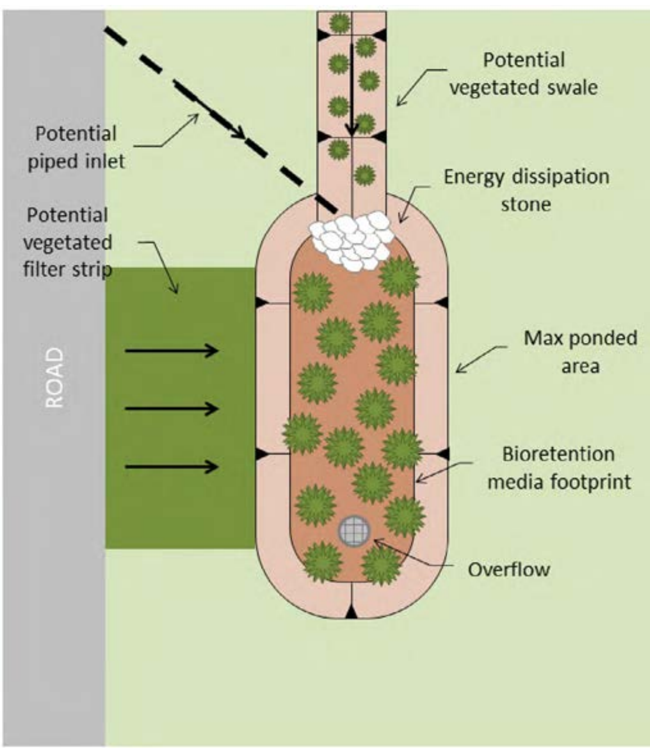


Figure 2. Plan view.

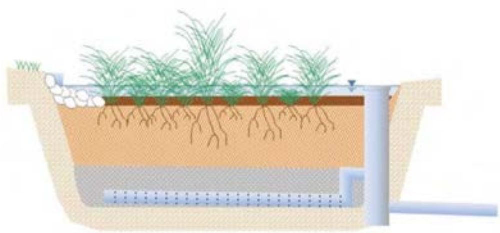
Example Inspection and Maintenance Activities

Activity	Frequency
GENERAL INSPECTIONS	
Accumulation of trash and debris	Annually or semi-annually depending on loading
Eroded facility areas	
Sediment accumulation	
Extended standing water	
Vector or rodent issues	
Identify any needed corrective maintenance that will require site-specific planning or design	
ROUTINE MAINTENANCE	
General	
Remove trash and debris	Annually or semi-annually depending on loading
Repair eroded facility areas	
Remove minor sediment in forebay	
Vegetation	
In arid climates, irrigate as recommended by a landscape professional, typically for the first 3 years to establish vegetation	As needed
Remove undesirable vegetation	Annually
Reseed or replant areas of thin or missing vegetation	Annually
Mulch	
Remove and replace mulch in areas where significant sediment (>1 inch) has accumulated	Annually
Add an additional 1 to 2 inches of mulch; replace any mulch that is removed	As needed
Media Layer	
Rake to scarify media to promote infiltration while removing and replacing mulch	When replacing mulch
Replace media in areas that experience scour	When fixing erosion
Inflow, Underdrain, and Outflow Structures	
Check energy dissipation function and add riprap	As needed
Remove accumulated sediment from inlets and outlets	As needed
Flush underdrain	As needed (less often)
CORRECTIVE (MAJOR) MAINTENANCE	
Replace top 3 to 6 inches of media layer and replace vegetation	Estimated every 10 years (highly site specific)

Activity	Frequency
Replace full depth of media and replace vegetation	Estimated every 30 years (highly site specific)
Replace aggregate drainage layer	As needed if silted in
Repair structural damage to inlets, outlets, and underdrain and/or replace these elements	As needed if at end of usable life
Prepare documentation of issues and resolutions for review by appropriate parties; modify O&M Plan if needed	Before major maintenance
Document major maintenance activities; record modified O&M Plan and as-built plan set if needed	After major maintenance
Take photographs before and after from the same vantage point	Before and after

Bioretention with Underdrains BMP 06

Alternative names: *bioretention, biofiltration, retention swale*



I-5 Exit 298, Portland, Oregon. (Photo credit: Geosyntec Consultants.)

VOLUME REDUCTION PROCESSES	
●	Overall Volume Reduction Potential
●	Infiltration
◉	Evapotranspiration
○	Consumptive Use
◉	Baseflow-mimicking Discharge

URBAN HIGHWAY APPLICABILITY	
●	Ground level highways
●	Ground level highways with restricted cross-sections
◉	Ground level highways on steep transverse slopes
◉	Steep longitudinal slopes
◉	Depressed highways
◉	Elevated highways on embankments
○	Elevated highways on viaducts
●	Linear interchanges
●	Looped interchanges

● High ◉ Moderate ○ Low

Description

Bioretention consists of a shallow surface ponding area underlain by porous soil media storage reservoirs and optional porous stone storage layers. Runoff is captured within and directed to the bioretention area, infiltrates into the soil medium, and is discharged through an underdrain. Vegetation is a critical element of bioretention design and typically includes grasses, sedges, and small woody plants and shrubs. Selection of vegetation should vary by climatic region. Storage capacity is dependent on ponding depth and media and stone porosity. Where soil infiltration rates permit, storage can be enhanced by installing a stone reservoir beneath the underdrain. This category of BMPs is suitable for a wider range of conditions than bioretention without an underdrain and can be used to mimic natural baseflows. Additional reductions in volume are possible from infiltration into subsoil where conditions permit.

Bioretention designs with underdrains typically include a stone layer below the amended media layer, with an underdrain that discharges at an elevation above the bottom of the stone layer. This creates a “sump” of water that leaves the system by infiltration only. When the capacity of the sump layer is exhausted, treated water discharges via the underdrain. Between storm events, runoff captured in the bioretention medium above the sump layer slowly discharges via the underdrain, producing a long-duration low-volume flow (depending on outlet controls) that is similar in many ways to shallow groundwater baseflow in undeveloped/predevelopment watersheds.

Volume Reduction Processes and Performance Factors

Volume reduction in bioretention with underdrains is achieved through infiltration below the underdrains of the system (unless lined), ET, and baseflow-mimicking discharge, where applicable. Volume reduction performance is dependent on subsoil infiltration rates, vegetation, and underdrain flow controls to ensure that captured runoff exits the cell between storm events. Vegetation and plant roots play an important role in maintaining and regenerating infiltration and ET rates as well as supporting a healthy biological community in the soil medium for treatment.

General DOT Experience

Bioretention facilities have been successfully implemented within the highway and roadway environments in various locations across the United States. With the regulatory trend toward volume control and dispersed treatment, some DOTs are installing larger numbers of these types of BMP. For example, Maryland SHA is installing more than 20 bioretention cells in one interchange project. Studies summarized by Hirschman et al. (2008) estimate volume reduction from bioretention with underdrains (bioinfiltration) from 20% to 65% with an average estimated reduction of 40%. In studies in the International BMP Database, bioretention systems with underdrains have shown moderate to high reductions in stormwater volumes on average (Geosyntec and Wright Water Engineers 2012).

Applicability and Limitations

Site and Watershed Considerations

- Bioretention with an underdrain is suitable for all soils provided the system medium has sufficient permeability.
- Bioretention can be used in many urban applications where water can be routed to a depressed area. The shape of a bioretention area is not critical to its function, and it is common for facilities to be roundish, irregular, or linear. Thus, bioretention tends to be more flexible to a wide variety of sites than many other BMPs.
- Bioretention with underdrains can be incorporated into narrower spaces by using vertical retaining walls as the bioretention cell edges.
- Terraced bioretention cells can be constructed on shoulders and areas with steeper slopes. Underdrains can mitigate issues with infiltration in steeper areas.
- In linear configurations, bioretention can serve a conveyance purpose and allow reduction in piping requirements.
- Watersheds with high sediment loads (such as from disturbed open space) may result in premature clogging of the system.

Geotechnical Considerations

- Bioretention with underdrains may still allow lateral and vertical flow of water from the system unless lined with an impermeable barrier; related considerations apply.
- The underdrain outlet structure controls the relative amount of infiltration that occurs (and associated geotechnical risk) and can be adaptively managed as necessary.

Groundwater Quality and Water Balance Considerations

- In areas with very high soil infiltration rates or shallow groundwater tables, captured stormwater may not be sufficiently treated prior to contact with groundwater.
- In areas with existing groundwater contamination, bioretention cells can be lined to keep treated stormwater out of contact with groundwater and discharged only via the underdrain.

Safety Considerations

- Bioretention soils are highly porous and uncompacted. Therefore, barriers should be used, where appropriate, to prevent errant vehicles from entering the bioretention cell, or bioretention cells should be located out of the clear zone.

Regional Applicability

- Bioretention has been applied successfully across a broad range of climates; plant and soil media must be selected to be compatible with the local climate. Salt loadings in cold climates may influence plant selection.
- If roads are sanded, providing a pretreatment system to settle sands is recommended.
- In northern climates, bioretention underdrains should be installed at least a foot below the frost line where practical and be appropriately oversized to accommodate for sub-freezing conditions.
- Irrigation is typically required for plant establishment. Vegetation should be planted as early as possible to account for a shorter growing season in colder regions.

New Projects, Lane Additions, and Retrofits

- Given suitable soil, space, and groundwater conditions, bioretention cells are relatively straightforward designs that can be incorporated into new projects.
- Retrofit projects will be similar in relative costs for bioretention systems, provided there is adequate space and suitable site conditions, particularly if depressions exist. Additional costs of excavation and possible amendments may be incurred during construction.
- Prefabricated bottomless planters are widely available, and can be installed in more narrow applications with moderate costs, assuming sufficient conditions are met.
- Retrofitting an existing bioretention system with underdrains will involve significant excavation, piping, controls, and possible amendments to the medium and/or stone. Including underdrains in new construction is recommended if there is a possibility that they will be needed to supplement infiltration.

Use in a Treatment Train

- Pretreatment of runoff to reduce particulate matter and suspended solids will increase the life of the bioretention cell and reduce required maintenance.

- Pretreatment can be provided prior to the bioretention cell by use of vegetated conveyance features or a forebay.
- Stormwater runoff in excess of the bioretention cell's storage capacity can be conveyed to additional BMPs by use of overflow controls such as weirs.

Enhancements and Variations

Slow flow velocities and mitigate steep slope effects. Bioretention can be used wherever there is open, fairly level space. When slopes exceed 6%, check dams can be used to create level ponding areas within the bioretention.

Adaption to narrow spaces. Bioretention cell geometry is flexible and is easily adapted to the narrow spaces commonly available in the urban highway ROW. Vertical impermeable liners can be used in tight areas to prevent road base stability from being compromised.

Increase storage capacity. A variety of factors can be adjusted to increase storage capacity. A stone layer can be included beneath the underdrain. The depth of the bioretention medium can be adjusted. Additionally, the composition of the bioretention medium can be adjusted to increase porosity. This can be accomplished through the addition of sand, zeolite, expanded shale, compost, or other soil amendments. Research is ongoing to determine which mixtures provide the highest porosity without compromising pollutant removal performance.

Provide overflow. Stormwater runoff in excess of the bioretention cell's storage capacity can be conveyed to additional BMPs by use of overflow controls, such as weirs. This variation can provide a means to effectively deal with bypass flows and mitigate possible flooding effects.

Energy dissipation. Deflection weirs, obstructions, and stone may be used to dissipate energy of influent flows and help prevent scour and possible additional loading of sediment to downstream facilities.

Extended detention. Perimeter berms or site topology can be used to provide additional storage capacity above the max ponding depth. If extended detention is implemented, multiple overflow controls should be considered to reduce flooding potential and ensure proper drainage.

Active control. Internet-based technology has recently allowed more widespread deployment of forecast-enabled, real-time active controls for systems with underdrains. This approach can improve the applicability and performance of these systems by making informed decisions about when and at what rate to release stored water based on storage conditions and forecasted rainfall.

Highway Design

Bioretention cells may also provide safety benefits for roadway users under certain circumstances. The vegetation in bioretention cells may reduce glare and act as a crash cushion for errant vehicles.

Resilient Design Features

Bioretention with underdrains should have the underdrain placed at the bottom of the infiltration layer and tied into an adjustable outlet structure such that the amount of retained depth can be adjusted. The perforated underdrain pipe shall be placed in between drain rock to prevent fine sediments from clogging and prohibiting the functionality of the underdrain pipe. In cold climates, the underdrain should be extended below the frost line and/or oversized to prevent freezing of the underdrain or the filter media.

Consider using an outlet orifice to control the rate of flow through the media rather than the hydraulic conductivity of the media. This allows a higher permeability fill media (more space for fine sediment accumulation) with a greater margin of safety on media (soil) clogging without diminishing treatment performance.

A sacrificial/topsoil layer (minimum of 2 to 3 inches) can be incorporated that will function as a pretreatment device to limit pollutants from entering the engineered soil media layer. The ongoing replacement of the topsoil layer will promote longevity for the BMP. Rehabilitation of soils to achieve a minimum of 1 in./hr infiltration rate within the vegetated conveyances will further enhance infiltration and groundwater recharge. The vegetation cover (plants, shrubs, trees, etc.) shall be at a minimum of 80% to enhance water quality.

In bioretention cells with underdrains, water stored above the underdrain will exit through the underdrain. This is considered detention storage. Detained water ultimately leaves the bioretention cell through the underdrain or the bypass structure, and some form of downstream conveyance will be necessary. A limited amount of retention will occur as a result of ET and exfiltration into the subsoil. Retained water is permanently taken out of the system. In addition, retention/recharge storage can be provided by adding a gravel layer below the underdrain. This “dead” storage will be drawn down over time by exfiltration into the subsoil. In cells without underdrains, all water is retained, because it is lost to ET or exfiltration into the subsoil. The portion lost to ET is relatively small compared with exfiltration, especially as the storm size increases. However, volume reductions from ET may be significant in dry seasons or geographic regions.

Capital cost of bioretention with an underdrain is about 2/3 higher than without an underdrain for the same capture efficiency and volume reduction. Annualized cost per unit of load reduction performance for bioretention with underdrain is about half the cost as without an underdrain for bacteria, most metals, and TSS, yet about twice the cost for the same removal performance of total lead and nutrients (Taylor et al. 2014). Therefore, selection should consider water quality treatment prior to discharge and the potential impacts to receiving waters.

Depending on the season, geographic location, and type of vegetation, irrigation may be needed during plant establishment. These factors will also determine the irrigation frequency. “Established” means that the soil cover has been maintained for at least 1 year since replanting. Native plants may require less irrigation than non-natives. In periods of extended drought, temporary supplemental irrigation may be used to maintain plant vitality. Irrigation may be done using an automatic system or manually by landscape maintenance workers.

Additional References

Massachusetts Stormwater Handbook, Volume 2, Chapter. 2. Stormwater Best Management Practices (MassDEP). Contains detailed BMP Fact Sheets, with figures, design considerations, construction and maintenance guidance. http://www.mass.gov/eea/docs/dep/water/laws/i-thru-z/v2c2.pdf.

North Carolina State University. Bioretention at North Carolina State University Fact Sheet C-2, Bioretention Cell. 2017. NCSU-BAE Assisted Design Chapters of NCDEQ Stormwater Design Manual. Fact sheet includes detailed schematics, design, media, planting plan recommendations, suggested plant species. Available online at https://ncdenr.s3.amazonaws.com/s3fs-public/Energy%20Mineral%20and%20Land%20Resources/Stormwater/BMP%20Manual/C-2%20%20Bioretention.pdf.

Oregon State University et al. 2006. *NCHRP Report 565: Evaluation of Best Management Practices for Highway Runoff Control*. Transportation Research Board of the National Academies, Washington, D.C. Manual intended to provide the highway engineer with selection guidance toward implementation of BMPs and LID facilities for control of stormwater quality in the highway environment. Includes detailed schematics, cost tables for different items in each BMP. http://www.trb.org/Publications/Blurbs/158397.aspx.

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Washington Department of Ecology. Stormwater Manual for Western Washington. BMP T7.30: Bioretention Cells, Swales, and Planter Boxes. 2012. Available online at https://fortress.wa.gov/ecy/publications/summarypages/1210030.html.

New Jersey Stormwater Best Management Practices Manual. Fact Sheet 9.1 – Bioretention Systems. Chapter 9 contains detailed design, construction, maintenance; sizing and applicability of bioretention systems, including with and without underdrain. Available online at http://www.njstormwater.org/bmp_manual/NJ_SWBMP_9.1.pdf.

Key Planning Level Design Parameters for Volume Reduction

Conceptual Design Parameter	***Description***	***Representative Range***
Footprint area	The area covered by the surface of the bioretention cell.	Typically, 100 to 2,000 sq-ft; can potentially be much larger
Effective footprint area	The portion of the total facility footprint area that provides storage and infiltration during typical operations. For planning level design efforts, the effective footprint can be considered to be the ponded water area when the system is at half of its design ponding depth.	Slightly smaller than total footprint area
Ponding depth	The maximum water depth above the surface of the bioretention medium prior to overflow.	Typically, 0.5 to 1.5 feet; can potentially be increased if plant selection and soil infiltration rates are suitable.
Engineered soil medium thickness	The thickness of the engineered soil medium layer.	Typically, 1 to 4 feet
Stone storage layer thickness	The thickness of the optional stone storage layer if provided.	Typically, 0 to 2 feet
Available pore storage capacity	The effective void space of engineered soil media or stone reservoirs that is available for water storage.	Typically, 0.2 to 0.35
Total storage depth	The effective depth of water stored within the bioretention cell. It is a function of ponding depth, sump storage, bioretention medium thickness and porosity, and the thickness and porosity of the optional stone storage layer.	Typically, 0.75 to 4 feet
Design media filtration rate	The rate at which water is assumed to enter and move through the engineered filter media.	Typically, greater than 2 in./hr and less than 12 in./hr
Design soil infiltration rate	The rate at which water is assumed to infiltrate into the subsurface soils for the purpose of design and benefits evaluation. This should be the rate of infiltration below the amended soil layer or stone reservoir.	Any; partial infiltration (upturned elbow design) can potentially be used as low as approximately 0.01 in./hr
Underdrain discharge stage	The stage at which water begins to discharge from the underdrains (typically controlled via upturned elbow).	Typically, 0.5 to 2 feet above the bottom of the storage reservoir if internal water storage is provided
Sump storage	The effective depth of water stored within the sump layer below the outlet elevation of the underdrain (typically controlled via upturned elbow).	Typically, 0.2 to 0.8 feet, accounting for porosity of stone below underdrain discharge stage

Example Conceptual Design Schematic

Figures 1, 2, and 3 show cross-section view, an example design of outlet control structure, and plan view, respectively.

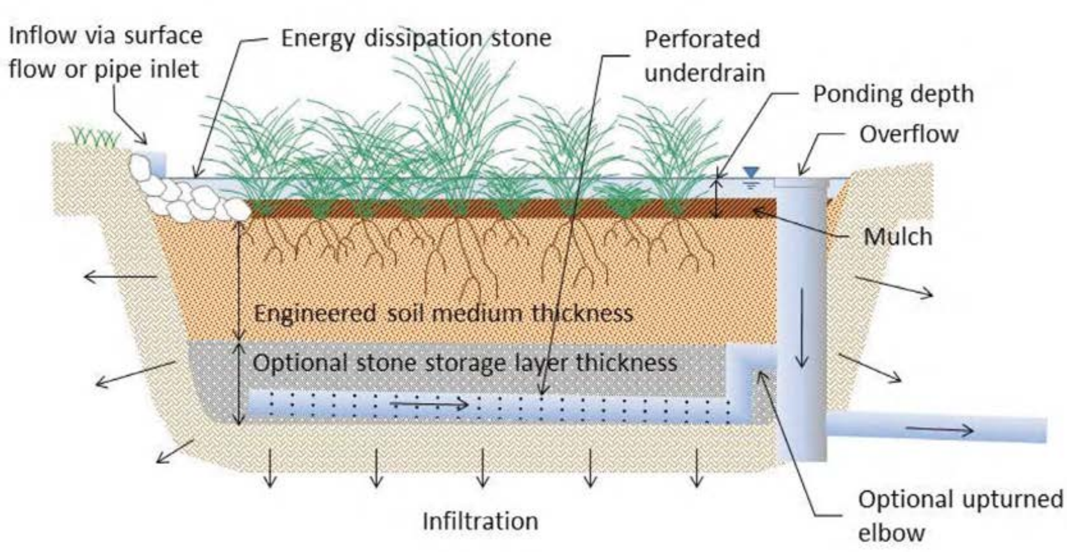
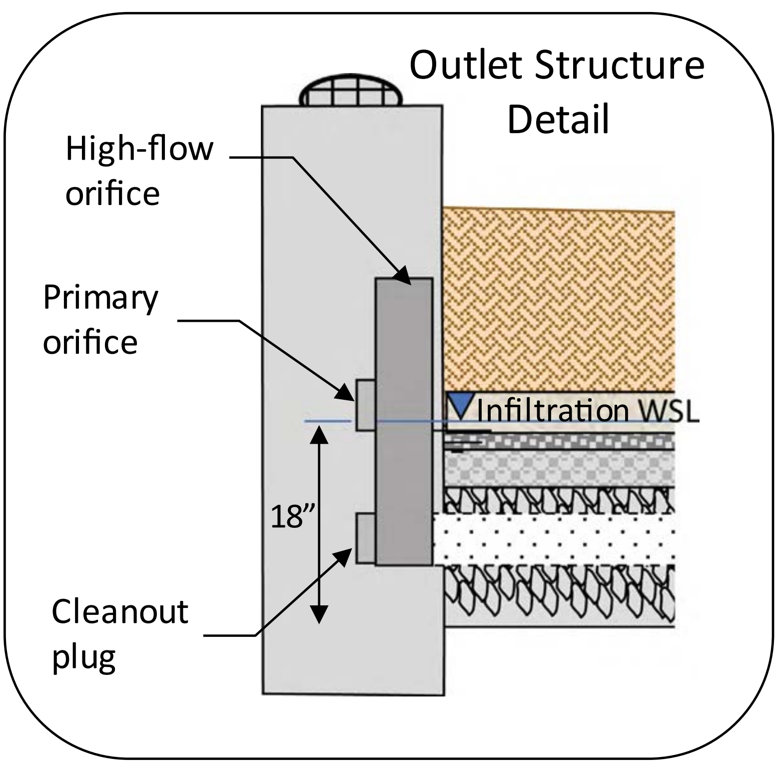


Figure 1. Cross-section view—upturned elbow.



WSL: water surface level.
Figure 2. Example design of outlet control structure.

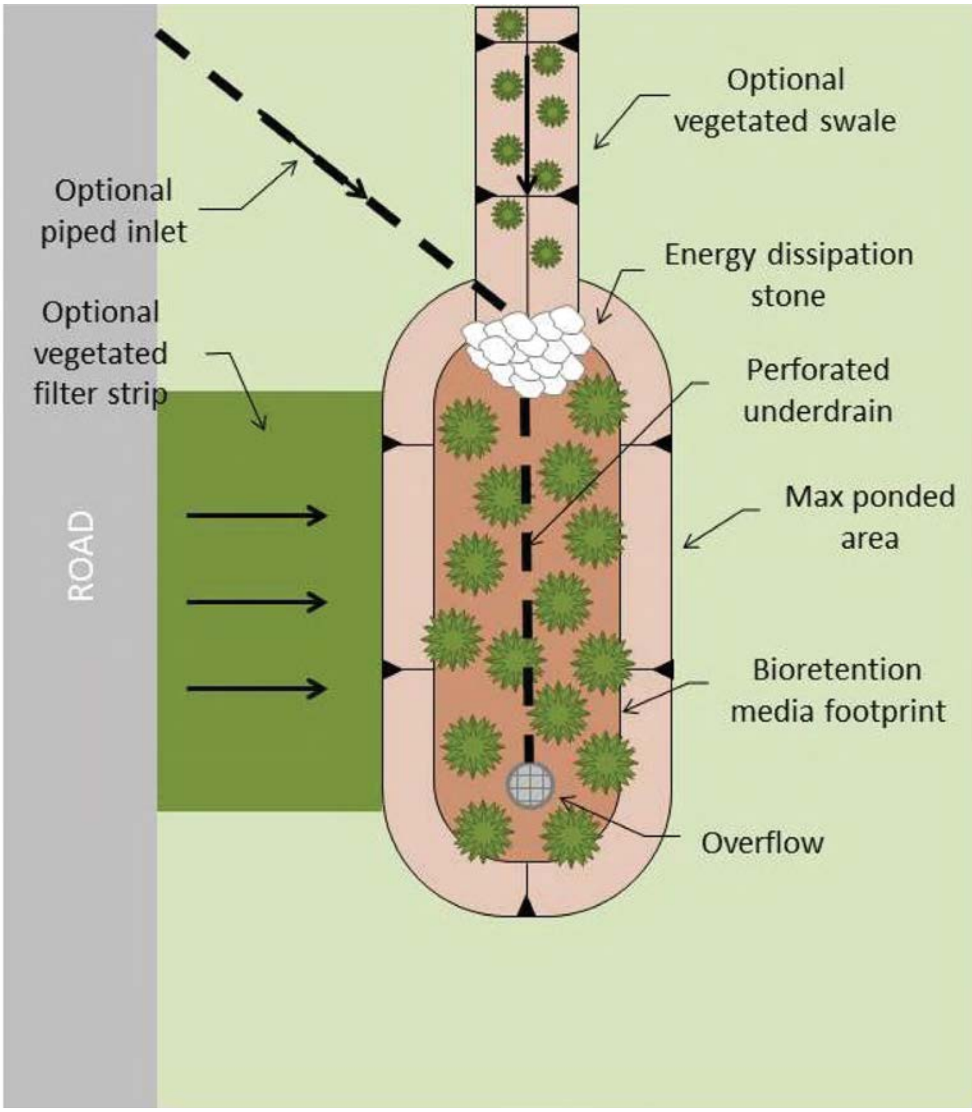


Figure 3. Plan view.

Example Inspection and Maintenance Activities

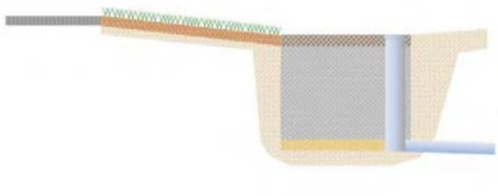
Activity	Frequency
GENERAL INSPECTIONS	
Accumulation of trash and debris	Annually or semi-annually depending on loading
Eroded facility areas	
Sediment accumulation	
Extended standing water	
Vector or rodent issues	
Identify any needed corrective maintenance that will require site-specific planning or design	
ROUTINE MAINTENANCE	
General	
Remove trash and debris	Annually or semi-annually depending on loading
Repair eroded facility areas	
Remove minor sediment in forebay	
Vegetation	
In arid climates, irrigate as recommended by a landscape professional, typically for the first 3 years to establish vegetation	As needed
Remove undesirable vegetation	Annually
Reseed or replant areas of thin or missing vegetation	Annually
Mulch	
Remove and replace mulch in areas where significant sediment (>1 inch) has accumulated	Annually
Add an additional 1 to 2 inches of mulch; replace any mulch that is removed	As needed
Media Layer	
Rake to scarify media to promote infiltration while removing and replacing mulch	When replacing mulch
Replace media in areas that experience scour	When fixing erosion
Inflow, Underdrain and Outflow Structures	
Check energy dissipation function and add riprap	As needed
Remove accumulated sediment from inlets and outlets	As needed
Flush underdrain	As needed (less often)
CORRECTIVE (MAJOR) MAINTENANCE	
Replace top 3 to 6 inches of media layer and replace vegetation	Estimated every 10 years (highly site specific)
Replace full depth of media and replace vegetation	Estimated every 30 years (highly site specific)
Replace aggregate drainage layer	As needed if silted in

Activity	Frequency
Repair structural damage to inlets, outlets, and underdrain and/or replace these elements	As needed if at end of usable life
Prepare documentation of issues and resolutions for review by appropriate parties; modify O&M Plan if needed.	Before major maintenance
Document major maintenance activities; record modified O&M Plan and as-built plan set if needed	After major maintenance
Take photographs before and after from the same vantage point	Before and after

Infiltration Trench

BMP 07

Alternative names: *exfiltration trench*



(Source: Maryland SHA.)

VOLUME REDUCTION PROCESSES	
●	Overall Volume Reduction Potential
●	Infiltration
○	Evapotranspiration
○	Consumptive Use
○	Baseflow-mimicking Discharge

URBAN HIGHWAY APPLICABILITY	
●	Ground level highways
●	Ground level highways with restricted cross-sections
○	Ground level highways on steep transverse slopes
○	Steep longitudinal slopes
⦿	Depressed highways
○	Elevated highways on embankments
○	Elevated highways on viaducts
●	Linear interchanges
●	Looped interchanges

● High ⦿ Moderate ○ Low

Description

This category of BMP consists of a stone-filled trench that provides subsurface storage of stormwater runoff and allows water to infiltrate through the bottom and walls of the trench into subsoils. Pretreatment for infiltration trenches is commonly provided via vegetated conveyance, such as swales or filter strips. Infiltration trenches tend to be well suited to the linear highway environment because they are generally constructed in a linear configuration and their surface tends to be nearly flush to existing grade. They tend to be located away from the travel lanes and shoulders but may be within the “clear zone” dedicated for errant vehicles to recover.

Volume Reduction Processes and Performance Factors

Volume reduction in infiltration trenches is achieved through infiltration into the surrounding subsoil. Efficient performance is dependent on storage capacity and adequate subsoil infiltration rates to ensure that enough captured runoff exits the trench between storm events.

A variation to infiltration trenches includes underdrains that can provide additional volume reduction performance and operational flexibility in the form of baseflow-mimicking discharge.

General DOT Experience

Infiltration trenches have been widely used across the United States. When properly designed and infiltration rates are maintained, volume reductions are high on average. The most common problem incurred with infiltration trenches is clogging.

A BMP retrofit pilot program final report by Caltrans (2004) notes that for events smaller than the water quality (WQ) design storm, volume reduction for infiltration trenches was 100%. When designs incorporate less pretreatment and involve soils with lower infiltration rates, the Virginia Department of Conservation and Recreation (2013) notes that volume reduction estimates should be reduced to 50%.

Proper design and maintenance of infiltration trenches is critical to their performance. Maryland Department of the Environment found in an early study that 53% of the infiltration trenches they inspected were not operating as designed (Lindsey et al. 1991). This high failure rate has been attributed to clogging, resulting from lack of pretreatment, inadequate maintenance, and insufficient subsoil infiltration rates.

Applicability and Limitations

Site and Watershed Considerations

- Use of infiltration trenches requires soils with infiltration rates high enough to ensure proper drainage between storm events. Without significant amendments, this is critical to infiltration trenches being considered feasible.
- Proper exfiltration of captured stormwater from infiltration trenches requires that the groundwater table be at least several feet below the bottom of the trench.
- Native soils must have sufficiently high hydraulic conductivity to permit complete infiltration within the design drawdown period. Additionally, infiltration trenches are not suitable in karst formations because they have the potential to create sinkholes or to intersect low-resistance pathways to groundwater.
- Steep longitudinal and/or transverse slopes can have geotechnical issues that make it harder to provide a level pool for water storage.

Geotechnical Considerations

- Infiltration trenches must be located a sufficient distance from the roadway such that infiltration will not compromise its structural integrity. Use of infiltration trenches along steep transverse slopes may require enhanced protection of slope integrity.

Groundwater Quality and Water Balance Considerations

- There must be sufficient separation from the seasonally high groundwater table and water supply wells to reduce the potential for contamination. Typical separation discharges are 2 to 10 feet above groundwater and 100 to 150 feet from wells.
- In areas with very high soil infiltration rates or shallow groundwater tables, captured stormwater may not be sufficiently treated prior to contact with groundwater. In these situations, designs may need to be pretreated or be adjusted to enhance treatment and prevent groundwater contamination.

- Use of infiltration trenches to provide more infiltration than historically present or characteristic of similar sites in the region may alter a site's water balance in undesirable ways.

Safety Considerations

- Infiltration trenches should not present a significant hazard to errant vehicles. If a filter strip is used for pretreatment, the cross-slope should be less than 4H:1V. Observation wells and overflows should not protrude more than a few inches above the trench surface.
- If a piped inlet is used, the pipe openings should be cut flush with the transverse slope in order to reduce the potential that the pipe will be struck head-on by an errant vehicle. Pipes with diameters greater than 24 inches should be covered with traversable grates.

Regional Applicability

- Infiltration trenches have been applied successfully across a broad range of climates.
- In cold climates, infiltration trenches may need to be oversized to accommodate snowmelt events, and conveyance modifications are required to protect against freezing.
- Winter sanding of roads can clog an infiltration trench without adequate pretreatment, and winter salting will increase the potential for chloride contamination of groundwater. By keeping the trench surface free of compacted snow and ice, and by ensuring that part of the trench is constructed below the frost line, the performance of the infiltration trench during cold weather will be greatly improved.

Urban Highway Opportunities

- Infiltration trenches can be readily applied to shoulders with low slopes and medians.
- The linear nature of infiltration trenches makes them useful in the tight spaces common to urban highways. Pretreatment can be included with vegetated conveyance or the use of an in-line sedimentation forebay. Impermeable liners can be used to protect the integrity of the road base.

New Projects, Lane Additions, and Retrofits

- Infiltration trenches may have small incremental costs in new projects, because grading and fill can be balanced and landscaping would otherwise be installed; incremental costs may be greater in lane additions and retrofits.
- Retrofitting existing roadways to include infiltration trenches can be an effective method for reducing runoff volumes and impermeable surface area. Incremental costs may be higher in retrofit situations because there may likely be a need for excavation and fill operations.
- Retrofitting an existing infiltration system with underdrains will involve significant excavation, piping, controls, and possible amendments to media and/or stone. Including underdrains as a backup option in new construction is recommended.

Use in a Treatment Train

- Pretreatment of runoff to reduce particulate matter and suspended solids is recommended to prevent clogging.
- Pretreatment can be provided as vegetated conveyance or a sedimentation forebay. Additional BMPs could also be located prior to infiltration trenches, provided sufficient routing is incorporated.
- Stormwater runoff in excess of the infiltration trench's storage capacity can be conveyed to additional BMPs by the use of overflow controls such as weirs.

Enhancements and Variations

Increase storage capacity. Storage capacity can be enhanced by increasing the depth of the stone reservoir provided that sufficient depth to and distance between groundwater is maintained. Storage capacity can also be increased with the selection of stone materials that have higher effective porosity.

***Provide robust pretreatment to extend the life of the system*.** Clogging is the principal cause of infiltration trench failure and resulting maintenance requirements. Pretreatment to remove sediments and particulate matter prior to entering the infiltration trench can significantly improve system performance and reduce the potential for clogging. Pretreatment practices such as grit chambers, swales with check dams, filter strips, or sediment forebays/traps should be a fundamental component of the BMP.

Provide backup outlet where feasible. Including an underdrain (normally closed) can provide a low-cost backup in the event that the infiltration rate declines with time. If infiltration rates decline, the outlet can be opened, and flow can be controlled to achieve a combination of volume reduction and flow control until the system infiltration rate can be restored.

***Reduce compaction during construction*.** The highest infiltration rates will be achieved if care is taken to avoid compaction of the bottom of the trench during construction. Laying a 6-inch layer of sand on the bottom of the trench will help to avoid compaction as the trench is filled with stone. Trenches should be constructed at the end of the development construction to avoid inputs of sediment.

Resilient Design Features

Include a coarse sand filtration layer near the surface that can be more easily replaced in the event of clogging, can reduce migration of sediment into the underlying storage area, and can provide treatment.

Provide a high level of pretreatment.

Carefully design upstream BMPs to avoid scour. If pretreatment BMPs, such as filter strips or swales, experience erosion, then this can clog infiltration trenches.

If a high level of adaptability is desired, then install piping such that the system could later be converted to a bioretention facility with underdrains if needed. The 2 to 3 feet of trench could be replaced with media and a ponding area, and the remaining trench could serve as the infiltration sump and underdrain system.

Additional References

California Stormwater Quality Association. California Stormwater BMP Handbook: New Development and Redevelopment. TC-10, Infiltration Trench. 2003. Available online at https://www.casqa.org/sites/default/files/BMPHandbooks/TC-10.pdf.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 8: Infiltration Practices v.1.9. 2013. Fact sheet on infiltration practices including design guidance, construction and feasibility. http://chesapeakestormwater.net/category/publications/design-specifications/.

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Washington State Department of Transportation, Highway Runoff Manual. 2014. Chapter 5 includes fact sheets for stormwater BMPs. Available online at http://www.wsdot.wa.gov/Environment/WaterQuality/Runoff/HighwayRunoffManual.htm.

Key Planning Level Design Parameters for Volume Reduction

Conceptual Design Parameter	***Description***	***Representative Range***
Footprint area	The area covered by the surface of the infiltration trench.	Typically, 100 to 2,000 sq ft; can be any size with appropriate flow distribution
Stone storage layer thickness	The thickness of the stone storage layer.	Typically, 2 to 10 feet
Porosity	The effective void space of the stone storage layer.	Typically, 0.3 to 0.4
Effective storage depth	The effective depth of water stored within the infiltration trench. It is a function of the depth and porosity of the stone storage layer.	Typically, 0.5 to 4 feet
Side wall to bottom area ratio	The ratio of system surface area in the side walls versus the bottom area.	Depends on geometry, for narrow deep systems, side wall area may equal more than 5 times the bottom area
Design infiltration rates	The rate at which water is assumed to infiltrate into the subsurface soils for the purpose of design and benefits evaluation. This should be the rate of infiltration below the stone reservoir layer.	Typically require at least 1 to 3 in./hr for sufficient drawdown of storage

Example Conceptual Design Schematic

Figures 1 and 2 show the cross-section and plan views, respectively.

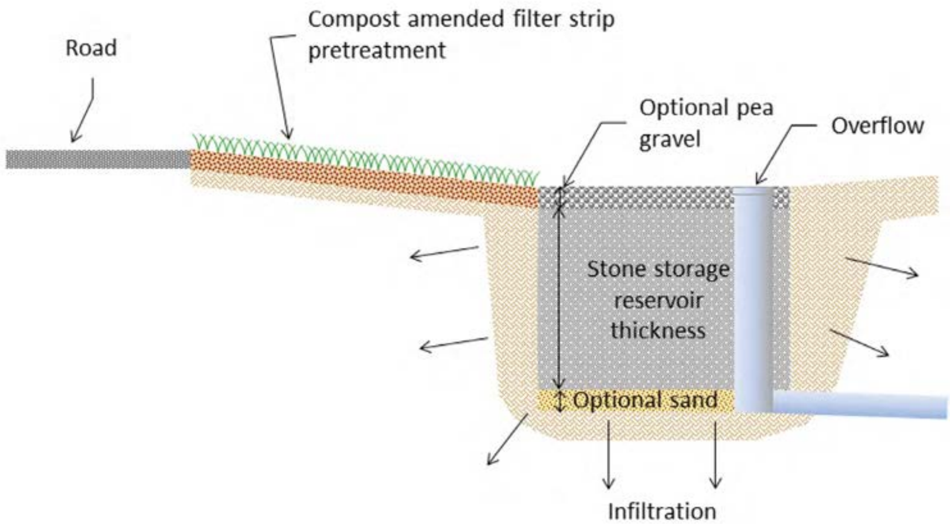


Figure 1. Cross-section view.

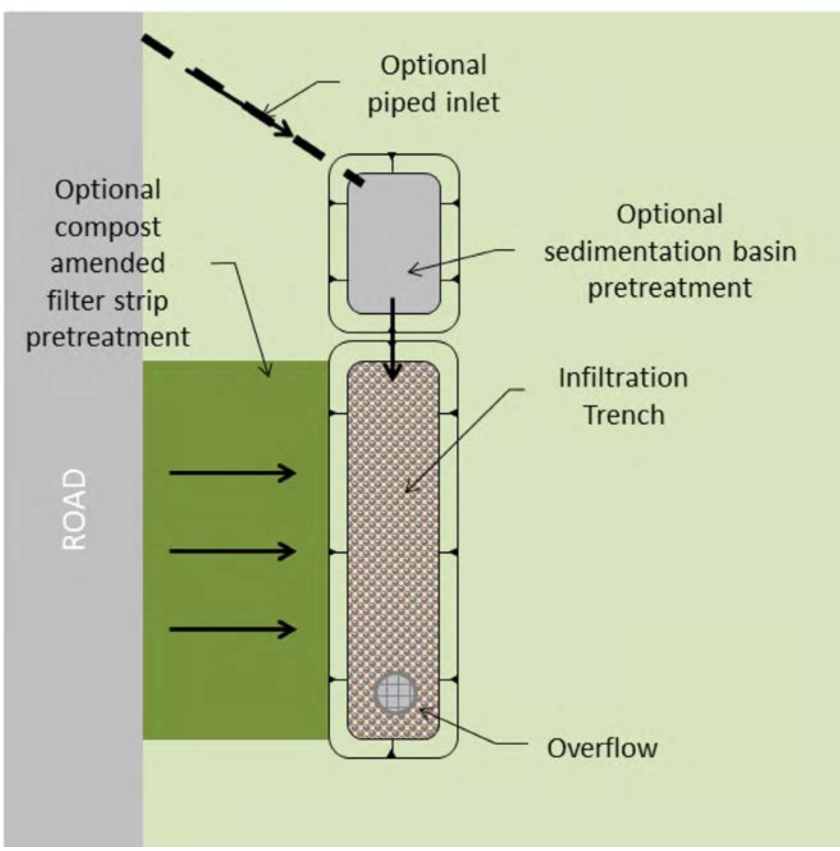


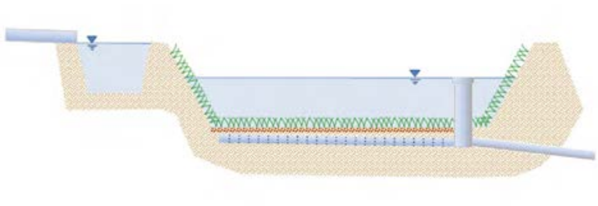
Figure 2. Plan view.

Example Inspection and Maintenance Activities

Activity	Frequency
GENERAL INSPECTIONS	
Identify eroded facility areas in facility or upstream	Annually
Observe and record drawdown rate via the observation port	
Estimate degree of sediment accumulation in the surface pea gravel or sand layer, thickness of surface layer or depth of penetration	
Identify any needed corrective maintenance that will require site-specific planning or design	
ROUTINE MAINTENANCE	
Pea Gravel/Sand Filter Layer	
Remove sediment via scraping of the top layers of this layer and replace with clean washed pea gravel or sand	Annually or when sediment has accumulated to a depth of more than 2 inches within the surface layer
Replace full depth of pea gravel	When fully comingled with sediment
Upstream Sediment Control	
Repair any eroded areas that are contributing elevated sediment to the BMP	As needed
Maintain pretreatment systems	As needed
CORRECTIVE (MAJOR) MAINTENANCE	
Excavate the entire facility, rehabilitate bottom and sides via over-excavation, and replace aggregate layers. Aggregate layers can be reused if they are washed before replacement.	When infiltration rate drops below acceptable infiltration rate
Repair structural damage to inlets and outlets	As needed
Prepare documentation of issues and resolutions for review by appropriate parties; modify O&M Plan if needed	Before major maintenance
Document major maintenance activities; record modified O&M Plan and as-built plan set if needed	After major maintenance
Take photographs before and after from the same vantage point	Before and after

Infiltration Basin BMP 08

***Alternative names:** percolation basins, recharge basins*



VOLUME REDUCTION PROCESSES	
●	Overall Volume Reduction Potential
●	Infiltration
◉	Evapotranspiration
○	Consumptive Use
○	Baseflow-mimicking Discharge

(Photo credit: Google Earth.)

URBAN HIGHWAY APPLICABILITY	
◉	Ground level highways
○	Ground level highways with restricted cross-sections
○	Ground level highways on steep transverse slopes
○	Steep longitudinal slopes
○	Depressed highways
○	Elevated highways on embankments
○	Elevated highways on viaducts
◉	Linear interchanges
●	Looped interchanges

● High ◉ Moderate ○ Low

Description

Infiltration basins are relatively large, shallow basins that have relatively little vegetation. Their contours appear similar to detention basins, but they do not have a surface discharge point below their overflow elevation. Infiltration basins are typically located in relatively permeable soils. While all infiltration systems may cause geotechnical hazards if inappropriately sited, infiltration basins may pose a higher risk, because they tend to capture runoff from a larger area than most BMPs and concentrate infiltrated volume in a localized area. Infiltration basins can be designed with detention surcharge above the infiltration volume to provide a combination of volume reduction and peak flow mitigation.

Infiltration basins are different from bioretention basins, in that they typically do not include an engineered soil medium, and vegetation is either absent or consists of a simple grass ground cover. They are also typically constructed at a larger scale, although it may be possible for bioretention to be constructed at similar scales in some cases.

Volume Reduction Processes and Performance Factors

Volume reduction in infiltration basins is achieved through a combination of infiltration and ET. Efficient performance is dependent on adequate subsoil infiltration rates to ensure that captured runoff exits the basin between storm events. Pretreatment to prevent clogging is important for the longevity of infiltration basins and can be provided via vegetated conveyance or a sedimentation forebay. Additional mechanical pretreatment measures exist, including cartridge filtration or centrifugal separation if hydraulic and grade constraints allow.

General DOT Experience

Infiltration basins have been widely used across the United States. When properly designed and infiltration rates are maintained, volume reductions are high on average. The most common problem incurred with infiltration basins is clogging.

A BMP retrofit pilot program final report by Caltrans (2004) notes that if properly designed, volume reduction should be 100% due to complete infiltration. In one of the two basins monitored by Caltrans, one was observed not to be draining within the design maximum of 72 hours most likely because of poor soil characteristics.

Applicability and Limitations

Site and Watershed Considerations

- Use of infiltration basins requires soils with infiltration rates high enough to ensure proper drainage between storm events.
- Proper infiltration of captured stormwater from infiltration basins requires that the groundwater table be at least several feet below the bottom of the basin.
- Native soils must have sufficiently high hydraulic conductivity to permit complete infiltration within the design drawdown period. Additionally, infiltration basins are not suitable in karst formations, because they have the potential to create sinkholes or to intersect low-resistance pathways to groundwater.
- These BMPs require significant space and the ability to form a level pool. This makes them unsuitable for constrained ROWs and steep transverse or longitudinal slopes.

Geotechnical Considerations

- Infiltration basins must be located a sufficient distance from a roadway to maintain the roadway structural integrity.
- Use of infiltration basins along steep transverse slopes should be minimized and will likely require enhanced protection of slope integrity.

Groundwater Quality and Water Balance Considerations

- There must be sufficient separation from the seasonally high groundwater table and water supply wells to reduce the potential for contamination. Typical separation discharges are 2 to 10 feet above groundwater and 100 to 150 feet from wells; however, groundwater mounding risk can be high for infiltration basins, because they may require greater separation to groundwater.
- In areas with very high soil infiltration rates or shallow groundwater tables, captured stormwater may not be sufficiently treated prior to contact with groundwater. In these situations, designs may need to be adjusted to enhance treatment and prevent groundwater contamination.

- Use of infiltration basins to provide more infiltration than historically present or characteristic of similar sites in the region may alter a site's water balance in undesirable ways.

Safety Considerations

- Because infiltration basins involve fixed obstacles and side slopes that may exceed 3H:1V, they should ideally be located outside of the clear zone (typically in the range of 22 to 32 feet from driving lanes). If this distance cannot be achieved, a barrier parallel to the direction of traffic should be used between the road and the BMP.

Regional Applicability

- Infiltration basins have been applied successfully across a broad range of climates.

Urban Highway Opportunities

- Infiltration basins have relatively straightforward applications to shoulders with low slopes and medians where sufficient space is available.
- Because infiltration basins generally capture runoff from larger areas than other BMPs, they may be difficult to apply to urban highway settings with limited space or constrained ROWs.

New Projects, Lane Additions, and Retrofits

- Because of their large footprint and setback requirements, infiltration basins are more easily incorporated into new construction projects in the highway setting.
- Where available space exists however, retrofit opportunities are possible and can provide significant volume reduction.
- Retrofitting an existing infiltration system with underdrains will involve significant excavation, piping, controls and possible amendments to medium and/or stone. Including underdrains in new construction is recommended.

Use in a Treatment Train

- Pretreatment to reduce particulate matter and suspended solids will increase the life of the infiltration basin and system efficiency and reduce required maintenance.
- Pretreatment can be provided to stormwater through vegetated conveyance to the system by the use of a sedimentation forebay and/or mechanical devices such as cartridge filtration.
- Stormwater runoff in excess of the infiltration basin's storage capacity can be conveyed to additional BMPs by use of overflow weirs.

Enhancements and Variations

Provide robust pretreatment to improve efficiency and extend the life of the system. Clogging is the principal cause of infiltration basin failure and maintenance requirements. Pretreatment to remove sediments and particulate matter prior to entering the infiltration basin can significantly improve system performance and reduce the potential for clogging of the media and subsoils.

Amend soil and plant with deep rooted vegetation. Deep rooted plants can help maintain infiltration pathways, soil aeration, and healthy soil processes. Soil amendments can also better capture pollutants in infiltrating water.

Provide backup flow control outlet. Including an underdrain (normally closed) can provide a low-cost backup in the event that the infiltration rate declines with time. If infiltration rates decline, the outlet can be opened and flow can be controlled to achieve a combination of volume reduction and flow control until the system infiltration rate can be restored.

Distribute inflow. Spreading the flow into infiltration basins can reduce the potential for scour and heavy sediment accumulation in certain areas.

Resilient Design Features

Consider including a sacrificial layer of coarse sand or media on the surface that can be more easily replaced in the event of clogging and can provide treatment.

Resiliency can be improved by incorporating elements of bioretention design such as a media filtration layer and underdrain. The underdrain should remain plugged during normal operations and may be opened if infiltration rates decline and adaptation to a filtration-based design is needed.

Vegetation establishment on the basin floor may help reduce the clogging rate.

Infiltration basins should always be preceded by a pretreatment facility. Sediment can be more easily removed from a forebay or pretreatment system than from the infiltration basin itself.

Additional References

California Stormwater Quality Association. California Stormwater BMP Handbook: New Development and Redevelopment. TC-11, Infiltration Basin. 2003. Available online at https://www.casqa.org/sites/default/files/BMPHandbooks/TC-11.pdf.

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Massachusetts Stormwater Handbook. Detailed BMP Fact Sheets, with figures, design considerations, construction and maintenance guidance. http://www.mass.gov/eea/docs/dep/water/laws/i-thru-z/v2c2.pdf.

Washington State Department of Transportation, Highway Runoff Manual. 2014. Chapter 5 includes fact sheets for stormwater BMPs. Available online at

http://www.wsdot.wa.gov/Environment/WaterQuality/Runoff/HighwayRunoffManual.htm.

Key Planning Level Design Parameters for Volume Reduction

Conceptual Design Parameter	***Description***	***Representative Range***
Footprint area	The area covered by the surface of the infiltration basin.	Can be up to 0.5 acre or greater; commonly less in urban highway environment
Effective footprint area	The effective area of the infiltration basin for storage and drawdown estimates; typically assumed to be measured as the water surface area at mid-ponding depth.	Typically, somewhat smaller than the total footprint area
Ponding depth	The distance between the floor of the basin and the overflow elevation.	Typically, 2 to 4 feet; may be higher if infiltration rates allow
Design infiltration rates	The rate at which water is assumed to infiltrate into the subsurface soils for the purpose of design and benefits evaluation.	Typically, 3 in./hr or greater is needed to provide reliable performance and reduce magnitude of mounding
Initial permeability of sacrificial surface layer	The initial permeability of the sacrificial layer of coarse sand or media in the bottom of an infiltration facility.	Approximately 10x higher than underlying media to improve lifespan before clogging occurs

I-5 Exit 102, Tumwater, Washington. (Source: Google Earth.)

Example Conceptual Design Schematic

Figures 1 and 2 show cross-section and plan views, respectively.

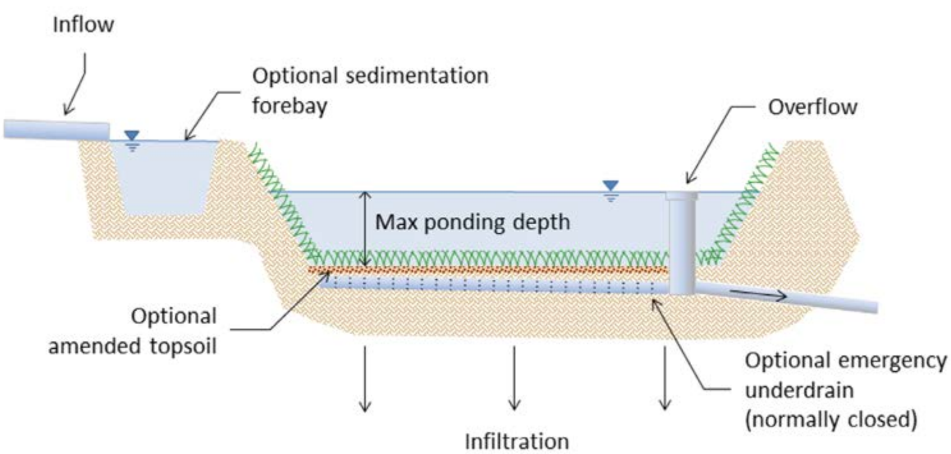


Figure 1. Cross-section view.

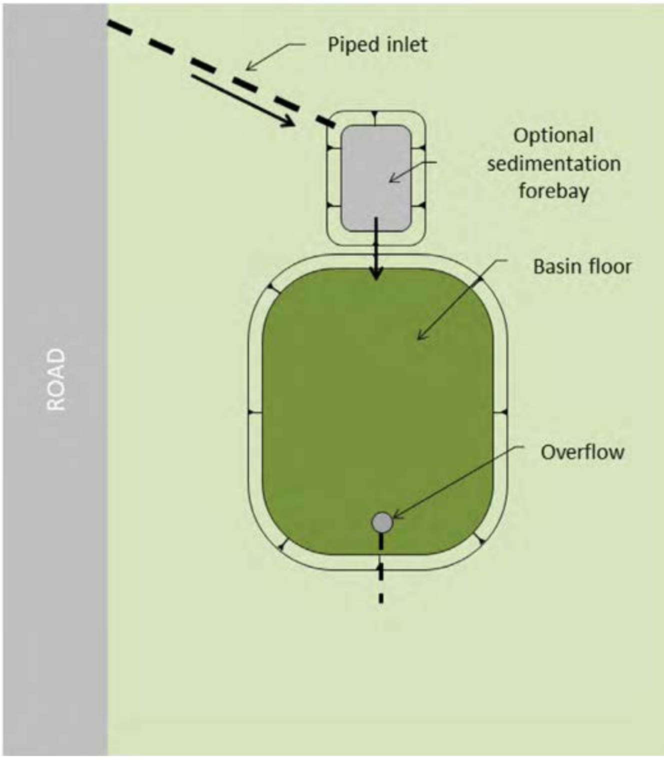


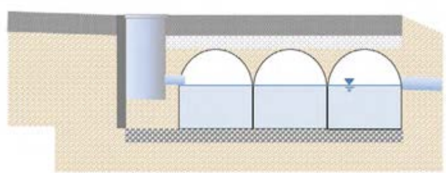
Figure 2. Plan view.

Example Inspection and Maintenance Activities

Activity	Frequency
GENERAL INSPECTIONS	
Identify eroded facility areas	Annually
Observe and record drawdown rate	
Estimate degree of sediment accumulation	
Depth of sediment migration into sacrificial sand/media layer (if present)	
Identify areas of compromised plant health or density	
Identify any needed corrective maintenance	
ROUTINE MAINTENANCE	
Sediment, Trash, and Debris	
Remove trash from facility	Each visit as needed
Remove sediment from forebay if greater than 25% of the forebay volume	As needed
Remove sediment from pretreatment system per manufacturer's recommendations	Per manufacturer recommendation
Vegetation (if basin is vegetated)	
In arid climates, irrigate as recommended by a landscape professional, typically for the first 3 years to establish vegetation	As needed
Remove undesirable vegetation	Annually
Replant or reseed areas of thin or missing vegetation	Annually
Scrape soil from top 3 to 6 inches of infiltration bed and reestablished vegetation if present	As needed
Sacrificial Sand or Media Layer	
Scrape and replenish when clogged or when sediment has migrated more than halfway through the sacrificial layer	As needed
Inflow and Outflow Structures	
Check energy dissipation function and add riprap	Annually
Inspect inlets and outlets and remove accumulated sediment	Annually
Repair structural damage to inlets and outlets	As needed
CORRECTIVE (MAJOR) MAINTENANCE	
Overexcavate to 1 to 2 feet and replace with permeable fill material to restore infiltration rates	As needed
Prepare documentation of issues and resolutions for review by appropriate parties; modify O&M Plan if needed	Before major maintenance
Document major maintenance activities; record modified O&M Plan and as-built plan set if needed	After major maintenance
Take photographs before and after from the same vantage point	Before and after

Infiltration Gallery BMP 09

Alternative names: *underground infiltration systems, infiltration vaults*



(Photo credit: WSDOT.)

VOLUME REDUCTION PROCESSES	
●	Overall Volume Reduction Potential
●	Infiltration
○	Evapotranspiration
○	Consumptive Use
○	Baseflow-mimicking Discharge

URBAN HIGHWAY APPLICABILITY	
●	Ground level highways
⦿	Ground level highways with restricted cross-sections
○	Ground level highways on steep transverse slopes
○	Steep longitudinal slopes
⦿	Depressed highways
○	Elevated highways on embankments
○	Elevated highways on viaducts
●	Linear interchanges
●	Looped interchanges

● High ⦿ Moderate ○ Low

Description

Infiltration galleries include a broad class of BMPs that consist of storage reservoirs located belowground preceded by pretreatment systems. Water is pretreated, routed into the systems, and infiltrates into subsoil. A range of potential options are available for providing storage, including use of open graded stone or a variety of engineered storage chambers (concrete, plastic, or metal). There are also a range of potential locations where infiltration galleries can be placed, including below parking areas, below access roads, below travel lanes, or a range of other locations.

Volume Reduction Processes and Performance Factors

Volume reduction is achieved solely through infiltration. The degree of volume reduction achievable is a function of the subsoil infiltration rates and effective depth of the storage reservoir. Because of the potential for decline in performance as a result of clogging of sub-surface systems, the long-term volume reduction is also a function of the level of pretreatment provided.

General DOT Experience

While case studies on the effectiveness of infiltration galleries in the highway environment are currently limited, their use in some states, such as Minnesota, is increasing. Monitoring studies for several infiltration galleries around the City of St. Paul, Minnesota, found that runoff volumes were reduced by 60% to 100% and more often above 90% (including snowmelt) (Alms and Carlson 2012). An important note is that depending on design, there is a possibility that these facilities meet the EPA definition for class V injection wells (https://www.epa.gov/uic/class-v-wells-injection-non-hazardous-fluids-or-above-underground-sources-drinking-water). It should also be noted that without adequate pretreatment, injection galleries have the potential for groundwater contamination (Pitt et. al. 1994). If properly designed, infiltration galleries have the ability to reduce runoff volumes by 98%.

Applicability and Limitations

Site and Watershed Considerations

- Infiltration galleries are suitable for sites with sufficiently permeable subsoils and where significant amounts of infiltration will not result in water balance or geotechnical issues.
- Subbase must be level for proper functioning and stability while still maintaining permeability. On sloped sites, they can be constructed as a series of level benches.
- Infiltration galleries can be used on road shoulders and medians and under roadways. They can be favorable in constrained areas where there is insufficient space for vegetated BMPs.
- Native soils must have sufficiently large hydraulic conductivity to permit complete infiltration within the design drawdown period. Additionally, underground infiltration is not suitable in karst formations because they have the potential to create sinkholes or to intersect low-resistance pathways to groundwater.
- Steep longitudinal or transverse slopes can have geotechnical issues associated with full infiltration BMPs. Additionally, steep longitudinal slopes can make it challenging to provide a level-bottomed pool.
- Designers should consider space requirements for pretreatment facilities and maintenance access.

Geotechnical Considerations

- Where underground infiltration is used in areas that support traffic (e.g., breakdown lanes, travel lanes, parking lots, etc.), the system and its associated subgrade preparation must be designed with adequate load bearing capacity and must not have negative impacts on adjacent pavement structures.
- Impermeable vertical barriers can be used between the underground infiltration installation and the roadway to avoid compromising road integrity from excess infiltration, but drainage systems should allow the adjacent subbase to drain freely.
- Use of underground infiltration along steep transverse slopes may require enhanced protection of slope integrity.

Groundwater Quality and Water Balance Considerations

- There must be sufficient separation from the seasonally high groundwater table and water supply wells to reduce the potential for contamination. Typical separation discharges are 2 to 10 feet above groundwater and 100 to 150 feet from wells.
- In general, infiltration galleries represent a higher risk of groundwater contamination than other BMPs, and pretreatment should be provided unless underlying soils are determined to provide adequate pollutant attenuation capacity.
- In areas with very high soil infiltration rates or shallow groundwater tables, captured stormwater may not be sufficiently treated prior to contact with groundwater. In these situations, designs may need additional pretreatment.
- Use of infiltration galleries allows negligible ET, therefore the use of these systems has the potential to alter the water balance of a site compared with natural conditions (e.g., more infiltration).

Safety Considerations

- Infiltration galleries are installed beneath standard paved shoulders and should not pose any additional hazards to drivers. Inlet grates should be flush with the road surface and fully traversable.

Regional Applicability

- Infiltration galleries can be used across a wide range of climates.
- Infiltration galleries will generally continue to function under normal freezing conditions.

New Projects, Lane Additions, and Retrofits

- Because infiltration galleries are generally large and require significant grading, excavation, geotechnical and structural requirements, they are more easily incorporated into new construction.
- Retrofit projects will likely incur significant costs because they would contain many of the elements of new construction and additional removal of existing constraints.
- In both new and retrofit situations, designs of infiltration galleries should carefully consider the EPA classification of underground injection wells to avoid additional permit requirements.

Use in a Treatment Train

- Pretreatment is strongly recommended to improve long-term system efficiency and reduce the potential for failure and the need for maintenance related to clogging. Pretreatment also reduces the potential for groundwater contamination.
- Stormwater runoff in excess of the infiltration system's storage capacity can be conveyed to additional BMPs if sufficient hydraulic grade lines exist or if pumps are included.

Enhancements and Variations

Advanced pretreatment to extend life and protect groundwater quality. Clogging is the principal cause of infiltration gallery failure and resulting maintenance requirements. Infiltration galleries may also pose the highest level of risk of groundwater contamination among stormwater BMPs. Pretreatment to remove sediments and particulate matter prior to entering the infiltration basin can significantly improve system performance and reduce the potential for clogging. Advanced pretreatment methods such as cartridge media filters, bioretention with underdrains, or other advanced filtration systems should be considered. Pretreatment devices such as deep-sump catch basins, proprietary separators, and oil/grit separators are typical.

Storage geometry. Dry wells can be considered as a variation to this BMP. They are typically deeper than they are wide, such that these systems tend to be deeper than typical infiltration galleries and infiltrate primarily from their walls instead of from their bottom. Dry wells may be advantageous if permeable soil layers are located at a significant depth.

Storage materials. Reservoir chambers can be filled with rock, or they can be constructed of arch sections, plastic matrices, or perforated pipes.

Storage in Road Subbase. Storage in the pore space of an open-graded road subbase may be appropriate in the urban highway environment. It would essentially be a variation of permeable pavement, with flows routed to the subbase via a conveyance system rather than through a permeable wearing course. This could reduce the cost of the system compared with permeable pavement and may address concerns about durability and maintenance of the permeable wearing course. However, the ability to provide pretreatment and effective flow distribution may be challenges associated with this variation.

Resilient Design Features

If an acceptable treatment system is used upstream of the BMP for pretreatment, then any water not infiltrated in the infiltration gallery would be treated. This can make performance and compliance less sensitive to actual infiltration rate.

Advanced pretreatment can extend life and avoid clogging. Additionally, there is a need for adequate maintenance access to allow for rehabilitative maintenance.

It could be possible to design an underground infiltration vault such that it may be converted to a media filter in the future.

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Massachusetts Stormwater Handbook, Volume 2, Chapter 2. Stormwater Best Management Practices (MassDEP). Contains detailed BMP Fact Sheets, with figures, design considerations, construction and maintenance guidance. http://www.mass.gov/eea/docs/dep/water/laws/i-thru-z/v2c2.pdf.

Key Planning Level Design Parameters for Volume Reduction

Conceptual Design Parameter	***Description***	***Representative Range***
Footprint area	The area covered by the infiltration gallery.	Any
Effective storage depth	The effective depth of water stored within the infiltration gallery. It is a function of the depth and porosity of the storage layer and dimensions of the chambered reservoir.	Typically, 6 inches to more than 8 feet deep, as a function of system type and underlying infiltration rate
Design infiltration rates	The rate at which water is assumed to infiltrate into the subsurface soils for the purpose of design and benefits evaluation. This should be the rate of infiltration below the reservoir layer.	Most suitable where soils are 3 in./h or greater to accommodate ponding depths and avoid mounding issues
Filter course	A bed of sand or small stone placed at the bottom of the excavation to provide bedding, storage, and reduce the need for compaction of the subsoil during construction.	6 to 12 inches

Example Conceptual Design Schematic

Figures 1 and 2 show cross-section and plan views, respectively.

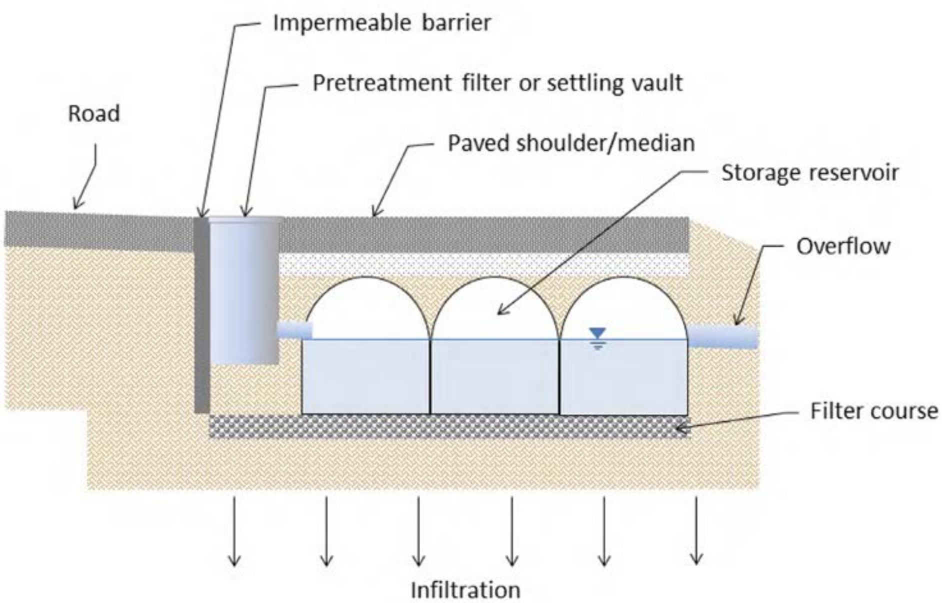

Figure 1. Cross-section view (example of arch gallery sited in breakdown lane).

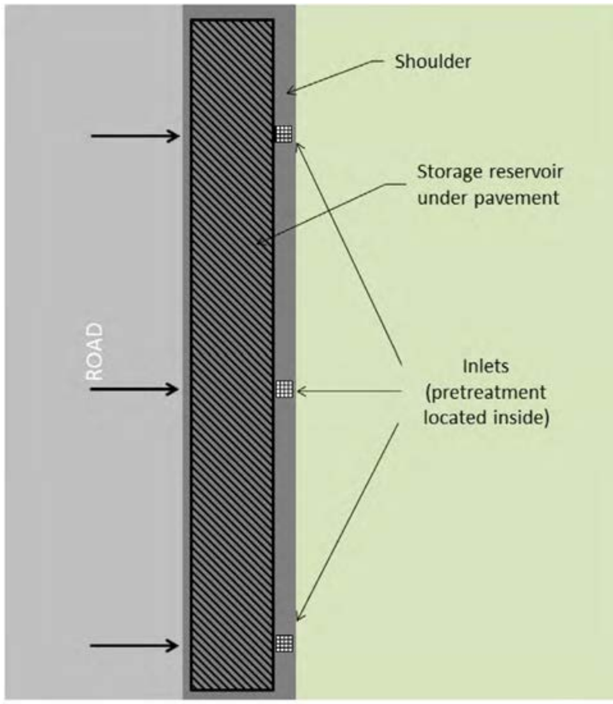

Figure 2. Plan view (example of siting in breakdown lane).

Example Inspection and Maintenance Activities

Activity	Frequency
GENERAL INSPECTIONS	
Inspect condition of pretreatment BMP to determine need for maintenance	Annually
Inspect degree of sediment accumulation chambers if possible	
Observe and record drawdown rate	
Identify any needed corrective maintenance that will require site-specific planning or design	
ROUTINE MAINTENANCE	
Pretreatment System	
Remove accumulated trash and debris	Each visit as needed
Remove sediment from pretreatment system per manufacturer's recommendations or when sediment storage volume is more than 50% full	Per manufacturer recommendation or as needed
Inflow and Outflow Structures	
Inspect inlets and outlets and remove accumulated sediment	Four times per year during wet season, including inspection just before the wet season
Repair structural damage to inlets and outlets	As needed

Activity	Frequency
CORRECTIVE (MAJOR) MAINTENANCE	
It is not typically practical to maintain the storage reservoir or infiltrating surface; plan for overall reconstruction when infiltration falls below the design infiltration rate.	Estimate frequency of clogging maintenance using guidance Appendix F
If infiltration has declined and the system has the flexibility to be adapted to serve as a biotreatment BMP with partial infiltration (e.g., through use of a proprietary BMP as a pretreatment system), then adjust outlet to infiltrate a shallower depth of water and operate as biotreatment with partial infiltration system while infiltration rates allow. This can extend the period before rehabilitation is needed.	As needed and acceptable
Prepare documentation of issues and resolutions for review by appropriate parties; modify O&M Plan if needed	Before major maintenance
Document major maintenance activities; record modified O&M Plan and as-built plan set if needed	After major maintenance
Take photographs before and after from the same vantage point	Before and after

Glossary of Key Terms in Infiltration BMP Fact Sheets

Adaptable outlets: Refers to outlets or outlet control structures that can be readily adapted by O&M crews without significant construction effort or new permitting.

Base: The layer of aggregate material below the road surface course.

Baseflow-mimicking discharge: A discharge that is controlled to a slow rate, approximately mimicking natural baseflow recession curves. This discharge is reasonably similar to the hydrologic response of a natural watershed.

Check dams: Shallow berms or obstructions placed in a BMP to slow the flow of water and promote treatment or infiltration processes.

Clear zone/errant vehicle recovery zone: An unobstructed, traversable roadside area that allows a driver to stop safely or regain control of a vehicle that has left the roadway.

Consumptive use: The use of water from a BMP for on-site consumptive needs, such as irrigation or toilet flushing.

Corrective (major) maintenance: Maintenance, rehabilitation, or reconstruction activities that are associated with unforeseen issues or are triggered at the end of the usable life of a BMP.

Cross slope: Refers to the slope of the embankment or shoulder on which the BMP is located in the direction perpendicular to the travel lanes. This may be different than the transverse slope.

Discharge stage: The elevation of water in an infiltration BMP at which the BMP begins to discharge to the storm drain or surface water conveyance system.

Impermeable liners or barriers: Refers to a plastic membrane, compacted clay layer, or other layer that limits movement of water.

Lane addition/redevelopment project: Refers to a project involving re-alignment, lane addition, or other roadway construction work within an existing developed right of way (ROW). (Contrast with **retrofit project** or **new development project**.)

Longitudinal slope: Refers to the overall slope of the ROW in the direction of the travel lanes.

New construction/new development project: Refers to a project involving construction of a new segment of roadway in a previously undeveloped or much less developed ROW. (Contrast with **retrofit project** or **redevelopment project**.)

Outlet control: A design approach for bioretention BMPs in which the flow through the soil media bed is primarily controlled by an outlet control structure affixed to the underdrains of the system rather than limited by the hydraulic conductivity of the bioretention soil media.

Outlet control structure: A structure designed to control the level and/or rate of water discharge from a BMP.

Resiliency: In the context of stormwater BMPs, resiliency can be defined as the ability to tolerate, adapt to, and/or rapidly recover from adverse conditions, such as incomplete site investigations, construction impacts, elevated sediment loading, contaminant spills, extreme storm events, lack of maintenance, change in tributary area characteristics, and change in design goals.

Retrofit project: A type of project that principally involves retrofitting a roadway with a stormwater BMP for the purpose of providing treatment of existing paved surfaces. This may not be associated with a roadway. (Contrast with **lane addition** or **new construction**.)

Right of way (ROW): For the purpose of this Guidance Manual, ROW is defined as the legal parcel within which the roadway project is constructed.

Routine maintenance: Maintenance activities that are reasonably foreseeable and are performed on a normal interval.

Sacrificial soil layer: A sacrificial soil or media layer consists of a layer of material (sand, soil, or engineered media) placed over the top of less permeable underlying soil to serve as an embedded pretreatment layer. Because of its higher permeability, more sediment can be loaded on this layer before it approaches the limiting rate of the underlying layer.

Storage reservoir: A compartment of a BMP, typically a gravel layer, that serves as a storage reservoir belowground. This reservoir is below the underdrain discharge elevation or discharge stage.

Subbase: The constructed or native material below the base layer.

Supplemental drainage pathway: A drainage pathway provided to ensure drainage if the primary intended drainage pathway becomes clogged or otherwise occluded.

Surface course: The upper layer of the road including the pavement and potentially the bedding layer.

Transverse slope: Refers to the overall slope of the land that the highway crosses, perpendicular to the direction of the travel lanes. This may be different than the cross slope of the shoulder or embankment immediately adjacent to the road.

Travel lanes: A lane for the movement of vehicles traveling from one destination to another, not including shoulders.

Treatment train: The use of two or more BMPs sequentially to manage stormwater.

Underdrain discharge elevation: The elevation at which water begins to discharge from the underdrains of a BMP. This may be controlled by the elevation of the underdrains or via an outlet control structure. This is normally associated with the elevation at the top of the storage reservoir layer.

The conceptual design tables in these fact sheets introduce and define additional terms that relate to BMP design parameters and dimensions.

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Appendices B through J

The following appendices can be found on the TRB website (www.trb.org) by searching for "*NCHRP Research Report 922*".

Appendix B: Infiltration Estimation Method Selection and Interpretation Guide
Appendix C: Roadside BMP Groundwater Mounding Assessment Guide and User Tool
Appendix D: Guide for Assessing Potential Impacts of Highway Stormwater Infiltration on Water Balance and Groundwater Quality in Roadway Environments
Appendix E: Guide to Geotechnical Considerations Associated with Stormwater Infiltration Features in Urban Highway Design
Appendix F: BMP Clogging Risk Assessment Tool
Appendix G: Whole Lifecycle Cost and Performance Example
Appendix H: Example Construction-Phase Checklists for Inspector and Contractor Training
Appendix I: Summary of Infiltration Issues Related to Cold and Arid Climates
Appendix J: BMP Case Study Reports

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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