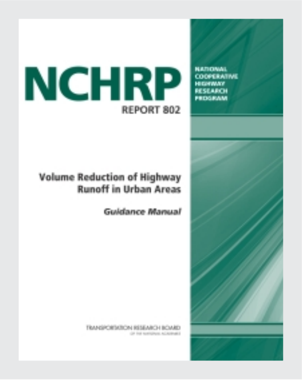

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 802

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Guidance Manual

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Christopher Hedges
Staff Officer
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This guidance manual provides practical, research-based evaluation and implementation practices for the reduction of stormwater volumes in urban highway environments. The manual outlines a five-step process for the identification, evaluation, and design of feasible solutions for runoff volume reduction based on site-specific conditions. It is accompanied by a CD-ROM containing a Volume Performance Tool to assist the user in efficiently estimating the performance of volume reduction approaches and understanding the effects and sensitivity of local climate patterns, design attributes, and site conditions. The manual also includes a set of volume reduction approach fact sheets and a user guide for the Volume Performance Tool. This guidance manual will be useful to DOT managers, project staff and design engineers, permit writers, consultants, and planners.

Reduction of stormwater has long been recognized as an effective method for controlling the impacts of urbanization on water resources. Key benefits of reducing stormwater volume can include: (1) reducing pollutant loads to receiving waters, (2) reducing potential for channel erosion, (3) increasing groundwater recharge and augmenting water supply and stream base flow, and (4) reducing peak runoff flow rates. Implementing volume reduction approaches (VRAs) in a highly urban setting presents a number of challenges and constraints due to the limited space and lack of appropriate soils for typical stormwater management practices such as infiltration, evapotransiration, on-site use, and flow control. Under NCHRP Project 25-41, a research team led by Geosyntec Consultants developed a five-step process for runoff volume reduction. The steps include: (1) establish volume reduction goals, (2) characterize the project site and watershed, (3) identify potentially suitable VRAs, (4) prioritize VRAs, and (5) select VRAs and develop conceptual designs. The manual was developed based on an extensive literature review, synthesis of available information, and focused technical analysis.

The accompanying Volume Performance Tool is an Excel-based spreadsheet application that calculates an estimate of long-term volume reduction based on user-provided location and planning-level project information. The project final report and appendices are available electronically on the TRB website as *NCHRP Web-Only Document 209*.

CONTENTS

Acronyms and Abbreviations

BMPs: Best management practices
CONUS: Conterminous United States
CWA: Clean Water Act
DCIA: Directly connected impervious area
DDOT: District of Columbia Department of Transportation
DOT: Department of transportation
EISA: Energy Independence and Security Act
ESA: Endangered Species Act
ET: Evapotranspiration
ET_o: Reference evapotranspiration
FS: Factor of safety
IWS: Internal water storage
LID: Low-impact development
MAP-21 Act: Moving Ahead for Progress in the 21st Century Act
MCTI: Multi-chamber treatment train
MEP: Maximum extent practicable
MS4: Municipal separate storm sewer system
NCDC: National Climatic Data Center
NPDES: National Pollutant Discharge Elimination System
NPV: Net present value
NRC: National Research Council
O&M: Operations and maintenance
ODOT: Oregon Department of Transportation
PFC: Permeable friction course
ROW: Right-of-way
SCMs: Stormwater control measures
SWMM: Storm Water Management Model
TMDLs: Total maximum daily loads
U.S. EPA: United States Environmental Protection Agency
USGS: United States Geological Survey
VRAs: Volume reduction approaches
WEF: Water Environment Federation
WERF: Water Environment Research Foundation
WLAs: Waste-load allocations
WLC: Whole life-cycle costs
WSDOT: Washington State Department of Transportation

Glossary of Key Terms

Agronomic Demand—The amount of irrigation required to meet plant water needs. In contrast, irrigation that exceeds agronomic demand would be expected to evaporate as standing water, infiltrate below the root zone of plants, or run off via overland flow.

Average Annual Capture Efficiency (also known as capture efficiency)—The estimated percent of long-term average annual runoff volume that is managed/controlled by a stormwater control measure.

Base flow—The portion of stream flow that comes from the sum of deep subsurface flow and delayed shallow subsurface flow. Base flow 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), also known as *stormwater control measure (SCM)*—Although best management practice is the more commonly used term, stormwater control measure may be a better or more accurate term since "best" may be arbitrary, ill-defined, and have no true superlative meaning.

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

Catchment (also known as subcatchment, 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. EPA to implement pollution control programs such as the National Pollutant Discharge Elimination System (NPDES).

Climate Divisions (also known as climate zones)—Defined for the purpose of this report as the 344 climate divisions in the conterminous United States (CONUS), defined by the National Climatic Data Center (NCDC), and analogous zones defined for U.S. land outside of the CONUS.

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.

Continuous Simulation Modeling—A method of hydrological analysis in which a continuous time series (e.g., a period of years) of precipitation and climatic data are used as input, and infiltration, evapotranspiration, and runoff are calculated on a continuous basis. The outputs of continuous simulation models are typically continuous time series of watershed and SCM 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 greater cost-effectiveness results when the ratio of effectiveness to cost is higher.

Crop Coefficient—The crop coefficient is a dimensionless number that is multiplied by the reference evapotranspiration (ET_o) value to arrive at the rate of evapotranspiration (ET) for a given type of vegetation. The resulting ET can be used to help an irrigation manager schedule when and how much irrigation should occur. It can also be used to estimate the amount of ET likely to be lost from an SCM. Crop coefficients vary by vegetation type, stage of growth of the vegetation, season, and other factors.

Design Criteria—In this context, design criteria refers to the set of requirements that serve as the basis for designing an SCM 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 Parameters—The qualitative and quantitative physical characteristics that are used in the design process to describe and analyze a given SCM 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 SCMs. Design storms may be statistically derived hypothetical events or real events that have been observed.

Directly Connected Impervious Area (DCIA)—Impervious areas that are hydraulically connected to the conveyance system and to the basin outlet point without being routed across a pervious surface, such as landscaping, a soft-bottomed conveyance element, or a soft-bottomed SCM. Most roadways may be categorized as DCIAs.

Discharge Rate—In this context, discharge rate refers to the rate at which water is discharged from an SCM.

Disconnection (also known as 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 an SCM is recovered as a result of water discharging from the SCM, making storage volume available for subsequent storm events.

Drawdown Time—The time required for an SCM 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 an SCM system meets its goals for all stormwater flows reaching the SCM, including flow bypasses. For example, effectiveness is a function of capture efficiency, percent volume reduction, and effluent pollutant concentration. See *performance* and *efficiency* for complementary definitions.

Efficiency—A measure of how well an SCM or SCM 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 that 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 (and infeasibility criteria)—Specific qualitative or quantitative criteria that are used to identify conditions under which a given stormwater management approach is considered to be feasible or infeasible.

Flood Control Regulations—In this manual, flood control regulations are considered to be requirements in place to reduce the risk of damage to public property or hazards to public safety resulting from runoff from large storm events. For example, flood control regulations may require peak runoff flow rates be matched pre-project to 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.

Flow Duration—A statistical approach for evaluating continuous hydrographs that consists of quantifying the cumulative duration of flows within a given range of flows or above a given flow rate.

Flow Duration Control—A hydrologic control strategy including specialized detention and discharge structures designed to reduce excess post-project flow durations for a designated range of flows based on continuous simulation models of runoff from both pre-project and post-project site conditions, comparing flow durations for the designated range of flows, in order to mitigate development-caused hydromodification.

Geotechnical Considerations—In this manual, geotechnical considerations refer specifically to factors related to geotechnical design and performance of soil structures when considering infiltration of stormwater. Considerations are landslides, liquefaction, settlement, and other factors.

Green Infrastructure—Open spaces, natural areas, and functional landscaping that manage stormwater using natural and engineered functions to reduce flooding risk and improve water quality.

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

Harvest and Reuse (also known as rainwater harvesting)—The process of capturing rainwater or stormwater runoff, storing it, and making it available for subsequent use.

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

Hydraulic Loading—The ratio of stormwater inflow (volume/time) to an SCM divided by the surface area of the SCM 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 compare between SCM configurations.

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 time series of flow discharge (i.e., runoff rate, inflow rate, outflow rate) versus time.

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

Hydromodification Control—Management techniques that reduce the potential for impacts caused by hydromodification.

Hydromodification Impact—The physical response of stream channels to changes in runoff and sediment yield caused by land use modifications.

Hyetograph—A time series of rainfall intensities versus time.

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.

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 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.

In-Stream Control—Modification of a receiving channel as a technique for managing hydromodification impacts or improving water quality.

Interflow (also known as shallow interflow)—The flow of water through the upper soil zones into a stream. In comparison to base flow, 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.

International BMP Database—A publicly available research database that contains results of SCM studies independently conducted and submitted by researchers throughout the United States and several other countries. www.bmpdatabase.org.

Irrigation Efficiency—The ratio of plant irrigation needs met to the amount of irrigation water applied. A value of 0.75 refers to a condition in which 1 in. of irrigation water must be applied to satisfy 0.75 in. of plant water needs. Surplus water may be lost to evaporation, runoff, or deeper percolation.

Liquefaction—A seismically induced geological hazard that can result in damage to structures as a result in 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.

Low-Impact Development (LID)—LID is an approach to land development (or redevelopment) that seeks to manage stormwater as close to its source as possible and minimize downstream discharges. LID employs principles such as preserving and recreating natural landscape features, minimizing effective imperviousness to create functional and appealing site drainage that treats stormwater as a resource rather than a waste product.

Maximum Extent Practicable (MEP)—A standard, established by the 1987 amendments to the Clean Water Act, 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." *Maximum extent practicable* is not defined by the CWA.

Municipal Separate Storm Sewer System (MS4)—A conveyance or system of conveyances (including roads with drainage systems, municipal streets, catch basins, curbs, gutters, ditches, manmade channels, and storm drains) designed for collecting or conveying stormwater, which is not a combined sewer, which is not part of a publicly owned treatment work, and is owned by a public body approved under Section 208 of the Clean Water Act that discharges into the waters of the United Sates.

National Pollutant Discharge Elimination System (NPDES)—A provision of the Clean Water Act 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 U.S. EPA.

Off-Line SCM or Volume Reduction Approach (VRA)—Off-line SCM or VRA systems receive flow from a flow-splitter structure such that the maximum inflow to the system is restricted and peak flows are designed to bypass around the system without treatment.

On-Line SCM or VRA—On-line SCM or VRA systems receive all of 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 SCMs or VRAs—SCMs or VRAs that are implemented within the boundary of a project site. In contrast, see *regional SCMs or VRAs.*

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

Overland flow—Flow of water across the land surface in a down-gradient direction. Sheet flow, shallow concentrated flow, and channelized flow are forms of overland flow.

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 to be partially feasible to meet the design goal.

Performance—A measure of how well an SCM 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 since 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 affect 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.

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

Reference Evapotranspiration (ET_O)—The evapotranspiration that occurs from a standardized plot of vegetation that has been studied extensively, generally consisting of a well-irrigated, dense grass that completely shades the soil surface.

Regional SCMs or VRAs (also known as watershed-scale SCMs)—SCMs implemented within the local subwatershed, typically outside and downstream of the project boundary or treating nearby areas. In contrast, see *on-site SCMs or VRAs.*

Right-of-Way (ROW)—For the purpose of this manual, defined as the legal parcel within which the urban roadway project is constructed.

Roadway Design Regulations—For the purpose of this manual, 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 of a surface during a period of interest.

SCM System (also known as BMP system)—A system including the SCM/BMP and any related bypass or overflow. VRAs are a type of SCM.

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

Shoulder—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 is generated from a project site.

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

Stormwater Control Measure (SCM), also known as a best management practice—A device, practice, or method for removing, reducing, retarding, or preventing targeted stormwater runoff quantity, constituents, pollutants, and contaminants from reaching receiving waters.

Total Maximum Daily Load (TMDL)—The calculation of the maximum amount of a pollutant that a water body 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 waste-load 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.

Urban Highway—Refers to a range of limited access roadway and freeway types described within this manual.

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

Volume Reduction Approach (VRA), also known as volume reduction practice, volume reduction SCM, volume reduction BMP—An approach, inclusive of structural SCMs, source controls, and site design practices, which is intended to achieve volume reduction of stormwater runoff.

Water Balance (also known as 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 SCM system, a local groundwater system, or a regional groundwater system.

Water Balance Analysis—In the context of this manual, water balance analysis refers to the consideration of the ultimate fate of retained stormwater (e.g., percolation, interflow, ET, beneficial use) such that potential adverse effects on local systems can be evaluated.

Watershed Characteristics—Characteristics of the watershed in which a project is located that may influence goals for volume reduction and/or the amount of volume reduction that can be achieved. For example, topography, regional groundwater table, and regional water balance.

Whole Life-Cycle Costs—An economic assessment, expressed in monetary value, considering 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 capital and O&M costs.

CHAPTER 1

Introduction

This chapter introduces the purpose and origin of *NCHRP Report 802: Volume Reduction of Highway Runoff in Urban Areas: Guidance Manual*, the regulatory and policy drivers for designing for volume reduction, the intended users and uses of this guidance, and the organization of the remainder of the document. The major questions addressed in this chapter are:

- What does this manual seek to achieve?
- What is the scope of this manual?
- What regulatory issues and national and local policies are intended to be addressed and informed by this manual?
- Who are the intended users?
- How should this manual be used?
- How is this manual organized?

1.1 Statement of Purpose

Volume reduction of surface runoff is an important element of controlling stormwater impacts on water quality and stream functions in urban areas. Key benefits of volume reduction for stormwater management are:

- Load reduction of pollutants to receiving waters,
- Decreased potential for channel erosion by reducing the cumulative energy of stormwater discharged to stream channels,
- Potentially increasing groundwater recharge and augmenting water supply or stream base flow, and
- Reduced peak runoff flow rates.

Due to various constraints and other design objectives associated with the urban highway environment, many conventional volume reduction approaches commonly applied in other land uses are not applicable or require careful application in this space-constrained environment. In addition, the assessment of feasibility of volume reduction approaches (VRAs) in the urban highway environment must consider a broad suite of factors. As a result, incorporation of volume reduction approaches can add complexity to transportation project planning, design, construction, operations, and maintenance. Finally, limited information about cost, maintenance requirements, and life span of VRAs in the highway environment is available to support decision making.

The intent of this guidance manual is to provide practical, technically defensible, and comprehensive guidance for the evaluation and implementation of volume reduction practices in a wide range of urban highway environments. Scenarios, such as varying project types, site conditions, and climate zones, are included, along with practical recommendations on conditions specific to urban highway projects. The current state of the practice for achieving volume reduction is incorporated. Meanwhile, this manual also introduces potential innovative approaches specifically tailored to the urban highway environment.

In the preparation of this guidance manual, the research team recognized that some state departments of transportation (DOTs) have already been implementing volume reduction approaches to some extent and have certain processes in place for making decisions about applying VRAs, while other DOTs are earlier in the process of evaluating and implementing VRAs (or stormwater management approaches in general). The purpose of this guidance manual is to serve all DOTs at a uniform level of detail, regardless of the state of each DOT's current program. As a result, different DOTs may use this guidance manual in different ways.

1.2 Regulatory and Policy Background

Reduction of runoff volumes has long been recognized as an effective method for controlling the impacts of urbanization on water resources. In areas with suitable soil conditions, infiltration systems have been widely applied to manage stormwater runoff for flood control purposes. For example, the City of Portland operates approximately 9,000 infiltration sumps in the eastern part of the city that capture the runoff from storm events and have eliminated the need for a regional stormwater conveyance system in this area (City of Portland, 2013). Eliminating the need for such hard infrastructure can have substantial cost savings. Other regions, such as the Sun Valley watershed in Los Angeles County, California, have voluntarily embraced volume control approaches as part of addressing flood control, water quality, and water supply objectives (Los Angeles County Department of Public Works, 2013).

The term "low-impact development" (LID) refers to an approach for managing runoff from new development projects [U.S. Environmental Protection Agency (U.S. EPA), 2013a]. This approach emphasizes controlling the rates and volumes of stormwater runoff close to its source in order to reduce the impacts of development on downstream receiving waters and conveyance systems. This approach does not necessarily include relying on infiltration for flood control, but for reducing water quality and hydromodification impacts on receiving waters.

LID approaches have seen varied degrees of adoption in different applications across the United States, most notably in state and local regulations governing stormwater management from new development projects. However, the paradigm for stormwater management in many areas of the country included minor emphasis on runoff volumes; instead it focused on capturing, treating, and releasing stormwater runoff to remove target pollutants, while simultaneously controlling peak rates of runoff to address flooding risks, where necessary (National Academy of Sciences, 2008).

The National Research Council (NRC) report *Urban Stormwater Management in the United States* (National Academy of Sciences, 2008) identified a number of recommendations for improving stormwater management approaches and regulations, including a greater emphasis on hydrology (i.e., runoff volumes, flow rates) in managing stormwater runoff. Consistent with this report's recommendations, municipal separate storm sewer system (MS4) permits issued to state and municipal permittees, including DOTs, as part of the National Pollutant Discharge Elimination System (NPDES) have increasingly emphasized volume reduction for new development and redevelopment projects. Similarly, Section 438 of the Energy Independence and Security Act (EISA) and accompanying U.S. EPA guidance includes requirements to control volumes and rates of stormwater runoff from projects that involve development or redevelopment of federal facilities (U.S. EPA, 2007a). While EISA is not applicable to highways, it is indicative of overall trends in stormwater management. Finally, the U.S. EPA has published the "MS4 Permit Improvement Guide" (U.S. EPA, 2010), based in part on the NRC's 2008 recommendations, which includes guidance for state and federal regulators to develop MS4 permits that include greater emphasis on surface runoff volume control. Volume control is already encouraged in some MS4 permits issued to DOTs—for example, Caltrans (California State Water Resources Control Board, 2012) and District of Columbia Department of Transportation (U.S. EPA, 2011)—and volume control provisions may apply on a broader scale to roadway projects as part of the NPDES/MS4 permit system in the near future.

Other drivers for incorporation of volume reduction into highway projects are the Moving Ahead for Progress in the 21st Century (MAP-21) Act, which uses a performance-based approach for the reauthorization of federal aid highway and highway safety projects as well as trends toward sustainability rating systems such as the Institute for Sustainable Infrastructure Envisio Rating system (U.S. DOT, 2012), and FHWA's Sustainable Highways Self-Evaluation Tool, INVEST.

Drivers for retrofits of highways to reduce runoff volumes are primarily found as part of the implementation of total maximum daily loads (TMDLs), which includes the development of waste-load allocations (WLAs) and subsequent identification of management actions by various dischargers within the watershed to achieve these WLAs (U.S. EPA, 2012). For DOTs, actions to achieve WLAs may include retrofits of existing roadways or participation in regional approaches with other dischargers to address their apportioned share of the required reduction in loading. Runoff volume is not commonly identified as a pollutant in TMDLs [for example, see the recent successful court challenge of the Accotink Creek TMDL (Virginia DOT et al., v. U.S. EPA et al., 12-CV-775, U.S. District Court for Eastern Virginia)]; however, the enforcement and implementation of TMDLs may encourage management actions involving volume reduction. Additionally, there are examples of TMDLs that include volume of runoff as a surrogate for pollutant loads and impairments (U.S. EPA, 2013b). In the future, volume control retrofits may also be required within the MS4 permits as indicated in the U.S. EPA MS4 Permit Improvement Guide (U.S. EPA, 2010).

A more comprehensive presentation of these regulations and their applicability to volume control methods is included in this guidance in Section 3.1.

1.3 Intended Users and Uses

Incorporating VRAs into the highway project development process can add complexity and introduce additional feasibility and desirability considerations when compared to a standard highway stormwater management design processes. However, in appropriate conditions, the incorporation of VRAs can also result in reduced infrastructure requirements and accrue important water quality protection benefits. As such, the need was identified for practical guidance to facilitate safe and effective incorporation of volume control into highway designs, where feasible and appropriate.

This guidance manual is intended to be used by a range of user types, for different purposes, in the planning and design process for new projects, lane addition projects, and retrofit projects. At the early project planning level and program management level, this manual can be used to facilitate a mutual understanding among the design team regarding volume reduction goals and the way that volume reduction considerations will be incorporated into the project development process. Similarly, this manual can be used to scope the additional or alternative analyses that may be needed in the design process as part of achieving volume reduction or demonstrating its infeasibility.

At later stages of planning, this manual may assist in identifying feasible VRAs and conducting early site investigations to identify project-specific opportunities and constraints to allow for refined estimates of achievable levels of volume reduction. This manual is also intended to support designers by contributing site-specific approaches to prioritize, select, evaluate, and apply VRAs.

Last but not least, this manual may serve as a resource for permit writers and compliance staff when considering the level of volume reduction that may be achievable in the urban highway

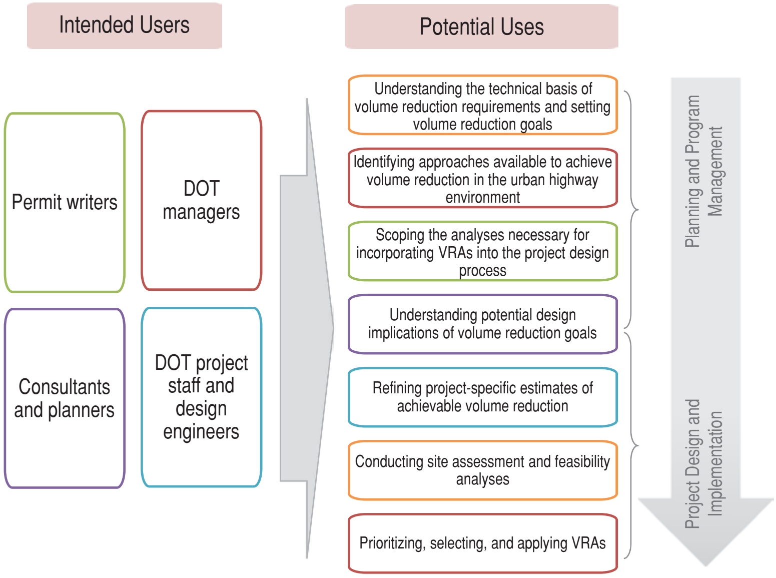


Figure 1. Intended users and potential uses.

environment and potential adverse impacts associated with volume reduction designs. Figure 1 summarizes the range of users and potential uses, organized in approximate chronological order from planning-level to design-level uses.

As introduced in Section 1.1, the use of this manual may also vary depending on whether a DOT (or regulatory agency) is earlier in the process of evaluating and implementing VRAs (or stormwater management approaches in general) or already has an established program. For users earlier in the process of evaluating and implementing VRAs, this manual could be used as the technical basis and associated guidance for developing a program; the majority of the manual may be of interest, including the stepwise process described in Chapter 2 and the supporting technical information in later chapters and appendices. For users working within an established program, this manual could be used as a technical reference for specific issues encountered in the administration of the program or on specific projects or as a potential basis for improving their existing process or criteria; however, certain sections, such as the stepwise approach and background, may be of limited value. The latter suite of users may need to be more selective about how the contents of this manual are used within their programs and may need to identify topic areas in which their program-specific processes and criteria supersede those in the manual.

While this manual provides detailed and methodical guidance for selecting and implementing VRAs, supplemented with checklists and schematics consistent with a conceptual design level of detail, it does not provide criteria for the detailed design of specific volume reduction facilities. This manual considers operations and maintenance activities and costs as key considerations in the feasibility and prioritization of VRAs; however, it does not provide detailed guidance for operations and maintenance. Instead, this manual provides references to other documents that provide information in these areas.

1.4 Organization of the Guidance Manual

This manual approximately parallels the example stepwise process described in Section 2.1. It is intended to provide supporting guidance as the user proceeds through each general step.

Chapter 2 describes a step-by-step model approach for incorporating volume reduction techniques into an urban highway project and describes how this manual can be used to support planning and analysis at each project phase.

Chapter 3 provides a baseline characterization of the urban highway environment related specifically to achieving surface runoff volume reduction. The intent of this chapter is to orient the user to the regulatory context for achieving volume reduction, the basic concepts central to volume reduction, and the general considerations that exist for applying volume reduction approaches within the urban highway context. This chapter primarily supports Step 1 of the stepwise process (establish volume reduction goals) and Step 2 (characterize project site and watershed).

Chapter 4 provides a focused menu of potentially practicable approaches specific to volume reduction in the urban highway environment and describes these approaches in sufficient detail to distinguish key conceptual design parameters and applicability. VRAs are described in a series of fact sheets that are included in Appendix A. This chapter is intended to serve as a resource for Step 3 (identify potentially suitable VRAs) and Step 4 (select VRAs and develop conceptual designs).

Chapter 5 provides the user with information to help evaluate, compare, and ultimately select applicable volume reduction approaches for a project. This chapter includes evaluation criteria, an approach for screening and selecting VRAs, and an introduction to the Volume Performance Tool (available on the CD-ROM that accompanies this report) to support site-specific quantitative analysis of volume reduction approaches. It is also intended to serve as a resource for Step 3 (identify potentially suitable VRAs) and Step 4 (select VRAs and develop conceptual designs). Chapter 5 also introduces watershed-scale approaches for achieving volume reduction.

Technical appendices include content that is directly relevant to the application of this manual but focuses on a specific technical topic area. The appendices include Appendices A and B, which are published as part of this report, and Appendices C through F, which are included in *NCHRP Web-Only Document 209.*

- **Appendix A: Volume Reduction Approach Fact Sheets**—provides three- to five-page fact sheets for each of the nine VRAs identified in Chapter 4, including VRA-specific information for selection and conceptual design of VRAs.
- **Appendix B: User's Guide for the Volume Performance Tool**—provides instructions for using the Volume Performance Tool to conduct site-specific assessment of potential volume reduction performance.

1.5 Limitations

This manual has a variety of potential uses and includes guidance on many technical areas; however, a number of important limitations should be understood in the use of this manual:

- While this manual may be useful to provide technical support to the development and implementation of local stormwater management ordinances, it is not intended to establish policy or criteria related to stormwater management or volume control. The user should refer to local ordinances for specific requirements and criteria.
- Due to the importance of considering and the variability of site-specific conditions in various technical analyses (e.g., infiltration feasibility assessment, geotechnical studies and design), it is not possible for this manual or its appendices to provide specific numeric or other recommendations that are universally applicable. Where possible, this manual provides typical

numerical ranges and guidance. However, professional expertise and judgment must be exercised by qualified professionals based on site-specific information to develop project plans and designs. The project team provides no warranty, expressed or implied, for the recommendations provided in this manual or its appendices.

- The primary audience for this manual is professionals involved in stormwater management. While this manual includes topic areas that overlap with related disciplines (e.g., geotechnical engineering, hydrogeology), the discussions of these topic areas are primarily intended to facilitate a common understanding between disciplines on key concepts rather than to elaborate on, much less cover, discipline-specific topics. This manual is not intended to serve as a detailed guide for professionals in other disciplines (e.g., geotechnical engineers, hydrogeologists) to conduct their analyses.

These limitations apply to the entire manual and its appendices; to avoid unnecessary redundancy, they are not repeated in other locations.

CHAPTER 2

Stepwise Approach for Incorporating Volume Reduction in Urban Highway Projects: How to Use This Manual

As introduced in Chapter 1, the incorporation of volume reduction approaches into urban highway projects can yield significant benefits, but VRA analysis can also increase the complexity of the project development process. Planning and designing for volume reduction can introduce new elements that need to be coordinated with other aspects of the design. Additionally, planning and designing for volume reduction can require additional site and watershed information. With careful planning, the acquisition of this information can have a relatively minor impact on project cost and schedule; however, if not anticipated, the addition of these steps may result in project delays and more significant incremental costs. Like other design goals, volume reduction goals may need to be adjusted during the course of the project as designs evolve and additional information becomes available.

To help simplify this process, this chapter describes an example step-by-step approach for incorporating volume reduction techniques into an urban highway project. This chapter is intended to help answer the questions:

- How should I approach incorporating volume reduction into my project?
- What resources are provided in this manual to help me at each step?
- What are the advantages of taking a systematic approach?

2.1 Example Approach and Corresponding Manual Resources

The example stepwise approach described in this section is based on a typical project development process that progresses from project planning, to site investigation and preliminary design activities, to project design and implementation. This process has been developed based on the following considerations:

- What types of project decisions are made at each phase of the project?
- What information is needed to support decisions at each phase?
- What information is practicable to obtain at each phase?
- What other investigation or design activities are typically ongoing at each phase?

The example stepwise approach is illustrated schematically in Figure 2 and described in the paragraphs that follow.

Step 1—Establish Volume Reduction Goals. The first step in this example process is to establish volume reduction goals for the project. Volume reduction goals can be informed by:

- Regulatory requirements such as MS4 permits, TMDL implementation plans, or other motivations (see Sections 1.2 and 3.1);

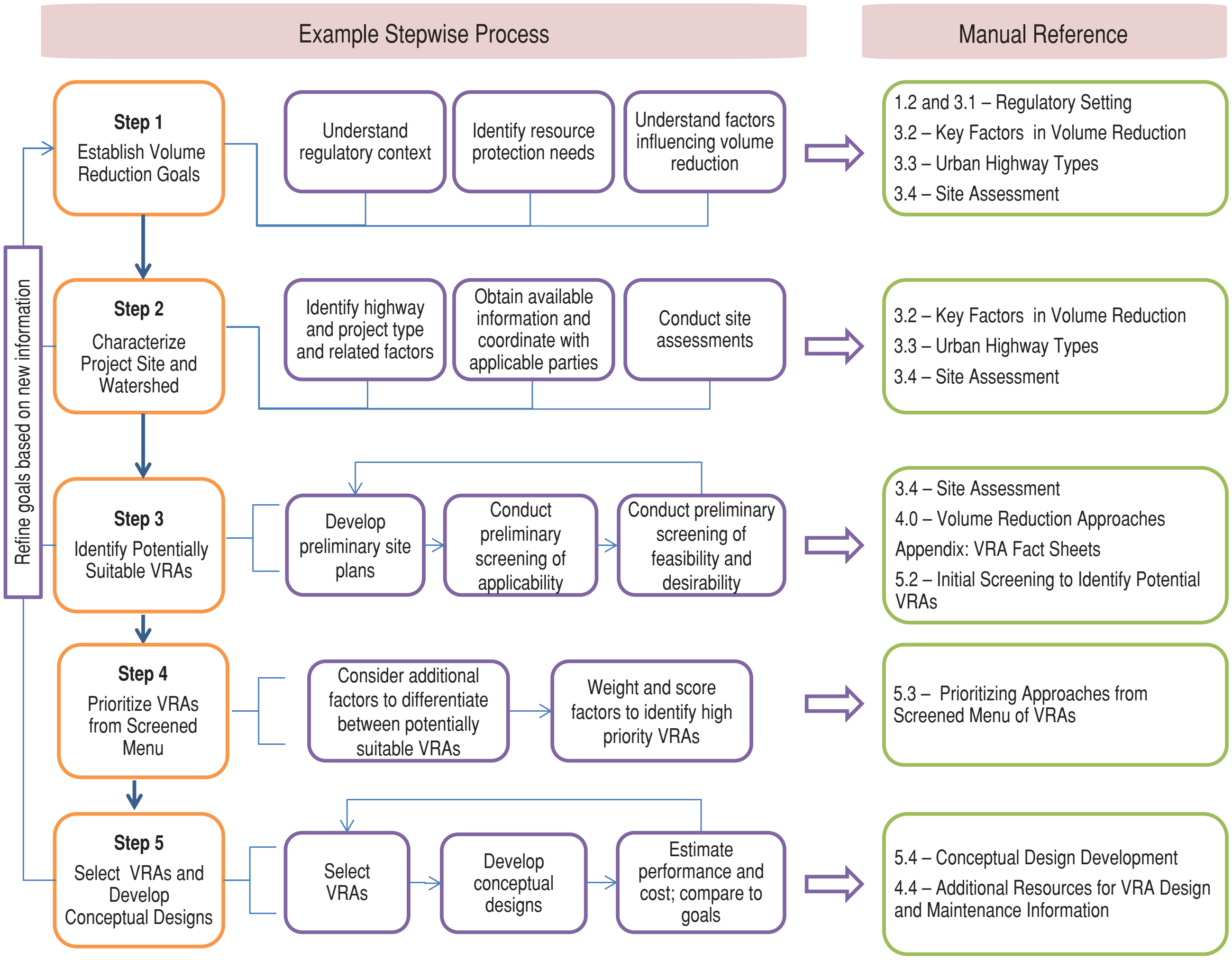


Figure 2. Example stepwise process for incorporating volume reduction into project development.

- Resource protection needs, such as groundwater recharge, protection of sensitive receiving waters, and participation in a voluntary watershed planning process (see Section 3.4);
- Resource protection constraints, such as groundwater protection criteria or sensitive hydrogeologic systems that could reduce the desirability of infiltration in certain areas (see Section 3.4);
- Other highway design goals, such as mandates for traffic capacity and safety (see Section 3.1); and
- The anticipated amount of volume reduction that is feasible given understanding about site conditions (Section 3.4), technical factors influencing volume reduction (Section 3.2), and factors implicit in the project and highway type (Section 3.3).

Because certain additional information relevant to volume reduction goals may be obtained or may arise throughout the planning and design processes, the establishment of volume reduction goals is an iterative process that may need to be refined as the project proceeds. Nonetheless, the early establishment of goals is an important step as it influences the types and scope of investigations and analyses that need to be planned. Such goal establishment also allows for an initial screening to identify the VRAs that may be the most applicable.

Step 2—Characterize Project Site and Watershed. Characterization of the project site is an iterative process that can be initiated early in the planning process and may continue throughout the development of project designs. Site characterization may take a number of forms, including desktop data review, field investigations, and coordination with applicable agencies.

Initial information about the site, watershed, and project type known at the onset of planning is useful for the establishment of volume reduction goals. As part of project planning, additional site characterization efforts may be needed to support the early assessment of VRA feasibility. For example, when attempting to achieve volume reduction goals, a general assessment of infiltration rates and groundwater conditions is usually needed early in the process to estimate the extent to which volume reduction is possible. Guidance for general site-assessment activities at the planning phase is described in Section 3.4 and the appendices.

Site investigation activities tend to become more focused as the design process progresses. For example, once a specific volume reduction facility is selected and sited, focused infiltration testing and groundwater-level measurements can be obtained in the specific vicinity of that facility to establish design infiltration rates and identify potential depth to groundwater issues. Section 3.4 and the appendices provide guidance for focused site-assessment methods at different design phases.

Because site characterization requires time and budgeting, investigation of site conditions is only recommended to the extent that information is needed to support decision making at the current project phase. For example, if it is known that infiltration for a site is not practicable based on sensitive geotechnical conditions, then there would be limited value in also conducting an analysis of infiltration rates or groundwater quality considerations. Section 3.4 and the appendices provide guidance related to the role of site investigation at different design phases.

Step 3—Identify Potentially Suitable VRAs—Preliminary Screening and Site Planning. Chapter 4 describes a fairly broad menu of VRAs, including systems that are located within different zones of the highway environment and that rely on different mechanisms for volume reduction. Chapter 4 also describes the properties of these VRAs and how they compare on a relative basis.

The goal of Step 3 is to narrow the broader menu to a focused list of VRAs that appear to be most compatible with the specific project type, site conditions, and volume reduction goals. Section 5.2 describes a screening process that is intended to help efficiently rule out approaches that are clearly unsuitable and to assist with narrowing the list to support project planning and design.

The other key element in this step is the development of the preliminary project layout. Because many VRAs are integrated within roadway features, early site planning can simultaneously assist with the preliminary screening and selection of VRAs. By considering site design as an interrelated element of volume reduction planning, a greater degree of volume reduction may be achieved while still meeting multiple other site design requirements through optimized placement and design. The degree of flexibility within roadway layouts varies and may be constrained by overriding factors such as grades/topography, utilities, connection with existing roadways, and geometric design. However, at the early planning phase, there are typically greater opportunities to adjust layout than in later phases of design.

Step 4—Prioritize VRAs from Screened Menu. After conducting the screening and site planning activities discussed in Step 3, multiple VRAs may be identified as feasible and desirable for a site. The goal of this step is to prioritize the list so that it can be further narrowed down from the list of potentially suitable VRAs to a reduced suite that is selected specifically for more detailed evaluation for the project. Section 5.3 provides a systematic approach for prioritizing the VRAs that passed the initial screening process in Step 3. Factors that may be relevant for prioritization include:

- Relative life-cycle costs,
- Relative operations and maintenance (O&M) impacts on agencies,

- Relative reliability,
- Relative safety, and
- Potential performance relative to volume reduction goals.

By ranking systems based on these factors, the most potentially favorable options can be identified and then evaluated and selected in Step 5.

Step 5—Select VRAs and Develop Conceptual Designs. Based on the results of Steps 3 and 4 and designer preferences, VRAs are selected and incorporated into project designs. The final step covered by this manual is the development of conceptual designs that incorporate the screened and prioritized menu of VRAs. Guidance related to this step is provided in Section 5.4, including guidance for developing conceptual site and VRA designs, using modeling tools for decision support and design refinements, estimating costs of conceptual designs, and adapting conceptual designs to converge with project goals.

Developing and analyzing VRAs at a conceptual design level can facilitate analyses of benefits and costs of VRAs. These analyses can help refine volume reduction goals with respect to what is achievable for a given site and help identify design adaptations that would allow performance and cost to better converge with project goals. Conceptual design analysis can also help the designer understand the sensitivity of design parameters to help focus further testing or investigation as part of developing final designs. For example, if infiltration rate is found to be a sensitive design parameter, then more focused testing can be planned to help reduce uncertainty in this parameter.

2.2 Advantages of a Systematic Approach for Incorporating Volume Reduction

Highway project development includes a variety of diverse conditions and constraints that must be evaluated and considered to arrive at a final design. Many DOTs use a structured project development process. While no two design processes are the same, a similar systematic approach typically underlies the overall development process (i.e., initial site characterization precedes planning and environmental clearance, which is sought before full-scale detailed design activities commence). A systematic approach for design development helps ensure that the necessary information is collected at the appropriate time to help avoid project delays and added expenses.

Similarly, a systematic approach for incorporating volume reduction in highway design has a number of advantages. First, it helps ensure that volume reduction goals are considered early in the process, in concert with the other goals of the project. Second, it helps ensure that information is collected at the appropriate time, and the analyses that are scoped are suited to the level of information available and the decisions that need to be made at each phase. Third, taking a systematic approach helps identify opportunities for volume reduction that may not be identified in a more ad-hoc process. This is especially useful when the design team has relatively little experience with volume reduction design and does not have a good feel for the opportunities available. Finally, a systematic approach helps ensure that constraints and unintended consequences are considered and applied appropriately in informing volume reduction approaches and reasonable volume reduction goals. A systematic identification of constraints may be especially important in demonstrating to regulators or reviewing authorities why volume reduction goals may need to be refined or waived for a particular project or portions of a project.

While this manual is written to facilitate a systematic approach, as described in Section 2.1, the manual does not require users to follow this approach in sequential order. In each section, the underlying technical bases and considerations are introduced alongside of the more structured processes and associated tools (e.g., checklists, worksheets, flowcharts) associated with a systematic process.

CHAPTER 3

Volume Reduction in the Urban Highway Environment

This chapter provides a baseline characterization of the urban highway environment as that relates to achieving surface runoff volume reduction. It is intended to orient the user to the regulatory context for achieving volume reduction, the basic concepts central to volume reduction, and the general considerations that exist for applying volume reduction approaches within the urban highway context. It also provides guidance for site investigations recommended to support volume reduction design. This chapter supports Step 1—Establish Volume Reduction Goals and Step 2—Characterize Project Site and Watershed as identified in Section 2.1.

3.1 Regulatory Context

This section introduces the current regulatory requirements for reduction of urban stormwater runoff, including those that are applicable to highways and other land uses. Trends in regulations and potential regulations that may apply to highways in the future are introduced. This section also introduces other regulations and design principles that are important in highway project development and that may influence the application of volume reduction approaches.

This section will help the user answer the following questions:

- Why is volume reduction being considered for urban highway runoff?
- What are the benefits of volume reduction?
- What volume reduction mandates are currently in place or may be applicable for roadways in the future?
- How do safety, roadway design (e.g., geometrics, subbase), and flood control regulations (e.g., detention) interact with stormwater volume management on an urban highway project?
- How do overlapping design goals affect the application of volume reduction approaches?

3.1.1 Current Volume Reduction Mandates and Trends in Stormwater Management Regulations

Benefits of Volume Reduction in Stormwater Management

Urban Stormwater Management in the United States (National Academy of Sciences, 2008) identified a number of recommendations for improving stormwater management approaches and regulations. Among these recommendations is a greater emphasis on hydrology (e.g., runoff volumes, flow rates) in managing stormwater runoff. Reducing runoff volumes has a number of key benefits as part of a stormwater management approach, including:

- **Reducing the loading of pollutants to receiving waters.** Volume reduction is among the most effective treatment mechanisms for removing pollutants (Strecker et al., 2005; Oregon State University et al., 2006). In comparison to treat-and-release systems, volume reduction tends to achieve more complete removal of pollutants.

- **Reducing the potential for channel erosion.** Volume reduction reduces the cumulative energy of stormwater discharged to stream channels, which can reduce the potential for channel erosion. While channel erosion can also be controlled via careful flow control (with or without volume reduction), the use of volume reduction can result in a better match to the total flow volume than a stream received from the project site in the natural condition and, therefore, better mimic natural habitat and sediment transport regimes (U.S. EPA, 2009; Santa Clara Valley Urban Runoff Pollution Prevention Program, 2005).
- **Augmenting water supply and base flow.** Infiltration of stormwater can potentially increase groundwater recharge and augment water supply or stream base flow. When a site is developed and water is infiltrated in VRAs, this tends to result in a shift in the water balance involving a reduction in evapotranspiration (ET) and an increase in deeper percolation and groundwater recharge (see Appendix D, published as part of *NCHRP Web-Only Document 209*). This can be advantageous when an aquifer is used for water supply or contributes to base flow to streams, and the additional volume of recharge would be beneficial. Augmenting base flows can also help address water quality impairments, such as dissolved oxygen or eutrophication problems, by reducing stagnation and increasing flux through the system.
- **Potentially reducing peak runoff flow rates.** When volume reduction approaches are designed for the purpose of controlling the volume or peak flow rate of runoff in severe events, they can be part of an overall peak flow control strategy.

These benefits have been well demonstrated in literature and practice.

The Clean Water Act and NPDES Permits

The major regulatory framework for stormwater management from highways in the urban environment stems from the Clean Water Act (CWA), which was established in 1972 to regulate the discharge of pollutants to the surface waters of the United States. In 1987, the CWA was amended to regulate stormwater discharges as point sources through the implementation of a permitting program using NPDES (U.S. Senate, 2002). Discharges from MS4s are included under the NPDES permit requirements. Municipalities, roadways, educational institutions, and other public works can all be considered MS4s. Phase I of the NPDES implementation covers specified industrial facilities, larger construction sites (greater than 5 acres), and MS4s that serve populations of 100,000 or greater. Phase II of NPDES implementation covers smaller MS4s and construction sites that are at least 1 acre in size. The permitting of DOTs differs by states, as discussed in the following and also as discussed in detail in *Cost and Benefit of Transportation Specific MS4 and Construction Permitting* (Austin, 2010).

MS4 Permits and DOTs

DOT projects are different from typical municipal and private projects in a number of important ways. First, they are typically characterized by their elongated linear nature, high degree of imperviousness, and tendency to cross multiple waterways, watersheds, and jurisdictions. Consequently, stormwater runoff from transportation projects typically discharges to a larger number of distributed points than typical construction projects in other land uses and may need to be managed at a greater number of locations along the length of the roadway. Second, in urban environments, there are typically impervious surfaces directly adjacent to highways, such as buildings, walkways, and local roads, which can produce runoff that drains directly onto or into the highway right-of-way (ROW). Highway permitting and project development must take into consideration how these flows are handled. Third, stormwater runoff from highways includes pollutants specific to transportation land uses and tends to have characteristics that differ significantly from the runoff from other or mixed land uses. Differences in stormwater characteristics may influence the selection of treatment processes. Fourth, projects in transportation corridors typically face many constraints for stormwater management, such as limited flexibility in geometric design, safety considerations, and space constraints due to long-reinforced design standards.

Because of these factors, it is common for states to address the permitting of DOTs differently than other permittees and to include requirements in DOT permits that differ from permits for other entities. The treatment of DOTs under the NPDES system by each state can generally be classified into six categories (Austin, 2010):

1. DOTs that are covered by a statewide Phase II MS4 general permit (permittees may include the entire state DOT, individual DOT districts, or DOTs within a specific region).
2. DOTs that have specific individual permits (including combination MS4-construction general permits).
3. DOT districts that are permitted individually within the state under various permit types.
4. DOTs that are co-permitted with surrounding Phase I and/or Phase II areas.
5. DOTs that have a combination of permit types.
6. DOTs that are not currently covered by an NPDES permit.

For the most part, individual states are responsible for writing both individual and general permits, with the exceptions of Alaska, Idaho, Massachusetts, New Hampshire, New Mexico, the District of Columbia, tribal lands, and U.S. territories, where the U.S. EPA is the responsible party.

TMDLs and DOTs

Section 303(d) of the CWA requires that states identify "impaired" waters that fail to meet their designated uses related to habitat and recreational activities. Specific plans to improve the water quality in these waters are required, including the determination of TMDLs of specific pollutants that can be discharged to a receiving water (U.S. Senate, 2002). U.S. EPA regulations require that a TMDL include WLAs, which identify the portion of the loading capacity allocated to individual existing and future point source(s). In some cases, WLAs may cover more than one discharger. As permittees that discharge to water bodies with TMDLs, DOTs are typically assigned WLAs. WLAs are typically incorporated into DOT permits, which may mandate stormwater retrofits to meet the assigned WLA. Currently, TMDL implementation is the primary regulatory driver for retrofit of urban highways. In the future, MS4 permits may require retrofit of best management practices (BMPs) into highways as part of a long-term plan for implementation.

Volume reduction approaches can be important elements of a DOT's strategy for meeting WLAs. Reducing the runoff volume from existing roadways via VRA retrofits can reduce pollutant loads to TMDL water bodies and also reduce the potential for in-stream sources of pollution, such as by erosion.

Other Water Quality Regulations Potentially Applicable to State DOTs

Other sections of the CWA that may pertain to stormwater management in the urban roadway environment are Section 401, which requires that construction projects comply with state water quality standards and other provisions, and Section 404, which requires mitigation of wetlands damaged by discharge or fill materials associated with construction activities. The 401/404 permitting process may provide a pathway for the federal government or states to issue additional requirements on DOT projects (U.S. Senate, 2002).

Construction general permits issued at the statewide level are primarily intended to regulate construction site stormwater runoff but may also provide a pathway for states to impose post-construction (i.e., permanent) stormwater control requirements on projects. For example, the California Construction General Permit (Order No. 2009-0009-DWQ) includes post-construction requirements for projects to mimic the predevelopment water balance of the site (California State Water Resources Control Board, 2009). This permit requires projects to retain stormwater up to the 85th-percentile, 24-hour precipitation event unless proven infeasible. These post-construction (i.e., permanent) stormwater control requirements apply to development projects that would otherwise not be required to install permanent BMPs as part of the Phase I or Phase II MS4 permitting program.

Trends Toward Volume Control in MS4 Permits

Traditionally, the CWA has not been interpreted to regulate stormwater runoff volumes; however, trends in MS4 permitting are moving toward incorporating runoff volume control into permit requirements to a greater degree. Channel protection standards are evolving from solely focusing on peak runoff rates to standards that call for more closely mimicking predevelopment hydrology in terms of both peak runoff rates and the total stormwater volume discharged or flow-duration requirements for certain portions of the flow regimes. Likewise, criteria for the selection of BMPs for water quality control are shifting toward a preference for BMPs that provide volume reduction versus those that primarily address pollutant concentrations through treatment and release.

In 2010, the U.S. EPA developed the MS4 Permit Improvement Guide (U.S. EPA, 2010) to provide suggestions to states and municipalities for ways to strengthen the effectiveness of MS4 permit requirements. It recommends establishing stormwater management performance standards that emphasize the use of stormwater controls that infiltrate, evapotranspire, and/or harvest stormwater in order to minimize the volume of stormwater discharged. It also suggests adopting requirements that explicitly address the modification of hydrologic cycles that occur when a site is developed through maintaining or restoring the predevelopment hydrology. The MS4 Permit Improvement Guide also acknowledges *Urban Stormwater Management in the United States*, which recommends an emphasis on hydrology.

The approaches described in the Permit Improvement Guide have been implemented in numerous areas. An example is the North Orange County MS4 permit issued by the Santa Ana Regional Water Quality Control Board (Order No. R8-2009-0030) in 2009. This permit required "priority development projects" to "retain" stormwater on-site (with no surface discharge) using infiltration, evapotranspiration, and/or rainwater harvesting BMPs to the maximum extent practicable (MEP) based on a "rigorous" feasibility analysis (California Regional Water Quality Control Board, 2009). Similar requirements are found in MS4 permits across California as well as in other regions. For example, the District of Columbia was issued an MS4 permit in 2011 that required on-site retention of 1.2 in. of stormwater from a 24-hour storm event. The retention standard may be achieved using a combination of infiltration, evapotranspiration, and stormwater harvesting (U.S. EPA, 2011).

Volume control measures have already been incorporated into a number of NPDES permits for state DOTs. For example, in 2012, the California Department of Transportation (Caltrans) was issued a renewed statewide NPDES permit, which requires the selection and sizing of BMPs to retain the 85th-percentile, 24-hour storm event. BMPs that incorporate infiltration, capture and use, or evapotranspiration of runoff are given preference (California State Water Resources Control Board, 2012). Similarly, the District of Columbia permit mentioned previously encompasses road projects sponsored by the District of Columbia Department of Transportation (DDOT) and applies the same 1.2-in. retention standard to these projects.

Trends Toward Volume Control in TMDLs

Historically, TMDLs have been developed for specific pollutants or pollutant groups. However, due to the extreme variability in source characterization, pollutant type, stormwater loadings, and the increasingly intensive land use seen across the country, it is difficult to establish TMDLs for many pollutants individually. In 2010, the U.S. EPA MS4 Permit Improvement Guide adopted guidance that recommends the use of surrogate parameters, such as volumetric stormwater flows, for evaluating TMDLs rather than specific pollutant discharge limits. This practice has already been implemented in U.S. EPA Regions 1 and 3, where flow has been used to track sediment loading and has been used in TMDLs as a proxy for pollutant loading (U.S. EPA, 2003).

At the time of writing, the future of flow-based surrogates in TMDLs was uncertain due to a recent successful court challenge of the Accotink Creek TMDL (Virginia DOT et al., v. U.S. EPA et al., 12-CV-775, U.S. District Court for Eastern Virginia, 2013). However, volume reduction may be an important option for DOTs in meeting WLAs as part of implementing TMDLs, particularly for pollutants that may be more challenging to address with treat-and-release stormwater management approaches, such as bacteria indicators.

The Endangered Species Act and Volume Reduction

The Endangered Species Act (ESA) was established in 1973 to protect threatened and endangered species and their habitats (U.S. Fish and Wildlife Service, 1973). Activities that may adversely affect these species and their habitats, such as stormwater discharges, are restricted under this act. A number of negative impacts associated with stormwater discharges, including erosion, hydromodification, and pollutant loading, can be reduced through implementing volume reduction strategies. While the application of the ESA varies widely depending on location, sensitive species, and project type, it is possible that volume reduction mandates could be imposed as part of complying with the ESA for transportation projects.

MAP-21 and Volume Reduction

The MAP-21 Act was passed in 2012 to reauthorize federally aided highway and highway safety construction programs through a more performance-based framework. One of the performance goals established is environmental sustainability (U.S. DOT, 2012), which requires that metropolitan planning organizations develop transportation plans that include provisions for stormwater management planning. Some of the approved planning approaches include watershed-based management strategies and mitigation banking. Additionally, the MAP-21 Act recognizes the role that volume reduction can play in minimizing environmental impacts by encouraging the adoption of permeable, pervious, or porous paving materials or systems designed to reduce environmental impacts, stormwater runoff, flooding, and/or pollutants by allowing the infiltration of stormwater in a manner mimicking predevelopment hydrology.

Other Regulatory Trends

The Energy Independence and Security Act passed in 2007 includes a provision in Section 438 that states that the "sponsor of any development or redevelopment project involving a Federal facility with a footprint that exceeds 5,000 square feet shall use site planning, design, construction, and maintenance strategies for the property to maintain or restore, to the maximum extent technically feasible, the predevelopment hydrology of the property with regard to the temperature, rate, volume, and duration of flow" (U.S. EPA, 2007a). Although this regulation does not cover highways, this mandate is indicative of the trends toward volume reduction observed in the municipal sector. The U.S. EPA's Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects Under Section 438 of the Energy Independence and Security Act (U.S. EPA, 2009) states that stormwater control measures that implement volume reduction, such as harvesting, infiltration, and evapotranspiration, are essential for reducing runoff volumes and pollutants loadings associated with small storms.

Also at the federal level, the U.S. EPA initiated a national stormwater rulemaking process in 2009 to establish a program that may require reduction of stormwater discharges from new and redeveloped sites. The new program may regulate reduction in discharges from existing developments as well. Some anticipated improvements include developing performance standards for new development and redevelopment to better address stormwater management in the planning and construction process, expanding the MS4 program to include minimum requirements and more comprehensive protection for all MS4s, and the establishment of specific requirements for transportation facilities. The schedule for release of draft rules is not known as of this writing. It is possible that performance standards established as part of this rulemaking process will include volume reduction standards either specifically or generally applicable to roadway projects.

Examples of Other Trends Toward Volume Reduction

There are a variety of examples that demonstrate trends toward stormwater volume reduction based on drivers other than stormwater quality management. For example, in Tucson, Arizona, a citywide ordinance requires implementation of rainwater harvesting for all new commercial developments for the explicit purpose of water conservation (Jackson, 2012). Stormwater harvesting systems, as well as infiltration of stormwater, are acceptable means of meeting this requirement. More recently, the city began offering rebates to residential customers that implement rainwater harvesting. While these approaches are implemented explicitly for water conservation, they also have benefits for stormwater management.

Similar examples of water conservation drivers exist in other states facing issues of water scarcity. For example, in Los Angeles County, California, the Council for Watershed Health has led the development of the Los Angeles Basin Water Augmentation Study. This study is a partnership between local water, public works, and wastewater agencies, the State of California, and the U.S. Bureau of Reclamation to evaluate the capacity and feasibility of stormwater management practices to augment water supplies (Council for Watershed Health, 2013).

Flood control goals have also motivated the use of volume reduction practices in some areas, most commonly achieved in large flood control basins that rely on infiltration for all or part of achieving peak flow and volume control. For example, the Los Angeles County Antelope Valley interim drainage criteria stipulate that the proposed-condition clear runoff volume match the existing-condition clear runoff volume for the 25-year storm (Los Angeles County Department of Public Works, 1987).

3.1.2 Other Design Objectives Within the Highway Project Development Process

A number of other design objectives and standards govern the development of projects within the urban highway environment; those with the highest significance are highway safety, geometric design, drainage, and flood control. In some cases, these design objectives and standards may restrict the type or extent of volume reduction approaches that can feasibly be implemented. In other cases, they may share mutual goals and benefit from the implementation of volume reduction approaches.

Highway Safety Standards and Volume Reduction

Highway safety laws, which are variable among states, remain a top priority when considering volume reduction practices. Based on the highway type and design speeds, safety regulations specify minimum safety criteria, such as shoulder widths and roadway slopes. Safety standards that are relevant to volume reduction approaches include:

- Geometric design standards,
- Vegetation and landscaping standards,
- Drainage standards.

These are considered in greater detail in the following sections.

Highway Geometric Design Standards

Highway geometric design refers to the layout of highways, both horizontally and vertically. AASHTO has published its "Green Book" (*A Policy on Geometric Design of Highways and Streets*) in various forms since the late 1930s, with the most recent edition issued in 2011 (AASHTO, 2011b). The Green Book provides a series of guidelines for geometric design within which the designer is afforded a range of flexibility. In order for the design criteria in the Green Book to become a standard, it must be adopted by a particular state (or may be set by court decision). The key requirements for minimum geometric design standards are related to safety (e.g., site distance, stopping distance, designs speed) and serviceability (e.g., land widths, overpass heights).

Because volume reduction practices require space and are typically located within the highway right-of-way, geometric design standards are important constraints in the application of volume reduction approaches. Geometric design standards can limit the flexibility of the designer in adjusting site designs to accommodate volume reduction. Geometric design standards also limit the features that can be located within the portions of the roadway that may be traversed by errant vehicles. Features associated with VRAs, such as slopes, depressions, inlet and outlet structures, soils with low structural strength, and vegetation, may have safety considerations. Safety considerations of VRAs are further discussed in Chapter 4.

Vegetation and Landscaping Standards

AASHTO's *Roadside Design Guide* (AASHTO, 2011a) and the FHWA's *Vegetation Control for Safety: A Guide for Street and Highway Maintenance Personnel* (FHWA, 2008) provide guidance for the types of vegetation that can be used in the road right-of-way. These guidance documents are incorporated in various ways into state highway regulations. In terms of safety, the proximity of landscaping and vegetation to a roadway can obscure or limit a driver's view of traffic control devices, other vehicles, wildlife, and pedestrians and bicycles. Larger vegetation, such as trees or hedges, which are often near highway shoulders or interchanges, may become obstacles if not maintained and placed properly. These criteria are particularly important to consider in evaluating and applying vegetated volume reduction approaches near travel lanes.

Drainage and Flood Control

Efficient and reliable drainage of stormwater from travel lanes is a critical safety consideration in the design of roadways. FHWA provides guidance for highway drainage design in *Highway Hydrology*, 2nd Edition, and the *Urban Drainage Design Manual, Hydraulic Engineering Circular 22*, Third Edition (FHWA, 2002 and FHWA, 2009). State DOTs typically adopt drainage criteria that specify acceptable hydrologic and hydraulic methods and minimum levels of service for travel lanes. The design of volume reduction practices must comply with these regulations and not interfere with the level of service needed for the drainage of travel lanes.

State and/or local agencies also typically regulate the rates and/or volumes of stormwater runoff discharging from highways to off-site receiving waters or conveyance systems to ensure that the discharge volumes do not cause or contribute to flooding of downstream areas. Typically this is accomplished through maintaining runoff volumes or flow rates within an acceptable percentage of predevelopment values for one or a set of design storm events. Additionally, when a highway is located within a federally established base or a 100-year floodplain, National Flood Insurance Program regulations will need to be met [Federal Emergency Management Agency (FEMA), 2012]. In general, volume reduction practices that are designed to manage runoff from smaller storm events (i.e., 85th percentile) have relatively little effect on peak flow rates for large, infrequent events; however, they may provide some benefit. Facilities may also be combined to provide volume reduction of smaller storms and peak flow reduction of large, infrequent storms (via detention).

3.2 Key Technical Considerations in Applying Stormwater Volume Reduction Practices

This section is intended to familiarize the user with volume reduction processes and introduce key technical factors in achieving volume reduction. It is intended to help the user answer the following questions:

- What is meant by "volume reduction"? What metrics are used for assessing performance relative to volume reduction?
- By what processes is the volume of stormwater runoff reduced?
- What are the most important technical factors in achieving volume reduction?
- How do the project type and the physical setting of the project influence opportunities and constraints for volume reduction?
- What are the obstacles to incorporating volume reduction approaches?

3.2.1 Volume Reduction Metrics

In a general sense, "volume reduction" refers to reducing the amount of stormwater runoff volume discharged to receiving waters via overland flow or a stormwater conveyance system. When assessing the performance of a certain practice or project in achieving volume reduction, it is necessary to use more specific metrics.

Table 1 summarizes various metrics that may be used to describe volume reduction performance as a function of resource protection goals and regulatory requirements.

Table 1. Summary of volume reduction metrics potentially applicable in the urban highway environment.

Metric/Description	Potential Applicability
Percent volume reduction – What is the relative change in long-term surface runoff volume? For example, how much less surface runoff volume does the site produce on a long-term average basis compared to the same site without controls? Compared to the site prior to the project or in the predevelopment condition?	• Quantify the benefit of VRAs to reduce long-term pollutant loading as part of a TMDL or other opportunistic retrofit action. • Demonstrate compliance with a project performance standard based on mimicking predevelopment discharge or managing a certain fraction of runoff (i.e., 80%).
Retention design storm – What is the largest storm event that can be retained by the VRA such that it does not cause surface runoff from the site? How does this compare to regulatory design-storm retention requirements?	• Compliance metric for design-storm–based retention standards (i.e., 85th-percentile storm based on a measured precipitation record). Note that a full description of the metric should also state the inter-event drawdown time assumed to ensure effectiveness. • Simple surrogate for long-term reduction in pollutant loads. • Simple surrogate for long-term reduction in stream energy and channel erosion.
Frequency of discharge – How does the change in the site and the use of VRAs change the frequency of site surface discharge? For example, how much less frequently does the water discharge from the site compared to the same site without controls? Compared to the site prior to the project or in the predevelopment condition?	• Evaluate how well VRAs mitigate increases in the frequency of runoff, which is a common impact of development.
Flow duration – What is the change in flows and durations of surface runoff? How does the use of VRAs influence the flow rates and durations of flows from the site compared to the same site without controls? Compared to the site prior to the project or in the predevelopment condition?	• Evaluate how well VRAs address flows that cause stream erosion. • Evaluate how VRAs may influence flow-dependent biological processes.

3.2.2 Volume Reduction Processes

Reduction of highway runoff can be achieved through using practices that incorporate infiltration, ET, and/or beneficial uses of captured runoff (U.S. EPA, 2010). Infiltration and evapotranspiration occur naturally to some degree in most conditions but may occur at different relative magnitudes when reducing runoff volume in the post-project condition from those that were present in pre-project or predevelopment hydrology (see Appendix D). The sections that follow discuss the role that each runoff reduction process plays in predevelopment, natural hydrology, and in reducing runoff volume in post-project conditions, both with and without VRAs.

Predevelopment Hydrology

Predevelopment or natural conditions refer to the undeveloped land left to naturally evolve in a given climate and geologic setting. The major types of natural vegetation in the United States are shrubs, grasslands, softwood forests, and hardwood forests (Kuchler, 1966; U.S. EPA, 2007b). The predevelopment hydrologic cycle is defined by several interrelated fluxes of water (Maidment, 1992). As precipitation falls, it is first subjected to interception by leaves and stems of vegetation, from which the intercepted water either evaporates or falls through to the ground surface. Precipitation reaching the ground surface is divided between infiltration (i.e., movement of water into the ground surface), surface runoff (i.e., movement over the ground surface), and evaporation. Water that moves into the ground surface is further subdivided between deep percolation to groundwater (i.e., vertical migration through the unsaturated zone of the subsurface soil), wicking and evaporation from the soil surface, uptake and transpiration by plants (i.e., in the root zone), and throughflow or interflow (i.e., lateral migration of water back to the ground surface down gradient from where it entered). The water that percolates to groundwater is divided between that which emerges as base flow in streams and that which flows to an aquifer (i.e., an underground layer of water-bearing permeable rock, gravel, sand, silt, or clay). Substantial transient storage exists in the predevelopment hydrologic cycle in the form of ponded and flowing water on the ground surface, soil moisture in unsaturated soil layers, and groundwater. Figure 3 illustrates the elements of the natural hydrologic cycle.

Predevelopment hydrologic response refers to the relative magnitude of the elements of the predevelopment hydrologic cycle. The unique response of each watershed is controlled by complex interactions between climate, vegetation, soils, topography, and geology. Definitions of predevelopment hydrology vary both by jurisdiction and location. In addition, some jurisdictions reference the existing conditions, or pre-project conditions, as the hydrologic baseline rather than predevelopment or natural conditions.

General Effects of Land Development on Hydrologic Response

Land development activities, including highway construction, tend to result in an increase in the amount of impervious cover, a decrease in vegetative cover, and the compaction of soils (incidental or intentional). Development may also result in the importing of water to the watershed via potable or non-potable municipal supplies. The typical effects of these changes on the hydrologic cycles include:

- Reduction in rainfall-derived infiltrated volume and the corresponding reduction in rainfall-derived deep percolations volumes, primarily as a result of the increase in impervious surface and reduction in soil infiltration rates due to compaction;
- Reduction in rainfall-derived evapotranspiration, primarily due to the removal of vegetation, removal of the duff layer (i.e., plant litter or dead plant material such as leaves and bark that have fallen to the ground and partially decayed) and surface interception storage, and the reduction in the storage capacity of the root zone via compaction;

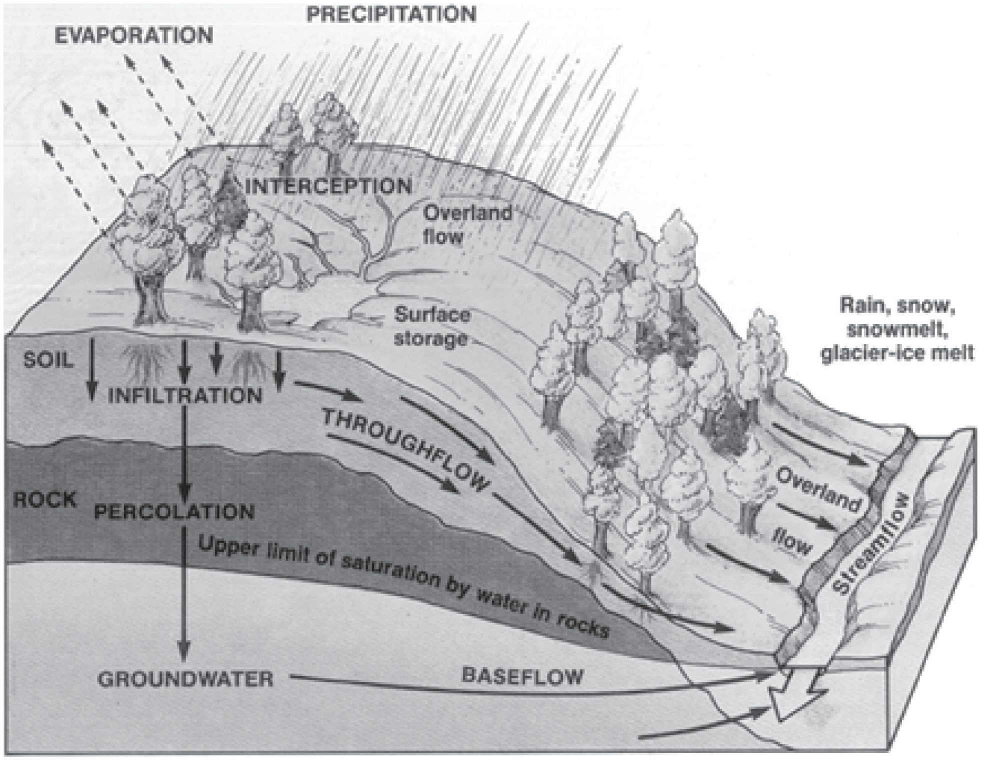


Figure 3. Major components of the natural hydrologic cycle. Source: http://snobear.colorado.edu/IntroHydro/geog_hydro.html. Notes: In this manual,* throughflow *is synonymous with* interflow*; as shown in this figure* evaporation *is intended to include* evaporation *and* transpiration*, collectively* evapotranspiration*.

- Increase in surface runoff, as a result of the increase in impervious surfaces and increased degrees of compaction, and also as a natural effect of reductions in the other two key elements of the hydrologic cycle; and
- Potential for increases in infiltration and percolation due to the introduction of irrigation water, as well as the potential for increases in dry-season ET as a result of a change in vegetation type and introduction of irrigation (Maidment, 1992).

Similar to the predevelopment hydrologic cycle, the post-development hydrologic response to development is also controlled by complex interactions between climate, vegetation, and soils and geology.

Effects and Roles of Volume Reduction Processes in Mitigating Changes in Hydrology

Each volume reduction process available to VRA planners and designers has specific attributes relative to its effects and roles in mitigating changes in the hydrologic cycle caused by land development. An understanding of these processes helps set reasonable expectations for their level of achievable performance and helps identify potential negative consequences that each could introduce.

Evapotranspiration occurs whenever water is present on the surface or in the root zone, at a rate controlled by the climatic conditions, the type of vegetation, and soil moisture conditions. ET follows seasonal trends, most strongly influenced by temperature but also influenced by wind speed, humidity, solar insolation, and plant life cycle. Rates of ET can range from near zero during cold, wet weather to more than 10 in. per month in hot, arid parts of the country (Vogel and Sankarasubramanian, 2005); however, even at peak ET rates, the rates of ET tend to be slower than precipitation rates and soil infiltration; at 10 in. per month, this corresponds to approximately 0.3 in. per day, or about 0.01 in. per hour on average. Of the factors that a VRA designer can control, the surface area of the VRA is the most important with respect to ET, followed by the storage provided in the soil and the type of vegetation selected. Limitations exist when trying to match pre-project ET flux rates when removing, compacting, or covering vegetated and soiled areas. This can result in an increase in recharge volume compared to pre-project conditions (discussed in Appendix D). The most effective VRAs for ET are those that cover a large area (e.g., a filter strip on a roadway shoulder) and have significant volumes of soil such that water is held in storage between precipitation events.

Infiltration into the soil occurs when water is present on the ground surface and is controlled by the infiltration rates of the soil, the land slope, and the rate of precipitation or melting of frozen precipitation (or inflow to a VRA). Initial infiltration rates into soil tend to taper off as additional water is infiltrated, until a steady-state, saturated infiltration rate is reached (Maidment, 1992). Soils can have saturated infiltration rates ranging from near zero for clays and bedrocks to an excess of 100 in. per hour for coarse sands and gravels (Maidment, 1992; Rawls and Brakensiek, 1983).

Percolation below the root zone occurs when rates of input exceed the capillary storage of the soils in the root zone and rates of ET over a sufficient period of time such that the moisture in the root zone exceeds the capillary suction storage (Maidment, 1992). In the natural hydrologic condition, peak infiltration capacities of porous soils are rarely approached because rates and quantities of rainfall are limited and a large percentage of precipitation is stored in the root zone. However, in the developed condition, VRAs typically receive runoff from areas much larger than their own footprint, which has the effect of applying higher flow rates and volumes of water over the area of infiltration, thereby approaching the infiltration capacity of the underlying soils more frequently and for longer durations. The effect is that infiltration-based VRAs, such as infiltration basins, infiltration trenches, bioretention/rain gardens, and pervious pavements, have the potential to effectively mitigate increases in surface runoff volume within a relatively small footprint. Actually, in many cases, because of the reduction in ET surface area of a site, they often tend to result in an increase in percolated volume when compared to natural or pre-project conditions. Increased infiltration over natural conditions may be advantageous for groundwater replenishment or, in some cases, may be detrimental (discussed in greater detail in Appendix D).

Harvest and use is a non-natural process in which stormwater is captured, held, and used for beneficial purposes, such as irrigation and non-potable water supply. The application of harvest and use for reducing stormwater runoff volumes is an emerging practice that has been applied in certain project types where stormwater can be used for irrigation, flushing of toilets, vehicle washing, cooling tower make-up water, or other uses. The rate of demand for harvested water is analogous to ET rates and infiltration rates in other systems. The ultimate fate of water that is used for beneficial purposes depends on the use—for example, water that is used for irrigation becomes ET or infiltration, and water that is used to flush toilets is conveyed to a wastewater treatment plant or septic system.

Hydrologically referenced discharge refers to the controlled release of stored water in such a way that flow rates and timing of discharge mimic natural surface hydrologic response. Research has suggested that controlled discharges from certain stormwater control measures may mimic the receding limb of the natural stream-flow hydrographs in some conditions (DeBusk et al., 2011). The implication of this finding is that the definition of what is "retained" may not be limited to only water that is discharged to deeper infiltration, ET, or harvest and use. Where VRA discharges are released to surface waters at rates that mimic natural base-flow rates following storm events, some or all of this treated discharge may also be considered as retained or reduced rather than as a direct surface discharge. This may have significant implications on the practicability of volume reduction in constrained environments, where means for draining BMPs between storms would otherwise be very limited or would introduce potential negative consequences, such as over-infiltration and the creation of dry-weather seeps. This concept is discussed further in Chapter 4.

A more comprehensive discussion of the VRAs applicable to the urban highway setting and their relative reliance on ET, infiltration, beneficial uses, and hydrologically referenced discharge is presented in Chapter 4.

3.2.3 Physical Setting and Site Design Factors Influencing Volume Reduction Effectiveness, Feasibility, and Desirability

The effectiveness, feasibility, and desirability of volume reduction approaches are strongly dependent on the physical setting of the project and the project site design. These key terms are defined in the context of this manual in the following.

Effectiveness refers to how well VRAs achieve their overall goal of reducing surface runoff volumes, based on one of more volume reduction metrics.

Feasibility refers to whether it is physically and financially practicable to implement a volume reduction approach.

Desirability refers to whether the outcome of the approach would be the most advantageous to address the underlying issues, and whether negative consequences may result that outweigh the volume reduction benefits. An approach could be feasible but not desirable if, for example, a potential impact to other environmental media or infrastructure may result.

Physical setting refers to the physical characteristics of the project site, including climate characteristics, topography, soil, groundwater, and watershed properties (as well as the location of the project within the watershed).

Project site design refers to the project layout and earthwork, including vertical and horizontal alignment, slopes, location of landscaping relative to travel lanes, and alignment of storm drains. The proposed location and layout of VRAs are integral elements of site design.

The following sections introduce the key physical setting and site design factors that influence the effectiveness, feasibility, and desirability of volume reduction approaches. Evaluation and feasibility criteria for VRAs are described in greater specificity in Chapter 5.

General Factors Influencing Effectiveness of VRAs

The effectiveness of a VRA for achieving volume reduction is primarily a function of (1) the capacity of the VRA to capture and store stormwater runoff and (2) the ability of the VRA's volume reduction processes (i.e., infiltration, ET, and harvest and use) to recover the storage capacity of the VRA during and between storm events.

VRA storage capacity. The capacity of a VRA to capture and store runoff is controlled, in part, by the size of the storm that the VRA is designed to address. The volume of storage provided in the VRA can include ponded water storage (either above or below ground and surface exposed or in a tank) and the pore capacity of soils or stone reservoirs. The capacity of a VRA to capture runoff is also a function of the ability to convey water to the VRA, which may be limited by topography or conveyance system design. Clearly, if storage capacity is provided in a location where water cannot be conveyed to it or is much larger than the volume of runoff that could be conveyed to it, then this storage capacity would have more limited effectiveness.

Storage recovery rates. The capacity of volume reduction processes to recover the storage capacity of a VRA is important for achieving long-term volume reduction. Systems that drain more quickly tend to allow greater capacity on average for subsequent storm events as well as greater volume reduction during events, which results in a greater fraction of long-term runoff volume being retained. The recovery pathways for a particular BMP depend on the facility configuration, site-specific soil conditions, and local climate. For example, the depth of storage in a VRA and the underlying infiltration rate control the time it would take for the VRA to drain completely (i.e., the drawdown time). Drawdown of stored water can be achieved through a combination of infiltration of captured stormwater into subsoil, slow release via an outlet (i.e., underdrains, after treatment in soil media), ET, and beneficial uses of captured water.

The minimum storage recovery rate for a VRA should be set to ensure that project goals are met on a long-term basis. Therefore, the storage recovery rate is a critical factor in determining whether a VRA is feasible. Where the storage recovery rate is lower than project goals, some level of volume reduction may still be feasible, but it may need to be augmented with other discharge pathways (e.g., treated surface discharge) to provide reliable long-term performance, or significant additional storage may need to be provided over and above required sizing. Typically, a drawdown time in the range of 24 to 72 hours is acceptable [Orange County Public Works, 2011; Water Environment Federation (WEF)/ASCE, 1998]. However, the sensitivity of drawdown time on long-term volume reduction is strongly dependent on local precipitation patterns. Therefore, drawdown criteria should be established on a location-specific basis to achieve intended design goals. For example, Orange County established a maximum drawdown time of 48 hours for BMPs (Orange County Public Works, 2011). This limit was set based on the results of a continuous simulation analysis, which demonstrated that this drawdown time in combination with storage set at the water quality design volume would result in at least 80% capture of average annual runoff volume. However, Orange County also allows longer drawdown times to be used if compensatory increases in storage volume are also provided. Similarly, systems that can drain more quickly may be able to provide less storage volume.

Figure 4 provides an example nomograph from the Volume Performance Tool (on the CD-ROM that accompanies this report) to illustrate the dual roles of storage volume and drawdown time in long-term performance. Various combinations of storage volume and drawdown time can result in the same level of long-term volume reduction performance. This nomograph is the result of a large number of continuous simulation runs in the U.S. EPA Storm Water Management Model (SWMM). Figure 5 is also developed from the Volume Performance Tool and illustrates the trend between drawdown time and long-term performance for various cities representing distinctly different climates. It can be seen that different sensitivities to drawdown time exist in different regions. Where rainfall tends to have lower intensities and extended events (e.g., Portland, OR and west of the Cascade Range in the Pacific Northwest in general), the sensitivity to drawdown time is high, while in areas where events are typical shorter with more space between consecutive events (e.g., Austin, TX), the sensitivity to drawdown time is less. In all cases, the role of drawdown time on long-term performance is appreciable and must be considered in feasibility analyses.

Chapter 5 describes the Volume Performance Tool, which has been developed to estimate volume reduction effectiveness based on selected site-specific factors. Table 2 and Table 3 provide an introduction to how physical setting and project site design influence volume reduction effectiveness.

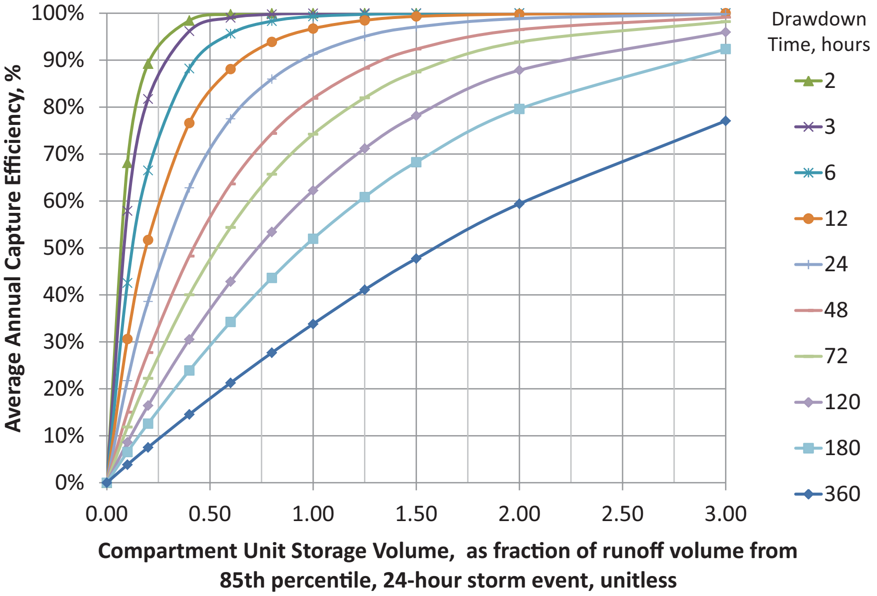
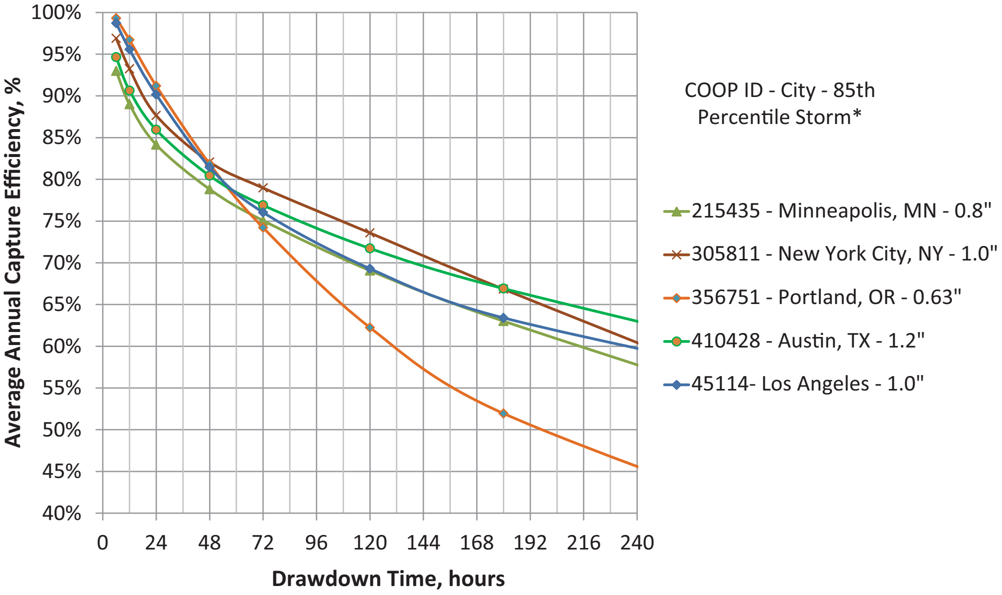


Figure 4. Example nomograph illustrating the influence of storage volume and drawdown time on long-term capture efficiency (and volume reduction)—example Portland, OR—COOP ID: 356751. Developed from the Volume Performance Tool.



*For each city, the unit storage volume was set to the runoff from the 85th percentile, 24-hour precipitation depth

Figure 5. Example chart illustrating the influence of drawdown time on long-term capture efficiency (and volume reduction)—five cities. Developed from the Volume Performance Tool.

Table 2. Influence of physical setting on effectiveness, feasibility, and desirability of volume reduction approaches.

Factor	Indicators/Metrics	Influence on Effectiveness	Influence on Feasibility and Desirability
Local climate	• Average precipitation intensity, depth, duration, and seasonal characteristics • Typical inter-event dry periods • ET rates and patterns of ET relative to precipitation • Freeze/thaw cycles	• A given VRA design will achieve better volume reduction in climates with lower intensities and depths of rainfall (holding inter-event times fixed) and where precipitation occurs more evenly throughout the year. • A given VRA design will achieve better volume reduction in climates where average inter-event dry periods are longer (holding intensities and depths of rainfall fixed). • High ET rates (high temperatures, sunny, low humidity) allow for increased reduction via ET, particularly when high ET conditions are present between rainfall events in the wet season. Climates that receive the majority of rainfall when ET is low tend to have lower potential for ET-based volume reduction.	• Areas that experience frequent freeze/thaw cycles may present challenges for design of some VRAs. • Roads in cold climates may require additional salting for safety reasons, which may pose an elevated risk of groundwater contamination. • Arid or semi-arid regions that have longer dry periods may not be able to sustain VRAs with certain vegetation or permanent pools. In addition, the tendency for concentrated precipitation periods reduces the effectiveness of harvest-and-use systems.
Soil and geologic characteristics and conditions	• Soil type • Infiltration rate • Level of compaction • Depth to bedrock	• Sandy, loamy soils with good infiltration rates can allow infiltration VRAs to drain more quickly than would tighter soils. • Soils that are uncompacted or lightly compacted tend to have higher infiltration rates than similar soils that are compacted. • Shallow depth to bedrock may result in groundwater mounding that limits the reliable rate of infiltration.	• Clay soils tend to have low infiltration rates, and their structural strength tends to be more sensitive to moisture content than sandy soils; the combination of these factors may greatly reduce feasibility of infiltration in clay soils. • Compaction of fine-grained soils may be necessary for structural stability but may greatly reduce the infiltrating capacity of soils. • Expandable and collapsible soils pose challenges for volume reduction. • Sandy or gravelly soils with low organic content and high infiltration rates may pose an elevated risk of groundwater quality impacts.
Groundwater conditions	• Depth to seasonally high groundwater table • Potential for groundwater mounding • Karst aquifers[1]	• Shallow groundwater may result in groundwater mounding that limits the reliable rate of infiltration or causes infiltration VRAs not to drain during high groundwater conditions. • Infiltration in karst aquifer regions may lead to the development of sinkholes in VRAs or down gradient.	• Shallow groundwater may render infiltration infeasible or undesirable due to potential for groundwater contamination, geotechnical stability issues, or groundwater table impacts. • Karst aquifers provide a direct pathway for groundwater contamination and can result in catastrophic subsidence (sinkholes).
Topography	• Longitudinal slope • Cross-slopes • Spacing between low points	• Highways with longitudinal slopes may provide more opportunity to route stormwater to preferred locations than flat sections; they also may allow fewer and more centralized VRAs. • Spacing of low points may dictate locations and spacing of VRAs. • Highways on steeper cross-slopes tend to have steeper embankments and less space in rights-of-way for VRAs. • Steep slopes may limit the types of vegetated conveyance systems that can be used (higher velocities, more potential for erosion).	• Highways on steep cross-slopes tend to have greater quantities of cut and fill and tend to have greater potential for geotechnical issues, including impacts from saturated soils that result in landslides. • Very flat areas may have limited groundwater flow gradient and more potential for mounding.
Watershed characteristics, project location in watershed, and adjacent land uses	• Watershed topography/ slope • Degree of development of watershed • Upstream drainage area • Proximity to adjacent structures • Off-site drainage to project • Presence of ephemeral streams	• Where watershed-scale approaches are available in coordination with adjacent landowners, more effective volume reduction may be achieved than with approaches within the right-of-way (see Section 5.5 for more information). • Off-site drainage into the right-of-way may dilute highway runoff and reduce effectiveness for addressing highway pollutants; however, projects may show net benefits if off-site drainage can be addressed in project VRAs. • If off-site drainage into the right-of-way has high sediment loading, clogging of infiltration VRAs may occur more quickly.	• Buildings, utilities, or roadways in close proximity to the right-of-way may pose feasibility constraints for infiltration. • Smaller watersheds with significant development may be more sensitive to potential water balance impacts of VRAs (i.e., if upstream development has already increased percolation compared to natural conditions and additional percolation may cause increases in groundwater elevations or base-flow discharges and resulting impacts on ephemeral streams). • Off-site drainage into the highway from pollutant hot spots, such as industrial land uses, may pose risks to groundwater if water is infiltrated.

1 – Karst aquifers are geological formations that are composed of soluble bedrock that conduct water through larger conduits created by the dissolution of rock, often connecting directly to groundwater reservoirs. They are often characterized by large interconnected caves and can contain sinkholes.

Table 3. Influence of project type and layout on effectiveness, feasibility, and desirability of volume reduction approaches.

Factor	Indicators/Metrics	Influence on Effectiveness	Influence on Feasibility and Desirability
Project type	• New project • Modification of existing roadway (e.g., lane addition) • Retrofit project (e.g., rebuilding of existing lanes)	• New projects may have more flexibility to allow space for VRAs than modifications or retrofits. • New projects may provide better ability to protect soils from compaction during construction. • Modifications and retrofits provide opportunities to address existing roadway runoff and can result in net reduction in runoff volume compared to existing conditions.	• Impacts on existing utilities, structures, and other infrastructure from infiltration may be more difficult to avoid in modification and retrofit projects. • Existing rights-of-way can have greater potential for existing soil or groundwater contamination. • Incremental costs may be lower in new projects and modifications than retrofits, particularly when (1) VRAs include elements that offset traditional design costs (i.e., permeable pavement in place of traditional pavement), or (2) VRA costs are heavily dependent on excavation, which can be balanced as part of a new project.
Highway type	Highway segment type can be used as a composite indicator of many of the other factors listed in this table. See highway-type fact sheets in Section 3.3 for a description of typical highway segment types and key opportunities and constraints specific to eight standard urban highway types.		
Amount of open space in medians and shoulders	• Ratio of tributary area to receiving area • Slope of open space • Future proposed development restrictions (i.e., median reserved for future land additions) • Sediment generation	• Higher volume reduction is possible when ratios of VRA area to tributary area are higher. • Shallower slopes tend to provide more opportunity for volume reduction (wider suite of and larger VRAs; slower velocities). • Open space further from travel lanes may allow a broader suite of VRAs to be used; may allow lesser compaction below VRAs. • Reduction in long-term effectiveness if part or all of VRA is removed as part of future development plans. • Sediment loading in VRA tributary area may reduce effectiveness of infiltration VRAs (clogging).	• Open space in shoulders and medians may have a dedicated role in errant vehicle recovery; restrictions in usage may apply. • Open space further from travel lanes may allow infiltration with lower risk of geotechnical issues. • In good soil conditions, bioretention and other infiltration-based VRAs have the capability to capture and retain stormwater runoff from areas that are much larger than their respective footprint areas. • VRAs that rely primarily on ET for volume dissipation require large surface areas to maximize the extent of contact with the atmosphere.
Shoulder width and usage	• Expected traffic on shoulders • Shoulder width	• Wide shoulder widths may allow for larger storage reservoirs for permeable shoulders (see Chapter 4).	• Lower traffic loading on shoulders may allow for more cost-effective implementation of permeable shoulders (see Chapter 4).
Interchange spacing and type	• Spacing • Type (diamond, cloverleaf, etc.) • Alignment with outlet points	• Intersections may provide large open spaces conducive for infiltration into soils with less compaction. • Intersections may allow for greater ponding depths and a wider range of vegetation selection. • Where water can be effectively routed to intersections, the regional scale of VRAs may allow for more effective maintenance. • New crossings and interchanges may present opportunities to manage existing runoff from existing roadway.	• See interchange-type fact sheets in Section 3.3 for key opportunities and constraints specific to diamond and cloverleaf intersections.
Proposed grading and drainage	• Elevation differentials between travel lanes and adjacent land • Depth of cut and fill • Embankment slopes • Drainage pathways • Storm-drain alignments	• The ability to route runoff to shallow vegetated slopes improves volume reduction performance compared to steeper slopes or more concentrated inputs. • Fill areas tend to be highly compacted, which tends to reduce infiltration rates. • Embankment slopes influence the depth of ponding that can be provided; more challenging to provide storage volume.	• Infiltration in the vicinity of fill structures and embankments may increase the potential for geotechnical hazards. • Connections to off-site drainage can restrict placement of VRAs. • Grading can present an opportunity for volume reduction in new projects if VRAs are accounted for in the project balance of cut and fill (i.e., negligible incremental cost for excavation).
Highway landscaping/ vegetation	• Type, location, and density of vegetation and landscaping • Location of soil amendments	• The use of vegetation in medians or shoulders can enhance infiltrating capacity, operate as natural pretreatment to VRAs, and increase visual attractiveness.	• Vegetation has the potential to interfere with a driver's line of sight or cause collision hazards; use should be limited by these considerations. • Soil amendments may not be permitted in errant vehicle recover zones if strength of soil would be significantly reduced.
Maintenance access	• Proximity to travel lanes • Space for parking maintenance vehicles • Slopes leading to VRA areas	• Maintenance is critical for long-term effectiveness of VRAs; designing to allow for efficient maintenance tends to improve long-term effectiveness.	• Where maintenance would require lane shutdowns, the cost of maintenance can increase significantly.

General Feasibility and Desirability Factors

The feasibility and desirability of VRAs is strongly influenced by site-specific and watershed factors as well as the nature of the specific VRA. In general, feasibility and desirability are assessed by asking three fundamental questions:

1. **Is it physically possible to implement a certain VRA based on the site conditions?** For example, do soil or geologic (e.g., bedrock) conditions render infiltration rates negligible? Does the site layout present no opportunity for a specific type of VRA?
2. **Would the use of a certain VRA have the potential to result in undesirable physical consequences to the project or the site environs?** For example, would the use of a VRA pose an unacceptable elevated risk of groundwater contamination? Or would infiltration in excess of natural conditions potentially cause geotechnical issues or down-gradient habitat concerns?
3. **Does the cost required to construct the VRA or mitigate potential risks posed by the VRA outweigh the volume control benefits it would achieve?** For example, it may be physically possible to infiltrate water into clay soils at some small level and possible to mitigate soil stability issues associated with infiltration; however, the resulting benefit may not warrant this added project expense of additional area consumed or costs.

Chapter 5 provides a framework for addressing these questions.

3.3 Urban Highway Types

Urban highways vary greatly in their attributes and physical settings relative to achieving volume reduction. The general implications of physical setting and project layout are introduced in the previous section. While each urban highway project will have unique attributes, the exercise of classifying highway types into categories can be a useful tool for understanding potential opportunities and constraints in different highway types. This section of the guidance manual identifies eight different urban highway types and describes the characteristics that are common to each. Overall, this section is intended to help the user answer the following questions:

- What is the range of highway project types covered by this guidance manual?
- How does highway type influence opportunities and constraints for volume reduction?

3.3.1 Project Attributes and Types

This manual categorizes urban highways into eight different representative highway types based on geometric design variations typical of urban freeway design as described in Chapters 8 and 10 of AASHTO's *A Policy on Geometric Design of Highways and Streets* (AASHTO, 2011b). Each of these highway types is intended to encompass a variety of geometric configurations that are common in urban highway environments and to represent these grouped configurations in a manner that allows for cohesive and effective guidance on the constraints and opportunities for volume control particular to each type. Some highways may contain more than one of the highway types described, in which case guidance found in the fact sheets should be combined. For example, a single highway project may include a ground-level highway segment, a looped interchange, and a depressed highway segment. Guidance from the three fact sheets associated with these highway types could each be used for the respective sections.

Six of the highway types describe linear highway sections, and the remaining two types describe common interchange types. The eight representative highway types are:

- Ground-level highway segments
- Ground-level highway segments with restricted cross-sections
- Highway segments on steep transverse slopes
- Depressed highway segments
- Elevated highway segments constructed on embankments
- Elevated highway segments constructed on viaducts
- Linear interchanges
- Looped interchanges

The sections that follow include fact sheets that contain the basic geometry, important elements of the physical setting, opportunities for stormwater volume reduction, and typical plan views and cross-sections of each representative highway type. The fact sheets also present the key constraints that may limit the implementation of certain VRA types due to feasibility and desirability factors. For example, many VRAs have space and slope requirements for safety and efficiency purposes that could limit their application in certain highway applications.

3.3.2 Ground-Level Highway Segments

Ground-level highway segments are found in both urban and rural settings but are more common in rural settings because of lower expense, high design speeds, greater availability of space, fewer conflicts with surface streets (under-crossings and overpasses), and less concern about highway noise. Where ground-level freeways are found in urban areas, these types of segments are most often found in suburban areas and the urban fringe.

Defining Physical Features

- Wide medians and greater outer separations and borders are designed to provide aesthetically pleasing greenbelts and to insulate the freeway from the surrounding areas.
- Ground-level highway segments are often slightly elevated above adjacent areas based on drainage and earthwork considerations.
- Curbs and concrete barriers are uncommon.
- Medians and shoulders are generally constructed with shallow slopes designed to allow for errant vehicle recovery.
- Access roads and ramps may run parallel to travel lanes.
- Dispersed overland flow to ditches and inlets is common.

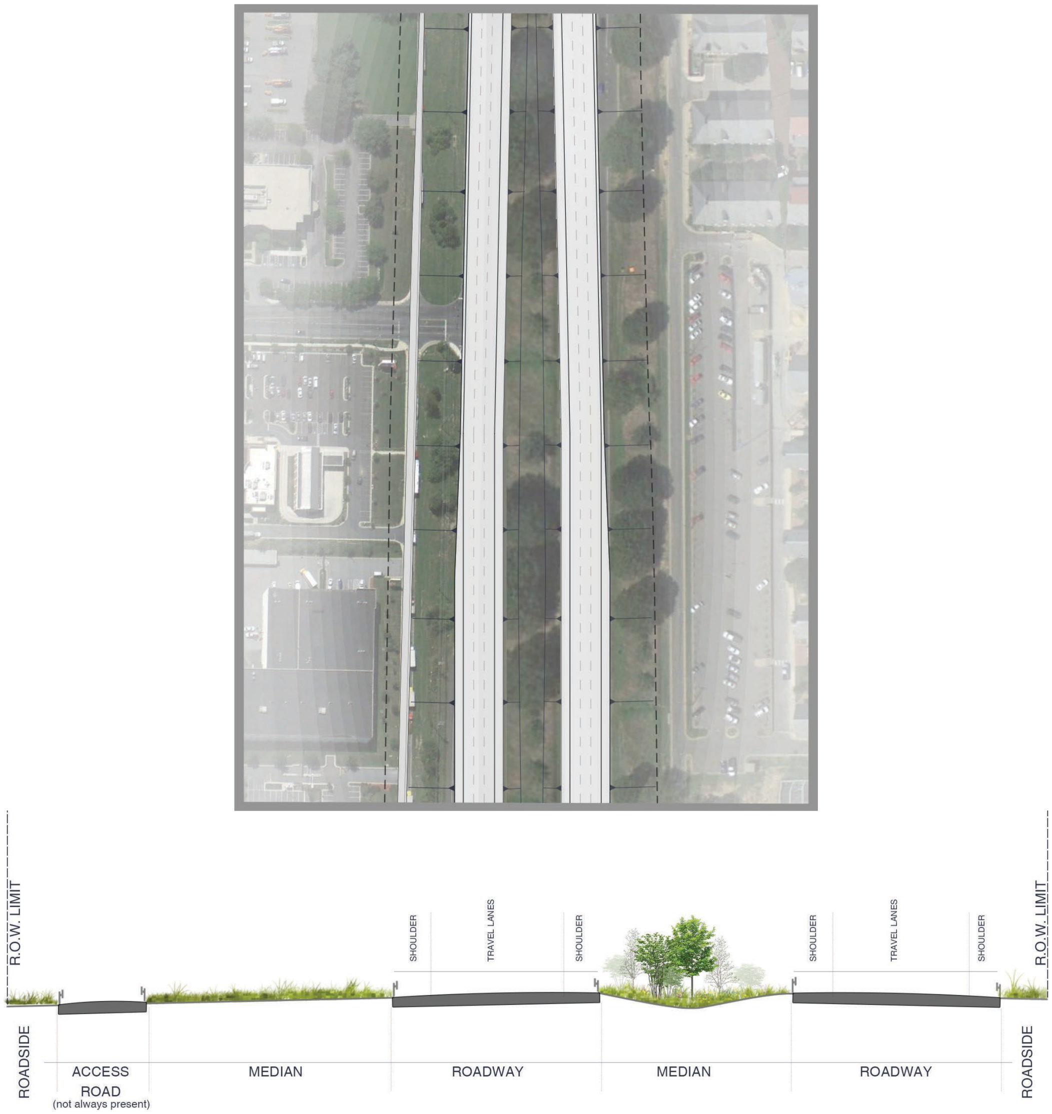
Key Constraints for VRAs Related to Highway Type

- The errant vehicle recovery purpose of medians and shoulders must be maintained after VRAs are installed; this may limit landscape selection, the potential use of compost amendments, and the use of depressed-basin–type VRAs.
- Elevation differentials between the roadway and potential VRA locations may be limited with respect to routing of stormwater and design of VRAs.
- Long-term plans may include subsequent paving of areas that would otherwise be used for VRAs.

Key Opportunities for VRAs Related to Highway Type

- Shallow shoulder slopes can be constructed to enable dispersion of stormwater.
- Long stretches of uninterrupted shoulder and median area provide opportunities for VRAs with linear geometry.
- Wide shoulders may allow VRAs to be located well away from travel lanes; a broader suite of VRAs may be used.

Example Plan and Profile



Not to Scale

- Vegetated conveyance features are common in standard sections, reducing the incremental costs of VRAs.

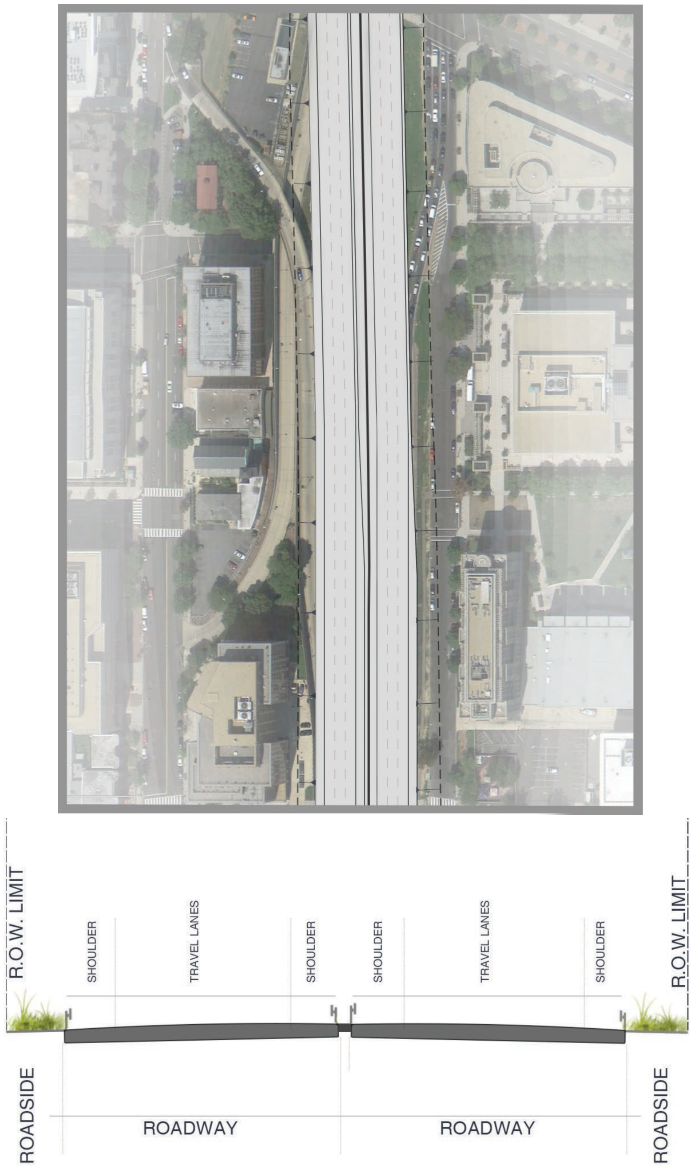
3.3.3 Ground-Level Highway Segments with Restricted Cross-Sections

Ground-level highway segments with restricted cross-sections are common in the urban highway environment as a result of the common need to provide high traffic capacity within a limited right-of-way width. Right-of-way area is commonly influenced by the limits of existing development or natural topographic features. Ground-level highway segments can evolve to become more constrained as subsequent projects add lanes or other infrastructure within an existing right-of-way.

Defining Physical Features

- Segment cross-sections are often entirely paved, including the median. Some pervious area may remain on the shoulders or in the median.

Example Plan and Profile



Not to Scale

- Curbs commonly collect and convey stormwater runoff to storm-drain inlets rather than to open swales.
- Frontage roads may be present.
- The highway is usually slightly elevated above adjacent ground as dictated by drainage and earthwork considerations.

Key Constraints for VRAs Related to Highway Type

- Space for vegetated VRAs may be limited.
- Access for construction and maintenance activities may be limited or require lanes to be shut down.
- Buildings, foundations, retaining walls, or sound walls outside of the right-of-way may be located closer to the travel lanes than in many other highway types.

- Concrete barrier dividers are common.
- Where lane addition/expansion projects eliminate pre-existing stormwater measures, the new projects may need to provide control for the total affected area (existing and proposed).

Key Opportunities for VRAs Related to Highway Type

- Shoulders or medians may present an opportunity for narrow vegetated VRAs or permeable pavement surfaces. Shoulders and medians are generally located down gradient from roadway travel lanes.
- Piped conveyances may allow water to be transported to regional VRA opportunity locations at interchanges with minimal incremental conveyance cost.
- The potential for adjacent slope failures or lateral water migration is reduced compared to elevated sections because roadway elevations are roughly at-grade.

3.3.4 Highway Segments with Steep Transverse Slopes

Highway segments with steep transverse slopes are common where highways traverse hilly or mountainous terrain. This may occur in both urban and rural areas. These types of segments can have various degrees of restriction, as influenced by right-of-way width and the steepness of the cross-slope. This category is generally reserved for segments with cross-slopes of greater than about 10%. Segments with shallower cross-slopes may be better covered by guidance for ground-level segments (Sections 3.3.2 and 3.3.3).

Defining Physical Features

- Cross-sections are typically restricted; acceptable horizontal and vertical alignments are generally obtained by creating cut slopes and fill slopes.
- Because the roadway width has significant implications on the height of the cut-and-fill slopes, the widths of shoulders and medians are typically minimized in these types of segments.
- Interceptor drains may be installed to limit stormwater flowing along or over the roadway from uphill areas and to limit collected water flowing toward the uphill embankment from crowned or super-elevated sections.
- Where downslopes are not excessively steep, water from the roadway may be allowed to sheet flow. However, drainage must be intercepted before draining to private property.

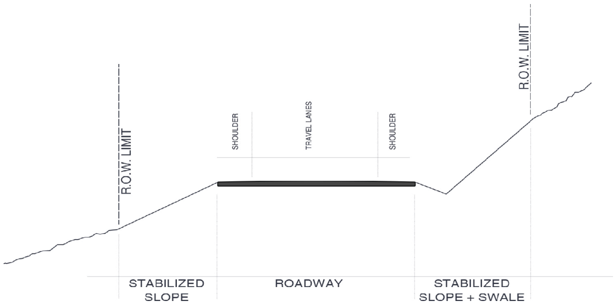
Key Constraints for VRAs Related to Highway Type

- Space limitations related to restrictive cross-sections (Section 3.3.3) and embankment cross-sections (Section 3.3.6) are commonly applicable in these segment types.
- Space for vegetated VRAs may be limited.
- Access for construction and maintenance activities may be limited or require lanes to be closed.
- Slope stability and retaining-wall issues may be of specific concern in this highway segment type.
- Much of the roadbed typically exists as compacted fill.

Key Opportunities for VRAs Related to Highway Type

- Elevation differences associated with the topography may allow water to be piped to regional VRA opportunity locations at interchanges.
- Where the cross-slope is shallow or moderate, there may be opportunity to disperse water to vegetated areas downslope or use vegetated conveyance elements.

Example Plan and Profile



Not to Scale

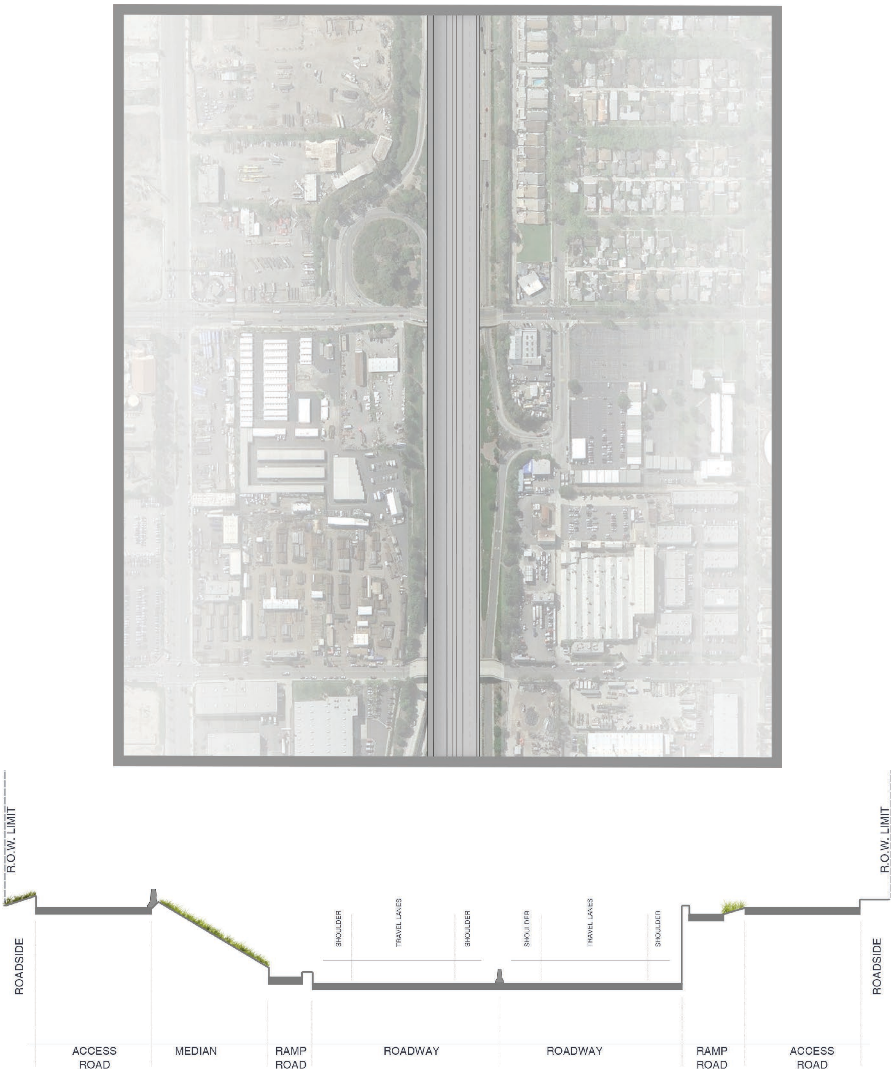
3.3.5 Depressed Highway Segments

In a depressed highway segment, the roadway is depressed below adjacent ground levels. Either sloped embankments or vertical retaining walls may be used to tie the cross-section into the existing grade. Depressed highway segments are typically found in locations where surface streets cross frequently (as overpasses) or where road roadway noise is an issue.

Defining Physical Features

- Depressed segments are usually found in highly urbanized areas.
- Segments can be depressed to varying degrees, typically controlled by minimum vertical clearance criteria for overpasses (16 ft; FHWA, 2007).
- Cross-sections are often highly restricted; the toe of embankments or retaining walls tends to be located very close to the shoulder.

Example Plan and Profile



Not to Scale

- Concrete barrier dividers are common.
- In less restricted settings, medians and vegetated shoulders may exist.
- Ramps are used to connect to surface streets.

Key Constraints for VRAs Related to Highway Type

- Opportunities for dispersion and vegetated conveyance are limited because the road tends to be the lowest part of the section; storm drains are typically used for conveyance.
- Extra precautions are commonly taken in drainage design to remove stormwater from the road surface quickly and efficiently (i.e., tighter spacing of inlets than other types).
- Because these segments are commonly found in highly developed areas, the section is usually restricted, and little or no vegetation exists in the shoulder or median.
- Access for construction and maintenance activities may be limited and require lanes to be shut down.

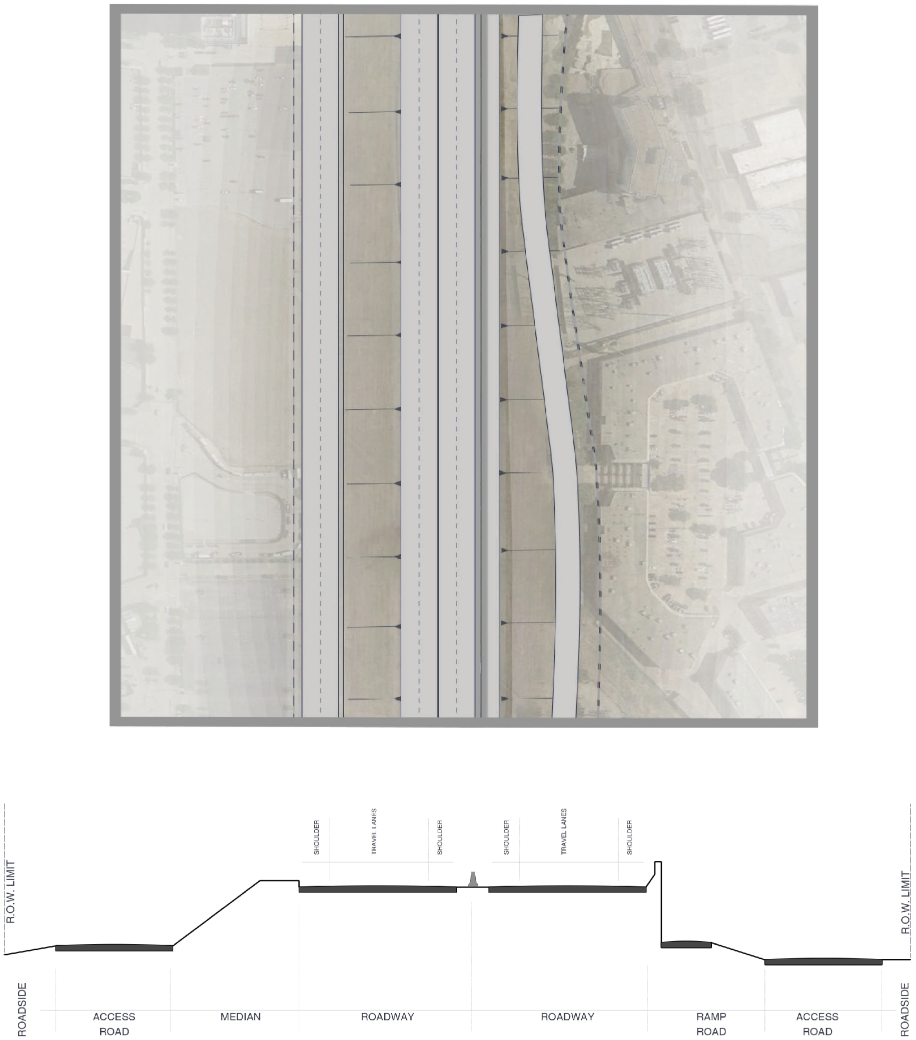
Key Opportunities for VRAs Related to Highway Type

- Geotechnical considerations associated with infiltration may be mitigated, in part, because the infiltrating surface would be at a lower elevation than slopes and adjacent structures/infrastructure.
- Pumping may be required for drainage purposes in cases where runoff cannot be conveyed to an outlet via gravity flow. This may present an enhanced opportunity for routing of stormwater to capture-and-use systems.

3.3.6 Elevated Highway Segments on Embankments

Elevated highway segments on embankments are found mostly in suburban areas where crossing streets are widely spaced and where grading designs provide adequate material for fill. However, they are also found in many urban areas. The total widths of elevated roadway sections vary considerably; however, the total width required is comparable to the total width needed for depressed highways (AASHTO, 2011b).

Example Plan and Profile



Not to Scale

Defining Physical Features

- The earth embankment is usually of sufficient height to permit intersecting surface roads to pass below, based on minimum vertical clearance criteria (16 ft, FHWA, 2007).
- Earthen embankments are typically 6H:1V to 3H:1V (AASHTO, 2011b) and are usually not designed to allow errant vehicle recovery; guardrails are common.
- If desired, earthen sloped embankment areas are available for planting of smaller trees, provided that line-of-site criteria are maintained.
- Linear ramps or cloverleaf ramps may be used to traverse slopes to connect to surface streets.
- Embankments are normally constructed on compacted fill.

Key Constraints for VRAs Related to Highway Type

- Slope stability and retaining-wall issues may be of specific concern in this highway segment type.
- Where retaining-wall embankments are used, very limited vegetation may be present.
- Embankment slope tends to limit applicable VRAs.
- Access for construction and maintenance activities may be limited for VRAs installed on an embankment.

Key Opportunities for VRAs Related to Highway Type

- If space is available at ground level, infiltration-based VRAs may be practical at locations away from the toe of slope or footing of the foundation.
- Where slopes are relatively shallow, dispersion to an amended road shoulder may be possible.
- When separate embankments are built for each direction of traffic, opportunities may exist for VRAs in the median.
- Geotechnical design may be able to accommodate some infiltration in roadway or embankments.
- Open space at interchanges tends to be lower in elevation than the highway surface.

3.3.7 Elevated Highway Segments on Viaducts

Elevated highway segments on viaducts (also known as aerial segments) are found primarily in densely developed urban areas where space is limited and significant constraints exist for a surface-level highway. Elevated highways on viaducts tend to be very expensive. Aerial segments are commonly found at interchanges as well, and share many characteristics of linear aerial segments. Aerial segments present unique considerations for achieving volume reduction.

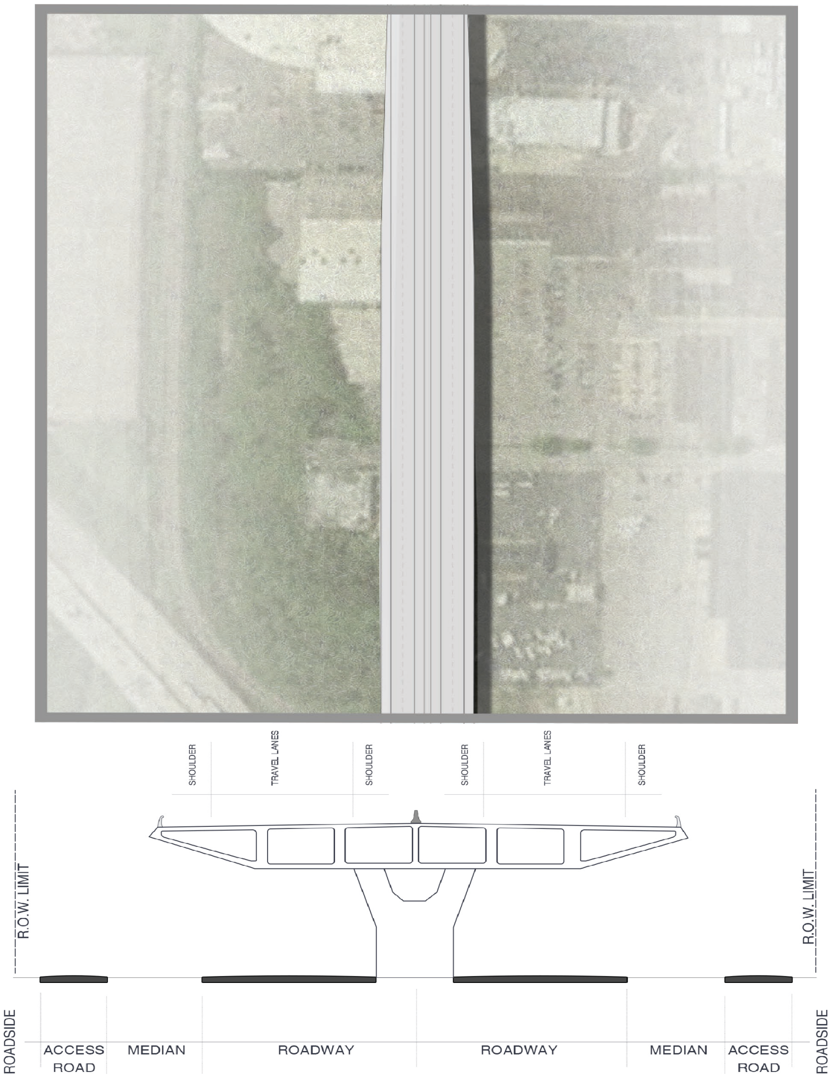
Defining Physical Features

- The degree of elevation varies greatly but is not important for volume reduction considerations.
- Supporting columns of the viaduct are positioned to provide reasonable clearance on each side and to leave much of the ground-level area free for other urban uses.
- Space under the structure may be used for a variety of urban needs, such as surface-street traffic, parking, or even buildings and playgrounds.
- Where right-of-way widths are highly limited, a two-level structure may be designed in place of the conventional two-way, one-level structure.
- Constraints and opportunities may be more strongly influenced by the conditions that exist below the viaduct.

Key Constraints for VRAs Related to Highway Type

- There are no opportunities for infiltration in the aerial segment.
- Infiltration VRAs in the area below the roadway may pose specific considerations related to geotechnical stability of the viaduct support columns.
- Land ownership (if different below the roadway) may present issues that limit volume reduction opportunities.

Example Plan and Profile



Not to Scale

Key Opportunities for VRAs Related to Highway Type

- At the ground level, substantial opportunities for volume reduction may be present; highly dependent on ground-level conditions.
- Aerial segments may not result in a net addition of imperviousness; may be able to use existing VRAs or coordinate on joint stormwater management projects.
- Storage tanks may be incorporated into viaduct design to provide base-flow–mimicking flow control, equalization for ground-level VRAs, or storage for direct beneficial uses.
- Open space at interchanges tends to be at a lower elevation than the highway surface.

3.3.8 Diamond Interchanges

Interchanges between highways or between highways and local roads often vary in cross-section and combine a number of the highway types previously discussed. Interchanges present unique considerations for volume reduction design. Diamond interchanges include those where the leg connects one highway to another in a more-or-less linear fashion, creating long, narrow wedges of open space. There are a range of variations on diamond interchanges.

Example Plan View

Not to Scale

Defining Physical Features

- The cross-sectional geometry of interchanges is highly variable as a function of site-specific factors.
- Degree of cross-sectional restriction varies greatly.
- Diamond interchanges often enclose narrow wedge-shaped areas of unused space, providing a number of opportunities for stormwater retention.

Key Constraints for VRAs Related to Highway Type

- Constraints vary throughout an intersection, depending on the type of highway segment, per Sections 3.3.2 through 3.3.7.
- Where interchanges connect roadways at very different grades or in tight rights-of-way, vegetated slopes may be relatively steep or may be replaced by vertical retaining walls.
- Interchanges for depressed roadway sections tend to be located at a higher elevation than the main travel lanes.

- Access for maintenance may be limited and require lane closures in some cases. These closures may have significant traffic and maintenance labor implications.
- At the tip of wedges, plant selection may be limited by line-of-site and collision considerations.

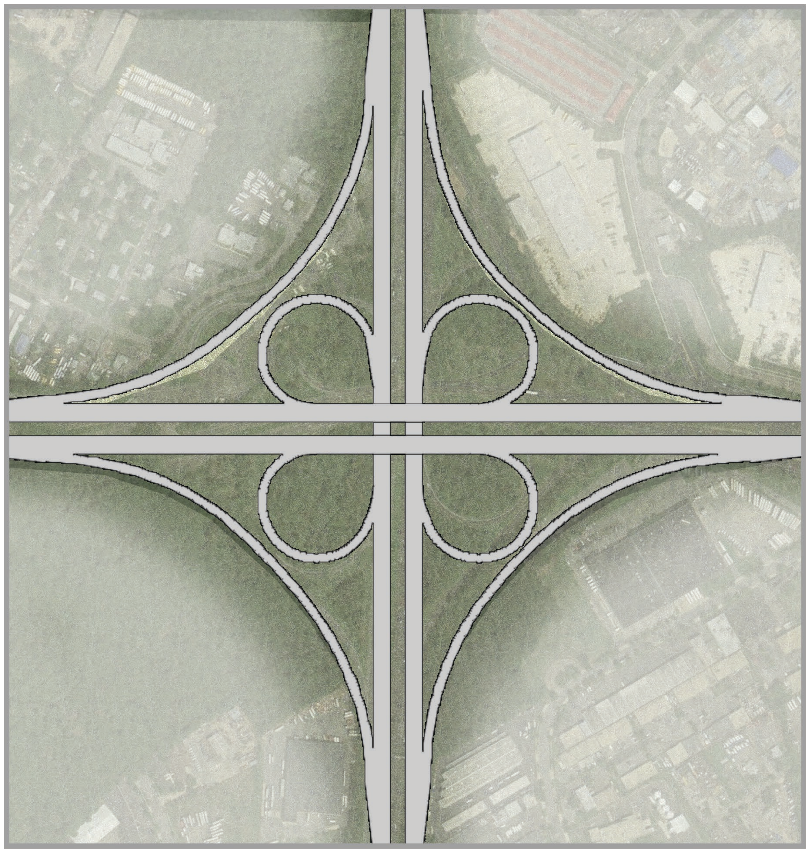
Key Opportunities for VRAs Related to Highway Type

- Wedge-shaped areas may provide substantial open space for construction of vegetated conveyance and basin-type VRAs.
- Geotechnical considerations may be partially mitigated as a result of adequate setbacks from compacted road base.
- Trees or bushes may be allowable within certain parts of interchange wedges and may increase water retention on site.
- Interchanges for elevated roadway sections tend to have open space located at a lower elevation than the main travel lanes.
- Where access is considered in roadway design, maintenance may be possible without requiring lane closures.

3.3.9 Looped Interchanges (Also Known as Cloverleaf Intersections)

Interchanges between highways or between highways and local roads often vary in cross-section and combine a number of the highway types previously discussed. Interchanges present unique considerations for volume reduction design. Looped interchanges include those in which

Example Plan View



Not to Scale

legs connect highways via a combination of external arcs and internal loops. There are a range of variations on looped interchanges.

Defining Physical Features

- Looped interchanges typically include a combination of segment types, including embankment segments, aerial segments, and at-grade segments.
- Available space dictates the radius of loops and curves, which influences design speeds and the degree of restriction of cross-sections.
- Looped interchanges enclose central circular areas of open space that are frequently unused.

Key Constraints for VRAs Related to Highway Type

- See constraints associated with diamond interchanges (Section 3.3.8)

Key Opportunities for VRAs Related to Highway Type

- See opportunities associated with diamond interchanges (Section 3.3.8).
- Because of their unique geometry, central loops tend to be less restricted (relative to topographic, geotechnical, and safety considerations) than wedge-shaped sections formed by diamond interchanges.

3.4 Site Assessment Activities to Support Volume Reduction Planning and Design

As discussed in Section 3.2, site conditions have an important influence on the amount of volume reduction that may be achievable as well as the types and locations of VRAs that may be applicable. Assessing the potential of a site for the implementation of volume reduction approaches requires the review of existing information and may include the collection of site-specific measurements, especially after VRAs are determined to be feasible. Available information regarding site characteristics, such as impervious cover, slope, soil characteristics, local groundwater conditions, and geotechnical conditions, should be assessed as part of site characterization efforts. In addition, specific explorations, such as soil and infiltration testing and groundwater-level measurements, may be necessary to determine and confirm if stormwater infiltration is feasible and to determine the appropriate design parameters for VRAs. Focused analyses, such as estimating the effects of the project on water balance and estimating the potential for groundwater mounding, may help supplement site investigation and data review efforts. This overall process is outlined in Figure 6.

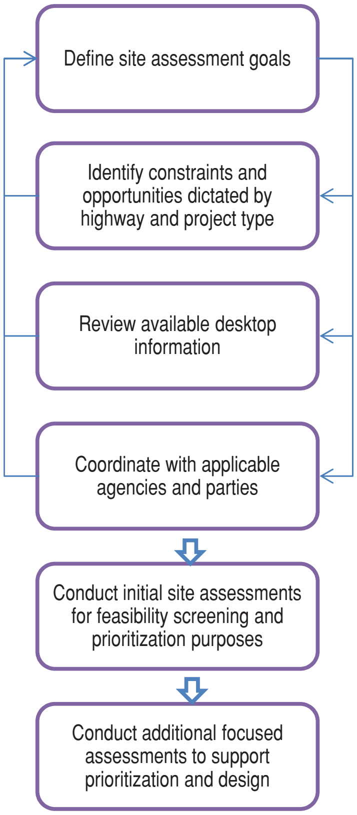


Figure 6. Example approach for site assessment.

Local planning and design requirements in effect for a project may describe minimum site-assessment requirements applicable to specific project types. In addition, certain activities are recommended (even if not required) to help ensure that opportunities for volume reduction are identified and potential volume reduction issues are considered. The following subsections are intended to provide recommendations for site assessment activities to support the incorporation of volume reduction into overall project planning and design. The recommendations are not intended to prevent the consideration of site-specific factors or substitute for the need to exercise sound engineering judgment. In addition, the recommendations are intended to be applied only to the extent that they are necessary to meet minimum site-assessment requirements. They are not intended to imply that each of these assessments must be conducted for every project if an equally reliable source of information is available in place of any of these analyses or if the analysis outcome is obvious and can be documented based on simpler analysis methods. For example, if groundwater is known to be very deep based on regional surveys or other available information, it is not necessary to conduct an evaluation of the exact water table depth or the potential for groundwater mounding.

What specific types of findings must be supported from site assessment activities?

The answer to this question varies depending on site conditions, the phase of the projects, and what types of VRAs are proposed. Section 3.4.1 provides guidance for determining what information is needed at which phase of a project. Sections 5.2, 5.3, and 5.4 provide guidance for how findings from site investigation activities can be used for determining the feasibility and desirability of VRAs and then for developing conceptual designs. Therefore, it is recommended that these sections be reviewed as part of planning for site assessment activities so that the scope of these activities is adequate to answer the key questions that designers will face at each phase. Additionally, users should familiarize themselves with the types of VRAs that are available/approved for use, so that the attributes of these practices are considered in site assessment (see Chapter 4 and Appendix A or local guidance for the applicable menu of VRAs).

3.4.1 Phasing of Site Assessment Activities

To improve the efficiency of site assessment, specific efforts should be phased, with consideration of the information needed to inform decisions at each point in the project. The types of information and assessment methods that may be applicable to screen and prioritize potential VRAs at the planning phase may be inadequate to support design-level efforts. Conversely, the degree of rigor needed for design-level investigations may be cost-prohibitive for planning phase assessments. In general, planning phase screening methods are used to identify VRAs and potential VRA locations that can be definitively dropped from consideration and to help prioritize VRA types and locations among those that remain. Design-level assessment methods tend to be more focused on precisely quantifying conditions relevant to the specific VRAs and locations selected.

Guidance for conducting site assessment activities related to soil infiltration capacity, groundwater considerations, and geotechnical considerations is provided in Appendices C, D, and E, respectively. These resources provide a systematic guide for phasing assessment activities by helping to describe the methods that are applicable at the planning and design phases. A general discussion of appropriate planning-level and design-level site-assessment methods is provided in the following sections.

At both the planning and design phases, the specific screening and feasibility criteria applicable to the project should be considered in scoping site-assessment activities. For example, if the feasibility criterion for depth to groundwater is in the range of 10 ft below the ground surface, then it may not be necessary to conduct borings to 50 ft to characterize groundwater levels as they specifically relate to VRA selection and design. Specific feasibility criteria and approaches for interpreting the results of site assessment efforts in the context of feasibility screening and prioritization are described in Chapter 5. Additionally, the availability of data from other sources should be considered in scoping field assessment efforts.

Planning Phase Site Assessment

Site assessment efforts should ideally be initiated early in the design process so that volume reduction approaches can be incorporated into the project layout as it is developed. At this phase, it may still be possible to adjust the project layout to preserve areas that provide good opportunities for VRAs and configure project grading and drainage so that water can be routed to these areas. There are many factors that influence highway design and result in lesser opportunities for adjustment to layout (e.g., alignment) than other types of projects; however, adjustments to grading and drainage routing to improve volume reduction opportunities may still be possible if this is initiated early in the design process. At this phase of project development, the project team is faced with two key questions:

- Where within my project area are VRAs feasible?
- What VRAs are potentially suitable for my project?

The amount of information available to answer these questions at the planning phase of project development may vary. For example, at this phase, project planners may have access to extensive geotechnical investigation reports from previous projects, the results of early investigations for the project of interest, and other information, or may be faced with much more limited data, such as county soil maps and anecdotal evidence about groundwater levels in the vicinity.

Generally, the burden of proof is lower at this phase of project assessment, and, therefore, simpler and more efficient screening methods may be appropriate. Methods that are used at this phase are commonly referred to as "screening methods" or "prioritization methods." These methods do not seek to definitively establish feasibility or establish final design parameters; however, their efficiency allows screening to be conducted over a greater spatial extent and for a broader menu of potential VRAs than would be feasible using more detailed site-assessment methods. Programmatic analysis may be possible at some DOTs or in some states, where ready data are available.

Planning-level screening methods do tend to contain more potential for error than more detailed methods; hence, discretion of the design team is needed to balance the cost of data acquisition with the level of certainty needed at this phase. In the absence of specific local guidance, the decision of what data to collect at the project planning phase, and at what resolution, should be based on project-specific factors and questions, such as:

- How variable in space and time are the conditions (e.g., groundwater elevations) at the site? Can I reliably interpolate between a lesser number of data points?
- What are the project goals relative to volume reduction? How important is it to provide an exhaustive investigation and quantification of volume reduction opportunities? Do applicable regulations require a rigorous demonstration that volume reduction is conducted to the maximum degree possible?
- How much would more rigorous investigation methods cost as a portion of the project budget? Could other design costs potentially be reduced (e.g., for conveyance, flood control) if increased budgets were allocated to thoroughly investigating volume reduction opportunities?

Finally, planning-level screening may be the only evaluation needed to inform selection and placement of potential VRAs. If a certain site characteristic conclusively rules out a certain type of VRAs or VRA locations, then it is not necessary to conduct additional site-assessment activities to further support this finding. For example, if contaminated soils rule out infiltration in a certain area of a site, then it is likely not necessary to conduct infiltration rate assessments in that area.

Design-Phase Site Assessment

At the VRA design phase, a more detailed and accurate assessment is typically needed to (1) establish specific design parameters (e.g., infiltration rate), (2) demonstrate that the selected VRAs can be safely implemented in the selected locations (e.g., via slope stability calculations), and (3) demonstrate that potential negative consequences have been addressed (e.g., by characterizing and mitigating potential for groundwater contamination). At this phase of project development, the project team is faced with three key areas of questions:

- What design parameters should I use to design volume reduction facilities? What factors of safety should I apply?

- Is the design safe? How does the design mitigate unacceptable levels of risk?
- Is the design protective of potential unintended consequences for other media? Are risks of impacts mitigated to acceptable levels?

Site assessment activities and design calculations conducted at this phase bear a greater burden of proof to definitively answer these questions; however, they are typically focused on specific designs and specific VRA locations, which helps mitigate the need for more rigorous analyses. Additionally, some analyses, such as for slope stability, may be required regardless of whether VRAs are proposed and may not represent a significant incremental cost. Similarly to planning phase assessments, trade-offs exist between the costs of investigations and analyses and the quality and resolution of the data available to support design decisions. The value obtained from each design-level assessment activity can be improved by:

- Using a tiered approach for investigation (i.e., planning-level screening in advance of design-level testing), such that more rigorous design-level tests are conducted only in areas where VRAs are likely to be placed;
- Using proven assessment methods that are acceptable to local jurisdictions and provide reliable information; and
- Selecting methods that are applicable for the project conditions.

This guidance manual provides general recommendations for design-level site-assessment methods. Because of the important role of site-specific conditions in design-phase analyses, it is expected that professional judgment and discretion will play a large role in planning and conducting the assessment activities needed at the design phase. The site assessment categories discussed include:

- Topography and drainage patterns,
- Off-site drainage and adjacent land uses,
- Soil and geologic conditions,
- Local weather patterns,
- Groundwater considerations,
- Geotechnical considerations,
- Existing utilities,
- Harvested-water demand,
- Responsible agencies and other stakeholders,
- Local ordinances, and
- Watershed-based and other joint planning opportunities.

Sections 3.4.2 through 3.4.12 provide guidance related to each of these categories. Sections 5.2, 5.3, and 5.4 provide guidance for how findings from site investigation activities can be assimilated into determining the feasibility and desirability of VRAs and then developing conceptual designs. Table 4 provides a checklist of typical goals for site assessment at each phase of project planning and summarizes potential site assessment activities.

3.4.2 Topography and Drainage Patterns

The site's topography should be assessed to evaluate surface drainage, identify topographic high and low points, and identify the current and future presence of steep slopes, all of which have an impact on the type of VRAs that may be most applicable and beneficial for a given project site (as summarized in Table 2). Topography and drainage patterns are also key factors in identifying potential locations for VRAs. Topographic assessment and mapping should document existing-condition impervious areas, drainage patterns, the interface of site topography with adjacent parcels/rights-of-way (e.g., manufactured slopes), and any other topographic features of interest to site layout or stormwater management.

Assessment of site topography relative to volume reduction design can generally be accomplished via review of the topographic survey conducted at the outset of the project. At early planning phases, it may be necessary to use more approximate data sources, such as the United States Geological Survey (USGS) quadrangle maps or digital elevation models available

Table 4. Checklist of site assessment goals and activities.

Planning Phase		
Underlying Goals of Site Assessment	***Addressed? (Y/N)[1]***	
Have the volume reduction goals for my project been identified?		
Have VRAs that are potentially suitable for my project been identified?		
Have areas within my project area where VRAs are feasible been identified?		
Is there additional information that I will need to obtain as part of design-phase assessments to confirm these findings and complete the design?		
Site Assessment Activities Potentially Applicable	**Assessed[2]**	**N/A[2]**
Topography and drainage patterns – Section 3.4.2		
Off-site drainage and adjacent land uses – Section 3.4.3		
Preliminary infiltration capacity assessment – Section 3.4.4, Appendix C		
Preliminary water balance and groundwater quality screening – Section 3.4.6, Appendix D		
Geotechnical risk assessment (major issues) – Section 3.4.7, Appendix E		
Existing utilities – Section 3.4.8		
Harvested-water–demand assessment – Section 3.4.9		
Responsible agencies and other stakeholders – Section 3.4.10		
Local ordinances – Section 3.4.11		
Watershed-based and other joint planning opportunities – Section 3.4.12, 5.5		
Other, as determined via professional judgment of design team		
Design Phase		
Underlying Goals of Site Assessment	***Addressed? (Y/N)[1]***	
Have I identified design parameters that I should use to design volume reduction facilities? Have appropriate factors of safety been identified?		
Is the design safe? Has the design mitigated unacceptable levels of risk?		
Is the design protective of potential unintended consequences for other media? Are risks of impacts mitigated to acceptable levels?		
Is additional information or oversight needed at the construction phase to confirm design assumptions?		
Additional Site Assessment Activities Potentially Applicable	**Assessed[2]**	**N/A[2]**
Design phase infiltration rate evaluation and factors of safety, as needed – Section 3.4.4, Appendix C		
Focused groundwater-related analyses, as needed – Section 3.4.6, Appendix D		
Geotechnical design parameters and mitigation measures, as needed – Section 3.4.7, Appendix E		
Other design-level analyses and refinements, as determined via professional judgment		

1 – See Sections 5.2 and 5.3 for more guidance on documenting findings of suitability and feasibility; See Section 5.4 for guidance on developing conceptual designs.
2 – Include results of site assessment activities or explanation of why they are not applicable as part of project submittal documentation.

from the National Elevation Dataset. Many resources are available as part of the USGS National Map (http://nationalmap.gov/viewer.html) to facilitate approximate assessment of site topography. Project design schematics can be used to assess post-project topography.

3.4.3 Off-Site Drainage and Adjacent Land Uses

Off-site drainage is an important factor in the layout of the project site and in determining appropriate VRAs. Off-site flows that enter or cross the project area may pose challenges for implementing VRAs, such as excessive flow rates, high sediment loadings of interest that can lead to clogging of VRAs, and high pollutant loadings relative to potential impacts on groundwater quality. Opportunities to keep off-site flows separate from on-site flows should be assessed. Off-site flows may present opportunities for a project to provide additional volume reduction or provide volume reduction in alternative ways. For example, a project could have flows managed from off-site and show a net benefit with respect to the hydrologic impact. It may also be possible to address off-site flows in one portion of the project to compensate for lack of volume reduction opportunities in other portions.

Locations and sources of off-site run-on onto the project site should be identified as part of early site-assessment efforts. Assessment efforts should include characterization of the locations of off-site flows, the relative magnitude of these flows, and the land uses and potential pollutant sources associated with these flows. Key pollutants relevant to volume reduction feasibility include sediment, nutrients, pathogens, and salts. More guidance on potential impacts on groundwater quality is provided in Section 3.4.5 and Appendix D.

3.4.4 Soil and Geologic Conditions

The site's soil and geologic conditions should be determined to evaluate the capacity of a site for stormwater infiltration and to identify suitable and unsuitable locations for siting infiltration-based VRAs. Among volume reduction processes, infiltration has the greatest potential to achieve substantial volume reduction in space-constrained highway settings. However, site soil conditions influence the rate at which water can physically enter the soil and determine the amount of infiltration that can be feasibly and desirably achieved with consideration of geotechnical issues, groundwater quantity and quality, and utilities. Site assessment approaches for soil and geologic conditions may consist of:

- Review of available geologic or geotechnical reports on local geology to identify relevant features, such as depth to bedrock, rock type, lithology, faults, and hydrostratigraphic or confining units;
- Review of previous geotechnical investigations of the area; and
- Site-specific geotechnical or geologic investigations, such as borings and infiltration tests.

These geologic investigations may also identify shallow water tables and past groundwater or soil contamination issues that are important for BMP design (see Section 3.4.5). Geologic investigations should seek to provide an assessment of whether soil infiltration properties are likely to be uniform or variable across the project site.

A wide range of potential methods for characterizing soil and geologic conditions are discussed in greater detail in Appendices C and E. These range from planning-level methods to characterize approximate levels of infiltration potential and areas that may be most suitable for infiltration, to design-phase methods for establishing infiltration rates and assessing geotechnical issues. Finally, in areas where fill will be important, it is important to understand the characteristics of the fill material. Where there are cuts, it is important to understand soil conditions at the cut elevation.

3.4.5 Local Weather Patterns

As introduced in Section 3.2.3, local weather patterns have an important influence on the natural hydrologic regime of a site as well as on the suitability, design, and performance of VRAs. Key information regarding local weather patterns is as follows:

- Typical storm sizes (e.g., 85th-percentile, 24-hour storm depth).
- Peak storm intensities (e.g., 2-year peak flow) that would influence energy dissipation requirements.

- Relative seasonal patterns of rainfall and ET (i.e., is ET typically high between storm events? For how many months is ET greater than precipitation, and vice versa?).
- Average annual rainfall depth.
- Typical length of dry season(s).
- Portion of precipitation that occurs as snow.
- Continuous time series of precipitation and ET, if available, to support site-specific modeling.

The Volume Performance Tool can be used to obtain some of this information for nearby gages (although not always the most local gage). Other information can be obtained from local or nationwide resources. The National Climatic Data Center (http://www.ncdc.noaa.gov/) and the Oak Ridge National Laboratory Distributed Active Archive Center (http://www.daac.ornl.gov) provide free data downloads and publications of climatic data at a nationwide scale.

3.4.6 Groundwater Considerations

Site groundwater conditions should be considered prior to the siting, selection, sizing, and design of VRAs. Specific guidance on evaluating groundwater considerations is provided in Appendix D. Site assessment activities related to groundwater generally include:

Groundwater levels. The depth to seasonally high groundwater tables (normal high depth during the wet season) beneath the project site may preclude infiltration. Depth to seasonally high groundwater levels can be estimated based on well-level measurements or redoximorphic methods. For sites with complex groundwater tables, long-term studies may be needed to understand how groundwater levels react in wet and dry years.

Groundwater and soil contamination. In areas with known groundwater and soil pollution, infiltration may need to be avoided if it could contribute to the movement or dispersion of soil or groundwater contamination or adversely affect ongoing cleanup efforts, either onsite or down gradient of the project. Mobilization of groundwater contaminants may also be of concern where contamination from natural sources is prevalent (e.g., marine sediments, selenium-rich groundwater), to the extent that data is available. If infiltration is under consideration in areas where soil or groundwater pollutant mobilization is a concern, a site-specific analysis should be conducted to determine where infiltration-based VRAs can be used without adverse impacts.

Stormwater pollutant sources. Certain pollutants found in stormwater have the potential to have impacts on groundwater quality. Research conducted by Pitt et al. (1994) on the effects from stormwater infiltration on groundwater found that the potential for contamination due to infiltration of stormwater is dependent on a number of site factors, including the local hydrogeology and the chemical characteristics of the pollutants of concern (as well as the level of treatment that runoff receives prior to infiltration or as it is infiltrating). Chemical characteristics of stormwater that influence the potential for groundwater impacts include high mobility (low absorption potential), high solubility fractions, and abundance of pollutants in urban runoff. The chemical characteristics of the subsurface soils relate to how mobile pollutants are in the vadose zone. The depth to groundwater has also been found to be an indicator of the potential for contamination. Site assessment efforts specific to potential impacts of stormwater infiltration on groundwater quality include:

- Identification of pollutant hot spots in tributary areas within the project or in drainage from off-site areas,
- Characterization of soil properties, and
- Characterization of depth to groundwater.

Appendix D provides more information on evaluating the risk of groundwater contamination from stormwater sources.

Coordination with resource agencies. Infiltration activities should be coordinated with the applicable groundwater management agency, such as groundwater providers or resource protection agencies, to ensure that groundwater quality is protected. It is recommended that coordination be initiated as early as possible during the planning process to determine whether specific site-assessment activities apply or whether these agencies have data available that may support the planning and design process.

Groundwater recharge. Infiltration of stormwater can provide the benefit of recharging groundwater; however, groundwater recharge is not an implicit benefit of infiltration in all cases. Some areas of a site may provide pathways for water to recharge groundwater, while other areas may have a less efficient connection to groundwater or connect to a perched groundwater aquifer that is not used for water supply purposes. If groundwater recharge is desired, the site characterization should attempt to identify areas where infiltration would have the greatest benefit for groundwater recharge. Generally, a greater fraction of infiltrated water reaches groundwater in cases where there is a relatively direct hydrogeologic connection between the surface and an aquifer.

Groundwater/surface water interactions. Groundwater discharge to surface water is generally a primary source of dry-weather base flows in perennial stream systems. Intermittent and ephemeral systems are often characterized by groundwater discharge during some portions of the year and streams losing flow to groundwater during other portions of the year. These systems may be sensitive to minor changes in groundwater levels, which could result from increased infiltration compared to the existing condition. In such systems, increases in groundwater levels could potentially increase the duration of dry-weather base flows in intermittent and ephemeral drainages. These changes may have significant impacts on riparian habitat and geomorphology and affect species that favor these drier habitats. If intermittent or ephemeral drainages are located adjacent to or down gradient of the project, an assessment of the site water balance and potential impacts on groundwater/surface water interactions may be warranted.

3.4.7 Geotechnical Considerations

Infiltration of stormwater can cause geotechnical issues, including: (1) impacts on utilities, (2) settlement and volume changes, (3) slope instability, and (4) impacts on foundations or retaining walls. Stormwater infiltration temporarily raises the groundwater levels or soil moisture near the infiltration facility, such that the potential geotechnical conditions are likely to be of greatest significance near the area of infiltration and diminish with distance. If infiltration is considered, a geotechnical investigation should be performed for the infiltration facility to identify potential geotechnical issues and geological hazards that may result from infiltration and potential mitigation measures to reduce risks to acceptable levels.

Appendix E provides guidance for evaluating potential geotechnical issues at the planning phase and the design phase. In general, assessment activities include:

- Assessment of topography and drainage (see Section 3.4.2),
- Assessment of soil and geologic conditions (see Section 3.4.4), and
- Assessment of groundwater conditions (see Section 3.4.5).

These assessments provide initial information to assess potential geotechnical issues associated with stormwater infiltration. Focused site-assessment activities and analyses may be needed to assess specific issues identified in planning-phase screening efforts. A licensed geotechnical engineer should determine recommendations for focused investigation and analysis of geotechnical issues based on soil boring data, drainage patterns, and the current requirements for stormwater management. Implementing the geotechnical engineer's requirements is essential to prevent damage associated with infiltration in the roadway environment.

3.4.8 Existing Utilities

The locations of existing subsurface utilities may limit the possible locations of certain VRAs and may constrain site design. Additionally, the condition of utilities is relevant. For example, trenches that do not contain lateral cutoff walls (to prevent concentrated flow within trenches) may present a more substantial risk for infiltration in their vicinity (e.g., sinkhole formation). The location and condition of utilities can generally be obtained as part of the topographic survey.

3.4.9 Harvested-Water–Demand Assessment

If harvest-and-use approaches are under consideration for a project, a site assessment should include an assessment of the reliable demand for harvested water during the times of the year when precipitation and runoff occurs. A phased assessment method is recommended.

First, at the planning level, the assessment should seek to answer the following types of questions to determine if harvest and use of stormwater is potentially applicable:

- Is irrigation used for landscaping in the right-of-way?
- Are there any facilities in the right-of-way (e.g., maintenance yards) that could make use of non-potable water for toilet flushing, vehicle washing, cooling tower make-up water, or other uses?
- Are there any adjacent land owners that have expressed interest in harvesting roadway runoff?

If the answer to any of these questions is yes, then additional assessments may include:

- Evaluation of the magnitude of the demand during the times of year when precipitation occurs. Is the demand present during the wet season? Would it be possible to store water to be available for use during the times of year when it is in demand?
- Evaluation of the legality and desirability of using harvested water. Is harvesting of runoff legal based on water rights laws? What uses of harvested water are allowable per applicable public health codes? Is reclaimed water available in the area, such that the use of reclaimed water during the wet season would have a higher priority than use of harvested stormwater?

Finally, if harvested water is selected for use (per decision criteria described in Section 5.3), then it may be necessary for site assessment activities to quantify the actual demand profile for the site via measurements or other methods.

3.4.10 Responsible Agencies and Other Stakeholders

Early site-assessment activities should include the identification of responsible agencies and other stakeholders that may influence decision making for the project. Potential information obtained through coordination with these parties may include:

- Identification of local watershed-based stormwater management planning efforts or other joint planning opportunities (see Section 3.4.11);
- Understanding of local minimum criteria for site assessment, feasibility determination, and design;

- Acquisition of data related to soil, groundwater, utilities, foundations, and so forth that may inform the planning and design process; and
- Identification of real or perceived potential impacts of stormwater infiltration on environmental resources or adjacent land owners.

3.4.11 Local Ordinances

Early site-assessment activities should include the identification of local ordinances that may influence the goals and constraints related to achieving volume reduction for a given project. As introduced in Section 3.1.1, stormwater runoff from DOT projects is typically permitted under the CWA/NPDES system at a state or regional level; however, in some cases, local ordinances for stormwater management (e.g., TMDL plans, flood control) may apply to urban highway projects. Additionally, local ordinances related to resource protection (e.g., groundwater protection ordinances) may prescribe specific limitations or methods related to discharges to other media (e.g., groundwater). Local ordinances may also relate to geotechnical design, flood control, or other aspects of project development.

3.4.12 Watershed-Based and Other Joint Planning Opportunities

Watershed-based approaches may provide greater opportunity for volume reduction than can be safely and reliably achieved in the right-of-way. Early site-assessment activities should seek to identify potential watershed-based opportunities or other joint planning opportunities that may be applicable for the project. Section 5.5 provides more information about identifying and evaluating these options.

CHAPTER 4

Volume Reduction Approaches

This chapter describes a focused menu of primary VRAs that has been developed to provide the user with options for achieving surface runoff volume reduction in the urban highway environment. Section 4.1 begins with identification of stormwater control measures (SCMs) that are currently found in stormwater guidance and literature that also have volume reduction benefits. This section also introduces recent and ongoing research and pilot projects as part of identifying emerging concepts for volume control. From these sources, the menu of primary VRAs is identified (Section 4.2). Appendix A provides fact sheets for each of the primary VRAs identified in this chapter. These fact sheets provide VRA-specific information about applicability, siting and selection considerations, and conceptual design parameters. Section 4.3 summarizes information contained in the VRA fact sheets as well as the supporting appendices to provide a relative comparison and overview of VRA attributes and considerations. Section 4.4 provides additional references for VRA design and maintenance information.

4.1 Identification of Potential VRAs from Stormwater Guidance and Literature

While the urban highway environment presents unique challenges for achieving volume reduction, experience with SCMs in the highway environment as well as other land uses provides a basis for beginning to compile a menu of potential volume reduction approaches. SCMs with volume reduction benefits have been applied to highways in many jurisdictions (Oregon State University et al., 2006; Geosyntec Consultants et al., 2011), and some have been monitored extensively (www.BMPdatabase.org). Additionally, SCMs based fully or partly on volume reduction processes have been applied in municipal rights-of-way and other municipal land uses for many years; some aspects of these experiences are relevant to the urban highway environment. This section is intended to help the user answer the following questions:

- What volume reduction approaches have been applied in the urban highway environment?
- How are the volume reduction approaches that have been applied to other land uses applicable to the urban highway environment?

4.1.1 Inventory of SCMs in Highway Guidance and Literature

Previous nationwide research by Oregon State University et al. (2006), Geosyntec Consultants et al. (2011), and Strecker et al. (2005) identified a broad menu of SCMs that are applicable to the highway environment and identified the unit operations and processes associated with these SCMs, including volume reduction processes. Table 5 summarizes the SCMs referenced by these documents, identifies whether volume reduction is provided by each SCM, and provides a synthesis of the applicability of SCMs in the urban highway environment based on review of these literature sources.

Table 5. Inventory of SCMs identified by in previous nationwide stormwater guidelines.

SCM	Relative Volume Reduction Potential	Potential for Consideration as an Urban Highway VRA
Bioretention without underdrains	●	Yes
Bioretention with underdrains	⦿	Yes, unless lined with impermeable barrier
Bioslopes/filter strips	⦿	Yes
Capture and use/rainwater harvesting	⦿	Possible, limited demand for harvested required would limit extent of applicability
Catch basin controls	N/A	No volume reduction benefit
Compost/media filters	⦿	Yes, unless lined with impermeable barrier
Constructed wetlands	○	Not typically designed for volume reduction
Detention basins/extended detention basins	⦿	Yes, based on incidental volume reduction benefits
Dry wells	●	Possible, risk to groundwater quality may limit applicability
Green roofs	⦿	No, very limited applicability
Gutter filters	N/A	No volume reduction benefit
Hydrodynamic and gross solids removal devices	N/A	No volume reduction benefit
Infiltration basins	●	Yes
Infiltration galleries/tanks/vaults	●	Yes
Infiltration trenches/strips	●	Yes
Oil–water separators	N/A	No volume reduction benefit
Permeable overlays	○	Volume reduction benefit not demonstrated; likely very minor
Permeable pavement shoulders	●	Yes
Permeable pavement travel lanes	●	Potential, with adequate structural design
Pollution prevention/street sweepings	N/A	No volume reduction benefit
Proprietary disinfection, ultraviolet disinfection, flocculation, package plants, etc.	N/A	No volume reduction benefit
Sand filters	⦿/○	Incidental volume loss if unlined/Negligible volume reduction if lined
Soil amendments in landscaped areas	⦿	Yes
Subsurface flow wetlands	○	Not typically designed for volume reduction
Vegetated swales	⦿	Yes
Wet basin/retention ponds	○	Not typically designed for volume reduction
Wet vaults	N/A	Not typically designed for volume reduction

●: Volume reduction is primary removal process

⦿: Significant incidental volume reduction expected; in some cases, may achieve high volume reduction where conditions are favorable; these VRAs also provide treatment processes for conditions when volume reduction capacity is exceeded.

○: Potential for minor volume reduction in some conditions; primary reliance on other treatment processes for pollutant load reduction

N/A: No volume reduction processes present.

The International BMP Database (www.BMPdatabase.org) included 533 studies as of March 2013, of which more than 25% (142 studies) were conducted in the highway environment. Table 6 and Figure 7 provide a summary of the studies contained in the International BMP database that relate to the highway environment. Among these studies, biofilter strips and swales, bioretention, detention basins, and porous pavements have potentially significant volume reduction benefits. This inventory provides an indication of systems for which empirical performance data exist, although the BMP database does not necessarily represent the relative distribution of SCMs currently in use nor does it necessarily represent the trends in future uses of SCMs.

Table 6. Transportation-related study sites in the International BMP Database.

BMP Category	Total	State DOT								
		CA	DE	FL	MD	NC	TX	VA	WA	WI
Biofilter (Strip)	**40**	34				3	2	1		
Biofilter (Swale)	**24**	6		6		2		10		
Bioretention	**3**		1					1	1	
Composite (Train)	**6**			1		4		1		
Control	**2**						2			
Detention Basin	**13**	5					2	6		
Manufactured Device	**21**	9	7		1			3		1
Media Filter	**15**	11	1				2	1		
Porous Pavement	**7**					4	3			
Retention Pond	**3**	1		2						
Wetland Basin	**5**							5		
Wetland Channel	**3**			1		2				
Total	**142**	**66**	**9**	**10**	**1**	**15**	**11**	**28**	**1**	**1**

Note: "Control" refers to DOT sites that have been monitored without BMPs as control sites.

4.1.2 Relative Frequency of Application of SCMs by State DOTs

In a survey of DOT representatives conducted in 2012 (Venner et al., 2013), respondents from all 50 states plus Puerto Rico and the District of Columbia provided rankings of the relative frequency of various SCM types. Table 7 summarizes the findings of this survey and indicates which SCMs provide volume reduction. In descending order, the five most common BMP types are vegetated swales, rock swales, roadside filter strips, dry detention basins, and wet ponds/retention basins. The top 10 are rounded out by infiltration basins and trenches, compost-amended slopes, wetland swales/channels, and oil/water/grit separator vaults. Similar to the inventory of studies extracted from the International BMP Database, this inventory does not necessarily forecast what will be used in future projects; however, it provides an indication of the SCMs that have seen extensive application in the highway environment.

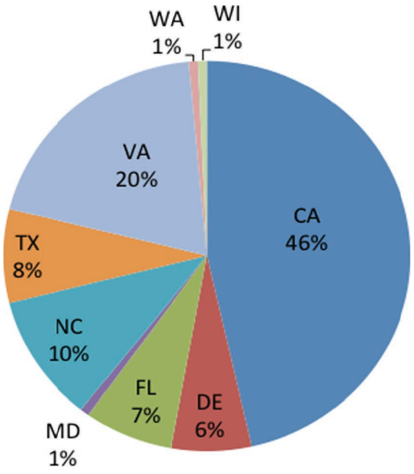


Figure 7. Distribution of DOT studies in the International BMP Database (March 2013).

Table 7. Relative frequency of use of SCMs by state DOTs.

SCM Name Used in Venner 2013 Survey	Frequency Score[1]	Volume Reduction Provided?[2]
SCMs used “frequently” and “sometimes” by state DOTs		
Vegetated swale	86	⦿
Rock swale	52	⦿
Filter strip	47	⦿
Dry detention basin	44	⦿
Wet pond/retention basin	31	○
Infiltration basin	16	●
Infiltration trench	11	●
Compost-amended slope	10	⦿
Wetland swale/channel	10	○
Bioretention/rain garden	5	⦿/●
Wetland basin	3	○
SCMs used “rarely” and “never,” according to state DOTs		
Hydrodynamic device	-4	N/A
Permeable shoulders or parking	-7	●
Catch basin insert	-9	N/A
Sand filter	-10	○
Permeable (open-graded) friction course overlay for water quality	-13	○
Underground detention vault	-13	○
Bioslope/ecology embankment/filter strip with soil amendment/media filter drain	-19	●
Underground infiltration vault	-26	●
Dry well (class V injection well)	-26	●
MCTT – multi-chamber treatment train (e.g., with tube settlers)	-31	N/A
Batch detention (real-time automated outlet)	-33	⦿

1 - Positive numerical factors were tabulated for “frequent” and “sometimes” responses, and negative numerical factors were tabulated for “rarely” and “never” responses. 2 – Ranking based on closest match to inventory of SCMs provided in Table 5. ●: Volume reduction is primary removal process; ⦿: Significant incidental volume reduction expected; other unit processes also provided; ○: Potential for minor volume reduction in some conditions; N/A: No volume reduction processes present.

4.1.3 Recent Research and Emerging Concepts in Volume Reduction Approaches for Urban Highways

This section highlights several areas of recent research related to volume reduction and volume reduction approaches to identify new and emerging concepts that may be applicable in achieving volume reduction.

International BMP Database Volume Reduction Technical Report

The International BMP Database contains over 530 BMP studies, a portion of which include data that relate to the volumetric performance of stormwater controls. An analysis of the volumetric data contained in the BMP database can help provide a better understanding of the benefits that BMPs can be expected to provide for volume reduction. Table 8 summarizes category-level analysis of studies in the BMP database to evaluate relative magnitudes of volume reduction performance.

The BMP categories considered in this analysis appear to exhibit substantial volume reduction potential. Variability in study performance is relatively high, likely indicative of variability in site conditions, BMP design, monitoring design, climate, and other factors. Nonetheless, this analysis suggests that volume reduction is appreciable in many cases, even when systems are not designed specifically for volume reduction or include underdrains.

A 2012 addendum to this analysis evaluated volume reduction performance of bioretention studies in greater detail, including factorial analysis of bioretention performance as a function

Table 8. Study total relative percent volume reductions.

BMP Database Category	No. of Monitoring Studies	25th Percentile	Median	75th Percentile	Average
Biofilter – grass strips	16	18%	34%	54%	38%
Biofilter – grass swales	13	35%	42%	65%	48%
Bioretention (with underdrains)	7	45%	57%	74%	61%
Detention basins – surface, grass lined	11	26%	33%	43%	33%

Relative volume reduction = (study total inflow volume – study total outflow volume)/(study total inflow volume).
Source: Poresky et al., 2011.

Table 9. Relative volume reduction statistics for bioretention studies.

Analysis Group	No. of Studies	25th Percentile	Median	75th Percentile	Average
All studies	20	42%	66%	98%	66%
No underdrains	6	85%	99%	100%	89%
With underdrains	14	33%	52%	73%	56%

Source: Poresky et al., 2011.
Notes: Studies with underdrains include systems with elevated underdrains and internal water storage. Analysis included additional data from seven additional studies of bioretention with underdrains that were not available in 2011; therefore, results are not expected to be the same as those shown in Table 8.

of precipitation event size and facility design parameters. Table 9 provides a summary of bioretention volume reduction performance, including studies divided into those without and with underdrains. This analysis suggests that site factors and design parameters play an important role in volume reduction performance, but that, on average, bioretention tends to achieve high levels of volume reduction. Specifically, it appears that an internal water storage (IWS) zone in bioretention systems with underdrains, created by an elevated outlet from the underdrain system, shows potential benefits for volume reduction performance. The IWS/elevated underdrain concept can also be incorporated into other VRA designs such as permeable shoulders.

Increased Bioretention Usage in Urban DOT Projects

Anecdotal evidence suggests that bioretention has perhaps seen the most significant upward trend in terms of usage in highway environments in recent years. For example, in a recent survey conducted by Venner Consulting, Maryland State Highway Administration responded that it is installing 80 permanent BMPs, mostly rain gardens, in one interchange. Two recent urban highway projects constructed by the Oregon DOT (ODOT) in Portland have incorporated bioretention cells, in one case adjacent to a bridge abutment, and in another within an interchange down gradient of a bridge reconstruction project (Figure 8). A recent project completed by DDOT involved the installation of three bioretention areas within an interchange (Figure 9).

In North Carolina, Luell et al. (2011) evaluated the hydrologic performance of bioretention areas that address bridge deck runoff (Figure 10). This research is relevant to urban highways since it evaluated the performance of undersized systems, similar to those that may be encountered in space-constrained urban conditions. While volume reduction performance declined with smaller size, the decline in performance was non-linear, such that sacrifices in performance were less than the reduction in size. This suggests that substantial benefits can be achieved even when the full sizing criteria cannot be provided.

Figure 8. Examples of ODOT bioretention installations. Left: Highway 99E Viaduct, Portland, OR; Right: I-5 Exit 298, Portland, OR. Source: Geosyntec Consultants.

Adaptation of Bioretention and Other Stormwater Controls for Low-Permeability Environments

Various recent research has been conducted related to the performance of bioretention in marginal soil conditions. Selbig and Balster (2010) studied rain gardens in clay soils in Wisconsin and found that a high level of volume reduction (nearly 100%) was achievable with appropriate sizing factors and a shallow design profile commensurate to site infiltration rates. Brown and Hunt (2011) reported on various experience using an internal water storage underdrain configuration (Figure 11) to enhance volume reduction in areas where soils were not adequately permeable to allow the installation of bioretention without underdrains. Underdrains can be configured in various ways to provide a storage zone while providing a supplemental pathway for water to discharge when infiltration capacity is exceeded. Recent guidance in California (Orange County Public Works, 2011; Ventura County Watershed Protection Department, 2011) has identified

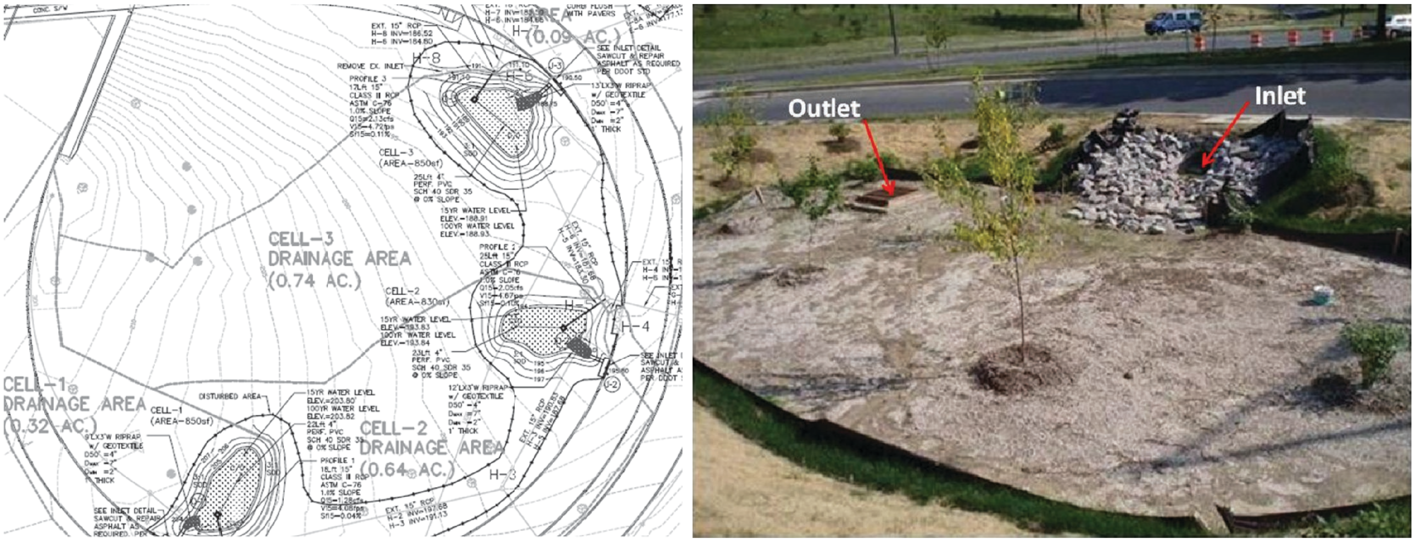


Figure 9. Design plans and constructed bioretention retrofit in DDOT interchange. Source: Geosyntec Consultants et al., 2011.

Figure 10. Bioretention cell in North Carolina DOT right-of-way researched by Luell et al. (2011). Source: Stacy Luell, Geosyntec Consultants.

bioretention with internal water storage (i.e., elevated underdrain) as a preferred approach for maximizing volume reduction when infiltration rates are measureable but are not adequate to support a full infiltration design without underdrains. A similar concept is applicable to permeable pavements, including permeable shoulders.

Advancement in Guidance for Washington State DOT Media Filter Drain

Media filter drains (formerly referred to as an "ecology embankments") were originally pioneered and demonstrated by Washington State DOT (WSDOT). A technology evaluation report prepared for ecology embankments for WSDOT (Herrera Environmental Consultants, 2006) showed both significant volume and load reductions up to, in some cases, 100%. Lessons learned from early applications of this technology led to revisions and refinement of design criteria, including various configurations. The WSDOT *Highway Runoff Manual* includes detailed design criteria for three configurations (side slope with underdrain, median configuration with underdrain, and side slope application without underdrain), and, at the time of this writing, WSDOT was in the process of developing guidance for additional configurations that was due to be published in 2014 with updates to WSDOT's *Highway Runoff Manual* (Personal communication,

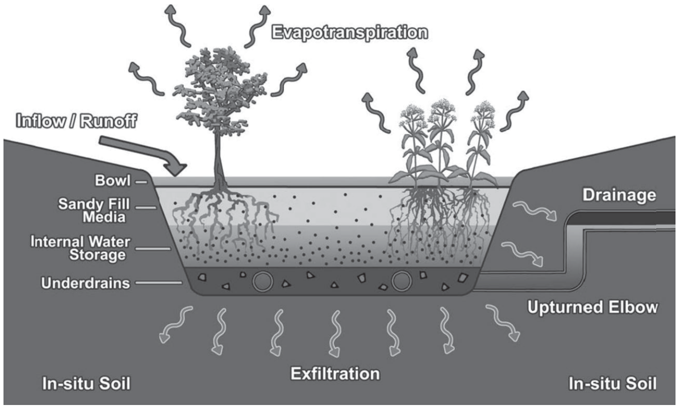


Figure 11. Schematic of a bioretention cell with an internal water storage layer. Source: Brown, 2009.

Figure 12. Media filter drain along SR 14 in Clark County, WA. Source: Washington State DOT, 2011.

Mark Maurer, April 18, 2013). Figure 12 shows an example implementation of a media filter drain, and Figure 13 shows an example schematic cross-section extracted from recent design guidance.

Adaptation of Permeable Pavements to High-Volume Roadways

Permeable friction course (PFC) overlays are not considered to be VRAs. However, research and development related to PFCs for highway applications has led to additional durability improvements to the permeable pavement wearing surface through the use of additives and higher-performance–grade binders. These additives have the potential to broaden application of permeable surfaces to highways with increased load/traffic demands, including full-depth permeable pavements that can achieve significant volume reduction. Additionally, recent project experiences and research have established empirical evidence for the potential suitability of

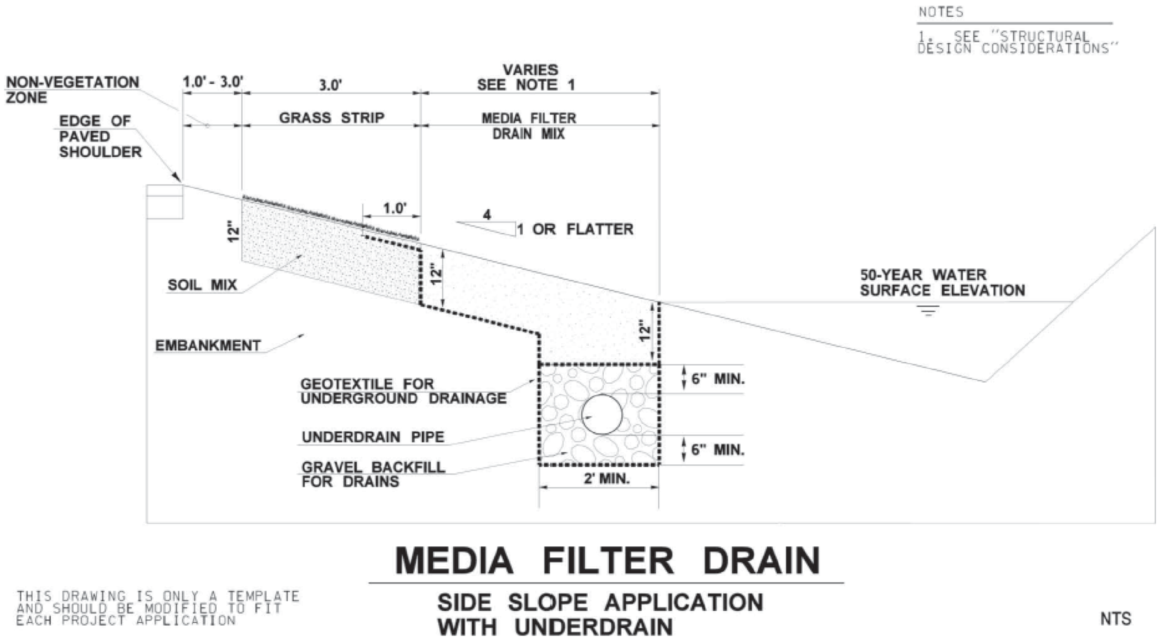


Figure 13. Media filter drain design guidance. Source: Washington State DOT, 2011.

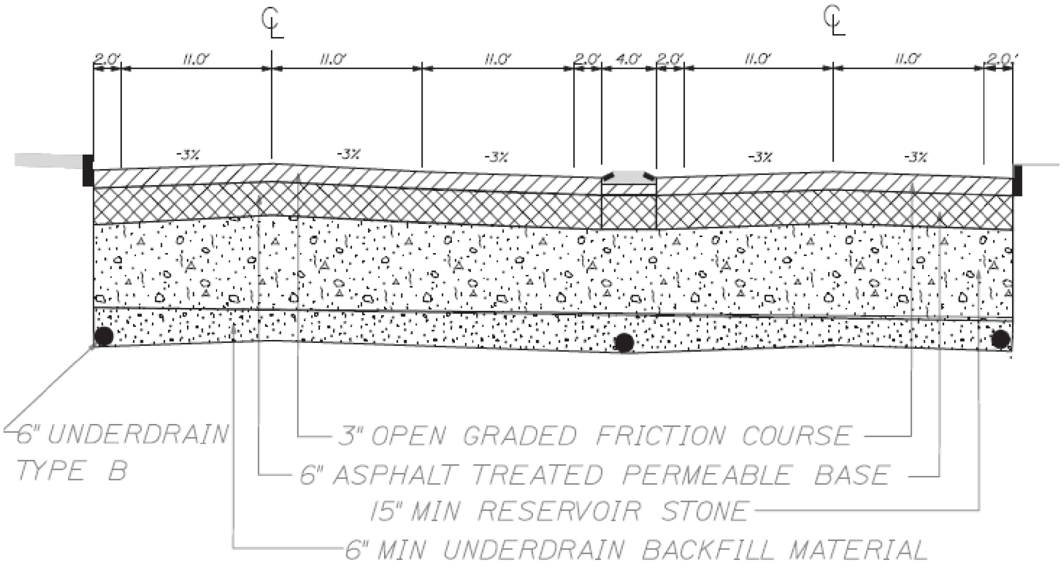


Figure 14. Structural profile of Maine Mall Road project. Source: Maine DOT, 2010.

permeable surfaces within high-volume roadways with heavy loadings (Maine DOT, 2010; see also Appendix F, which is part of *NCHRP Web-Only Document 209*).

In 2009, the Maine DOT constructed the first state DOT permeable-asphalt roadway in the northeast United States. The project includes a full-depth permeable pavement for 1,500 ft of a four-lane highway reconstruction for the Maine Mall Road in South Portland. In 2008 the average annual daily traffic for 2008 was 16,750 vehicles, including heavy truck traffic. Four years after construction, the durability is considered to be exceptional and permeability has been adequate, although maintenance (via vacuum sweeping) has been required to address track-on of sediments from adjacent roadways. Key advancements that allowed this project to support heavy loads were high-strength asphalt binders used in the surface wearing course, an asphalt-treated permeable base, and at least 21 in. of structural subbase material (Figure 14).

The University of California Pavement Research Center, in cooperation with Caltrans, conducted laboratory and modeling investigations to evaluate the structural and hydraulic performance of permeable pavement as highway shoulders that can be subjected to heavy loads (Wang et al., 2010; Jones et al., 2010; Chai et al., 2012). These studies found that the retrofit of roadways with permeable shoulders is technically feasible and is economically advantageous in freeways when compared to conventional stormwater structure installation (Chai et al., 2012, summarized by Kayhanian, 2012). Further, this research suggested that permeable shoulders could be effective for subgrade permeability of as low as 10^{-5} cm/s (0.014 in./hr). However, field-scale evaluation was not conducted, and as noted by Kayhanian, "any simulated design must be constructed and tested before implementation in highway or road environments." Permeable concrete applications are also being advanced through research sponsored by FHWA and others. At the time of this writing, Cackler et al. (2012) were evaluating a full-depth permeable concrete shoulder with photo-catalytic cement binder for water quality as well as air quality benefits in a 46,000 average annual daily traffic urban freeway in St. Louis. This pilot included development of full-depth permeable concrete shoulder designs capable of withstanding highway loadings.

Appendix F provides more in-depth discussion about the emerging applicability of permeable pavements as part of achieving volume reduction in the urban highway environment.

Development of Technical Guidance for Retain On-Site Requirements

The introduction of "retain on-site" requirements in non-DOT environments—for example, EISA legislation as well as various MS4 permits (see Section 3.1.1)—has introduced new considerations and challenges into the project design process in these areas. Thus far, these requirements do not apply to highways; however, the technical guidance associated with these requirements is transferrable, in part, to highway environments. Requirements to retain stormwater to the MEP based on "rigorous feasibility analysis" (Orange County Public Works, 2011), or similar language, have led to the development of accompanying technical guidance for project proponents and reviewing agencies. For example, the U.S. EPA (2009) issued Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects Under Section 438 of the Energy Independence and Security Act, which provides guidance on how to compute requirements as well as how to evaluate feasibility. Orange County developed its Technical Guidance Document for Preparation of Water Quality Management Plans, which provides a comprehensive set of criteria as well as a stepwise process for determining the feasible level of stormwater retention that can be provided on-site as well as criteria for meeting requirements in off-site locations (Orange County Public Works, 2011). While these efforts have not specifically focused on urban highways, many of the concepts developed out of these efforts are applicable to identifying feasible volume reduction approaches for reducing urban highway runoff. These efforts include feasibility criteria related to infiltration rates, water balance and groundwater quality, geotechnical issues, harvested-water demand, site planning, and other factors. They also identify the key questions that need to be asked at different phases of project development, from planning through design. For example, as part of project planning, the use of regional feasibility maps (see example in Figure 15) can help identify constraints that may exist in certain areas. Regional maps developed by local jurisdictions can serve as resources for evaluating infiltration feasibility for highway projects.

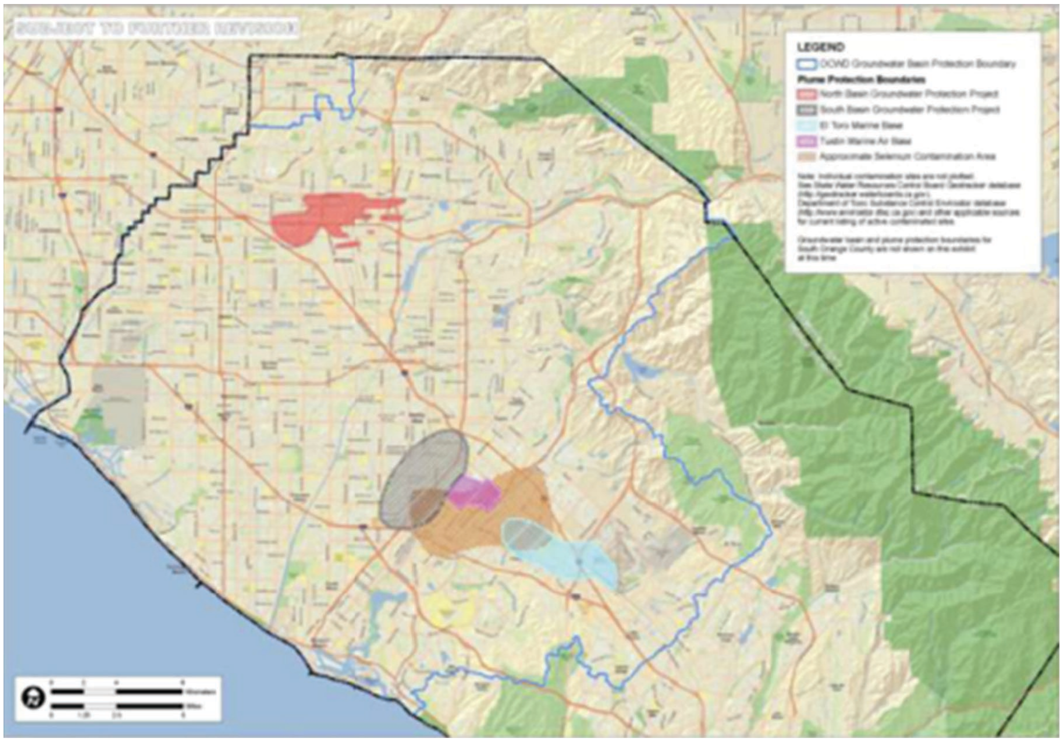


Figure 15. Example screening exhibit identifying mapped contaminant plumes in Orange County. Source: Orange County Public Works, 2011.

Research in Active Real-time Controls

Most current efforts in the field of stormwater engineering are focused on analyzing and developing designs that passively achieve target goals (e.g., peak attenuation, volume reduction, water balance, pollutant removal targets); however, passive systems rarely represent optimal solutions. Dynamic systems are particularly well suited for complex situations where timing, duration, peak control, volume reduction, use and reuse, or water quality are critically important. Recent advances in information technology infrastructure as well as hardware systems and software solutions are providing opportunities to achieve higher performance from stormwater controls through real-time, dynamic operation.

The Water Environment Research Foundation (WERF) initiated a project in 2011 to evaluate the use of highly distributed real-time control technologies for green infrastructure (e.g., advanced rainwater harvesting systems, actively controlled green roofs, wet detention basins, and underdrain bioretention systems) and demonstrate the role that these technologies can play in improving the functions of urban green infrastructure (Water Environment Research Foundation, 2011). As this research shows, active controls provide an opportunity to enhance volume reduction and flow-control performance of traditional controls by operating the outlet of the system based on precipitation forecasts, the status of system storage, or other real-time parameters. Through the use of logic algorithms, passive systems could be operated to provide longer hold times of captured water when new rainfall is not expected, thereby increasing the opportunity for infiltration and ET losses to occur. Real-time controls can also allow volume reduction practices to be operated in more marginal environments (such as those with low soil infiltration rates or sensitive water balance) where the system may need to be adaptively operated to balance volume reduction goals with issues associated with extended periods of standing water (e.g., plant health, vectors) and other factors. These benefits can sometimes be gained with relatively minimal infrastructure investments. Figure 16 shows an example outlet structure retrofit of a dry detention basin to improve volume reduction and flow-control performance.

These systems have the potential to change operations, maintenance, and monitoring regimes compared to passive systems. The outlet of the system is intended to be operated autonomously via the real-time data feeds and custom logic established as part of design; therefore, this type of system is not expected to increase operational burden substantially. However, the systems can also be observed by a manager via an online dashboard and operated via manual override if needed. Active feeds from these systems, such as of water levels and periodic photographs, can help determine needs for maintenance without routine site visits. Active feeds can also serve the role of long-term monitoring of system performance, with considerably reduced costs compared to traditional monitoring approaches.

Creative Storage and Discharge Approaches

The volume reduction performance of SCMs is primarily a function of how much runoff the system can store and the rate at which stored water can be infiltrated, evapotranspired, and/or used. By distilling the design of VRAs to these fundamental elements, there is potential to improve the volume reduction performance of existing or proposed VRAs through creative design adaptations.

Opportunities to increase storage potentially include:

- Selecting VRA treatment media with higher porosity,
- Using check dams to create ponding, and
- Using pore space in the subbase layers below traditional pavement surfaces as a storage reservoir.

Figure 16. Active control outlet structure retrofit of dry detention basin to increase volume reduction and flow-control benefits, Pflugerville, TX. Source: Geosyntec Consultants.

Opportunities to increase infiltration discharge rates potentially include:

- Piping pretreated discharge to deeper wells below compacted fills,
- Directional drilling to convey pretreated runoff to areas with better infiltration,
- Breaking up lower-permeability materials using ripping or blasting, and
- Using plant palettes with high ET rates (and capable of withstanding drought).

In each case, site-specific factors should be considered to ensure that using creative (and potentially unproven) methods does not result in unintended consequences.

4.2 Menu of Volume Reduction Approaches

Based on the information presented in Section 4.1, a focused menu of primary VRAs was identified. Section 4.2.1 provides an introduction to each primary VRA while Section 4.2.2 introduces other volume reduction concepts and approaches that can potentially supplement or support the primary menu of VRAs. The VRA fact sheets in Appendix A serve as an in-depth resource for each primary VRA, including volume reduction processes, applicability, safety considerations, and conceptual design schematics and parameter guidelines. Finally, Section 4.2.3

introduces site planning approaches that are integral to reducing runoff volumes and providing opportunities to incorporate VRAs. This chapter and the accompanying fact sheets in Appendix A are intended to help the user answer the following questions:

- What is the menu of volume reduction approaches available for my project?
- What are the system components, key processes, and key design parameters for these approaches?
- How are these approaches applicable to the urban highway environment?
- How are these approaches applicable across climate zones and watershed characteristics (e.g., soil types, topography, groundwater elevations)?

4.2.1 Primary Volume Reduction Approaches

Table 10 provides an introduction to the primary volume reduction approaches that have been identified for the urban highway environment and provides a simple graphical schematic associated with each VRA. Each of these VRAs is supported by a fact sheet that can be found in Appendix A.

4.2.2 Other Potential Volume Reduction Concepts and Approaches

Several additional volume reduction concepts and approaches have been identified from guidance manuals and literature that may have applicability in some urban highway projects as part of a volume reduction strategy.

Harvest and Use and Land Application

Harvest and use consists of capturing runoff in storage features and providing a distribution system to use the captured water to help meet non-potable water demands in the project footprint or the project vicinity. Storage can be provided in an open pond or reservoir, an underground tank or vault, or in another storage feature. Demands for harvested water within the urban highway environment may include landscape irrigation, wash water for maintenance vehicles (at maintenance yards), toilet flushing (at rest areas or maintenance yards), or other uses potentially associated with the project type or with adjacent land uses. The performance of harvest and use is strongly dependent on how much demand is present for the water, particularly during the times of year when precipitation or melt occurs; therefore, the applicability of harvest-and-use systems is highly site specific and is likely to be very limited in general for urban highway environments.

Land application is a variation of harvest and use that involves capture of water and application of this water to pervious areas at a rate that exceeds the agronomic demand (i.e., rate at which plants actually use water). Water is generally applied at a rate that is informed by the infiltration rate of the underlying soil such that land application does not result in surface runoff. Because excess water beyond agronomic rates is primarily infiltrated, geotechnical factors associated with infiltration as well as issues related to water balance should be considered in determining whether land application is feasible for a given project.

Incidental Volume Reduction in Other SCMs

Beyond the VRAs identified in Section 4.2.1, other SCMs may have the potential to achieve some incidental volume reduction even if not designed specifically for this purpose. For example, recent analysis of the International BMP Database (Poresky et al., 2011) suggests that dry detention basins with permeable bottoms can achieve an average of approximately 30% volume reduction. Volume reduction may also be important in some wetland and wet pond systems that drain down periodically or have permeable side slopes that when flooded absorb water,

Table 10. Introduction to primary menu of VRAs.

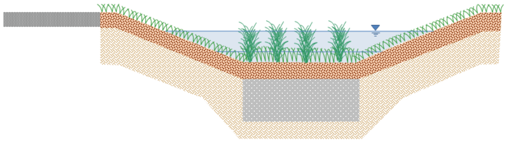
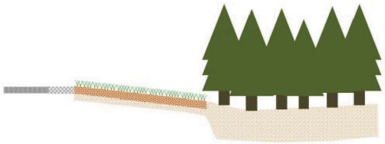
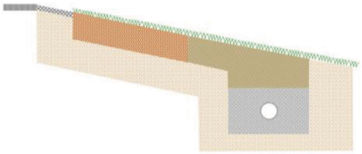
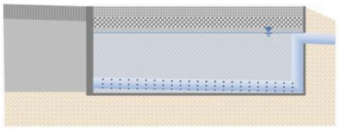
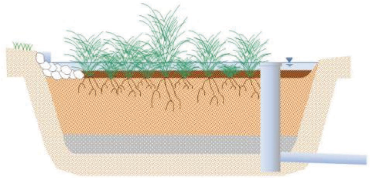
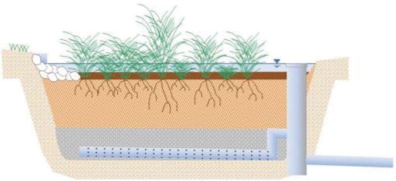
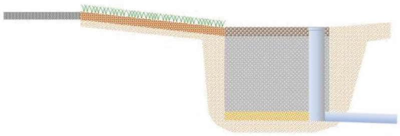
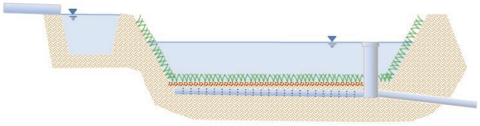
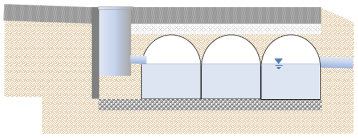
VRA 01 – Vegetated Conveyance This category includes engineered vegetated swales and other vegetated drainage features that serve the purpose of conveying stormwater runoff and can also provide significant reduction of stormwater runoff volume. Variations on this approach include an amended soil or stone storage layer to increase storage capacity and promote infiltration. A critical element of this VRA 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.	
VRA 02 – Dispersion This category consists of the dispersion of runoff toward existing or restored pervious areas for the purpose of reducing stormwater runoff volumes and achieving incidental treatment, and 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 evapotranspiration. Volume reduction performance can be improved with the use of flow spreaders, shallow slopes, and soil amendments. A critical element to this VRA is ensuring that dispersion areas support robust vegetative growth to stabilize the surface and maintain good infiltration rates.	
VRA 03 – Media Filter Drain This VRA consists of a stone no-vegetation zone, a grass strip, a 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 no-vegetation 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 VRA is typically installed between the road surface and a ditch or other conveyance located downslope. This VRA is based specifically on designs developed and applied by WSDOT.	
VRA 04 – Permeable Shoulders with Stone Reservoirs This VRA includes use of 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, from which it infiltrates into the subsoil and/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.	

Table 10. (Continued).

VRA 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. Engineered soil media is a central element of bioretention design and typically includes a mixture of sand, soils, and/or organic elements 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.	
VRA 06 – Bioretention with Underdrains This VRA is similar to VRA 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 (i.e., internal water storage zone). This category of VRA is suitable for a wider range of conditions than bioretention without an underdrain and can potentially be used to mimic natural base flows via careful control of discharges from the underdrain.	
VRA 07 – Infiltration Trench This category of VRA 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 a vegetated conveyance such as swales or filter strips. Infiltration trenches tend to be well suited to the linear highway environment as they are generally constructed in a linear configuration and their surface tends to be nearly flush to the existing grade.	
VRA 08 – Infiltration Basin Infiltration basins are relatively large, shallow basins that discharge water primarily via infiltration. Their contours appear similar to those of detention basins but do not have a surface discharge point below their overflow elevation. Infiltration basins are typically located in relatively permeable soils. 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 at a larger scale and typically do not include an engineered soil medium. Vegetative cover may also be different.	
VRA 09 – Infiltration Gallery Underground infiltration systems include a broad class of VRAs that consist of storage reservoirs located below ground 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 underground infiltration systems can be placed, including below parking areas, below access roads, or below travel lanes.	

media filters with permeable bottoms, and other controls not specifically identified as VRAs. Site-specific design information or monitoring data can be used to help estimate the potential incidental volume losses that may occur.

Real-Time Control of Outlets for Enhanced Volume Reduction Performance or Performance Monitoring

As introduced in Section 4.1.3, recent advancements and research in distributed real-time controls provide opportunities to improve the volume reduction and flow-control performance of traditional passive systems. For example, the use of active controls on the outlets from bioretention or other infiltration systems could allow water to be stored and infiltrated for longer periods when additional rainfall is not forecasted, thereby increasing volume reduction compared to a passive underdrained systems, but still allow the system to drain via a supplemental outlet when rainfall is forecasted (as determined from an Internet feed) or when the period of inundation (detected by a depth sensor) has exceeded a duration that would be of concern for plant health or vector issues. Another example configuration is retrofitting dry extended detention basins so that water can be retained for longer periods and enhanced infiltration can occur. This requires a relatively minor retrofit of the existing facility outlet structure (see WERF pilot project example in Figures 16 and 17). Real-time control systems can have the added benefit of providing continuous monitoring datasets, which can be used to identify needed maintenance or to evaluate long-term performance.

Hydrologically Referenced Discharge to Mimic Natural Hydrology

As introduced in Chapter 3, "hydrologically referenced discharge" refers to the controlled release of stored water in such a way that flow rates and timing of discharge mimic the natural hydrologic response, considering surface runoff and elevated base flow, associated with "shallow interflow" that follows rainfall events in some watersheds. DeBusk et al. (2011) hypothesize that the discharge from some stormwater controls can approximate shallow interflow response in North Carolina; it follows that potential exists to adapt discharge rates to local watershed response in other areas.

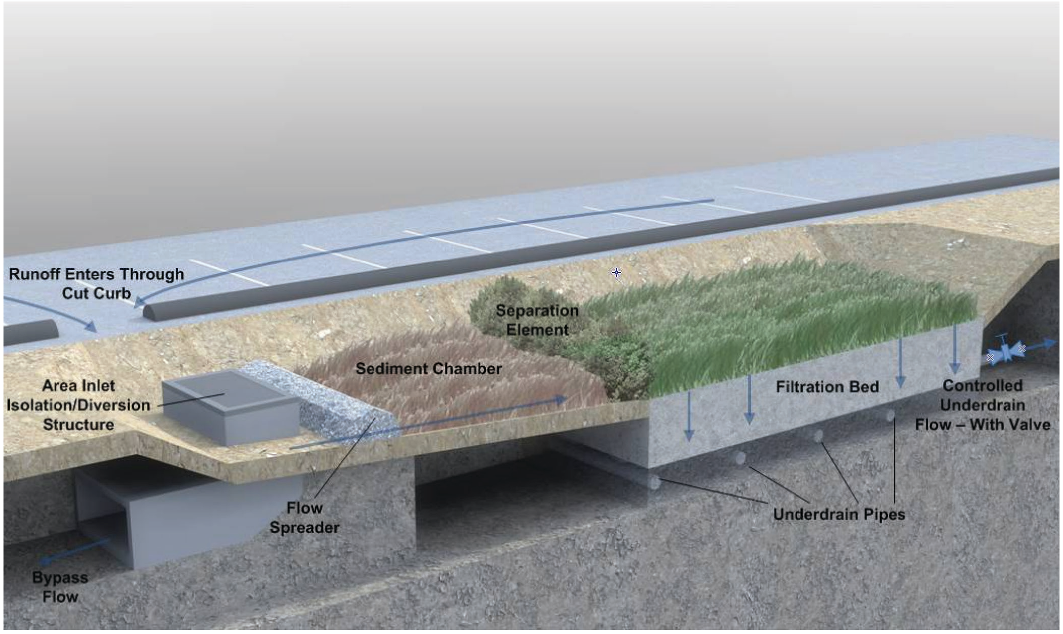


Figure 17. Example schematic of real-time–control bioretention outlet. Source: Geosyntec Consultants.

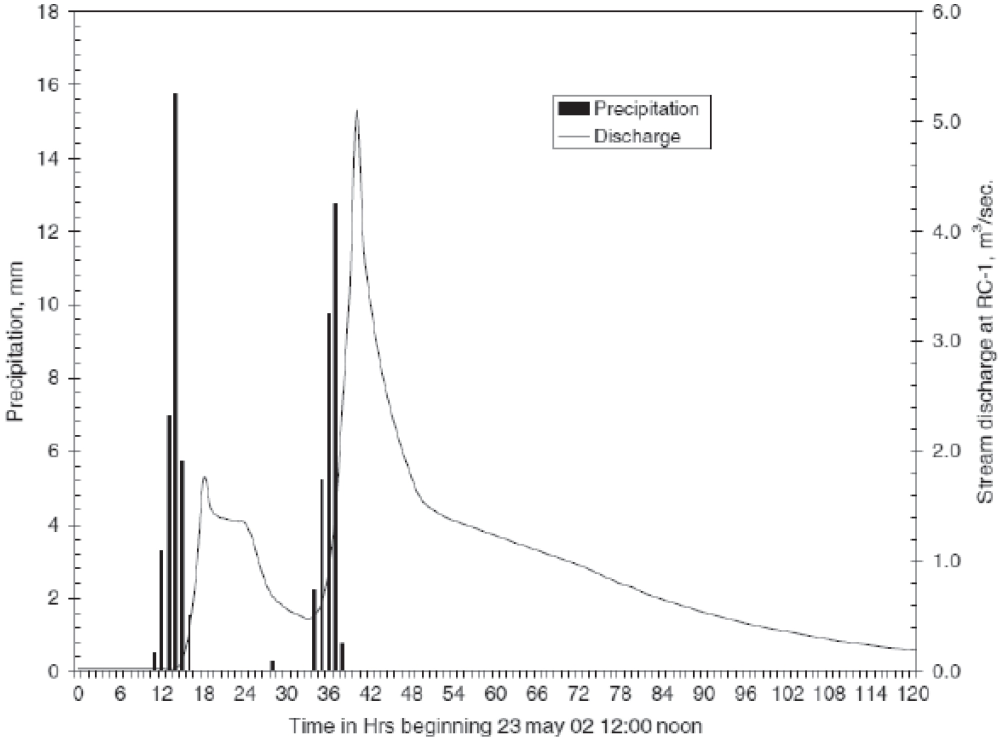


Figure 18. Example stream-flow hydrograph exhibiting shallow interflow response. Source: DeBusk et al., 2011.

Hydrologically referenced discharge is a recent concept that has not seen extensive application in addressing volume reduction requirements; however, it may be an important concept for balancing volume reduction goals with physical constraints such as shallow groundwater, low soil infiltration rates, and sensitive water balance conditions. In these cases, infiltration could have negative consequences. Additionally, a system with a controlled release may actually better mimic the natural hydrologic response than a system that only provides infiltration.

Hydrologically referenced discharge could be incorporated into any VRA that has an underdrain by providing a flow-control orifice or an active outlet control. A challenging aspect of this approach would be the determination of what range of flow rates would be considered to be equivalent to base flow as part of quantifying which portions of the discharge hydrograph should be considered "volume reduction." This would require a region-specific, watershed-specific, or site-specific analysis, such as DeBusk's assessment in North Carolina (Figure 18). Additionally, some discharge of pollutants would be inherent in the treated discharge.

4.2.3 Site Planning Approaches to Reduce Runoff Volume

Site planning is a fundamental tenant of LID guidance for municipal land uses. The Bay Area Stormwater Management Agencies Association guidance entitled *Start at the Source* (1999), as well as many other similar publications, have provided guidelines for development engineers and planners in laying out a development project to reduce impacts, including reducing runoff volume. Site planning in the urban highway context has different considerations and is not typically covered by existing guidance. Given the need to interface with existing infrastructure, meet the transportation and safety functions inherent in roadway projects, and work within a limited right-of-way, there tends to be less flexibility to incorporate many of the recommended site planning principles for stormwater management. However, if volume reduction goals are considered at an early planning phase, it may be possible to incorporate certain site planning approaches to reduce the runoff volume from the site and potentially achieve other benefits. The following sections provide guidance on planning principles, with specific emphasis on how these can be incorporated into urban roadway designs.

Early Identification of VRA Opportunity Locations

Opportunities for VRAs can be identified at an early stage of the project by considering the preliminary roadway alignment, preliminary infiltration rate screening, preliminary geotechnical screening, and preliminary groundwater quality/water balance screening. Guidance for a phased assessment of these last three factors is provided in Appendices C, D, and E, respectively. Early identification of areas within the project footprint where VRAs may be feasible can help ensure that these opportunities are made available for volume reduction purposes as each phase of designs is developed. For example, as various site layout alternatives are developed and considered, opportunities for VRAs can be identified, and the opportunities for VRAs can be included as a factor in the ranking and scoring of various alternative layouts.

For example, at the time of development of this manual, Illinois DOT was developing potential alternative designs for the "Circle" interchange in urban Chicago (http://www.circleinterchange.org). At the scale of planning shown in Figure 19, preliminary assessment of infiltration feasibility

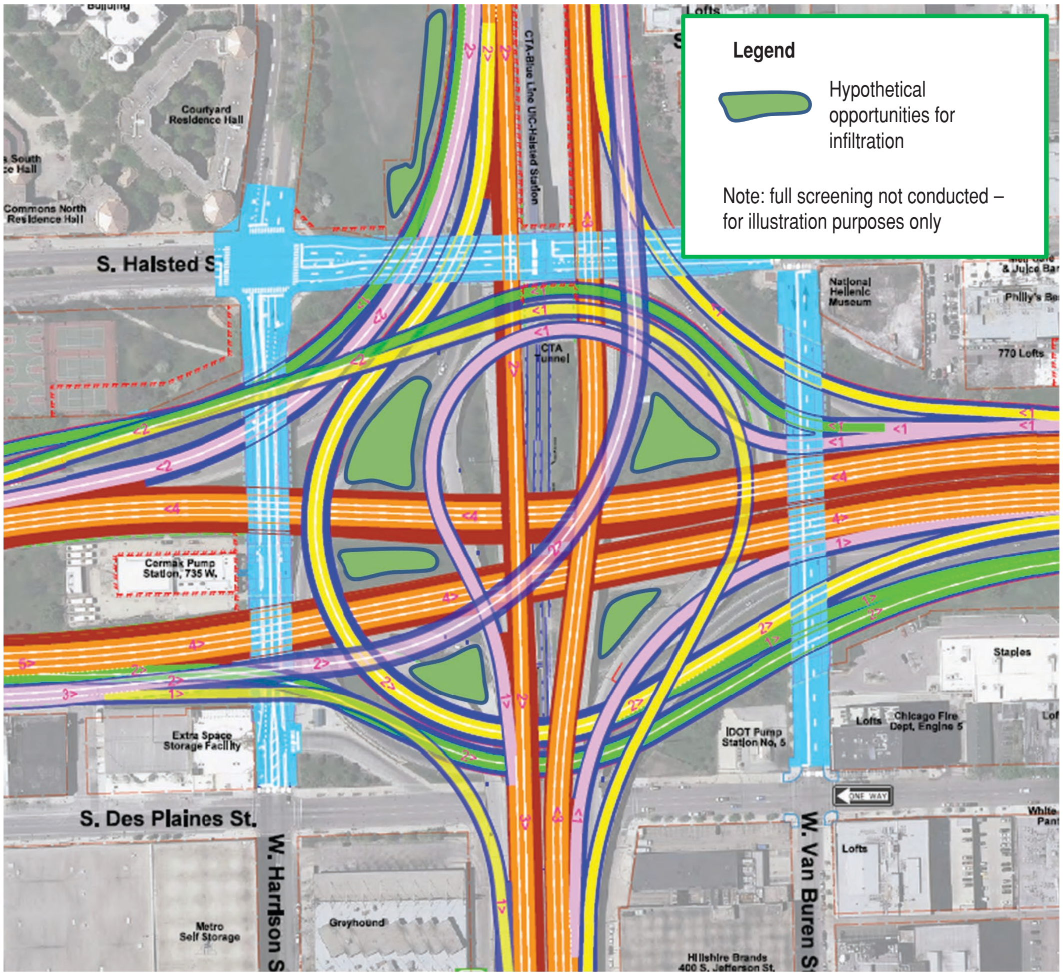


Figure 19. Example project layout alternative for the Circle interchange project in Chicago, IL. Source: Background image—Illinois DOT, http://www.circleinterchange.org. Illustration of hypothetical opportunities was added by the research team.

could be conducted, and if results were favorable, opportunity areas could begin to be identified for placement of VRAs such as bioretention areas, infiltration basins, and infiltration galleries. Working around critical infrastructure such as the light-rail tunnel, various utilities, and other constraints, project designers could attempt to reserve opportunity areas for VRA features. As designs progressed, other infrastructure could be designed to avoid these areas to the extent possible.

Develop Drainage, Grading, and Utility Configurations to Accommodate VRA Opportunity Locations

In addition to early identification of VRA opportunity locations, the development of drainage and grading configurations can be important in determining which VRA opportunities can be utilized. For example, looped interchanges typically represent one of the most significant opportunities for VRAs within the urban environment and have the potential space to support a wide variety of approaches, ranging from dispersion to bioretention areas to infiltration basins. However, using these locations for VRAs requires that water can be routed to these locations—this is a function of the alignment of storm drains, the road longitudinal profile, and the finished grade of the interchange island relative to the roadway surfaces. Where these factors can be adjusted within the site constraints to use the interchange area as a VRA, the overall outlook for achieving volume reduction performance can be significantly improved. Figure 20 illustrates an example of project drainage and grading configuration developed to facilitate the use of available space for an infiltration basin.

As another example, the design of permeable pavement shoulders requires that a supplemental drainage pathway be provided for runoff exceeding the storage and infiltration capacity of underlying soils. This is typically achieved via an underdrain system with connections to a roadside conveyance swale or an underground pipe. In the latter case, the alignment of the storm drain relative to the alignment of the permeable shoulder (and relative to the alignment of other utilities) can significantly influence the practicality of connecting underdrains to the storm drain at regular intervals.

Figure 20. Example of project drainage and grading configuration developed to use available space at interchange, Tumwater, WA. Source: Google Earth Professional.

Limit Footprint of Disturbance

Limiting the footprint of disturbance is a general principle that can potentially be incorporated into the grading design of some roadway projects as well as the construction-phase plans for equipment access and stockpiling of materials. During grading design, footprints of disturbance can be limited by attempting to leave areas at their natural grade, without cut or fill, when possible. Plans can identify limits of disturbance and include directions for clearing and grubbing and remedial grading activities not to be performed outside of these areas. Plans and specifications can also dictate that vehicle traffic access and stockpiling be prohibited in these areas. Limiting the footprint of disturbance is especially important for areas where dispersion (VRA 02) is proposed since it may be costly or impossible to fully restore a dispersion area if it is affected via compaction (incidental or intentional), topsoil removal, or other activities during construction. Similarly, the footprint of proposed infiltration VRAs should be protected from disturbance, to the extent possible, to help preserve infiltration rates and avoid costly efforts to restore infiltration capacity after other construction activities are complete.

Minimize Non-Essential Impervious Surfaces

Hardened surfaces are an essential element of transportation corridors. However, impervious surfaces that do not support an essential transportation function can add cost to a project and increase its runoff potential. The decision to pave or otherwise harden a surface that does not serve a transportation purpose may be informed by maintenance considerations associated with landscaping or the desire to prevent pathways for infiltration in the roadway prism. For example, decorative rock may have limited uses due to maintenance problems. However, opportunities may exist to use other approaches that are pervious or partially pervious, such as permeable pavement (designed for foot traffic only), decomposed granite, or native grasses that can have a minimal maintenance burden and may be favorable compared to pavement in terms of capital costs. Such an approach would help reduce runoff and reduce project costs. Potential opportunities to use pervious or partially pervious land covers include:

- Gravel, grassed, or permeable pavement medians (see example in Figure 21),
- Permeable pavement or gravel access roads,
- Degraded granite or permeable multi-use pathways,
- Vegetated or stone-lined ditches rather than concrete-lined conveyances (see example in Figure 21), and
- Directing access road or path runoff to adjacent permeable surfaces to help disconnect runoff.

Conserve or Amend Topsoil

In addition to the use of amended soil in VRAs (such as VRA 01—Vegetated Conveyance and VRA 02—Dispersion), soil amendments can be added to native soils or compacted shoulders to reduce the amount of runoff that originates from pervious areas themselves. Alternatively, stockpiling topsoil during clearing and grubbing activities and placing it over pervious areas at the end of the project can help reduce the cost of importing materials to amend soils. Compost amendments have been demonstrated successfully in the roadway environment as an initial treatment following construction to promote stabilization and vegetation growth as well as to reduce runoff volumes from pervious areas over the long-term (U.S. EPA, 2013c; Connecticut DOT, 1999; Black et al., 1999; Glanville et al., 2003; Washington Department of Ecology, 2011; Persyn et al., 2004). Figure 22 illustrates a healthy soil profile from guidance developed by the Washington State Department of Ecology (2011).

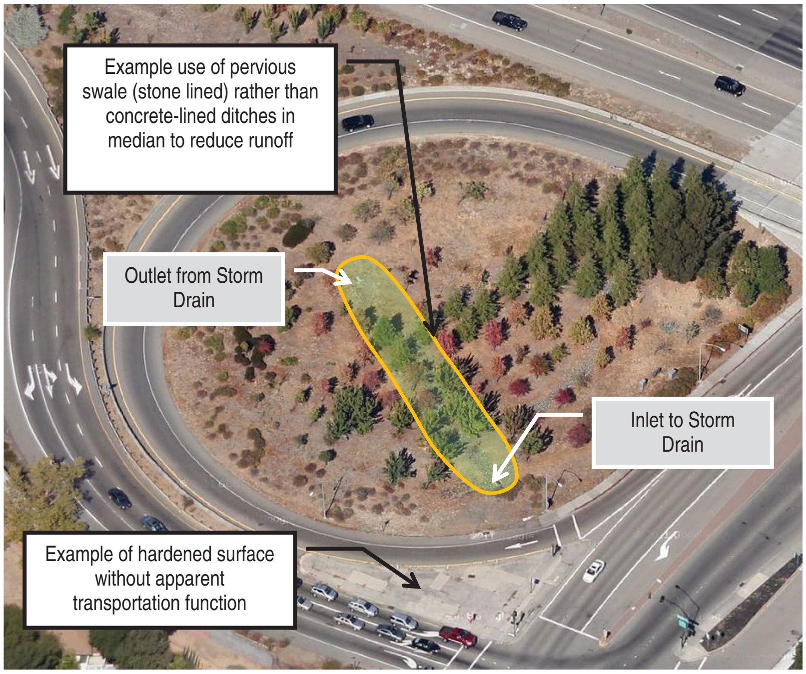


Figure 21. Example of opportunity to minimize impervious surface in project design (CA-680 at Olympic Blvd., Walnut Creek, CA). Source: Google Earth Professional.

4.3 Summary of VRA Attributes and Considerations

Each VRA has a distinct set of attributes and considerations that are inherent in its design and function. Fact sheets provided in Attachment A provide an extended summary of each of the primary VRAs. This section provides summaries of key attributes of each primary VRA to facilitate comparison as well as to serve as a concise reference. This section serves as the foundation for the prioritization and selection process that is described in Chapter 5.

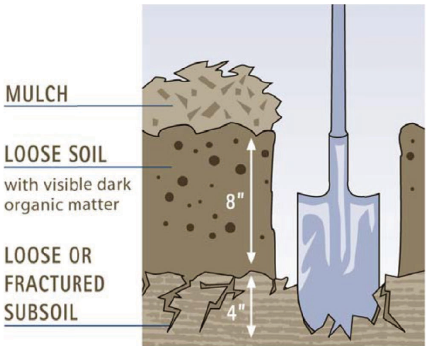


Figure 22. Example healthy soil profile. Source: Soils for Salmon, Washington Department of Ecology, http://www.soilsforsalmon.org/pdf/Soil_BMP_Manual.pdf.

4.3.1 Summary of Relative Volume Reduction Mechanisms and Potential Water Balance Issues by VRA

The amount of volume reduction achieved by a VRA, as well as the proportional split between deeper infiltration and ET that occurs in a VRA, is a function of the underlying infiltration rate of site soils, soil moisture-retention properties, plant root depths, rainfall intensity, and facility design characteristics, specifically the footprint and the depth of the BMP. When shallow BMPs with larger surface areas are used, the level of ET tends to increase due to the additional retained moisture content in the top layer of soils in closer contact with the atmosphere (Strecker and Poresky, 2009). In contrast, when deeper BMPs with smaller footprints are used, or when BMPs do not contain amended soil and vegetation elements, a greater portion of the water balance is associated with deeper infiltration, and ET plays a more minor role. In some cases, the presence of an underdrain can increase airflow through the soils, which may also increase ET potential in more porous soils/media.

While site-specific conditions are understood to influence performance, the inherent design attributes and spatial scales associated with each VRA can be used to establish the relative amounts of volume reduction and the approximate proportional split between deeper percolation and ET that can be expected. Based on the total volume reduction potential and the split between deeper percolation and ET, the relative potential to infiltrate a greater volume than natural can be estimated. Finally, inherent aspects of the design determine whether it is possible to design the VRA with an outlet control to provide base-flow–mimicking discharge in cases where this option is viable. Table 11 provides a relative comparison of the nine primary VRAs with respect to these factors.

4.3.2 Summary of Geometric Siting Opportunities and Footprint Requirements by VRA

Siting of VRAs within the urban highway environment is governed, in part, by the inherent geometric characteristics (i.e., shape) and sizing requirements (i.e., footprint) of each VRA and how these characteristics match the geometries and space constraints associated with the urban highway environment. In the case of some VRAs, geometric configuration is critical for providing the intended function. For example, a vegetated conveyance is inherently linear, while dispersion

Table 11. Summary of relative role of volume reduction mechanisms by VRA.

VRA	Total Relative Volume Reduction Potential	Relative Portion of Losses to Deeper Percolation in Typical Conditions	Relative Portion of Losses to ET in Typical Conditions	Relative Potential to Infiltrate More than Natural	Possible to Design for Base-Flow–Mimicking Discharge?
VRA 01 – Vegetated Conveyance	L/M	L/M	M	L/M	No
VRA 02 – Dispersion	M/H	L/M	M/H	L/M	No
VRA 03 – Media Filter Drain	M/H	L/M	M	L/M	No
VRA 04 – Permeable Shoulders	M/H	M/H	L	M/H	Yes
VRA 05 – Bioretention w/o Underdrain	H	M/H	M	M/H	No
VRA 06 – Bioretention w/Underdrain	M/H	M/H	M	L/M	Yes
VRA 07 – Infiltration Trench	H	H	L	M/H	Yes (w/underdrain)
VRA 08 – Infiltration Basin	H	H	L	M/H	Yes (w/underdrain)
VRA 09 – Infiltration Gallery	H	H	L	M/H	Yes (w/underdrain)

H: high; M: medium; L: low
Where dual rankings are shown, this indicates that ranking is significantly influenced by site conditions.

areas should have a relatively long flow path perpendicular to the roadway. VRAs such as infiltration basins are inherently larger and involved ponding of water within an impoundment such that they are practical only where there is a larger contiguous space with a relatively flat profile.

Additionally, the amount of space required is a function of the VRA type, as well as the climatic and soil conditions and the volume reduction goals. To provide a general perspective on the space needed for VRAs to achieve meaningful volume reduction, a case study analysis was conducted using the Volume Performance Tool. Design infiltration rates representative of hydrologic soil groups A and C (0.8 and 0.2 in./hr, respectively) were used for this assessment, and analyses were conducted on the Portland (OR) airport precipitation gage and the New Orleans (LA) airport precipitation gage. These gages represent distinctly different climates; Portland gets less precipitation on average (37 in. per year) than New Orleans (61 in. per year) and has an 85th-percentile, 24-hour storm depth (0.6 in.) that is less than half as large as that of New Orleans (1.4 in.). Additionally, Portland's precipitation is characterized by mostly frontal, low-intensity precipitation events, while New Orleans' precipitation is characterized primarily by convective events (i.e., thunderstorms and tropical storms). While many other combinations of climate characteristics exist across the United States, and many other soil conditions could be encountered, these scenarios provide a reasonable basis for developing an approximate range of potential size requirements. The primary purpose of this analysis was to demonstrate the potential impacts of VRA type, climate, soil type, and volume reduction goals on the required VRA footprint.

Table 12 summarizes the results of this analysis. Several key findings from the analysis can be used to inform a general understanding of how VRA selection, design goals, and site and climate conditions influence the sizes that may be required:

- In general, sizing was a function of location, design infiltration rate, and the volume reduction target.

Table 12. Case study assessment of general space requirements for VRAs.

Location and Hypothetical Volume Reduction Target	Portland, OR				New Orleans, LA			
	40% long-term capture		80% long-term capture		40% long-term capture		80% long-term capture	
Design Infiltration Rate	0.8 in./hr	0.2 in./hr	0.8 in./hr	0.2 in./hr	0.8 in./hr	0.2 in./hr	0.8 in./hr	0.2 in./hr
General VRA Type	Approximate Required Tributary Area Ratios (VRA Area as Percent of Tributary Area)							
Characteristic shallow-flow VRAs • VRA 01 – Vegetated Conveyance • VRA 02 – Dispersion • VRA 03 – Media Filter Drain Assuming 6-in. amended soil depth	1%	6%	4%	16%	8%	17%	30%	90%
Characteristic shallow-ponding VRAs • VRA 04 – Permeable Shoulders • VRA 05 – Bioretention w/o Underdrains • VRA 06 – Bioretention with Underdrains and IWS Assuming 1-ft storage	1%	3%	4%	8%	4%	7%	15%	25%
Characteristic deeper-ponding VRAs • VRA 07 – Infiltration Trench • VRA 08 – Infiltration Basin • VRA 09 – Infiltration Gallery Assuming 3-ft ponding	<1%	1%	2%	3%	1%	2%	4%	6%

Table 13. Summary of geometric siting opportunities by VRA.

Geometric Siting Opportunity	VRA 01 – Vegetated Conveyance	VRA 02 – Dispersion	VRA 03 – Media Filter Drain	VRA 04 – Permeable Shoulders	VRA 05 – Bioretention w/o Underdrains	VRA 06 – Bioretention with Underdrains	VRA 07 – Infiltration Trench	VRA 08 – Infiltration Basin	VRA 09 – Infiltration Gallery
Medians	X		X	X	X	X	X		
Shoulders, including breakdown lane and area within clear zone (less than approx.15% or 6H:1V)	X	X	X	X			X		X
Shoulders, outside of 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.

- Major increases in sizing tend to be required to improve volume reduction performance from 40% to 80% capture, suggesting that partial volume reduction is likely to be significantly more practicable in space-constrained highway environments.
- Soil infiltration rates were most sensitive in the performance of shallow-flow VRAs and least sensitive for VRAs with deeper ponding depths. However, it should be noted that deeper VRAs would take longer to drain, and much of the storage may need to be provided below ground to avoid vector issues if implemented in soils with lower permeability.
- In general, as the depth of storage in VRAs increased, the amount of space required for VRAs decreased.

Based on the relative space requirements interpreted from this analysis and based on a review of typical sizing guidance, the various geometric siting opportunities within the urban highway environment can be rated in terms of their suitability for each VRA. Table 13 provides a summary of the relative suitability of the various VRAs for different urban highway opportunities, considering the typical space associated with each opportunity as well the inherent shape of the opportunity. Figure 23 provides an example illustration of common geometric siting opportunities that may be present in the urban highway environment.

4.3.3 Summary of Potential Geotechnical Impacts Associated with Classes of VRAs

Geotechnical impacts may include impacts on utilities, slope stability, settlement/volume change, impacts on retaining walls or foundations, and impacts on pavement strength and durability. While a wide variety of factors contribute to the potential for geotechnical impacts (as discussed in Appendix E), the inherent location of certain VRAs within the urban highway

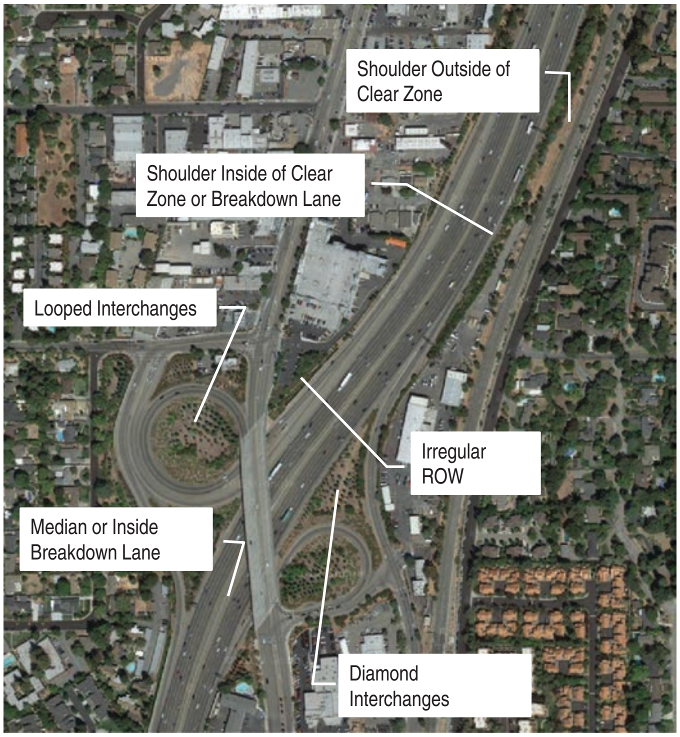


Figure 23. Key to common geometric opportunities within urban highway environments (hypothetical opportunities shown).

environment and the inherent unit processes provided by these VRAs (see Table 11) can be used to provide a relative assessment of potential geotechnical issues associated with different types of VRAs (Table 14).

4.3.4 Summary of Relative Potential Risk of Groundwater Quality Impacts Associated with VRAs

Groundwater quality impacts may include mobilization of contaminants in soil or groundwater, introduction of contaminants from stormwater runoff, and introduction of contaminants from spills. The potential for groundwater quality impacts are a function of many factors (as described in Appendix D), and the choice of VRA type has inherent implications for potential risks to groundwater quality. Constituents of concern in highway runoff may include nutrients, pesticides, organic compounds, pathogenic microorganisms, heavy metals, and salts.

Table 15 discusses factors related to VRA design that influence relative potential for groundwater quality impacts. “Pretreatment” is a general term that refers to providing an initial level of treatment that is provided to stormwater before it enters a VRA, such as filtering through grass, settling, centrifugal separators, and media filters.

Table 16 provides a synthesis of relative risk posed by each of the nine primary VRAs based on the discussion provided in Table 15. Note that a higher relative ranking does not necessarily imply that the VRA should not be used; however, it may be less favorable where other site conditions suggest a higher potential for groundwater quality issues. See Appendix D and Section 5.2 for guidance in evaluating overall feasibility of VRAs relative to groundwater quality issues.

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

Category of VRA	Characteristic Properties	Example Opportunities and Constraints Related to Geotechnical Issues[1]	
		Opportunities	Constraints
Direct infiltration into roadway subgrade *Example:* • *VRA 04 – Permeable Shoulders* • *VRA 09 – Infiltration Gallery*	• Broad footprint; may only receive direct rainfall or equivalent • Road subgrade has important structural considerations, particularly for flexible pavement design	• Broad footprint may allow infiltration in relatively dense soils • Standard roadway designs typically account for wetting of subgrade • Rigid pavement design (i.e., concrete) less sensitive to strength of subgrade	• Utilities in the right-of-way (ROW) • Settlement and volume change processes (i.e., consolidation, frost heave, swelling, liquefaction) • Reduction in strength of subgrade material from increase in moisture content
Infiltration in breakdown lane and near shoulders *Example:* • *VRA 03 – Media Filter Drain* • *VRA 04 – Permeable Shoulders*	• Outside of main travel lanes; significantly less loading • Smaller footprint; more concentrated zone of infiltration	• Shoulders designed to accommodate less traffic loading than travel lanes • Well-distributed inflow • Can have moderate to high tributary area ratio[2] • Linear configuration less susceptible to groundwater mounding than basin configurations • Underdrain with outlet can control amount of water infiltrated	• 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
Infiltration and Surface Dispersion in Clear Zone *Example:* • *VRA 02 – Dispersion* • *VRA 03 – Media Filter Drain*	• Allows incidental infiltration over relatively broad area; also provides ET • Typically coupled with a vegetated conveyance at toe of filter strip	• Drainage over shoulder is a typical design feature • Compost amended results in relatively limited increase in infiltration compared to standard design • Higher proportion of losses to ET than other VRAs	• May lead to erosion issues if applied on slopes that are too steep • Slopes may need to be compacted to same degree as mainline roadway • 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:* • *VRA 01– Vegetated Conveyance* • *VRA 05/06 – Linear Bioretention Variations* • *VRA 07 – Infiltration Trench*	• Tends to be located 10 or more feet from travel lanes • Typically effective water storage depth is between 6 in. and 36 in. • Tributary area ratio may be low • 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 ROW due to proximity to ROW line • Greater potential for mounding due to concentration of infiltrating footprint • May reduce stability of slopes if located near top or toe
Basins and localized depressions *Example:* • *VRA 05/06 – Bioretention (more centralized variation)* • *VRA 08 – Infiltration Basin*	• Typically located in more centralized locations • Typically have a relatively low tributary area 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 are provided to identify typical opportunities and constraints of the infiltration design feature. Additional opportunities and constraints may be present based on site-specific conditions. More information regarding risk indicators, design implications, and potential mitigation measures is provided in Chapter 3.

2 – "Tributary area ratio" refers to the ratio of the infiltrating surface to the total tributary area. A high tributary area ratio indicates that the infiltrating footprint makes up a large portion of the total tributary area, and vice versa.

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

Risk Factor	Discussion	Lower Risk Indicators ↔	Higher Risk Indicators
Footprint/tributary area 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
Strata at which infiltration occurs	When infiltration occurs below the strata of organic soil or closer to the groundwater table, there tends to be less assimilative capacity.	Systems infiltrating near the surface where soils have higher organic content and biologic activity	Systems infiltrating below the organic strata and not providing a treatment layer, such as imported amended soil (or other pretreatment)
Amount of infiltration occurring	In systems where a higher portion of losses occur to infiltration, the potential for groundwater impacts tends to be higher.	Systems with less infiltration, such as vegetated conveyances	Systems with more infiltration, such as underground infiltration systems
Potential for pretreatment or treatment within the VRA	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 VRA are limited, such as permeable pavement

Table 16. Relative ranking of potential groundwater quality risk by VRA.

VRA	Relative Risk of Groundwater Quality Impacts[1]	Key Characteristics Influencing Ranking
VRA 01 – Vegetated Conveyance	L	More limited infiltration, shallower ponding, and soil filtration of infiltrating runoff
VRA 02 – Dispersion	L	Shallower ponding; high soil contact ratio; amended/organic/biologically active soils
VRA 03 – Media Filter Drain	L	Shallow ponding; specialized media with high treatment capacity
VRA 04 – Permeable Shoulders	M/H	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
VRA 05 – Bioretention w/o Underdrains	L/M	Provide treatment for most constituents within media; can have relatively small footprint and deeper infiltrating surface
VRA 06 – Bioretention with Underdrains	L	Provide treatment for most constituents within media; infiltrate less water than bioretention w/o underdrain
VRA 07 – Infiltration Trench	M/H	Deeper profile typically below surface soil strata; pretreatment options may be limited
VRA 08 – Infiltration Basin	M	Deeper profile and typically smaller tributary area ratio, but soil can be amended to improve water quality
VRA 09 – Infiltration Gallery	M/H	Deeper profile typically below surface soil strata; pretreatment may not address all pollutants of concern

[1] Rankings are relative to other VRAs, not a complete ranking of total risk, which is also a function of pollutant sources and site conditions.

H: high; M: medium; L: low

Table 17. Summary of potential safety considerations by VRA.

Potential Safety Considerations	VRA 01 – Vegetated Conveyance	VRA 02 – Dispersion	VRA 03 – Media Filter Drain	VRA 04 – Permeable Shoulders	VRA 05 – Bioretention w/o Underdrains	VRA 06 – Bioretention with Underdrains	VRA 07 – Infiltration Trench	VRA 08 – Infiltration Basin	VRA 09 – Infiltration Gallery
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 (i.e., pipe inlets/outlets flush to slope)	X	X	X		X	X	X		
Stability of soil within clear zone, particularly if compost amended	X	X	X		X	X			
Vegetation management to remove collision hazards									
Vegetation management to maintain line of site		X			X	X		X	
Supplemental drainage to ensure free drainage of travel lanes in the event of clogging				X					
Low-speed vehicle maintenance activities or lane closures				X					X

4.3.5 Summary of Safety Considerations by VRA

A number of key safety considerations that may relate to the siting and design of VRAs include:

- 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, and
- Lane closures to facilitate low-speed maintenance activities within the right-of-way.

Based on its respective location within the highway environment and its inherent design attributes, each VRA has a different suite of factors that should be considered in design. Safety considerations that may apply to specific VRAs are discussed in the respective VRA fact sheets and are summarized in Table 17. These factors do not necessarily result in VRAs being considered infeasible but should be considered in selection, siting, and design.

4.3.6 Summary of Maintenance Activities by VRA

Maintenance activities of VRAs range from regular highway maintenance activities, such as trash control or vegetation management, which may be done regardless of whether a VRA is in place, to more VRA-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 that are 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 be taken to return the facility to its intended function. Tables 18 and 19 provide an inventory of routine maintenance activities

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

Routine Maintenance Activities	VRA 01 – Vegetated Conveyance	VRA 02 – Dispersion	VRA 03 – Media Filter Drain	VRA 04 – Permeable Shoulders	VRA 05 – Bioretention w/o Underdrains	VRA 06 – Bioretention with Underdrains	VRA 07 – Infiltration Trench	VRA 08 – Infiltration Basin	VRA 09 – Infiltration Gallery
Mowing	●	●	●	○	⦿	⦿	●	●	○
Maintain level spreading functions	⦿	⦿	⦿	○	○	○	⦿	⦿	○
Landscaping and weeding	○	○	○	○	●	●	⦿	⦿	○
Routine woody vegetation management	○	○	○	○	⦿	⦿	⦿	●	○
Sediment removal/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 VRA.

Corrective Maintenance Activities	VRA 01 – Vegetated Conveyance	VRA 02 – Dispersion	VRA 03 – Media Filter Drain	VRA 04 – Permeable Shoulders	VRA 05 – Bioretention w/o underdrains	VRA 06 – Bioretention with Underdrains	VRA 07 – Infiltration Trench	VRA 08 – Infiltration Basin	VRA 09 – Infiltration Gallery
Regrading to maintain level spread function		X	X						
Regrading to address sediment deposition or erosion	X				X	X		X	
Repairing of 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 clogged surfaces				X	X	X	X	X	X
Complete replacement of system components (full depth) to remediate clogged surfaces				X	X	X	X	X	X
Reseeding to provide needed coverage	X	X	X					X	
Significant revegetation 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

and corrective maintenance activities, respectively, that may apply to each of the primary VRAs. 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 VRAs in the highway environment is still limited to inform decision making. *NCHRP Report 792: Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices* (Taylor et al., 2014a) evaluates maintenance needs and whole life-cycle cost estimating tools for a variety of stormwater control measures, including VRAs.

4.3.7 Summary of Relative Whole Life-Cycle Costs by VRA

The initial cost of a VRA is only a part of the total expenditure needed to keep the system operational into perpetuity. Whole life-cycle costs (WLCs) include up-front capital costs as well as maintenance costs through the life span of the facility and the cost of replacing or restoring the facility at the end of its usable life. Future costs are typically expressed in terms of their net present value (NPV), where future costs are discounted based on when they occur and their assumed discount factor.

The use of WLC methods to compare VRAs is strongly recommended. Focusing only on capital costs can lead to a focus on minimizing the initial costs, which can lead to design decisions that result in greater life-cycle costs (Lampe, 2005). The maintenance, repair, and unplanned or premature failure of a component, either as a result of normal conditions, short-sighted design decisions (e.g., neglecting to provide pretreatment; lack of adequate maintenance access or safety), or unanticipated conditions, can account for a significant proportion of the overall costs associated with a VRA. Thus, when planning the construction of a VRA, the designer should develop relative WLC estimates, both to compare between different VRAs and to inform decisions (i.e., the cost of more robust pretreatment versus the cost of more frequent maintenance/replacement).

The WLC of VRAs can vary widely as the result of site-specific and regional differences (Washington State DOT, 2011). While conducting an economic appraisal of the VRA, a major difficulty is assessing the relative benefits and risks of technologies and projects. The same type of technology implemented at one location could have significantly different costs at another location as a result of different site conditions, project types, and regional factors (Lampe, 2005).

A significant source of variability in VRA costs is the baseline for comparison of costs. The baseline for estimating the cost of VRAs is the minimum set of design attributes that would have been required for the project. For example, if the project was still required to convey and treat runoff (regardless of the use of VRAs), then the costs of this scenario form the baseline; the net or incremental cost of VRAs should then account for additional costs as well as any avoidance of baseline conveyance or treatment costs that could be accrued. For example, if the use of a vegetated conveyance can reduce the amount of storm drains that must be constructed and the volume of water that must be treated, both of these costs could be subtracted from the capital cost of constructing the vegetated conveyance when comparing the VRA's net project cost.

The type of project being constructed is also important in terms of determining the costs that would be considered incremental to the project as a result of using VRAs. For example, in new roadway construction projects or major lane additions, bulk grading is typically considered to be an expense accrued by the overall project—project plans are often developed to balance cut and fill, where feasible, to avoid the expense of hauling material on or off site. Therefore, costs of excavation and hauling for construction of VRAs is typically shared by the overall project, with little incremental cost attributable to VRAs. Similarly, a new project would typically have been required to provide some type of vegetation or surface stabilization in the locations where VRAs are proposed. Therefore, the cost of vegetating a VRA would only be the incremental cost of the proposed VRA vegetation versus the baseline vegetation or stabilization plans had the VRA not been used. In contrast, projects conducted solely to retrofit roadways with VRAs have different considerations because the VRA improvements may be the only improvements being made as part of the project. In most cases, this results in a greater cost attributable to the VRA construction. For example, the cost of the VRA could include expenses such traffic control, utility relocation, hauling, clearing and grubbing, vegetation reestablishment, and other costs that would have typically been considered incidental to the overall project if the VRA had been constructed as part of a new project or a major lane addition. Yet another case is when a retrofit project is done simply to improve the volume reduction potential of an existing BMP, such as by modifying the outlet structure of an extended detention basin or by adding check dams to a vegetated ditch to improve infiltration. These types of retrofits can accrue relatively minor costs since they involve limited physical modifications.

In summary, many factors influence the cost that should be attributed to a VRA. The purpose of this section is to introduce the qualitative framework for comparing the relative costs of VRAs and understanding how site-specific factors may influence these costs. Section 5.4.5 provides more specific detail for developing VRA costs for a specific site once conceptual designs have been developed.

Whole Life-Cycle Cost Framework Terminology

This manual introduces a specific framework for calculating the various costs of a VRA. Key terms and concepts associated with this framework are introduced in the following:

Capital cost. A fixed-value, one-time expense caused by purchasing labor, land, materials, or equipment needed to bring a stormwater technology to an operable status. Appraisal and planning costs of the VRA, engineering design costs, site investigation costs, and the initial construction costs are all capital costs.

Baseline cost scenario. An alternative cost scenario to which the incremental (net) cost of a VRA is compared. Depending on regulatory conditions and project type, this could be a case where traditional technology is used—for example, a piped stormwater conveyance system to conventional treatment systems—or could be defined as the "no-action" option. This should be defined because it is necessary to calculate the incremental whole life-cycle cost of a VRA.

Net capital cost. This term is defined as the capital cost of the chosen VRA scenario less the capital cost of the baseline cost scenario.

O&M cost. The cost needed to preserve a technology's water quality, volume reduction, and conveyance function, and in some cases its aesthetics. This includes any labor, materials, and structural repairs over the life span of the technology. Functional maintenance costs help preserve the performance and safety of the VRA, whereas aesthetic maintenance costs help provide public acceptance of the technology and might reduce the need for functional maintenance.

Net O&M cost. The maintenance cost of a selected VRA less the maintenance cost of the baseline cost scenario. For example, if vegetation and trash management would be required for a road shoulder in the baseline case, this unit cost should be subtracted from the costs for vegetation and trash management for the VRA areas.

Life span. The amount of time before the VRA needs to be replaced or substantially reconstructed. A period that begins when the stormwater technology becomes functional and ending when that technology is decommissioned and disposed of or reconstructed. Understanding the life span of a VRA is important for computing WLCs and planning for future O&M costs.

Replacement cost. This is the cost to install a new VRA at the end of the current VRA's life span or substantially reconstruct the VRA. Some VRAs, such as dispersion, have a low replacement cost, primarily involving minor regrading and decompaction, whereas others, such as permeable shoulders, could have high replacement costs if excavation down to subgrade material is needed to regenerate the infiltration capacity of the system.

Discount factor. This is a factor used to compute the present value of future costs. It is typically calculated as the rate of return that could be obtained for cash on the open market minus the rate of increase in the cost of goods and services (i.e., inflation). If goods and services are expected to increase at the same rate as the growth of money invested in the open market, then the discount rate would be zero—implying that goods would cost the same in the future (in terms of present-day value) as they would today. Typically, it is assumed that goods and services will increase at a rate less than the rate of return on the open market; therefore, a positive discount rate is typically used. This implies that future costs are discounted in terms of present value. This factor is important for O&M and future purchases.

Whole life-cycle cost. The total cost of a stormwater technology throughout its life span; includes all capital costs, O&M costs, and disposal/decommissioning costs that are associated directly with the VRA, normalized to net present value. WLC is typically represented in terms of cost per year, and in present-day dollars.

Net whole life-cycle cost. The whole life-cycle cost of a VRA less the whole life-cycle cost of the baseline cost scenario. The net whole life-cycle cost is important because different technologies will have cost reductions in different stages of development (e.g., capital costs vs. O&M costs vs. disposal costs). Computations of WLCs are discussed further in Section 5.4.5.

Site-Specific Influences on VRA Whole Life-Cycle Costs

The actual costs of a VRA depend on a large number of site-specific factors and are thus difficult to estimate and especially difficult to generalize categorically. In addition, regional costs, such as permitting costs, regulatory requirements, and the state's construction economy, can cause cost difference between two similar sites. Managers should develop their own site-specific frameworks to calculate the cost of a VRA based on the considerations presented in the following paragraphs (Taylor et al., 2014b). The factors discussed in the following paragraphs represent important sources of variability.

Retrofits versus redevelopment versus new construction. The type of project greatly influences the net costs of a VRA. As introduced previously, implementing a VRA in a new construction project or major redevelopment project could result in limited increases in capital costs and possibly reduced net costs if baseline requirements, such as piped infrastructure and conventional treatment, can be reduced or avoided. The costs of building a VRA in a retrofit project are often the greatest. Most costs are associated with the VRA itself because the project is centered around the VRA, and thus costs like grading and soil removal are part of the VRA cost. For example, permeable shoulders can cost much less for new roadways (where the use of a permeable shoulder offsets the need for traditional pavement and base material) than retrofit applications (where costs include demolishing current shoulders and hauling existing base material away while installing new base material and the permeable top course).

Land allocation and land use costs. The cost of land is likely to create one of the largest differences in project costs. In some cases, DOTs could have a surplus of land in the ROW suitable for a VRA, while in other cases, the implementation of the VRA might require additional land purchases. In the latter case the cost of land can be extremely variable by location, depending on surrounding land use (Strassler et al., 1999) and location.

Project-scale and unit costs. Larger projects with fewer, large-scale VRAs can potentially be built at lower costs than smaller-scale projects or those that have many distributed controls. Larger-scale projects can have reduced managed costs per unit area. Additionally, each feature may have fixed costs (for example, inlet and outlet structure) regardless of size; therefore, the more elements, the greater costs may be. An exception would be if using more distributed controls helps avoid significant amounts or sizes of conventional drainage infrastructure either as a part of the actual road project or required downstream improvements.

Flexibility in site selection and site suitability. Site-specific parameters that influence costs include the ability to configure the site to allow efficient drainage design, the availability and accessibility of the work area, traffic control (in retrofit projects), site contamination, and existing infrastructure.

Regional performance-related parameters. The average annual rainfall, storm shape and characteristics, catchment area runoff characteristics, and climate will affect the VRA sizing and costs to meet a given objective. See Table 12 for an example of the influence of local rainfall patterns on sizing requirements to meet given design goals.

Soil type and groundwater vulnerability. These factors will determine if infiltration methods can be used and what kind of infiltration methods, including storage, are applicable to the site. In some cases, in low infiltration rate situations, additional required storage or attenuation will raise the cost of the VRA. An example case study is assessed in Table 12 regarding the influence of infiltration rates on the ability to meet project goals.

Planting. The availability of suitable plants for the site and region and the level of planting needed for a particular VRA or pollutant reduction goal will influence cost. Additionally, planting influences the maintenance costs and could add additional costs, such as for irrigation.

Level of experience of the designers and contractors. Design and construction costs generally vary across regions. However, traditional cost methods often overlook experience as a factor. Some areas in the United States have required stormwater water quality and volume controls for 20 years; in these areas, local design/engineering agencies and local contractors will more typically have the skills to design and build the VRAs more effectively. Such experience will help reduce unexpected initial costs and/or O&M costs.

Regulatory requirements. Different regions require varying water quality treatment and volume control limits. Differences in the acceptable limit for water quality constituent concentrations or volumes to be controlled will create different costs across VRAs due to design and construction costs. In addition, permitting costs will vary across regions and with project size. An example case study is assessed in Table 12 regarding the influence of design goals on the sizing requirements of VRAs.

Time of construction. Depending on the region, construction costs or delays due to weather or other seasonal construction considerations might influence the cost of implementing a VRA.

Summary of Typical Relative Costs of VRAs

The average or typical whole life-cycle cost of a VRA is difficult to estimate because of the variability in design and construction due to site-specific factors, as introduced previously. Additionally, information on whole life-cycle costs and life span to inform decision making is still limited. Table 20 represents the relative costs of select VRAs 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 versus retrofit projects,

Table 20. Relative comparison of typical VRA costs per volume of stormwater managed (adapted from Washington State DOT, 2011).

VRA	Capital Costs – New Roadway or Major Redevelopment[1]	Capital Costs – Retrofits or Minor Redevelopment	O&M and Replacement/ Reconstruction Costs	Effective Life Span[2]
VRA 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 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 VRA	**Low to Moderate** • Requires more frequent maintenance of debris removal and vegetation upkeep than 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
VRA 02 Dispersion	**Low** • Assuming no acquisition costs for the ROW; if land acquisition is needed, it 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; if land acquisition is needed, it 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 those with original construction	**50 to 100 Years** • Regrade level spreader • Decompact underlying soils, potentially add new amendments • Correct major erosion • Longer time period than for VRA 01 since water is spread over larger area
VRA 03 Media Filter Drain	**Low to Moderate** • Assumes no acquisition costs for land • Assumes 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[3]** • Regrade level spreader • Replace media if exhausted • Shorter time period than for VRA 01 and 02 because footprint tends to be smaller and more specialized media are used
VRA 04 Permeable Shoulders with Stone Reservoirs	**Low to Moderate** • Assumes new development or lane additions where permeable pavement net cost is cost over and above traditional pavement cost.	**High** • Requires excavation and hauling of previous roadway, import of new material • Equipment, labor, and installation costs are directly associated with VRA.	**Moderate to High** • Requires regular vacuum sweeping of shoulder to maintain permeability • Surface replacement may be required more frequently than for traditional pavement. • Full-depth replacement may cost more than initial construction. • If water is routed directly to subbase via inlets, sweeping is not needed, but earlier clogging of the subbase layer may occur.	**15 to 25 Years[4]** • Replace top course of permeable pavement due to structural wear • Fully excavate to restore infiltration capacity of subgrade • Dependent on sediment loading, traffic loading, and other factors; not well established
VRA 05/06 Bioretention	**Moderate** • Specialized planting and soil, so net cost increase should be considered over areas that would have been planted. • Assumes grading and conveyance is performed in conjunction with overall project • Costs can increase, and volume performance declines with use of an underdrain.	**Moderate to High** • Cost depends on cost of rerouting flows to specific areas. • Some aspects of site investigation and construction are not shared with overall project. • Possibility of additional land acquisition	**Moderate** • Regular maintenance of vegetation and trash needed, similar to baseline landscape maintenance. • May require restoration of surface infiltration capacity and replanting at regular intervals	**5 to 12 Years (Partial)** • Dependent on effectiveness of pretreatment • Partial reconstruction involves restoration of surface infiltration capacity and replanting. • Intervals may be longer if vegetation is robust. **25 to 50 Years (Complete)** • Complete reconstruction involves replacement of media/ structures/piping at less frequent intervals.
VRA 07 Infiltration Trench	**Moderate to High** • Requires several additional construction materials • Assumes no land acquisition • Can be incorporated into excavation plans	**High** • Cost depends on cost of rerouting flows to specific areas. • Some aspects of site investigation and construction are not shared with overall project. • Possibility of additional land acquisition	**High** • Requires maintenance of debris and sediment removal to maintain infiltration • Failures have been common • Replacement cost can be similar to new construction cost 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.

Table 20. (Continued).

VRA	Capital Costs – New Roadway or Major Redevelopment[1]	Capital Costs – Retrofits or Minor Redevelopment	O&M and Replacement/ Reconstruction Costs	Effective Life Span[2]
VRA 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 depends on cost of rerouting flows to specific areas. • Aspects of site investigation and construction not shared with overall project. • Possibility that additional land acquisition may be needed • Costs can be low if existing detention basin can be converted to infiltration.	**Moderate** • Requires debris and sediment removal to maintain infiltration. • Maintenance of any conveyance systems	**5 to 10 Years (Partial)** • Dependent on effectiveness of pretreatment • Partial restoration involves 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)** • Complete restoration involves 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.
VRA 09 Infiltration Gallery	**Moderate to High** • Excavation and piping can be incorporated into construction plans. • Assumes robust pretreatment system.	**High** • Cost depends on cost of rerouting flows to specific areas. • Aspects of site investigation and construction are not shared with overall project. • Assumes robust pretreatment system	**High** • Below grade, difficult to maintain • Requires debris and sediment removal to maintain infiltration • Requires regular maintenance of pretreatment system	**10 to 25 Years[5]** • Rough estimate, assuming robust pretreatment; could be much less without pretreatment • If gallery is accessible, it may be possible to restore capacity a limited number of times before reconstruction.

[1] Bullets provide explanation of and qualifications for ranking provided in table.
[2] Bullets summarize the activities associated with reconstruction at the end of the effective life span and provide explanation of basis for estimated life span.
[3] Based on WSDOT best professional judgment; systems have not been in place for full life cycle.
[4] Not provided by WSDOT; estimated from Ballestero et al., 2007; Low Impact Development Center, 2005.
[5] Best professional judgment; highly site specific and dependent on pretreatment methods used.

a separate column is provided for these two categories. This table is intended to be used for planning purposes only. A site-specific cost analysis is recommended to help select VRAs once conceptual designs have been developed (see Section 5.4.5 for guidance). *NCHRP Report 792: Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices* (Taylor et al., 2014a) evaluates whole life-cycle costs and develops whole life-cycle cost estimating tools for a variety of stormwater control measures, including VRAs.

4.4 Additional References for VRA Design and Maintenance Information

The VRA fact sheets contain references to selected design and maintenance manuals that may be useful in providing information to support more detailed design efforts for specific VRAs as well as maintenance planning. Selected references are also listed in this section to provide a resource for users seeking additional information to support VRA design and maintenance planning.

4.4.1 Selected Nationwide Guidance

The following nationwide guidance manuals may serve a supporting role in developing detailed VRA designs and developing maintenance plans:

- 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. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_565.pdf.

- Geosyntec Consultants et al. (2011). *NCHRP Report 728: Guidelines for Evaluating and Selecting Modifications to Existing Roadway Drainage Infrastructure to Improve Water Quality in Ultra-Urban Areas.* Transportation Research Board of the National Academies. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_728.pdf.
- Taylor et al. (2014a). *NCHRP Report 792: Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices.* Transportation Research Board of the National Academies.
- WEF. (2012). Design of Urban Stormwater Controls. WEF and ASCE Manual of Practice 23. WEF Press. https://www.e-wef.org/Default.aspx?TabId=192&ProductId=18172.
- Strecker et al. (2005). *Critical Assessment of Stormwater Treatment Controls and Control Selection Issues.* 02-SW-01. Alexandria, VA: Water Environment Research Foundation; London: IWA Publishing.
- Decentralized Stormwater Controls for Urban Retrofit and Combined Sewer Overflow (CSO) Reduction (WERF, Report 03-SW-3) http://www.iwapublishing.com/template.cfm?name=isbn184339748x.
- Low Impact Development Design Manual (3-210-10) (United States Navy) http://www.wbdg.org/ccb/DOD/UFC/ufc_3_210_10.pdf.

4.4.2 Selected State-Specific DOT Guidance

For reference purposes, Table 21 provides a selected inventory of recent state-specific DOT stormwater guidance manuals that may serve a supporting role in developing detailed VRA designs and developing maintenance plans. Users should adhere to local guidance and criteria, as applicable.

Table 21. Selected state-specific DOT manuals related to stormwater management.

State	Year Published	Publication Title
AZ	2009	ADOT Post-Construction Best Management Practices Manual For Highway Design and Construction http://www.azdot.gov/Inside_ADOT/OES/Water_Quality/Stormwater/PDF/adot_post_construction_bmp_manual.pdf
	1993	Highway Drainage Design Manual – Hydrology, http://www.azdot.gov/Highways/Roadway_Engineering/Drainage_Design/PDF/ADOTHighwayDrainageDesignManual_Hydrology.pdf
	2007	Highway Drainage Design Manual – Hydraulics, http://www.azdot.gov/Highways/Roadway_Engineering/Drainage_Design/PDF/ADOTHighwayDrainageDesignManual_Hydraulics.pdf
CA	2010	Caltrans Storm Water Quality Handbooks – Project Planning and Design Guide, http://www.dot.ca.gov/hq/oppd/stormwtr/ppdg/swdr2012/PPDG-May-2012.pdf
	2012	Caltrans Highway Design Manual, http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm
GA	2001	Georgia Stormwater Management Manual Volume 2, http://documents.atlantaregional.com/gastormwater/GSMMVol2.pdf
MA	2004	Storm Water Handbook For Highways and Bridges, http://www.mhd.state.ma.us/downloads/projDev/2009/MHD_Stormwater_Handbook.pdf
	2006	Massachusetts Project Development & Design Guide, http://www.mhd.state.ma.us/default.asp?pgid=content/designguide&sid=about
MD	2000	2000 Maryland Stormwater Design Manual – Volumes I and II, http://www.mde.state.md.us/programs/Water/StormwaterManagementProgram/SoilErosionandSedimentControl/Documents/MD%20SWM%20Volume%201.pdf
MN	2000	MnDOT Drainage Manual, http://www.dot.state.mn.us/bridge/hydraulics/drainagemanual/
	2009	Stormwater Maintenance BMP Resource Guide http://www.lrrb.org/media/reports/2009RIC12.pdf
NJ	2004	New Jersey Stormwater Best Management Practices Manual, http://nj.gov/dep/stormwater/bmp_manual2.htm
NV	2006	Storm Water Quality Manuals – Planning and Design Guide, http://www.nevadadot.com/uploadedFiles/NDOT/About_NDOT/NDOT_Divisions/Engineering/Hydraulics/2006_PlanningAndDesignGuide.pdf
NY	2010	New York State Stormwater Management Design Manual, http://www.dec.ny.gov/chemical/29072.html, http://www.dec.ny.gov/docs/water_pdf/swdm2010entire.pdf
OH	2012	Location & Design Manual, Volume 2 Drainage Design, http://www.dot.state.oh.us/Divisions/Engineering/Hydraulic/LandD/Pages/TableofContents.aspx
OR	2011	Hydraulics Manual, ftp://ftp.odot.state.or.us/techserv/geo-environmental/Hydraulics/Hydraulics Manual/Table_of_Contents_rev_Nav.pdf
PA	2010	PennDOT Drainage Manual, ftp://ftp.dot.state.pa.us/public/bureaus/design/PUB584/
RI	2010	Rhode Island Stormwater Design and Installation Standards Manual, http://www.dem.state.ri.us/programs/benviron/water/permits/ripdes/stwater/t4guide/desman.htm
SD	2011	Drainage Manual, http://sddot.com/business/design/forms/drainage/default.aspx
TX	2011	Hydraulic Design Manual, http://onlinemanuals.txdot.gov/txdotmanuals/hyd/hyd.pdf
WA	2011	Highway Runoff Manual, http://www.wsdot.wa.gov/publications/manuals/fulltext/m31-16/Chapter5.pdf (updates expected in 2014)
	2010	Hydraulics Manual, http://www.wsdot.wa.gov/publications/manuals/fulltext/M23-03/HydraulicsManual.pdf
	2012	Stormwater Manual for Western Washington, https://fortress.wa.gov/ecy/publications/summarypages/1210030.html

CHAPTER 5

Selecting and Applying Volume Reduction Approaches

This chapter provides guidance for incorporating VRAs into the urban highway environment, including identifying potentially suitable VRAs, prioritizing VRAs based on a number of factors, and developing conceptual designs to incorporate these VRAs into the overall project design. This chapter provides guidance for assimilating the site and project information available for the site (Section 3.4), the menu of potential VRAs and their attributes (Chapter 4), and other considerations, such as volume reduction goals and maintenance and funding considerations, to arrive at an overall volume reduction strategy for the project. This chapter is intended to support Steps 3, 4, and 5 of the overall stepwise process for using this manual described in Section 2.1 (see Figure 24).

5.1 Framework for Selecting and Applying Volume Reduction Approaches

This section introduces the underlying framework and technical bases that this manual adopts for identifying potentially suitable VRAs, prioritizing VRAs, and developing conceptual designs.

5.1.1 Considerations in Adopting a Custom Planning Framework Versus a Uniform Planning Framework

The decision of whether to *consider* volume reduction for a project is typically relatively straightforward. In some cases, volume reduction is incentivized by the potential for enhanced pollutant removal and hydrologic control, as well as for other benefits that can be achieved by controlling runoff volumes. In other cases, regulations may require volume reduction to be considered and may even require a demonstration that volume reduction has been applied to the MEP or similar language. However, after the decision has been made to consider volume reduction strategies, the decisions that follow can be multifaceted and require more careful consideration. For example, is volume reduction feasible and desirable given site conditions? How does one determine what level of volume reduction is feasible and desirable? Is volume reduction part of a reliable and economically sound long-term approach? Which specific VRAs should be part of this strategy?

The various factors related to volume reduction can be considered as part of a custom planning approach developed on a project-specific basis, or can be considered as part of a more structured, uniform framework. This manual presents a model or example uniform planning approach, but also includes discussion of the underlying bases of the model approach so that site-specific adaptations can be made by users. Users may prefer an approach that is a hybrid of these two approaches.

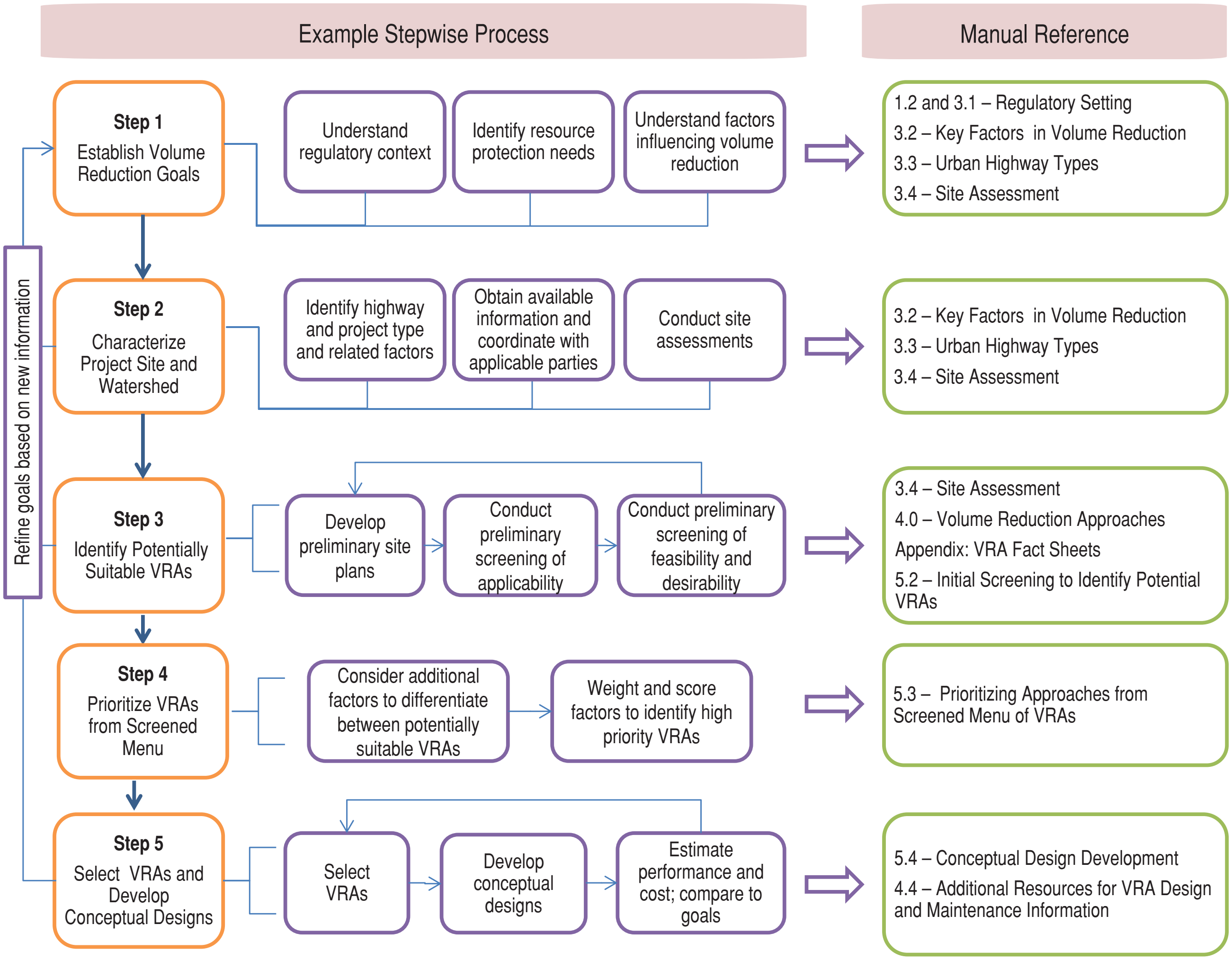


Figure 24. Overall stepwise approach for applying this manual.

5.1.2 Overview of Framework

The overall framework for volume reduction planning described in this manual is based on assimilating a number of factors, including (1) project goals, (2) site and watershed information, and (3) the available menu of VRAs, to yield a preferred plan for achieving volume reduction. The outcome of this framework is intended to yield a volume reduction plan that:

- Is applicable to the project type,
- Is feasible and desirable given site and watershed conditions,
- Uses VRAs that are compatible with the project site as well as the future redevelopment projections for the project area,
- Can be reliably and safely operated and maintained over the long term,
- Is consistent with project economic constraints, and
- Meets project volume reduction goals.

These considerations can be organized into an approximate hierarchy or order as part of developing a volume reduction plan. For example, it is logical to first conduct initial screening to identify potentially suitable VRAs such that only those approaches that are applicable, feasible, and desirable are carried through to more involved analyses such as conducting more thorough feasibility and desirability analyses and quantifying relative capital cost, operational expense, and performance. In general, the process of developing a volume reduction plan can be considered in three phases:

1. Initial screening to identify VRAs that are potentially applicable, feasible, and desirable (Section 5.2);
2. Prioritization of these VRAs on a relative basis (Section 5.3); and
3. Conceptual design evaluation relative to project goals and constraints (Section 5.4).

Table 22 introduces general factors (e.g., metrics, considerations) that should be considered as part of developing a volume reduction plan and describes the role that each factor plays in this process. Figure 25 illustrates the general planning steps that are recommended as part of developing a volume reduction plan for a project. This figure is intended to provide more detailed guidance on Steps 3, 4, and 5 of the overall stepwise process for using this manual (see Figure 24); it also provides reference to the specific section that supports each of these steps.

Table 22. General considerations in developing volume reduction plans.

Factors in Developing Volume Reduction Strategy		Role in Process of Developing Volume Reduction Strategies
Volume reduction goals	• What are the volume reduction goals for the project? • What is the burden of proof for evaluating volume reduction as a control option (e.g., demonstration of infeasibility)?	• Establish performance goals • Establish relative importance of a systematic VRA selection process
Feasibility and desirability	• Applicability factors – which VRAs are applicable for the site? • Physical feasibility factors – can volume reduction be physically achieved? • Desirability factors – would volume reduction have undesirable consequences?	• Screening – identification of potentially applicable, feasible, and desirable volume reduction processes and associated VRAs • Conceptual design development – development of design parameters and design elements related to performance and risk mitigation
Relative whole life-cycle costs	• What net cost increase is associated with building, maintaining, and replacing VRAs in comparison to a conventional project? • How does the cost of volume reduction compare to cost of conventional treatment?	• Initial prioritization – relative ratings of VRAs considered • Conceptual design development/evaluation – net cost comparison to budget allocation and other VRA options
Relative reliability and safety	• What are the failure mechanisms for the VRA? How would potential failure affect safety? Is a backup system needed for safety purposes? • How sensitive is the function of the system to site conditions and maintenance?	• Initial prioritization – relative ratings of VRAs considered • Conceptual design development – development of design elements to provide for safe operations over range of potential conditions
Relative O&M impact to agency	• What maintenance activities are required? Which activities would be new for the local DOT staff? • How much uncertainty is there in O&M requirements? • What is the ease of access for inspection and maintenance?	• Screening – is maintenance burden a fatal flaw? • Initial prioritization – relative ratings of VRAs considered • Conceptual design development – plan for access and maintenance in designs; O&M budget planning
Performance/effectiveness	• How well does the VRA achieve project volume reduction goals? How much will volume control contribute to addressing issues in this location/circumstance? • How sensitive is the VRA to design uncertainties and changes in maintenance conditions?	• Initial prioritization – relative ratings of VRAs considered • Conceptual design evaluation – comparison of performance to performance goals and comparison of VRAs considered

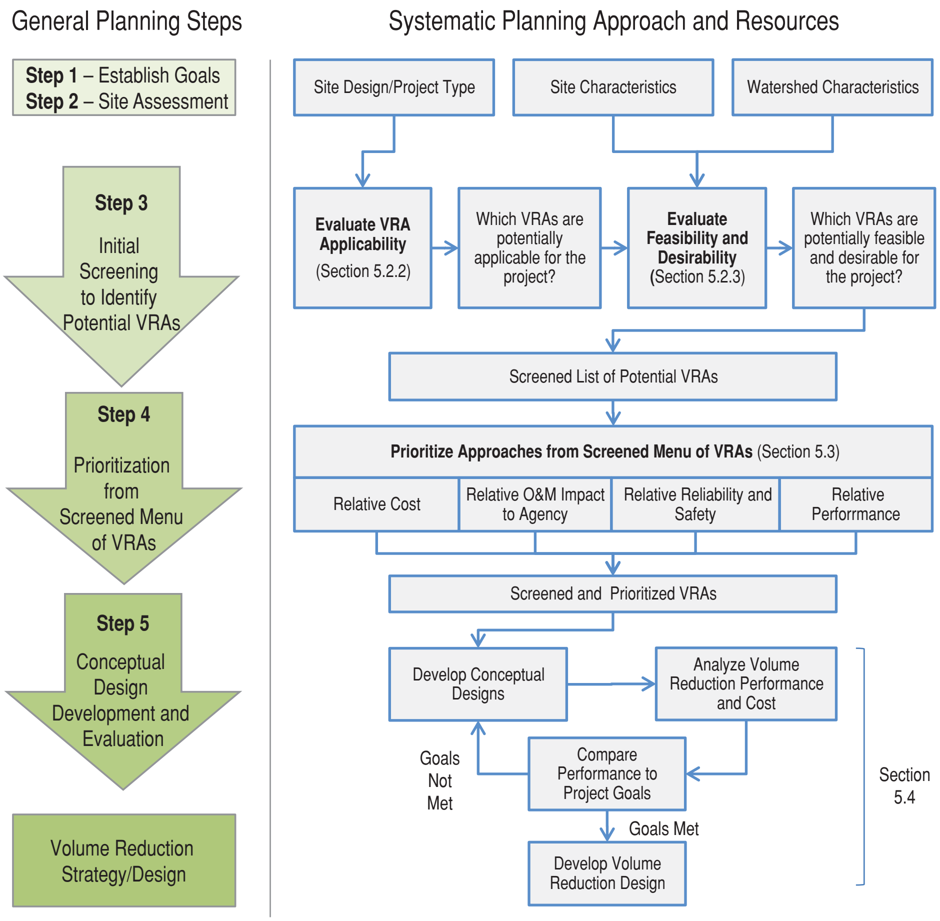


Figure 25. Overview of approach for developing volume reduction plans. Supports Steps 3, 4, and 5 of the overall stepwise process for using this manual (Figure 24).

5.2 Initial Screening to Identify Potential VRAs (Step 3)

Chapter 4 describes a relatively broad menu of potential VRAs and the locations within an urban highway project where these approaches could be located. However, for any given project, an initial screening effort can help identify those approaches that are potentially best suited for the project from those that are not applicable, infeasible, or undesirable. This process of initial screening helps identify approaches that are of interest for the project so that these approaches can be promoted to more careful evaluation. It involves three key steps:

- Step 3a—Develop site layout and geometric design (Section 5.2.1);
- Step 3b—Evaluate VRA applicability for project type and site design. Evaluate applicability of VRAs for each drainage area or portion of the project based simply on project type and site designs and the associated constraints and opportunities (Section 5.2.2); and
- Step 3c—Feasibility and desirability screening. Conduct initial screening-level evaluation of feasibility and desirability of VRAs for each drainage area based on the unit processes (infiltration, ET, harvest and use) that are feasible and desirable within the site and watershed (Section 5.2.3).

This approach may require an iterative effort between site planning and feasibility screening as part of making use of areas with opportunity for volume reduction. The following subsections provide guidance for these steps.

5.2.1 Step 3a—Develop Site Layout and Geometric Design

The primary inputs to this step are the geometric constraints and the transportation and safety objectives that are inherent to the project. This step should be informed by the volume reduction site planning principles described in Section 4.2.3. Initiating this step early in the project planning process can help identify and expand opportunities for VRAs by informing site layout and drainage planning. When attempting to incorporate VRAs into a project that has already been designed, opportunities tend to be more limited. This step may be an iterative step with Steps 3b and 3c. Note that for retrofit projects and minor redevelopment projects, opportunities to incorporate site planning principles may be limited.

The process used for site layout and geometric design will likely vary greatly between projects. Table 23 provides a checklist for documenting the inclusion of site planning principles into the project layout.

5.2.2 Step 3b—Evaluate VRA Applicability for Project Type and Site Design

The inputs to this step are an understanding of the project type and associated design features (Section 3.3) and the menu of VRAs that are available (Chapter 4). The expected output from this step is a list of the VRAs that are potentially applicable within the project area and the associated locations within the project area where these can potentially be applied. This step is perhaps the most straightforward step in the planning process; users who are familiar with the menu of VRAs available and the general site conditions of the project should find it relatively straightforward to identify locations where certain types of VRAs may be considered and which VRAs are clearly not applicable. However, the use of a systematic approach can help ensure and document that all opportunities have been considered. This manual provides the following resources to support this step:

- Section 3.3 provides fact sheets for eight standard highway segment types that generally encompass the range of site designs that may be encountered within the urban highway environment. Consulting these fact sheets can help identify the locations within a project where VRAs may be possible.

Table 23. Checklist of site planning principles.

Instructions:	*1. Enter Y, N, or N/A for whether the planning principle was incorporated.* *2. Provide discussion of how the site planning principle was incorporated, why it was not incorporated, or why it is not applicable to the project.*	
Planning Principle (See Section 4.2.3)	**Incorporated?**	**Description of How Principle Was Included or Rationale for Not Including**
Early identification of VRA opportunity locations		
Develop drainage, grading, and utility configurations to accommodate VRA opportunity locations		
Limit footprint of disturbance		
Minimize non-essential impervious surface		
Conserve and/or amend topsoil		

- Section 4.3 provides a summary of applicability of the menu of VRAs for general locations (i.e., medians, shoulders) within the highway environment.
- Appendix A provides VRA fact sheets that describe each VRA.
- Table 24 introduces factors for assessing applicability.
- Table 25 provides a multi-part checklist for documenting the factors that have been considered in determining the potential applicability of each VRA in the project.

Table 25 provides a template checklist and guidance for evaluating applicability factors and determining which VRAs are potentially applicable for the project.

5.2.3 Step 3c—Feasibility and Desirability Screening

The inputs to this step are an understanding of the watershed conditions and site conditions (Section 3.4), the menu of VRAs that are available (Chapter 4), and a narrowed list of VRAs that are potentially applicable (Section 5.2.; Table 25). The expected result of this step is a categorization of feasibility and desirability conditions and a further narrowed list of the VRAs that may be feasible and the most promising for achieving volume reduction under these conditions. This step is intended to be conducted early in the design process and is an initial screening process. This process is not intended to conclusively establish that certain VRAs are feasible; such a determination may require more detailed analysis of specific locations within the project. However, it is intended to help identify which VRAs are clearly not feasible and which VRAs have the best potential to match site conditions.

Table 24. Applicability factors.

Applicability Factor	Metrics to Determine Applicability
Geometric requirements for VRAs	Is the inherent shape of the VRA that is needed to provide its intended function compatible with the shape of the opportunity available? See Section 4.3.2.
Availability of space	Is there adequate space (indicated by the ratio of tributary area to potential VRA area) to provide meaningful volume reduction performance? See Section 4.3.2.
Presence of a storm-drain system	Is there a storm-drain system within the right-of-way to provide a connection for VRAs that rely on underdrains?
Presence of demand for harvested water	Is there a demand for harvested water within the project or project vicinity such that rainwater harvest and use could be considered?
Undeveloped adjacent land use	Is there undeveloped land for use adjacent to the project such that an easement could potentially be obtained to disperse water through a vegetated area?
Perennial base flow and/or extended recession limb in local streams	Do local streams exhibit base-flow and interflow patterns that could potentially be mimicked through a controlled release from VRA underdrains or outlet structures?
Planting requirements and irrigation needs	Is it practical to irrigate the site? Where plants are critical for the performance of the VRA, can plants be identified that are compatible with the irrigation available at the site? If it is not feasible to provide irrigation, and plants must be irrigated, then the VRA may not be applicable.
Locally available materials	Can construction materials be obtained locally or imported at a reasonable cost? It will be uncommon for materials to be unavailable, but materials may be more costly. For example, it may be challenging to obtain specialized binders required for permeable pavement for heavy traffic loadings.
Local jurisdiction acceptance	Do the local jurisdictions with responsibility for approving plans accept the VRA type? Can barriers to local approval be overcome?
Local contractor experience	For specialized installations, such as permeable pavements, do local contractors have the experience needed to ensure successful installation?

Note: These factors are considered to be initial screening factors for determining which VRAs are potentially applicable. The finding that a VRA is potentially applicable does not imply that a VRA is feasible and desirable. Feasibility and desirability factors are considered in Step 2.

Table 25. Checklist of site applicability.

	Part 1: Screening of Project Geometric Design and VRA Siting Opportunities Features									
Instructions:	*1. Enter Y or N in the "Project Features Present" row to indicate project attribute that is present in the project* *2. Match opportunity to VRAs that are potentially applicable in that location* *3. Enter result: Is there a potential location where each VRA could be sited?*									
Project Features with Potential Opportunity to Site VRAs:	**Medians**	**Shoulders, Including Breakdown Lane and Area Within Clear Zone**	**Shoulders, Outside of Clear Zone**	**Steeper Shoulders**	**ROW Locations with Limited Uses (i.e., Wide Spots, Irregular Geometries)**	**Adjacent Natural Areas**	**Looped Interchange Medians**	**Diamond Interchange Medians**	**Low Traffic Areas – Maintenance Yards, etc.**	**Result: Opportunity to Site VRA?**
Project Features Present:										
VRA	**Summary of Potential VRAs by Opportunity Area**									
VRA 01 Vegetated Conveyance	X	X	X		X		X	X	X	
VRA 02 Dispersion (within ROW)		X	X		X		X	X	X	
VRA 02 Dispersion (outside of ROW)						X				
VRA 03 Media Filter Drain	X	X	X	X	X		X	X		
VRA 04 Permeable Shoulders	X	X							X[1]	
VRA 05 Bioretention w/o Underdrains	X		X		X		X	X	X	
VRA 06 Bioretention w/Underdrains	X		X		X		X	X	X	
VRA 07 Infiltration Trench	X	X	X		X		X	X	X	
VRA 08 Infiltration Basin					X		X	X	X	
VRA 09 Infiltration Gallery										Y
Harvest and Use										Y
Base-Flow–Mimicking Discharge										Y

X = Potential VRA opportunity when geometric project feature is present. 1 – permeable pavement in general; shoulders not typically present.

Key:

Headings
User input
Guidance
No meaningful nexus with site geometric design features

Table 25. (Continued).

	Part 2: Screening of Overall Project Attributes					
Instructions:	1. *Enter project information in the "Enter Value that Applies to Project:" row to indicate project attribute that is present* 2. *Determine if VRA is compatible project-entered value* **3.** *Enter result in last column: Is the overall project compatible with the VRA? (Y or N)*					
Indicators of VRA Applicability:	**Typical Ratio of VRA Area to Impervious Area Needed**	**Presence of Water Demand**	**Presence of Storm-Drain System**	**Undeveloped Adjacent Land Use Acceptable for Dispersion or Land Application?**	**Perennial Streams**	**Result: Potential for VRA Based on Project Attributes?**
Enter Value that Applies to Project:						
VRA	**Summary of Attributes Required for VRA Applicability**					
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	▨	
Media Filter Drain	0.10 to 0.25	▨	▨	▨	▨	
Permeable Shoulders	0.10 to 0.25*	▨	▨	▨	▨	
Bioretention with Underdrains	0.01 to 0.10	▨	Important, unless grades allow underdrains to daylight	▨	▨	
Bioretention w/o Underdrains	0.01 to 0.10	▨	▨	▨	▨	
Infiltration Trench	0.01 to 0.10	▨	▨	▨	▨	
Infiltration Basin	0.01 to 0.10	▨	▨	▨	▨	
Underground Infiltration Gallery	0 (VRA within imperv. footprint)	▨	Important to enable pretreatment and discharge	▨	▨	
Harvest and Use	0 (VRA within imperv. footprint)	Required for applicability of harvest and use	Typically needed to convey water to storage tank	Indicator of potential for land application	▨	
Base-Flow–Mimicking Discharge Adaptation of VRAs	▨	▨	Typically needed to allow controlled underdrain discharge back to storm system	▨	More applicable when perennial or seasonal base flows are present	
Guidance	*Values shown indicate approximate minimum value to achieve meaningful volume reduction performance*	*Y/N – if N, then harvest and use is not applicable*	*Underground systems and systems with underdrains must generally discharge to a storm-drain system; additionally a storm-drain system allows pretreatment upstream of underground facilities*	*Applicable to determining if dispersion is possible in the event that space is not available in the right-of-way*	*Influences applicability of base-flow–mimicking discharge*	

See Part 1 of table for geometric opportunity screening. *Constructed within pavement footprint.

Key:

Headings
User input
Guidance
No meaningful nexus

(continued on next page)

Table 25. (Continued).

Part 3: Other Project-Specific Factors		
Instructions:	*1. Review guidance relative to project attributes* *2. Enter screening results (i.e., which VRAs 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: VRA 01 – Vegetated Conveyance VRA 02 – Dispersion VRA 03 – Media Filter Drains VRA 05/06 – Bioretention Vegetated VRAs 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 VRAs may not be applicable.	
Locally available materials	Does the VRA 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 VRA 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 have experience maintaining these systems?	

Key

Headings
User input
Guidance

This manual provides the following resources to support this step:

- Section 3.4 describes site assessment activities intended to characterize the site and watershed conditions relative to volume reduction design, including:
  - Phasing of site assessment activities—Section 3.4.1,
  - Topography and drainage patterns—Section 3.4.2,
  - Off-site drainage and adjacent land uses—Section 3.4.3,
  - Soil and geologic conditions—Section 3.4.4,
  - Local weather patterns—Section 3.4.5,
  - Groundwater considerations—Section 3.4.6,
  - Geotechnical considerations—Section 3.4.7,
  - Existing utilities—Section 3.4.8,
  - Harvested-water–demand assessment—Section 3.4.9,
  - Responsible agencies and other stakeholders—Section 3.4.10,
  - Local ordinances—Section 3.4.11, and
  - Watershed-based and other joint planning opportunities—Section 3.4.12.

Table 25. (Continued).

Part 4: Summary of Applicability and Suitability Screening		
Instructions:		1. *Review results of Parts 1 through 3* 2. *Enter screening results (Y or N)* 3. *Provide summary of rationale for screening result*
VRA	**Screening Results: Applicability**	**Summary of Rationale**
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		
Underground Infiltration Gallery		
Harvest and Use		
Base-Flow–Mimicking Discharge Adaptation of VRAs		

- Chapter 4 and Appendix A describe the menu of VRAs and provide a summary of considerations related to specific VRAs:
  - Section 4.3.1 describes volume reduction processes associated with each VRA and the relative risk of water balance.
  - Section 4.3.3 provides a summary of potential geotechnical impacts associated with infiltration by VRA.
  - Section 4.3.4 provides a summary of potential risk to groundwater quality by VRA.
- This section provides a flowchart for screening feasibility and desirability (Figure 26) as well as several other flowcharts and checklists to help document this process.

Overview of Feasibility and Desirability Screening Approach

This screening approach is based on a relative hierarchy of volume reduction processes and is intended to provide a logically structured approach for considering each of these processes as part of selecting VRAs.

1. **Infiltration.** Among volume reduction processes, infiltration tends to have the most significant potential for volume reduction but also has the most potential for negative consequences if not done carefully. As such, infiltration requires the most significant screening process for feasibility and desirability, and the results of this screening have primary influence on the selection of VRAs and the development of a volume reduction plan. For these reasons,

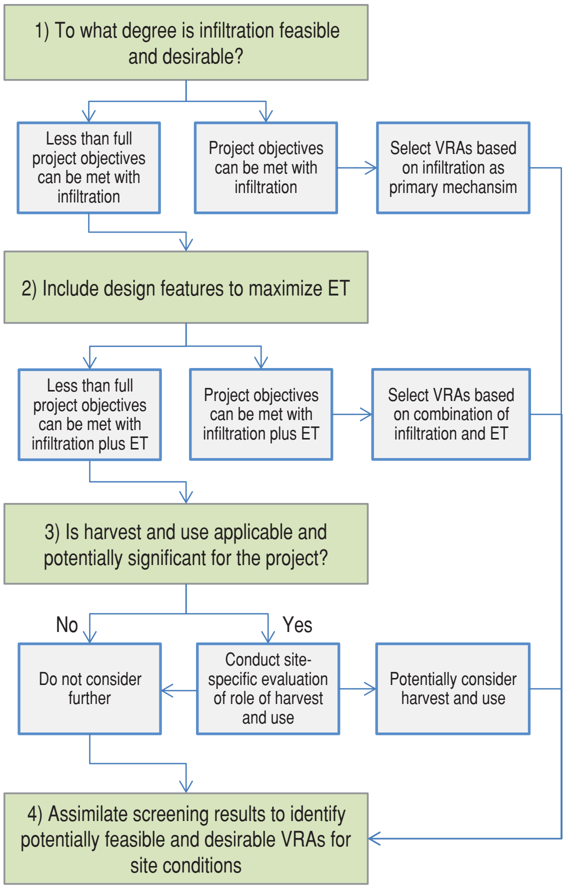


Figure 26. Feasibility and desirability screening process/flowchart (Step 3c).

a systematic process of evaluating infiltration feasibility and desirability is provided in this section, and it is recommended that this screening be done prior to screening other volume reduction mechanisms.

2. **Evapotranspiration.** ET is potentially a supporting mechanism for volume reduction in some VRAs; however, because ET is primarily a function of vegetated or exposed soil surface area, there is limited potential to increase ET losses without significantly changing the site plan, which would typically be in conflict with other project objectives. Additionally, ET poses no significant risks that would render it infeasible. Considerations are presented in this section for how infiltration systems and other vegetated systems can be designed to promote ET within the stormwater management approach that is developed.
3. **Harvest and use.** Screening of rainwater harvest-and-use approaches is initially addressed in Step 3b (evaluate VRA applicability for project type and site design), and is primarily a function of whether a harvested-water demand is present. As a reliable, year-round demand for harvested water is rarely present in the highway environment, it is expected to be rare that harvest and use would be applicable and would require a more rigorous feasibility and desirability screening. As such, narrative screening criteria are provided in this section, and a simple screening process is suggested, but more detailed guidance on harvest-and-use analysis is not provided.

The general approach for feasibility and desirability screening is shown in Figure 26.

Infiltration Infeasibility Screening

The primary questions that are evaluated as part of infiltration infeasible screening are:

- Is infiltration feasible and desirable?
- If so, what quantity of infiltration is feasible and desirable?

These questions are first addressed by determining whether factors exist that clearly preclude the use of infiltration (i.e., infiltration infeasibility screening criteria). If these factors do not exist, then the next question is whether factors exist that would make it infeasible or undesirable to infiltrate the full design volume or performance goal (i.e., full versus partial infiltration screening criteria). If these factors do not exist, then it is concluded that infiltration could be used as the primary volume reduction approach for the project (i.e., a full infiltration approach). If these factors do exist, then a portion of the design volume or performance goal could potentially be achieved by infiltration (i.e., a partial infiltration approach). This process is illustrated in the flowchart in Figure 27. As a result of this process, conditions can be characterized as being in one of three categories. This manual sets forth names and definitions for each of these categories to help facilitate the discussions that follow.

- **Category 1—Full Infiltration.** Infiltration of the full design volume or performance goal is feasible and desirable. More rigorous design-level analyses should be used to confirm this

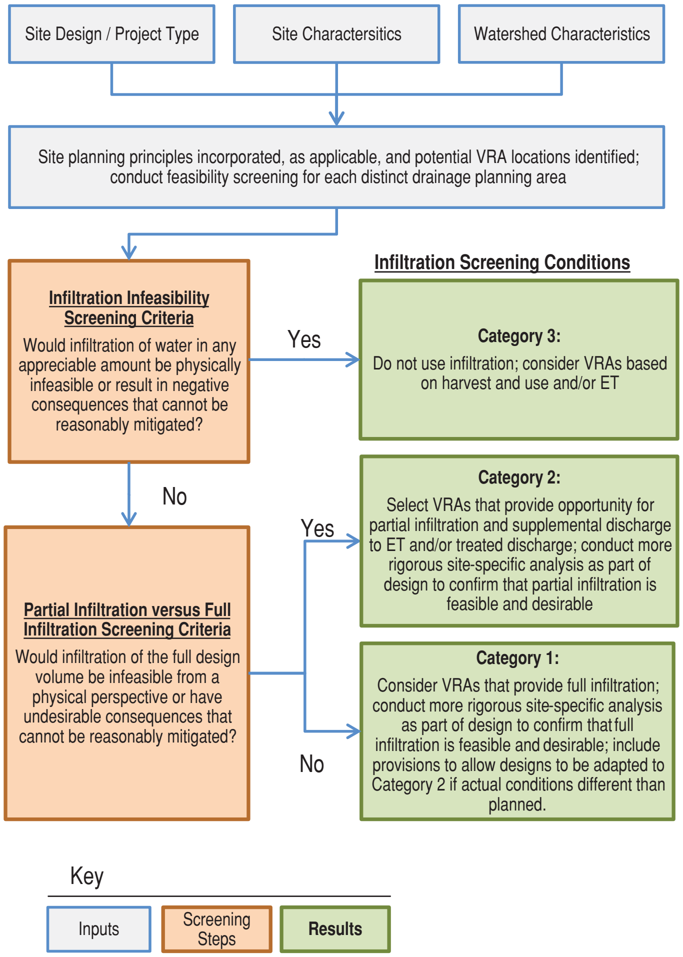


Figure 27. Infiltration feasibility and desirability screening flowchart.

classification and establish specific design parameters such as infiltration rate and factor of safety.

- **Category 2—Partial Infiltration.** Infiltration of a significant volume may be possible, but site factors indicate that infiltration of the full design volume or performance goal is either infeasible or not desirable. VRAs should include supplemental discharge to ET, harvest and use, or treated discharge.
- **Category 3—Limited or No Infiltration.** Infiltration of any appreciable volume should be avoided, either through selection of VRA or through VRA design features. Some incidental volume losses may still be possible. Other volume reduction mechanisms should be considered.

Table 26 provides specific screening criteria and a worksheet for evaluating the infiltration feasibility screening questions identified in Figure 27. The sections that follow provide guidance

Table 26. Checklist for initial feasibility and desirability screening of infiltration and partial infiltration.

<table>
<tr><td colspan="4"><u>Part 1 – Infiltration Infeasibility Screening Criteria</u>
Would infiltration of water in any appreciable amount be physically infeasible or result in negative consequences that cannot be reasonably mitigated?</td></tr>
<tr><td>Row</td><td>Screening Question</td><td>Yes</td><td>No</td></tr>
<tr><td>1</td><td>Do soil, geologic, or water table conditions prevent infiltration in any appreciable rate or volume? Refer to Appendix C* for guidance on evaluating infiltration rates.</td><td></td><td></td></tr>
<tr><td colspan="4">Provide basis:

Summarize findings of studies; provide reference to studies, calculations, maps, data sources, etc. Provide narrative discussion of study/data source applicability and why it was not feasible to mitigate low infiltration rates.</td></tr>
<tr><td>2</td><td>Would infiltration in any appreciable quantity pose significant risk of increasing geotechnical hazards that cannot be mitigated to an acceptable level? Refer to Appendix E* for guidelines on evaluating potential geotechnical risks.</td><td></td><td></td></tr>
<tr><td colspan="4">Provide basis:

Summarize findings of studies; provide reference to studies, calculations, maps, data sources, etc. Provide narrative discussion of study/data source applicability.</td></tr>
<tr><td>3</td><td>Would infiltration in any appreciable quantity pose significant risk for groundwater-related concerns? Refer to Appendix D* for guidance on groundwater-related infiltration feasibility criteria.</td><td></td><td></td></tr>
<tr><td colspan="4">Provide basis:

Summarize findings of studies; provide reference to studies, calculations, maps, data sources, etc. Provide narrative discussion of study/data source applicability.</td></tr>
<tr><td>4</td><td>Would infiltration violate downstream water rights?</td><td></td><td></td></tr>
<tr><td colspan="4">Provide basis:

Summarize findings of studies; provide reference to studies, calculations, maps, data sources, etc. Provide narrative discussion of study/data source applicability.</td></tr>
</table>

Table 26. (Continued).

<table>
<tr><th colspan="4"><u>Part 2 – Partial Infiltration Versus Full Infiltration Screening Criteria</u>
Would infiltration of the full design volume (i.e., a “full infiltration design”) be infeasible from a physical perspective or have undesirable consequences that cannot be reasonably mitigated, but partial infiltration is feasible?</th></tr>
<tr><td>Row</td><td>Screening Question</td><td>Yes</td><td>No</td></tr>
<tr><td>5</td><td>Is the estimated reliable infiltration rate below proposed facility locations less than the applicable threshold for the type of VRA being screened or the local-agency-specified value? See guidance that follows for selecting an appropriate infiltration rate threshold.</td><td></td><td></td></tr>
<tr><td colspan="4">Provide basis:
Summarize findings of studies; provide reference to studies, calculations, maps, data sources, etc. Provide narrative discussion of study/data source applicability.</td></tr>
<tr><td>6</td><td>Do geotechnical considerations, such as slope stability, groundwater mounding, or utilities, limit the amount of desirable infiltration to less than the full design volume? Refer to Appendix E* for guidelines on evaluating potential geotechnical risks.</td><td></td><td></td></tr>
<tr><td colspan="4">Provide citation to applicable study and summarize findings relative to the amount of infiltration that is desirable:
Summarize findings of studies; provide reference to studies, calculations, maps, data sources, etc. Provide narrative discussion of study/data source applicability.</td></tr>
<tr><td>7</td><td>Do groundwater quality considerations, such as shallow water table, or stormwater pollutants, limit the amount of desirable infiltration to less than the full design volume? Refer to Appendix D* for guidance on groundwater-related infiltration feasibility criteria.</td><td></td><td></td></tr>
<tr><td colspan="4">Provide citation to applicable study and summarize findings relative to the amount of infiltration that is desirable:
Summarize findings of studies; provide reference to studies, calculations, maps, data sources, etc. Provide narrative discussion of study/data source applicability.</td></tr>
<tr><td>8</td><td>Would reduction of runoff volume or increase in infiltrated volume compared to existing or predeveloped conditions cause potential water balance issues, such as change of seasonality of ephemeral washes or increased discharge of contaminated groundwater to surface waters? Refer to Appendix D* for guidance on water balance–related infiltration feasibility criteria.</td><td></td><td></td></tr>
<tr><td colspan="4">Provide citation to applicable study and summarize findings relative to the amount of infiltration that is desirable:
Summarize findings of studies; provide reference to studies, calculations, maps, data sources, etc. Provide narrative discussion of study/data source applicability.</td></tr>
</table>

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Table 26. (Continued).

Part 3 – Infiltration Screening Results **Check box that applies based on the screening results earlier in the table.**		
Row	Screening Question	Result
9	If any answer from lines 1 through 4 is yes, then infiltration of any volume is considered to be **infeasible** within the drainage area. The infiltration screening category is **Category 3 (Limited or No Infiltration).**	
10	If any answer from lines 5 through 8 is yes, infiltration may be possible to some extent but would not generally be feasible or desirable to achieve a full infiltration design. The infiltration screening category is **Category 2 (Partial Infiltration).** Additional design-level investigation and analysis may be needed to confirm or revise this classification.	
11	If all answers to lines 1 through 8 are no, a full infiltration design is feasible. The infiltration screening category is **Category 1 (Full Infiltration).** Additional design-level investigation and analysis is generally needed to confirm or revise this classification.	

*Appendices C through F are not published with this report but are part of *NCHRP Web-Only Document 209*.

for answering the feasibility and desirability screening questions posed in Table 26. References to “lines” in these sections refer to line numbers in Table 26.

Guidance for Screening Based on Infiltration Rate and Volume Limitations (Lines 1 and 5)

More detailed guidance for evaluating soil, geologic, and water table conditions is provided in Section 3.4 and Appendices C and D. A summary of this guidance is provided in the following relative to this feasibility screening process.

Factors potentially preventing any appreciable amount of infiltration include:

- Shallow impermeable (unweathered) bedrock,
- Certain clay soils with very low infiltration rates that cannot be improved with soil amendments to reach the depth of a layer with higher infiltration rate, and
- Seasonally high water table with potential to intersect with infiltrating surface.

Factors potentially limiting infiltration to less than full infiltration include:

- Low infiltration rates (see guidance on determining thresholds that follow); and
- Shallow bedrock, shallow groundwater gradient, or other limitations on the capacity of the infiltration receptor such that mounding or other factors would reduce infiltration rates or volumes that are physically feasible.

The infiltration rate threshold at which full infiltration design is no longer feasible is a function of the design of the VRA and also may be specified in local regulations or guidance. Thresholds typically range from 0.3 in. per hour to 1 in. per hour in existing practice. When not specified, an approximate threshold can be estimated on a VRA-specific basis by estimating the rate needed to drain water in a reasonable time between storm events. An example calculation is shown in Table 27.

Generally, systems that provide relatively shallow storage or that can allow longer drawdown times (such as subsurface storage) may be feasible where infiltration rates are lower. For vegetated systems or where storage depths are deeper, higher infiltration rates are generally needed. Establishment of a threshold for a region or a project should take into consideration long-term clogging as well as uncertainty in field test rates in comparing rates estimated from field testing to the threshold rates needed for reliable long-term performance.

Table 27. Example calculation of infiltration screening thresholds by VRA.

VRA Type	Typical Range of Storage Depth in Infiltration Compartment, ft	Typical Target Drawdown Times, hours (Typical Controlling Factor)	Resulting Screening Threshold for Full Infiltration, in./hr
Shallow-flow VRAs • VRA 01 – Vegetated Conveyance; • VRA 02 – Dispersion; • VRA 03 – Media Filter Drain	0.1 to 0.3	12 to 24 hours (plant survival; aesthetics)	0.05 to 0.3
Subsurface VRAs with shallow storage • VRA 04 – Permeable Shoulders • VRA 06 – Bioretention w/Underdrains and internal water storage	0.2 to 1.0	48 to 72 hours (long-term performance in sequential events)	0.03 to 0.25
Surface ponding VRAs with shallow storage • VRA 05 – Bioretention w/o Underdrains	0.5 to 2	12 to 24 hours (plant survival)	0.25 to 1.0
Surface ponding VRAs with deeper storage • VRA 07 – Infiltration Trench • VRA 08 – Infiltration Basin • VRA 09 – Infiltration Gallery	3 to 6	48 to 72 hours (vector issues; long-term performance in sequential event)	0.5 to 1.5

Guidance for Screening Geotechnical Considerations (Lines 2 and 6)

More detailed guidance for evaluating geotechnical considerations is provided in Section 3.4 and Appendix E. A summary of this guidance is provided here relative to this feasibility screening process.

Factors potentially preventing any appreciable amount of infiltration include but are not limited to:

- Soils with potential for volume change as a result of wetting (e.g., expansive soils) or freezing/thawing, where volume change could result in impacts on pavement or structures,
- Slopes where 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 allowed in design,
- Utilities that cannot be designed to avoid or accommodate some intrusion of infiltrated water, and
- Other factors as determined by a geotechnical engineer.

Factors potentially limiting infiltration to being less than full include but are not limited to:

- 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/piping if infiltration exceeds the allowable amount,
- Other factors as determined by a geotechnical professional.

As site conditions vary greatly, the determination of the level of infiltration that can be allowed should be evaluated on a site-specific basis. Appendix E provides more specific guidance for infiltration feasibility screening.

Guidance for Screening Groundwater Quality Considerations (Lines 3 and 7)

Guidance for evaluating groundwater quality considerations is provided in Section 3.4 and Appendix D. A summary of this guidance is provided here relative to this feasibility screening process.

Factors potentially preventing any appreciable amount of infiltration include:

- Soil or groundwater contamination where infiltration could exacerbate contamination or contaminant migration or interfere with cleanup efforts,
- High-risk runoff pollutant source areas (for example, vehicle maintenance facilities) where soils below VRAs have limited natural attenuation capacity, and
- Other critical factors identified as part of site assessment activities.

Factors potentially limiting infiltration to less than full infiltration include:

- Soils with limited attenuation capacity or shallow groundwater but low to moderate pollutant sources such that incidental/partial infiltration would not cause a significant risk,
- Soil or groundwater contamination in the vicinity of the project, where a potential rise in groundwater table associated with full infiltration could exacerbate contamination, migration, or cleanup efforts, and
- Other factors identified as part of site assessment activities.

Water Rights Considerations (Line 4)

While they are not believed to be common, there may be cases in which infiltration of water from an area that was previously allowed to drain freely to downstream water bodies would not be legal from a water rights perspective. Site-specific evaluation of water rights laws should be conducted if this is believed to be a potential issue in the project location.

Water Balance Considerations (Line 8)

Guidance for evaluating groundwater quality considerations is provided in Section 3.4 and Appendix D. Water balance considerations are typically not so severe that infiltration must be completely prohibited—indeed, the natural hydrology of a site typically includes some degree of deep percolation. However, water balance considerations could limit the amount of infiltration to less than full infiltration. A site-specific evaluation is typically needed to determine whether water balance impacts would potentially exist with a full infiltration design and to determine what level of infiltration would be acceptable.

Synthesis of Results (Lines 9, 10, and 11)

Lines 9, 10, and 11 provide directions for assimilating the results of lines 1 through 8 to determine an initial categorization of infiltration conditions as Category 1, 2, or 3.

Note that this is a screening-level categorization, which will typically be based on initial site-assessment results; therefore, it is not necessarily conclusive. Categorizations should be confirmed or revised based on more detailed design-level investigation and analysis. Appendices C, D, and E provide guidance for methods that are appropriate at the planning-phase screening step as well as design-phase investigations and analyses that may be required to confirm or refine the findings of initial screening methods.

Also note that the user does not necessarily need to investigate each of the questions asked in lines 1 through 8. A single "yes" answer in any section may control the feasibility and desirability of infiltration, and it may not be necessary to evaluate each factor to determine that infiltration is not feasible or not desirable. However, to reach a tentative determination that infiltration is both feasible and desirable at this screening step, each screening question should be evaluated.

VRA Selection and Design Considerations to Maximize ET Losses

Where vegetated BMPs are used, and where it is not feasible or desirable to meet full project goals with infiltration (i.e., Category 2 or 3 infiltration screening conditions), ET losses can contribute toward meeting project goals. VRAs that may provide significant or moderate ET losses include:

- VRA 01—Vegetated Conveyance,
- VRA 02—Dispersion,
- VRA 03—Media Filter Drain,
- VRA 05—Bioretention Without Underdrains,
- VRA 06—Bioretention with Underdrains, and
- Incidental soil soaking and drying or evaporation of permanent pools from traditional stormwater controls.

Table 28 contains a checklist of considerations for selection and design of VRAs to maximize ET losses.

Considerations for Conducting Site-Specific Analysis of Role of Harvest and Use

The applicability of harvest-and-use systems for reducing stormwater runoff volumes is primarily controlled by whether demand exists for harvested water of a magnitude that can reliably drain the stored volume in a reasonable time during the parts of the year when stormwater runoff occurs. If a reliable demand for harvested water is not present, then this approach should not be considered further. However, where a demand for harvested water is present and infiltration and ET are not feasible or desirable to meet project goals, it may be necessary (or required in some areas) to consider harvest and use to determine what role it can serve in reducing runoff volumes. This section provides general narrative criteria for evaluating harvest-and-use demand and potential effectiveness for runoff reduction and introduces a simple screening approach.

Table 28. Checklist for selection and design of VRAs to maximize ET losses.

Design Consideration	Incorporated into VRA Selection and Design (Y, N, or N/A)	Description of How VRA Was Incorporated or Basis for Not Incorporating
Use of vegetated VRAs where possible Benefit: Vegetation helps promote volume losses from its root zone in soils.		
Use of amended soils in vegetated VRAs Benefit: Amended soil improves soil moisture storage capacity and improves ET losses.		
Provide VRAs with largest footprint and shallowest ponding depth possible Benefit: ET is primarily a function of surface area, so can be increased when VRAs are shallower and have a broader footprint.		
Select climate-appropriate plant palettes. Benefit: Plants that provide higher levels of transpiration during the wet season and can withstand drought conditions are most appropriate (note: non–drought-tolerant species may exert an additional irrigation demand during summer months and should generally be avoided).		

Key Differences in Demand Calculations for Harvest-and-Use Feasibility Versus Water Supply Planning

It is important to note that harvested-water–demand calculations differ in purpose and methods from water demand calculations done for water supply planning. When designing harvest-and-use systems for stormwater management, a reliable method of relatively quickly regenerating storage capacity (i.e., using water) must exist to provide storage capacity for subsequent storms. Therefore, demand calculations for harvest-and-use VRAs should attempt to estimate the actual demand that is reliably present to drain stormwater cisterns during the wet season and especially within short-term (a week to a couple of weeks) series of storms that are typical in many areas of the country. This objective is fundamentally different from the objectives of water demand forecasting calculations done for water supply planning, which may err toward higher estimates of demand to provide conservatism to account for uncertainty. Harvested-water–demand calculations used to determine the feasibility of harvest-and-use VRAs should be based on estimates of actual expected demand that are reliably present to drain the cistern during the wet season.

Types of Harvested-Water Demand

Types of non-potable water demand that may exist in some cases in the urban highway environment are mostly related to service stations (sometimes found within the right-of-way, especially on toll roads), maintenance yards, and other occupied buildings and grounds within the right-of-way. Types of demand may include:

- Toilet and urinal flushing at rest areas and service stations,
- Irrigation of landscaping,
- Vehicle washing at maintenance yards or service stations, and
- Evaporative cooling (possible at service stations).

The following sections are divided between irrigation demand and non-irrigation demand. The primary distinctions between irrigation demand and non-irrigation demand are the seasonal pattern and reliability of the demand level and the treatment and disinfection that are required to use the water.

General Guidelines for Irrigation Demand Calculations

The following guidelines should be followed for computing harvested-water demand from irrigation:

- Irrigation rates should be based on the irrigation demand exerted by the types of landscaping that are proposed for the project or nearby areas that would be irrigated, with consideration given for water conservation requirements that may be applicable in some areas.
- Irrigation rates should be estimated to reflect the average wet-season rates (“wet season” defined based on local climate patterns) accounting for the effect of storm events in offsetting harvested-water demand.
- If reclaimed water is planned for use for landscape irrigation, then the demand for harvested stormwater should be reduced by the amount of reclaimed water that is available during the wet season, depending on local priorities.
- If land application of stormwater is proposed (irrigation in excess of agronomic demand; agronomic demand refers to the rate at which water is applied to satisfy plant irrigation needs), then feasibility screening for infiltration should be conducted. In addition, it should be considered that land application could result in greater quantities of runoff from pervious areas as a result of saturated soils at the beginning of storm events.

General Guidelines for Non-Irrigation Demand Calculations

The following guidelines should be followed for computing harvested-water demand for uses besides irrigation:

- Demand calculations should be based on the average rate during the wet season (defined based on local climate patterns) for a typical year.
- Demand calculations should include changes in occupancy or process use (vehicle washing, for example) over weekends and around holidays.
- Demand calculations should account for changes in demand with changes in long-term uses of the facility.
- For facilities with periodic shutdowns (for example, a maintenance yard that is used seasonally), a project-specific analysis should be conducted to determine whether performance of stormwater management can be maintained despite shutdowns. Such an analysis should take into consideration the statistical distributions of precipitation and demand—foremost the relationship of demand to the wet seasons of the year.

Evaluating Potential Stormwater Runoff Reduction

Based on the demand calculated for the project, the potential role for harvest and use for runoff reduction can be evaluated at the screening level. This can take the form of modeling to evaluate potential long-term performance or simple design event calculations to provide a rough indicator of potential performance.

To provide a rough screening-level indicator, the following steps are suggested:

1. Determine the storage volume that can be provided.
2. Divide this runoff volume by the reliable wet-season demand calculated for the project to compute a hypothetical, representative time for a rainwater harvesting tank to drain following an event.
3. Refer to locally applicable criteria for drawdown for stormwater management objectives to determine if the drawdown time would be acceptable. If local guidelines do not exist, evaluate the typical timing of storms to estimate drawdown goals. Table 29 provides an example of general screening criteria that could be used or adapted to determine potential effectiveness.

Table 30 provides a checklist for screening harvest-and-use feasibility.

Table 29. Example screening criteria for harvest-and-use systems.

Computed Drawdown Time of Design Storage Volume at Reliable Wet-Season Demand, Hours	Potential Role of Harvest and Use	Design Considerations
Less than ≈ 72 hours	Potential to achieve full volume reduction of the design storm without upsizing storage	Consider make-up water connection to satisfy demand when rain not present, if needed; tank will tend to drain relatively quickly following events.
≈ 72 hours to 2 weeks	Potential to achieve significant volume reduction; may require upsizing of tank to account for sequential storms during drain period	Potentially provide make-up water connection; Consider active controls to manage storage relative to forecasted rainfall
≈ 2 weeks to 2 months	Potential to achieve some volume reduction on long-term basis in some climates	Marginal for runoff reduction; may need to be coupled with water conservation goals to make sense; consider active controls to manage storage relative to forecasted rainfall
Greater than ≈ 2 months	Likely limited volume reduction on long-term basis	Decision to employ harvest and use would tend to be driven by water conservation objectives.
Combined sewer system with any on-site demand (discharge to sewer as needed in advance of precipitation)	With forecast-enabled active controls, systems could be programmed to discharge to combined sewer in advance of precipitation to alleviate wet-weather burden.	

Note: These criteria are hypothetical examples loosely based on the experience of the research team; location-specific criteria should be developed based on project design goals and local climate and demand patterns.

Table 30. Checklist for screening of harvest and use.

Screening Consideration	Project Screening Value	Discussion
Part 1: Is there a reliable wet-season demand?	**Y or N**	

Part 2: List the types of demand and the associated reliable wet-season estimated demand for each.

Demand Type (Enter All That Apply)	Estimated Reliable Wet-Season Demand, Gallons per Day
Total	

Part 3: Simple Demand-Based Screening Approach		
Enter storage volume, gallons		Estimate based on project goals, available space, and locally approved hydrologic methods
Enter total reliable wet-season demand, gallons per day		Estimate from Part 2
Calculate estimated drawdown time of stored water, days		Design-storm runoff volume/reliable wet-season demand
What potential role could harvest and use serve in volume reduction? (circle best fit)	Full volume reduction Significant partial volume reduction Limited volume reduction	Refer to local reference or Table 29 for example criteria

Part 4: If more advanced screening analysis or tool was used, enter summary of analysis and findings:

Assimilate Screening Results to Identify Potentially Suitable VRAs

Based on the results from the previous subsections, the user can develop a refined understanding of the role that each volume reduction process can be expected to serve in reducing runoff volumes. This can in turn guide the selection of VRAs that are compatible with the feasibility and desirability screening conditions that are identified. Table 31 provides a summary of the VRA types that are potentially best suited to each screening result category. This table is organized by infiltration screening category, consistent with the primary importance of infiltration feasibility and desirability conditions on VRA selection. Qualitative categorizations are included in this table based on average site conditions and design parameters; however, the volume reduction performance of VRAs may vary greatly based on site-specific conditions, design parameters, and climate. Quantitative estimates of volume reduction performance of VRAs based on site- and design-specific factors can be estimated using the Volume Performance Tool as discussed in Section 5.4.3.

Table 31. Summary of VRAs potentially suited for feasibility and desirability screening conditions.

Screening Condition	Potential VRAs and VRA Adaptations Best Suited to Infiltration Screening Conditions[1]
Category 1 – Full Infiltration *Select and design VRAs with emphasis on providing reliable infiltration*	• VRA 02 – Dispersion (where soils are permeable or sufficient dispersion area can be provided) • VRA 03 – Media Filter Drain (without underdrain) • VRA 04 – Permeable Shoulders (without underdrain or with elevated underdrain) • VRA 05 – Bioretention Without Underdrains • VRA 07 – Infiltration Trench • VRA 08 – Infiltration Basin • VRA 09 – Infiltration Gallery
Category 2 – Partial Infiltration, volume reduction supported by other processes *Select and design VRAs to promote allowable level of infiltration and maximize ET*	• VRA 01 – Vegetated Conveyance, including shallow sump or check dams if possible • VRA 02 – Dispersion (including micro-depressions, if practical) • VRA 03 – Media Filter Drain (typical design with underdrain) • VRA 04 – Permeable Shoulders (with elevated underdrains) • VRA 06 – Bioretention with Underdrains (can be enhanced with elevated underdrains) • Incidental infiltration in dry extended detention basins, where underlying soils are permeable
Category 3 – Limited or No Infiltration, volume reduction achieved primarily through other processes *Select VRAs to limit infiltration and provide ET, harvesting, and/or treated base-flow–mimicking discharge, as applicable*	• VRA 01 – Vegetated Conveyance (with amended soil and positive drainage) • VRA 02 – Dispersion (with amended soil and positive drainage) • VRA 03 – Media Filter Drain (underlain by low-permeability soil) • VRA 04 – Permeable Shoulders (lined or with underdrains at bottom of facility) • VRA 06 – Bioretention with Underdrains (lined or with underdrains at bottom of facility) • Harvest and use (if screening indicates potential volume reduction benefit) • Base-flow–mimicking discharge design • Incidental infiltration from traditional stormwater controls (other than extended detention basins that are more appropriately placed in Category 2)

1 – Qualitative categorizations are included in this table. Quantitative estimates of volume reduction performance of VRAs based on site-specific information and design parameters can be estimated using the Volume Performance Tool as discussed in Section 5.4.3.

5.2.4 Combined Results of Initial Screening Processes

Based on the analysis of applicability described in Section 5.2.2 and the screening of feasibility and desirability described in Section 5.2.3, the user can create a narrowed list of potentially suitable VRAs for further consideration. Using Table 31 as a checklist of potential VRAs, the applicability results summarized in Table 25 can be used to narrow down the potential VRAs within each screening category to only those that are potentially applicable to the site. For example, VRA 02—Dispersion may be feasible and desirable, but if geometric attributes do not provide any opportunity for its application, then it would be removed from consideration at this time.

5.3 Prioritizing Approaches from the Screened Menu of VRAs

Chapter 4 describes a relatively broad menu of potential VRAs and the associated locations within an urban highway project where these approaches could be sited. Section 5.2 describes a process for arriving at a screened list of potentially suitable VRAs based on applicability to the project and feasibility and desirability of volume reduction processes. When, after this screening process, multiple potential VRAs remain under consideration, a comparison of these VRAs based on other factors may be useful to prioritize those that should be considered further. This section outlines an approach for prioritizing from the screened list of VRAs. It is intended to help the user answer the following questions:

- How do considerations such as performance, reliability, cost, O&M, and project types (i.e., new roadway vs. widening vs. retrofit) factor into prioritization of VRAs?
- How can I determine how VRAs compare on a relative basis?

5.3.1 Overview of Prioritization Method

After identification of feasible and applicable VRAs, the user may simply select a preferred VRA from the screened menu based on professional judgment, experience, and knowledge of the site. This will likely be the preferred approach of experienced users. However, a systematic approach to prioritization has the benefit of providing a recorded basis for decision making and may appeal to some users who are less familiar with VRAs. This process generally considers the following factors:

- Relative whole life-cycle costs,
- Relative O&M impacts on agencies,
- Relative reliability,
- Relative safety, and
- Potential performance relative to volume reduction goals.

Guidance for considering each of these factors is provided in Section 5.3.2. The recommended process for assimilating these factors to arrive at a relative prioritization of VRAs involves (1) assigning weights of relative importance, (2) assigning a score to VRAs based on these factors, and (3) tabulating the weighted score for each. This process is further described in Section 5.3.3.

5.3.2 Considerations in Prioritizing VRAs

The prioritization method suggested by this manual involves weighting the importance of various factors and then scoring VRAs based on these factors. Each of the subsections that follow provides guidance for considering these factors and is intended to support the user in the weighting and scoring process.

Relative Whole Life-Cycle Cost Criteria

Whole life-cycle cost refers to the net present value of capital costs, O&M costs, and replacement costs, as well as the offsetting effects of avoided capital and maintenance costs. Whole life-cycle costs are typically considered to be an important factor in prioritizing stormwater controls. The following key factors should be considered in determining how VRAs compare on a relative cost basis:

For new and redevelopment projects, what is the ***net*** *cost of the VRA compared to a traditional roadway design?* This analysis should consider which costs are attributable to volume reduction and which costs could potentially be avoided through the use of the VRA. Examples of net cost considerations are:

- Installing VRAs could reduce or eliminate the cost (capital and O&M) of installing traditional stormwater treatment or flow-control features where these features would otherwise be required,
- Installing a vegetated conveyance instead of a piped conveyance could avoid the cost of pipe and inlets,
- Using permeable pavement would be offset in part by the avoided cost of traditional pavement,
- The cost of landscape installation and maintenance associated with VRAs would be offset in part by the avoided cost of normal landscape maintenance that would have been done for the area,

- Planning for the VRA feature in rough grading plans can help result in a net balance of cut and fill for the VRA such that excavation or hauling costs would not be incidental to the VRA construction, and
- Planning for VRAs may require more extensive investigation and analysis than for traditional roadway design.

For retrofit projects, what is the net cost of implementing the VRA considering the modifications that would be needed to existing infrastructure? Approaches that work with existing infrastructure, such as minor modifications to an existing swale, can be less expensive than approaches involving significant modification or replacement of materials, such as excavating pervious area to create a new swale where one did not previously exist. In this case, the ultimate condition may be identical with very different cost implications. As another example, excavating down to the base of an existing road shoulder to install permeable shoulders in a retrofit project where an existing traditional shoulder exists would be considerably more expensive than installing permeable shoulders as part of a lane addition.

Does the use of VRAs introduce additional complexity into the overall design, such as geotechnical analysis and design features that should be attributed to the VRA cost? Examples of incremental costs are:

- Cost of site assessment activities, such as infiltration rate evaluations, additional soil borings, and groundwater wells, specifically related to VRA planning and design;
- Design features required to address potential risks of negative consequences, such as impermeable liners or cutoff walls; and
- Additional expense in overall geotechnical designs as a result of higher factors of safety or greater assumed soil moisture being used in slope stability analyses (such as to account for the potential effects of infiltration).

How frequently do VRAs need to undergo major restorative maintenance or replacement? Design life is an important factor in whole life-cycle costs. Approaches that are well designed and constructed with enhanced pretreatment or more design resiliency tend to be more expensive to construct on a capital basis but may extend the life span of a facility and reduce whole life-cycle costs.

Section 4.3.7 provides a summary of relative whole life-cycle costs by VRA. However, it is important to note that the relative comparison of costs of different VRAs is highly site and project specific. The least expensive VRA in some cases may be more expensive in other cases. As a result, the values referenced in Section 4.3.7 should be reviewed and adjusted, as needed, based on site-specific information. Ultimately, costs used to compare to budgets should be estimated using line item costing methods that account for existing site conditions and added and avoided infrastructure, as discussed in Section 5.4.5.

Relative O&M Impacts on Agencies

Relative O&M impacts associated with VRAs are a function of the portion of the total life-cycle cost associated with O&M activities, as well as other impacts associated with O&M that may not be possible to value as explicitly, including traffic impacts associated with maintenance, agency expertise allocated to O&M programs, training and equipment for more specialized maintenance activities, and uncertainty in planning for maintenance activities.

The following guidelines for VRA prioritization would tend to result in lesser O&M impacts to agencies:

- Prioritizing VRAs that require maintenance activities similar to those regularly conducted by DOT personnel.

- Prioritizing VRAs that are currently in use and the agency has experience operating and maintaining.
- Introducing promising VRAs as pilot projects initially before using them on a broad scale.

To support ranking of VRAs, Table 18 and Table 19 in Chapter 4 provide a summary of routine and corrective maintenance activities, respectively, of each primary VRA.

Relative Reliability

Reliability refers to consistency and certainty in the long-term operation of a system. Considerations of reliability are interrelated with life-cycle cost and safety: where maintenance is frequently needed to provide reliable operation, whole life-cycle costs would increase; likewise, if design features are needed to ensure safety in the event of failure, this could add to the cost to the design. Table 32 summarizes failure mechanisms of VRAs and potential consequences of failure.

VRAs that include the following design features tend to provide higher reliability and should be ranked higher than VRAs that do not include these factors:

- Pretreatment to reduce potential for clogging.
- Supplemental pathway for treated discharge if volume reduction pathways decline—for example, an underdrain.
- Vegetation selected and maintained to reduce erosion and to help maintain or restore surface infiltration rates.
- Factors of safety used to account for long-term changes in infiltration rates and so forth.

The sensitivity of performance of the system to site conditions and maintenance is a key factor in evaluating reliability that can be assessed using modeling tools. For example, would the volume reduction performance be expected to change significantly if the infiltration rate declined by half on a long-term basis between maintenance events? Section 5.4 provides guidance for using modeling tools, including the Volume Performance Tool, as part of evaluating VRAs, which can be used to evaluate sensitivity and resiliency to changes in design parameters.

Relative Safety

Safety is a key consideration in designing VRAs. Section 4.3.5 identifies a summary of safety considerations by VRA. While the design of VRAs can generally be developed to address most safety concerns, there are inherent factors in VRA locations and design that may be more or less favorable for safety. User judgment should be used to assign a ranking of various VRAs on the basis of safety if this is a distinguishing factor in selecting VRAs.

Table 32. Failure mechanisms and potential consequences of failure.

	Potential Consequences of Failure				
Failure Mechanisms	Safety issues (e.g., Water on Roadway)	Vector Issues (e.g., Stagnant Water)	Aesthetic Issues (e.g., Plant Health, Exposed Soil)	Decline in Volume Reduction Performance	Pollutant Export
Surface storage does not drain per design		X	X	X	
Subsurface storage does not drain per design				X	
Erosion within VRA			X		X
Surface clogging of permeable shoulders	X			X	

Relative Performance in Comparison to Volume Reduction Goals (i.e., effectiveness)

Performance of VRAs is a function of many site-specific factors. Additionally, project-specific volume reduction goals may vary. As such, each of the VRAs identified has the potential to be effective in achieving certain goals that may be applicable to a project. Therefore, any categorical ranking of effectiveness should take into consideration project goals as well as VRA performance. In other words, the best performance is not necessarily required to meet project goals. However, the maximum relative volume reduction achievable by each VRA, as summarized in Table 11, can be used as a basis for relative prioritization, assuming it is desired for the project to reduce volumes to the greatest extent as would be feasible.

Ultimately, a quantitative analysis of VRA performance relative to project performance goals (i.e., effectiveness) is recommended as part of selecting a VRA. Section 5.4 provides guidance for considering VRA performance in design development and using modeling tools as part of developing designs.

5.3.3 Semi-Quantitative Prioritization of VRAs

Given that relatively few VRAs are likely to be identified for each location after applicability, feasibility, and desirability screening is conducted, an elaborate prioritization process may not be of great value. This manual suggests a simple weighting and ranking process to assimilate the prioritization factors described previously and provide a transparent record of the factors that were considered in selecting VRAs. This process involves three steps:

1. Assign relative importance (i.e., weight) to each of the prioritization factors identified in this section, or use user-specified prioritization factors. The weights should add up to 100%.
2. Identify VRAs that passed initial screening, as described in Section 5.2. VRAs not passing the initial screening should not be considered further as part of prioritization.
3. Assign relative score to each of the VRAs remaining after initial screening. Any relative scoring scale can be used; however, a simple ranking of 2, 1, 0 is likely adequate, where a higher score indicates a VRA that better meets the metrics defined for each factor. Rankings by VRA may vary from site to site depending on project type, site conditions, and other factors.

The template shown in Table 33 can be used to help organize inputs and conduct calculations.

5.4 Conceptual Design Development

The final step covered by this manual (Step 5) is the development of conceptual designs that incorporate the screened and prioritized menu of VRAs from Step 3 (Section 5.2) and Step 4 (Section 5.3). The purpose of this section is to provide guidance for evaluating various VRA options at a conceptual design level and ultimately incorporating the preferred VRAs into project conceptual designs. This manual does not provide design-level guidance; however, general recommendations are provided to help guide engineers in preparing plans that incorporate VRAs. Additionally, Section 4.4 provides references to nationwide and state-specific DOT-related design guidance materials that may serve as references for design development. This section is intended to guide the user on approaches/methods for answering the following questions:

- Based on the physical characteristics of my highway project and conceptual design parameters, how can I expect a given volume reduction approach to perform on an average annual basis?
- How does this effectiveness compare to other high-priority approaches?

Table 33. Example template for relative VRA prioritization.

Prioritization Factor	Weighting	VRA Score								
		VRA 01 – Vegetated Conveyance	VRA 02 – Dispersion	VRA 03 – Media Filter Drain	VRA 04 – Permeable Shoulders	VRA 05 – Bioretention w/o Underdrains	VRA 06 – Bioretention with Underdrains	VRA 07 – Infiltration Trench	VRA 08 – Infiltration Basin	VRA 09 – Infiltration Gallery
Passes initial screening? (Section 5.2) (Y or N)	**N/A**									
Relative life-cycle cost										
Relative O&M impacts on agency										
Relative reliability										
Relative safety										
Relative performance										
Other: *User specified*										
Weighted Prioritization Score Σ weighting × VRA score	**100%**									

Instructions:

1. Assign weighting for prioritization factors; if a factor does not apply to a given project, assign a weight of zero. The sum of weightings should equal 100%.
2. Identify VRAs that pass initial screening described in Section 5.2. VRAs that do not pass screening should not be considered in prioritization.
3. For remaining VRAs, assign a score based on each factor identified. Scores may vary from project to project depending on project type under consideration, agency experience and preference, or other factors. Higher scores indicate that the VRA would be better at meeting this factor.
4. For each VRA, compute the sum of weighting factors multiplied by the VRA scores. The total should be a value between 0 and 100% and can be used as a relative basis for prioritization of VRAs.

- What sizing of a given volume reduction approach is needed to meet my performance benchmarks?
- How can modeling tools be used to support conceptual design?
- Now that I have selected a suite of VRAs, what should I know about incorporating them into my plans?

5.4.1 Overview of Framework for Conceptual Design Development and Evaluation

Volume reduction performance is a function of many factors, including site and watershed conditions, climate patterns, and VRA sizing and design parameters. Similarly, costs are site-specific as a function of project type (i.e., new vs. redevelopment vs. retrofit), existing infrastructure in place, material costs, construction methods, and other factors. As such, a conceptual design-level analysis is necessary to provide a reliable evaluation of performance and cost in comparison to other VRAs and in comparison to project goals and constraints. The conceptual design development process may be an iterative process that evaluates a range of scenarios and adapts these scenarios iteratively to identify the conceptual design that best balances project goals with site and cost constraints. Figure 28 illustrates an example process for developing and analyzing conceptual designs.

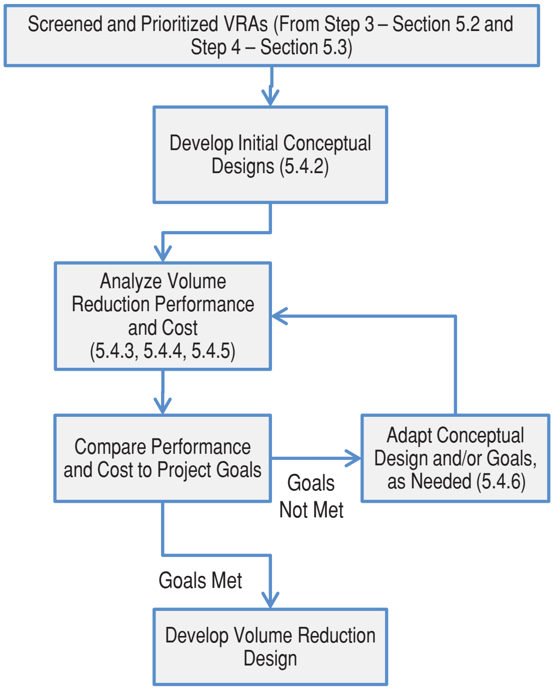

Figure 28. Example process for developing conceptual volume reduction designs (Step 5 in overall stepwise process for using this manual).

5.4.2 Developing Initial Conceptual Designs

Conceptual designs, by definition, do not contain adequate detail for construction but should include the key parameters needed to define how the system is intended to function and interact with other elements of the design. The conceptual design of VRAs should begin with initial site planning by considering the potential locations for VRAs, tributary areas to these VRAs, approximate footprints needed for VRAs, and the general grading requirements of these VRAs. As designs evolve and potential VRAs are selected for conceptual design-level evaluation, additional detail may be needed to provide adequate information to estimate performance and costs. However, particularly where multiple potential options or scenarios are being considered, a balance exists between providing enough detail to provide a reliable estimate of cost and performance with the time required to develop designs and the number of scenarios that can be reasonably evaluated. If costs are the deciding factor in selecting VRAs, then detail on costs for various scenarios may be needed.

The VRA fact sheets provided in Appendix A provide lists of conceptual design parameters that are important for volume reduction planning of each VRA as well as design schematics to help define these parameters and the function of VRAs. These parameters should generally be adequate to facilitate a conceptual design-level evaluation of performance and cost. Additionally, information obtained through site assessment activities may be important in developing conceptual parameters (e.g., underlying infiltration rate). Other design references identified in Section 4.4 may also provide valuable information regarding local design standards that may influence conceptual design development. Table 34 provides a summary of information typically needed to conduct a conceptual design-level evaluation and the typical source of this information in the planning process.

Table 34. Summary of conceptual design information.

Information Typically Needed for Conceptual Design Evaluation	Typical Source of Conceptual Design Information	
	New/Redevelopment Projects	Retrofit Projects
Tributary area to each VRA	Rough grade, precise grade plans	As-built drawings, existing topography, location of inlets, curblines, etc.
Tributary area hydrologic properties (imperviousness, slope, etc.)	Rough grade, precise grade plans	As-built drawings, existing topography, delineation from aerial or field
Effective footprint of VRA	Conceptual site plans	As allowed by current site
Other VRA conceptual design parameters (see VRA fact sheets)	Varies	Varies
Means by which water flows to VRA location (pipe, overland flow)	Drainage plans, developed/adapted with consideration for VRAs	As-built drawings, existing utility maps
Discharge point and parameters (storm-drain invert, water body, ditch, etc.)	Existing utility maps, proposed drainage plans	As-built drawings, existing utility maps
Results of feasibility screening (e.g., infiltration rates, groundwater issues, geotechnical issues) at each VRA location	Site assessment activities	Site assessment activities, previous documentation from original construction

Figure 29 shows an example of schematic design exhibits contained in the VRA fact sheets. Figure 30 provides examples of a preliminary conceptual site plan for a hypothetical VRA retrofit, illustrating that several options can be efficiently considered as part of a single conceptual design development process.

5.4.3 Using Modeling Tools for Decision Support and Conceptual Design Adaptation

Modeling tools that account for the various factors that affect performance and cost can have an important role in deciding which VRAs best meet project objectives and how these VRAs should be designed. The purposes of this section are to provide general guidance for using modeling tools to support VRA selection and conceptual design and to introduce the Volume Performance Tool (on the CD-ROM that accompanies this manual).

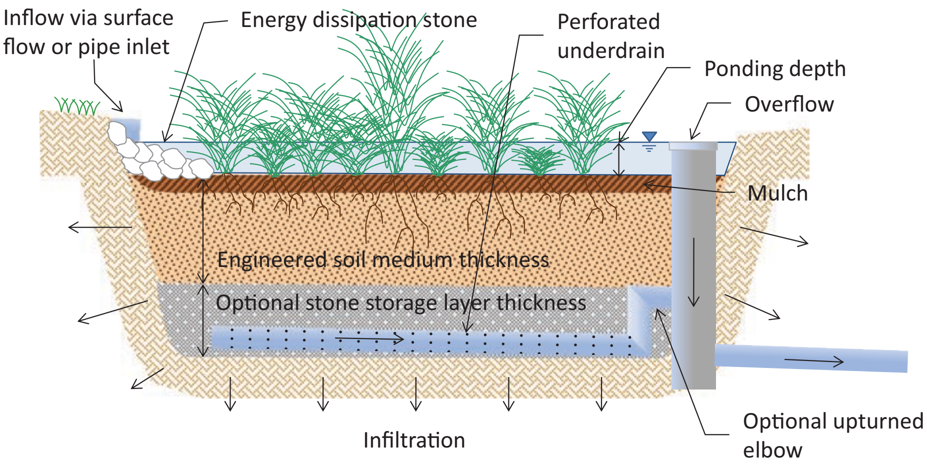

Figure 29. Example schematic design profile.

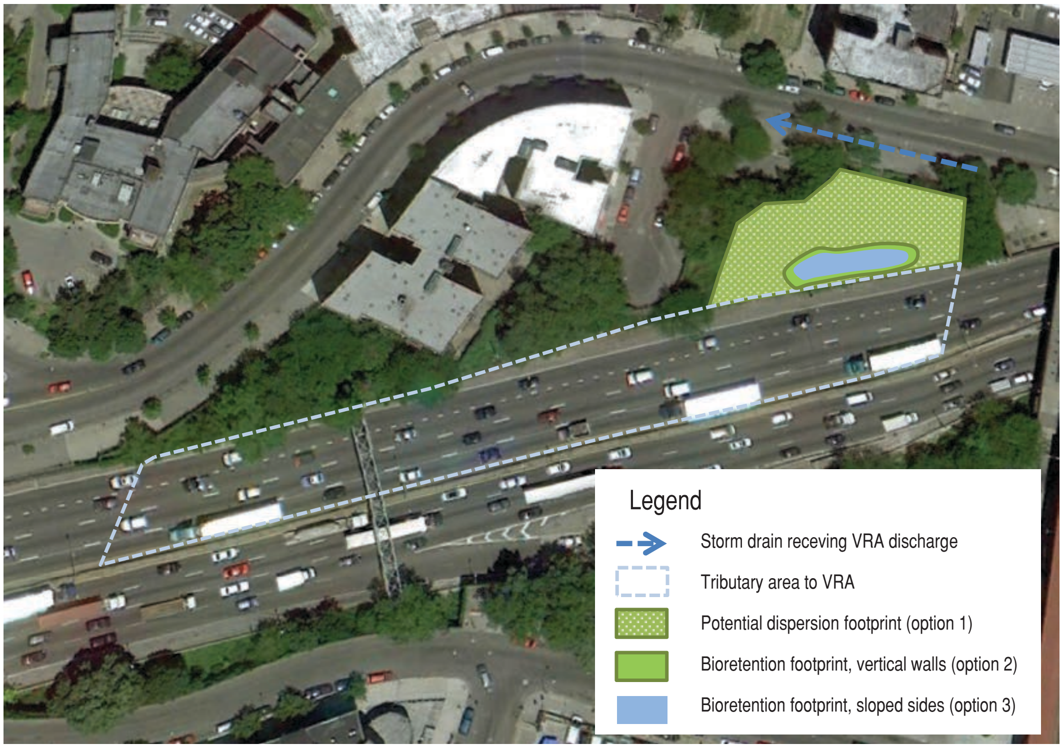

Figure 30. Example conceptual site plan, showing three example VRA options under consideration.

Sections 5.2 and 5.3 provide guidance for identifying which VRAs may be applicable, feasible, and desirable as well as guidance for considering factors such as maintenance, reliability, cost, and performance in selecting VRAs for detailed consideration. While there are specific numeric criteria associated with these decisions, the overall decisions of which VRAs to evaluate tend to be narrative and qualitative. After potential VRAs have been selected for further consideration, the use of numeric models can provide important feedback for VRA selection and conceptual design development. Models can be used to provide site-specific quantitative estimates of VRA performance and can help determine whether the overall volume reduction strategy will meet the performance goals of the project. Models can also be used to evaluate the relationship between sizing and design parameters and expected performance to help inform the conceptual design of VRAs. The discussion that follows provides guidance for using modeling tools to support decisions of which VRAs to use and what design criteria are appropriate.

Do the proposed VRAs achieve the project objectives? When project objectives are expressed in terms of the performance of VRAs, modeling (or the use of modeling-derived tools) is typically required to evaluate whether a proposed suite of VRAs achieves these objectives. Project objectives could take the form of:

- Example 1: Capture of the runoff from a given design event and subsequent recovery of storage volume (i.e., retain the 1.2-in. storm event and recover storage within 48 hours of the end of rainfall; note that a number of MS4 permits do not address the storage recovery, which is critical for VRA performance).
- Example 2: Reduction of at least a certain fraction of long-term runoff volume (i.e., 80% long-term volume reduction) in comparison to a case without VRAs.
- Example 3: Discharge volume limited to an amount less than or equal to a certain long-term runoff coefficient (i.e., 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: Reduction in the frequency of discharge from the site (i.e., reduce the frequency of discharge by 50% compared to baseline conditions without controls).

In some cases (such as Example 1), calculations can be relatively simple, and computer models are not necessarily required to demonstrate that the objective is met if the storage recovery is certain. However, whenever objectives are stated in terms of long-term performance or involve detailed calculations (such as routing of storm events or when storage recovery is less certain), modeling tools can be useful and even a necessity. Development and application of models will vary with the types of VRAs being considered and the nature of project objectives.

How do different VRAs compare in terms of relative performance? It may also be useful to use models to provide a side-by-side comparison of the performance of different VRAs that are under consideration for a given opportunity. As the performance of VRAs is a function of many variables, it may not be obvious which VRA would tend to provide the best performance within the site constraints. When evaluating multiple potential VRAs, the use of a simpler modeling framework may be appropriate to allow more rapid evaluation of different VRAs and VRA treatment train scenarios (i.e., multiple VRAs in series).

How do sizing and design parameters influence volume reduction and capture performance? Modeling tools can be used to help the user understand the relationship between design parameters such as storage volume, ponding depth, and infiltration rate and the estimated long-term performance of the system. These types of relationships can be useful early in the planning process to develop general requirements to meet project goals, such as to help estimate the amount of storage volume needed to approximately achieve a certain level of performance. These types of relationships can also be useful in developing more specific conceptual designs by helping one understand the performance implications of design decisions such as the ponding depth of stored water or the factor of safety to apply to the infiltration rate.

A wide variety of models could be used to characterize estimated volume reduction performance. Generally, modeling tools should be selected based on their ability to evaluate the project objectives, the amount of information available, local acceptance and guidance, and professional judgment. When performance goals are expressed in terms of long-term performance (such as in Examples 2 through 5), continuous simulation models (or relationships derived from continuous simulation models) are typically required to determine if these goals are met.

5.4.4 Introduction to the Volume Performance Tool

What Is the Volume Performance Tool?

The purpose of the Volume Performance Tool that accompanies this report is to assist the user in efficiently estimating the performance of VRAs and in understanding the effects and sensitivity of local climate patterns, design attributes, and site conditions. The tool is an Excel spreadsheet application that calculates an estimate of long-term volume reduction based on user-provided location and planning-level project information. The tool was informed by long-term continuous simulation modeling performed using precipitation data throughout the United States using various watershed and design parameters. This tool is intended to allow DOT staff and contractors to quickly evaluate the relative benefits of various scenarios and assists in developing sizing criteria. The tool covers the conterminous United States and includes modules for each of the nine primary VRAs identified in Section 4.2. Results are presented in terms of average annual volume reduction and estimated water balance in the project conditions with the VRA. The tool is available on the CD-ROM that accompanies this report and can also be downloaded by searching for *NCHRP Report 802* at www.TRB.org.

User's Guide and Tool Download Information

Appendix B is a user's guide for the Volume Performance Tool and contains its technical specifications and the underlying theory behind it.

Intended Use of the Tool for VRA Selection and Conceptual Design

The tool is intended to take the place of a planning-level continuous simulation model and, most simply, it is intended to provide an estimate of long-term VRA performance for a given set of input parameters. This type of feedback can have a number of potential applications in VRA selection and design.

Evaluate long-term performance in comparison to performance targets/standards. The tool can be used to estimate the long-term volume reduction (i.e., percent reduction of runoff volume compared to the baseline condition without controls) for a wide range of potential VRA configurations, including treatment trains. When goals are established in terms of long-term volume reduction, the results from the tool can be compared directly to project goals. Additionally, design parameter adjustments can be explored to improve performance and attempt to meet project goals.

Rapidly compare several VRAs for a given drainage area. Once a project location and tributary area have been parameterized, the tool allows various VRAs and VRA combinations to be evaluated by selecting different VRA types or changing VRA parameters. This allows side-by-side comparison of estimated performance for any number of user-defined scenarios.

Evaluate performance relationships and sensitivities of design parameters. The tool provides the ability to adjust design parameters and obtain near-immediate estimates of long-term performance (i.e., without the delay required for a continuous simulation model to run). This functionality can be used for an efficient manual evaluation of performance relationships and sensitivities. The tool also includes a standardized sensitivity analysis module. These types of analysis can help the user understand which parameters warrant further refinement in the design process (e.g., refining estimates of infiltration rate) and can help the user understand how performance could change with time as a function of normal operation (e.g., reduction of active storage capacity from sedimentation; reduction in infiltration rate from clogging).

Other Potential Uses of the Tool

A number of other potential uses of the tool may be useful for certain applications. Examples are to:

Quantify local precipitation statistics. The tool contains the results of an analysis of 347 precipitation gages across the conterminous United States. Key precipitation statistics, including the 85th-percentile and 95th-percentile 24-hour precipitation depths and average annual precipitation depths are provided after the user selects the gage that best represents the project. These statistics can be useful as part of design development.

Establish planning-level sizing targets. At the start of the planning process it may be useful to hold certain parameters fixed and simply vary storage volume or footprint over a representative range to develop general relationships between VRA size and the expected volume reduction performance. This can help identify how much space may be needed within a site to achieve a certain volume goal and provide early feedback on what goals are reasonable.

Evaluate potential regional variability in performance associated with a given design standard. By holding all other parameters fixed and changing the project location attributes, the user can quickly determine how much variability would be expected in performance as a function of project location if a uniform design standard were to be adopted across an entire jurisdiction (for example, a single design-storm depth across a state).

5.4.5 Estimating Whole Life-Cycle Costs of Conceptual Designs

Section 4.3.7 introduces the WLC estimating framework recommended for VRAs. This section provides more detailed guidance on calculating the net WLC of a specific VRA once conceptual designs of VRAs have been developed. Refer to Section 4.3.7 for introduction of key terms.

This process involves four steps: (1) developing net capital cost estimates, (2) developing net maintenance cost estimates and frequencies and estimated life span until replacement, (3) normalizing these costs to their present value, and (4) adding each cost component (capital, O&M, replacement) to yield the net WLC. These steps are detailed in the following paragraphs. Note that this approach specifically focuses on the costs of VRAs but includes approaches for isolating the net cost of using VRAs on a project compared to a baseline scenario (either without controls or with conventional controls). This approach seeks to quantify what VRAs would cost and also what the net cost to the project is factoring in savings or offset costs. An alternative approach for net cost estimating would be to conduct cost analysis of the entire project for scenarios without VRAs and with different VRAs included. This approach is discussed at the end of this subsection.

Step 1a—Identify Capital Cost Elements and Prepare a Quantity Survey. This requires identifying the items and quantity of items needed to construct a VRA and describing these items in enough detail to estimate their unit prices accurately. The items in a quantity survey will vary depending on the type of project.

Table 35 shows a general breakdown of the costs associated with each life-cycle stage of a VRA. Within each type of cost component, the estimator would identify several line items. As part of this step, the estimator should also estimate any quantities of infrastructure that could be reduced or avoided by using VRAs rather than traditional infrastructure. These should be entered into the quantity survey as a negative quantity. For example, if proposing 15,000 square feet of permeable pavement where traditional asphalt would have been constructed, include a negative quantity of 15,000 square feet for traditional asphalt.

Step 1b (Optional)—Determine the Portion of Common Expenditures That Are Attributable to VRAs. Some construction activities, such as mobilization, traffic control, clearing and grubbing, and excavation, would be required regardless of whether VRAs were installed as part of the project. That said, a portion of these common expenditures may be attributable to the VRA. One way to account for sharing of costs is to include a line item in cost tabulations that estimates the portion of a common expense that would be attributable to the VRAs. This is a value from 0% to 100%. Selecting 0% means that the use of VRAs would have no effect on that cost. For example, if a VRA is proposed inside of the overall limits of disturbance, the VRA would have no incremental effect on the overall clearing and grubbing expense for the project. A value of 100% means that the cost is entirely attributable to the VRA. For example, engineered bioretention media would have no part in the project unless bioretention were used. Certain costs items may be between 0% and 100%. For example, in estimating the line item cost for excavation and hauling associated with a VRA, the estimator should consider how much of that effort would have been incurred without the VRA as well as the cost implications of hauling that excavated material to another location within the site rather than to an off-site disposal area.

Step 1c—Develop Pricing Estimates for Individual Line Items. In this stage, the price of each item is determined. Various resources are available to assist in quantifying the cost of line items, including construction cost databases maintained by local agencies, nationwide

Table 35. Cost breakdown per life-cycle stage (adapted from Powell et al., 2005).

Cost Component	➔ Life-Cycle Stage ➔					
	Capital Costs			Maintenance Costs		
	Appraisal and Planning	Design and Site Investigation	Construction	O&M	Rehabilitation or Intermittent O&M	Disposal
Direct Costs						
Professional labor	Yes	Yes	Yes	Yes	Yes	Yes
Craft labor			Yes	Yes	Yes	Yes
Materials			Yes	Yes	Yes	
Construction equipment			Yes	Yes	Yes	Yes
Indirect Costs						
Administrative support	Yes	Yes	Yes	Yes	Yes	Yes
Overhead	Yes	Yes	Yes	Yes	Yes	Yes
Other Costs						
Permitting fees			Yes	Yes	Yes	Yes
Real estate costs	Yes		Yes			Yes
Energy and utilities costs				Yes		
Landscaping			Yes	Yes	Yes	Yes
Sampling and analysis		Yes		Yes		Yes
Disposal costs and fees			Yes	Yes	Yes	Yes

subscription services such as RSMeans (http://rsmeans.reedconstructiondata.com/), and resources specific to stormwater facilities such as WERF BMP whole life-cycle cost worksheets (Lampe, 2005). Table 36 shows an example of the results of a capital cost quantity survey and line item pricing. In this example, costs associated only with the VRA are calculated to separate shared project costs and costs of the VRA.

Step 2—Forecast O&M Activities and Estimate Costs. The frequency of maintenance will have a large influence on the overall maintenance costs. As introduced in Section 4.3.6, maintenance tasks often occur at either routine or intermittent frequency. Routine maintenance occurs on a predictable schedule and typically consists of inspections, vegetation management, and litter and minor debris removal. The cost of routine maintenance will vary based on the site and region.

Intermittent maintenance is often more costly per visit than routine maintenance. Intermittent maintenance usually consists of a structural repair or other corrective action to the VRA that requires more resources and is typically unplanned. Thus, when assessing the whole life-cycle costs of different VRAs, it is important to consider the O&M costs over the life span of the VRA, including an allowance for any unexpected costs. These include future financial, staff, and equipment costs to maintain the VRA.

Maintenance frequency tends to change with the aesthetic expectations for the facility, where higher visibility areas may require more frequent aesthetic maintenance (Strassler et al., 1999). For example, permeable pavements will require more functional maintenance like street sweeping/

Table 36. Example line item pricing template for capital costs.

	1	2	3	4	5	6
	Unit	Unit Cost	Quantity	Total Project Cost	Fraction of Cost Attributable to VRA	Cost Associated with VRA
Direct Construction Costs						
Construction item 1						
Construction item 2						
Avoided/Reduced Construction Costs						
Avoided cost item 1						
Avoided cost item 2						
Other Capital Costs						
Project management						
Engineering						
Topographic survey						
Geotechnical						
Other site investigation						
Landscape design						
Land acquisition (site, easements, etc.)						
Permitting and construction inspection						
Legal services						
Sales tax						
Subtotal						
Contingency (e.g., 20%)						
Total						

Key to Columns:

1 – Unit of measurement, for example, lump sum, cubic foot, square yard.
2 – Cost per unit.
3 – Total quantity associated with VRA; use column 5 to adjust for line items that may be shared with other systems; use negative for cost items that are avoided through the use of VRAs.
4 – Column 2 × Column 3.
5 – If cost is shared with other project elements, enter portion of line item attributable to the VRA itself.
6 – Column 4 × Column 5.

vacuuming (and the equipment necessary to sweep/vacuum), whereas bioretention areas might require regular upkeep of the vegetation both for performance and for public acceptance.

To develop a forecast of O&M activities, it is necessary to:

- Determine which activities are needed,
- Estimate the necessary frequency of these activities,
- Estimate the labor effort associated with these activities,
- Estimate the equipment costs associated with these activities,
- Estimate the other direct costs, such as materials and disposal, and
- Estimate the programmatic costs associated with VRA maintenance.

Similar to capital costs, O&M cost estimates should also include any costs that are avoided by use of the VRA compared to the baseline condition. Table 37 shows an example template that can be used to estimate O&M costs.

Additionally, the cost of major rehabilitation or replacement/disposal of the system can be estimated based on the life span of the system. The capital cost estimate prepared in Step 1 can be adapted to estimate the rehabilitation or replacement cost, although it is important to consider

Table 37. Example template for calculating costs of various O&M activities.

	1	2	3	4	5	6	7
Cost Item	Frequency (months between maint. events)	Hours per Event	Average Labor Crew Size	Average (pro-rated) Labor Rate/Hour ($)	Machinery Cost/Hour ($)	Materials and Incidentals Cost/Event ($)	Total Cost per Visit ($)
Routine Maintenance Activities (frequent, scheduled events)							
Activity A							
Activity B							
Corrective and Infrequent Maintenance Activities (unplanned and/or >3 years between events)							
Activity X							
Activity Y							
Avoided Maintenance Activities (activities that would have been required for the VRA area if not used as a VRA)							
Activity C							
Activity D							

Key to Columns

1 – Typical spacing between activities, in months. A value of 12 equates to an activity that is performed annually, on average.
2 – Crew labor hours per event; enter negative for avoided costs.
3 – Crew size.
4 – Average labor rate, averaged across the labor rates of typical crew members; may be different for different types of tasks.
5 – Fully loaded cost to have machinery on hand during the maintenance event; include all equipment anticipated to be needed; may be different for different types of tasks.
6 – Direct costs (e.g., material purchases, disposal fees); enter negative for avoided costs.
7 – {(Column 2) × [(Column 3 × Column 4) + (Column 5)] + (Column 6)} × (–1 for avoided costs).

the nature of the rehabilitation or replacement activities that would be needed for a given VRA. In some cases, rehabilitation or replacement would only cost a portion of the initial costs (e.g., replacing media and plants in a bioretention area without having to pay for piping and overall site improvements), while in other cases, rehabilitation or replacement could cost more than initial construction costs (e.g., deconstructing permeable shoulders, over-excavating to restore underlying infiltration capacity, and replacing the system with new material).

Step 3—Normalize Future Costs to Present Value. Costs or savings incurred in the future, such as equipment for disposal or maintenance, should be added to the WLC by computing their present value and summing to estimate the net present value of future cash flows. Using the estimated frequency of maintenance events and the net cost of maintenance events, a cash flow diagram of future net expenditures can be calculated.

Figure 31 shows a hypothetical and conceptual cash flow diagram for costs that may be accrued over the life cycle of a hypothetical VRA.

The NPV of each future cost event can be calculated as:

$$\mathrm{NPV} = \frac{R_t}{(1+i)^t}$$

Where t is the time of the cash flow, i is the discount rate as a fraction (0 to 1), and R_t is the net cash flow (cash inflow – cash outflow, at time t).

For example, at a discount rate of 3%, the present value of a $1,000 net expenditure incurred in 5 years would be calculated as:

$$\mathrm{NPV} = \frac{\$1{,}000}{(1+0.03)^5} = \$862$$

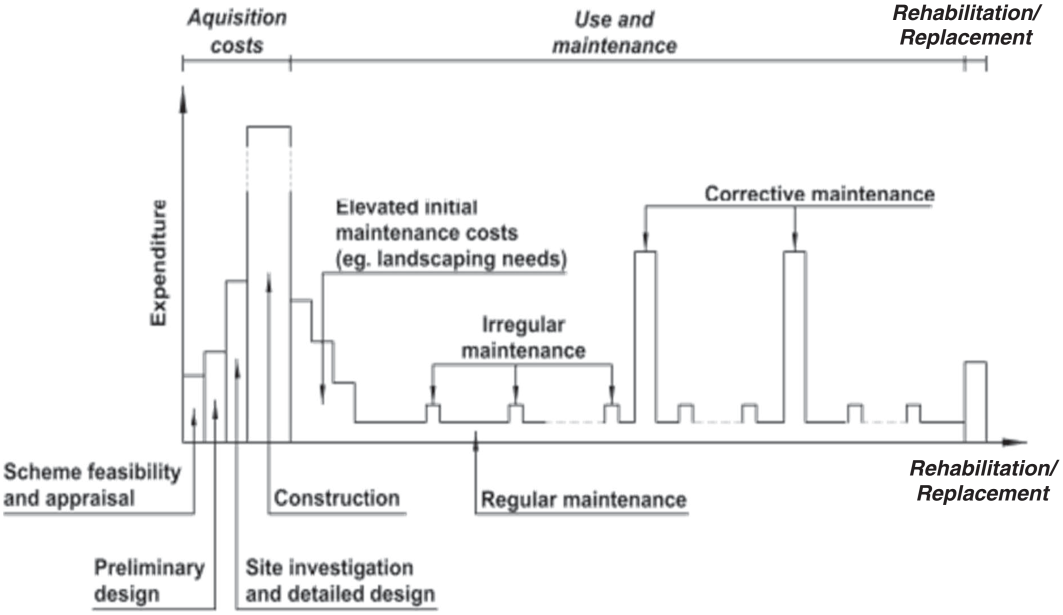

Figure 31. Life-cycle stages and associated costs of stormwater controls (adapted from Lampe, 2005).

The total NPV of future effort can be calculated by summing the NPV of each future event:

$$\mathrm{NPV}(i,N)=\sum_{t=0}^{N}\frac{R_t}{(1+i)^t}$$

Where N is the total number of periods.

Step 4a—Establish the Period for Evaluation. For comparison purposes between VRAs, different VRAs should be compared over the same time period and should each be compared for integer multiples of their life spans. The lowest common multiple can be used. For example, if VRA 01 had a life span of 30 years and VRA 02 had a life span of 12 years, it would be appropriate to use a period of 60 years (lowest common multiple of 12 and 30). For VRAs where replacement costs are not equal to construction costs, more than one life cycle should be evaluated to account for the fact that the second life cycle is not identical to the first life cycle.

Step 4b—Sum Elements to Compute Net WLC for the Period of Evaluation. The net WLC of a VRA for a given period of evaluation is calculated as follows:

Net WLC = Net Capital Cost + Net Present Value of Future Expenditures over Evaluation Period

If each element of this equation includes both the costs incurred and the costs avoided as a result of the use of VRAs compared to the baseline scenario (i.e., the net cost), then it should not be necessary to also compare the net WLC to a baseline WLC. This comparison is already embedded in the calculation.

If it is desirable to determine the NPV in terms of an annualize cost, the NPV of each scenario can be amortized over the period of evaluation (Newnan et al., 2008):

$$\text{Annualized Net WLC}=\text{Net WLC}\left[\frac{i}{1-(1+i)^{-n}}\right]$$

Where Net WLC is as calculated for the period of evaluation, i is the discount rate as a fraction (0 to 1), and n is the length of the period of evaluation (years).

So, for example, if the net WLC of a project for a 20-year period of evaluation is \$100,000, and the discount rate is 3%, the annualized net WLC would be:

$$\text{Annualized net WLC} = \$100{,}000\left[\frac{0.03}{1-(1+0.03)^{-20}}\right] = \$6{,}720 \text{ per year (present value)}$$

Alternative Whole-Project Approach. If a cost estimate is available for the entire project at the time when VRAs are being compared, then an alternative to this four-step approach could be used. This alternative approach would involve comparing versions of the entire project cost analysis with and without VRAs. This would explicitly account for any avoided infrastructure as well as costs shared between multiple aspects of the project, without the need to attempt to apportion these shared costs as discussed in Step 1b. Additionally, if future project maintenance is forecasted as part of the cost estimate for the entire project, this could be accounted for in maintenance and replacement costs of VRAs.

5.4.6 Adapting Conceptual Designs to Converge with Project Goals and Constraints

After developing initial conceptual designs and evaluating these designs, the user may find that the design achieves less volume reduction than the project goals or costs more than can be reasonably allocated. While it will not always be feasible to converge with project goals (i.e., project goals may need to be revisited), the following sections provide suggestions for adapting conceptual designs to increase volume reduction and reduce costs.

Potential Options for Increasing Volume Reduction Through Design Adaptation

Consider VRA design variations and enhancements to fit site opportunities and improve volume reduction. The VRA fact sheets identify a number of variations and enhancements, including geometric variations and minor design modifications that can potentially increase volume reduction or allow a VRA to fit into a constrained space. These options can be reviewed and incorporated, as applicable.

Increase storage volume. Providing a broader footprint provides more storage volume and can also increase infiltration losses. Additionally, providing a deeper profile can provide more storage volume within a given footprint, although the rate of infiltration losses does not generally increase significantly with increased depth so this modification tends to be less effective than increasing footprint; however, it may be more practical.

Improve utilization of the available footprint. Improving the uniformity of flow distribution in swales, dispersion, and media filter drain VRAs can increase the amount of the surface area that is effectively wetted in each storm event, increasing infiltration and ET losses. For VRAs with surface ponding, using vertical retaining walls rather than side slopes, where acceptable, can increase the effective footprint of the facility by reducing the partially effective footprint taken up by side slopes.

Consider real-time controls. Real-time controls can help balance competing factors in VRA design and operation by providing the flexibility to adapt system operations based on observed VRA status, weather forecast or actual data, or other data streams. For example, if soil infiltration rates were marginal, the use of real-time controls could allow the system to be operated either as a VRA (i.e., hold water back to infiltrate slowly) or a treatment BMP depending on the timing until the next storm is anticipated to arrive. If infiltration rates proved to be higher than estimated in design, more water could be infiltrated, while if infiltration rates were lower than estimated in design, treatment and detention could still be provided. This could also allow a lower factor of safety to be used in design since the consequence of overestimating infiltration rates would simply be more water treated rather than an infiltration system than does not drain.

Revisit site design and initial screening. In some cases, there may be flexibility in the site design to allow more room for VRAs or to reconfigure drainage to route more water where VRA opportunities are better. Additionally, in some cases, feasibility or desirability issues can be overcome with design elements to mitigate risk; however, it should be noted that design elements to mitigate risk could be cost-prohibitive in some cases.

Evaluate watershed-based options. Section 5.5 provides guidance for considering watershed-based options for volume reduction.

Potential Options for Reducing Costs

Account for avoided or shared costs. Studies have shown that, in some cases, the use of distributed practices that provide volume control can reduce project costs compared to traditional stormwater management approaches by avoiding or reducing traditional drainage infrastructure and reducing or eliminating the cost of traditional treatment and flow-control systems. Accounting for avoided costs (examples identified in Section 5.3.2) can significantly change the net cost that is attributable to a VRA. Additionally, some costs, such as bulk grading, erosion control, and other lump sum items, may be part of the project regardless of VRAs.

Phase construction to help avoid VRA-specific costs. In new and redevelopment projects, phasing can influence how much of the total grading, erosion control, and other costs would be borne by the VRA versus being attributable to the project as a whole. For example, grading an infiltration basin at the same time that the subgrade of a new lane is being constructed can help balance cut and fill and could save money compared to importing fill for the new lane and then exporting material excavated from the infiltration basin.

Coordinate retrofits with other construction activities. For retrofit situations, waiting to construct volume reduction retrofits until other work occurs in the area can help share costs such as traffic control, demolition of existing surfaces, hauling, and refinishing. The potential economic incentive of strategic scheduling can be evaluated at the conceptual design phase by identifying which cost items could be eliminated or reduced if work was coordinated as part of a larger project.

Use commonly available, local materials. Obtaining items such as gravel, plants, and media from local sources may reduce costs of shipping materials. Where local sources do not exactly meet applicable specifications, it may be worthwhile to attempt to identify an equivalent product locally that can be substituted.

Obtain current cost estimates for specialized products. Some specialized cost items, such as bioretention soil media or permeable paving surfaces, may initially be expensive in a given market; however, costs can decline over time as more suppliers carry the product and more contractors gain experience with installations.

Conduct pilot projects to narrow uncertainty in costs. When considering VRAs that are not well known to an agency or to local contractors, costs can be inflated by the uncertainty associated with not having local examples of past projects. Carefully planned pilot projects can be costly up front, but can result in long-term savings associated with the agency and contractor experience gained.

5.5 Watershed-Scale Approaches

This section is intended to provide the user with an introduction to watershed approaches for achieving volume reduction of urban highway runoff and help identify when a watershed approach may be more appropriate than controls located within the project site (referred to as "on-site controls"). This section is intended to help the user answer the following questions:

- What is a watershed-scale approach for achieving volume reduction?
- What are some indicators that a watershed-scale volume reduction approach may be applicable for my project? When might a watershed approach to volume reduction be more beneficial than a site-specific approach?
- Where can I learn more about watershed-scale volume reduction approaches?

As an introduction to watershed approaches, it is informative to first revisit the characteristics of on-site approaches. The term "on-site" refers to managing stormwater that is generated from a project at a location within the boundary of the project, before it discharges to a receiving water. On-site facilities are typically sized to manage runoff generated from the project site only (and in some cases, to address run-on from adjacent land uses that comingles with on-site runoff). The on-site management framework is a common regulatory paradigm for stormwater control from roadway projects.

In contrast, "watershed approaches" refers to a broad category of potential approaches that are intended to achieve the same or better watershed benefits as would be achieved via on-site approaches, but which differ from on-site approaches in some manner. For example, watershed-scale approaches may be located in different areas, address different sources of runoff, be constructed at different scales, or function via different mechanisms than on-site approaches. Typically, for regulatory acceptance, watershed approaches should provide their benefits within the same watershed as the project that they are intended to mitigate. In the context of this manual, watershed approaches are limited to those that would provide volume reduction benefits or address watershed issues related to volume reduction in the same watershed as the project.

There are a number of forms that watershed approaches can potentially take. These are summarized in Table 38. A row in this table is also included for on-site approaches as a point of comparison. As summarized in Table 38, watershed-scale approaches may have considerable benefits compared on on-site approaches and can potentially be part of a strategy to supplement or replace on-site approaches; however, they also have a number of technical and nontechnical considerations regarding their use. The applicability of watershed-scale approaches will vary by project location and type. In general, one or more of the following factors may indicate that a watershed approach may be applicable for a given project:

- The maximum volume reduction that can be feasibly achieved is significantly less than project goals (determined using the framework in the manual or another approach).
- Landscape-level infiltration feasibility screening (as discussed in this manual) indicates that downstream or nearby areas within the watershed have significantly better conditions for infiltration than the project site.
- Specific retrofit opportunities have been identified within the watershed, preferably downstream of the project and upstream of the receiving water.

Table 38. Summary of potential forms of watershed-scale approaches [personal communication, Neil Weinstein (2013)].

General Category	Manages Project Runoff?	Typical Location of VRA (Inside or Outside ROW)	Description	Potential Benefits and Rationales for Use	Potential Considerations
0) On-site management of project runoff	Yes	Within ROW	VRAs located within footprint of project *Example: linear bioretention along road shoulder at intersection*	• Simpler permitting process than watershed approaches • Addresses runoff close to source, where feasible • Does not typically require land acquisition or coordination with other dischargers	• May be limited opportunities for volume reduction; may result in more water treated and discharged versus reduced • May incur greater cost associated with construction at smaller scale and in constrained environment
1) Watershed-scale management of project runoff	Yes	Typically outside of ROW	VRA located outside of the project boundary, but receiving runoff from the project and potentially additional area; project runoff is managed before discharge to a receiving water. *Example: Infiltration basin constructed outside of the right-of-way collecting runoff from project plus adjacent roadway, or other land uses*	• Allow the VRA to have a larger footprint or be located in an area with more suitable conditions for volume reduction • Reduce cost via economy of scale • Address existing runoff; create capacity for future runoff or credits for mitigation banking approach • Potential for higher regulatory acceptance of other watershed approaches because water is managed before being discharged	• Land acquisition costs • Requires favorable opportunities down gradient of project but upstream of receiving water • Potentially greater up-front costs to size for larger watershed; could be recuperated as credits in mitigation bank • DOT runoff may be comingled with runoff treated from non-DOT areas; acceptance of liability
2) In-kind[1] management of other highway runoff	No	Inside or outside of ROW	VRAs installed to manage runoff from nearby section of roadway, but outside of project site; does not manage runoff from the project *Example: Retrofit VRAs into an existing interchange within the same watershed, but outside of project and not treating project runoff*	• Allow flexibility to select sites that are more conducive to volume reduction • Can avoid land acquisition or partnerships with other dischargers if constructed within ROW • Ensures that like-for-like land uses are addressed	• Need to develop accounting system to maintain credits into perpetuity • Depending on regulatory framework, may also require some level of treatment on site before discharge of project runoff to receiving water
3) In-kind[1] management of non-highway runoff	No	Inside or outside of ROW	Similar to Category 2, but involves management of runoff from other nearby land uses using VRAs; can be combined with Category 2 *Example: Retrofit VRAs for nearby runoff from other land uses that drains to same receiving water*	• Allow flexibility to select sites that are more conducive to volume reduction • Could be part of a larger regional credit banking effort in cooperation with other dischargers	• Requires demonstration of equivalency if different land uses retrofitted • Requires cooperation and agreements with other dischargers • Need to develop accounting system to maintain credits into perpetuity

Table 38. (Continued).

General Category	Manages Project Runoff?	Typical Location of VRA (Inside or Outside ROW	Description	Potential Benefits and Rationales for Use	Potential Considerations
4) **Out-of-kind[2] mitigation banking**	No	Typically outside of ROW	A general category used to refer to other approaches for achieving equivalent watershed protection benefits compared to on-site approaches, but possibly using different approaches/mechanisms *Example: Project pays into reforestation fund in lieu of on-site VRA; reforestation within watershed demonstrated to improve natural recharge to an equal or greater extent than on-site controls*	• Most flexibility to participate in approaches that may yield other benefits besides volume reduction • Approaches may be developed on a watershed-specific basis to more directly address impairments and avoid contributing to unintended consequences (e.g., water balance issues) • If degradation has already occurred from other development, could be more effective to put funds toward restoration than address minor portion of watershed with project-based controls	• Demonstration of equivalency of watershed benefits may be complicated or indirect • Typically requires framework to be in place to manage mitigation banking system or requires significant effort to create framework • Potential institutional issues related to maintaining equivalent or better benefits into perpetuity

1 – "In-kind" refers to control provided by similar types of facilities (i.e., VRAs), but in a different location.
2 – "Out-of-kind" refers to approaches based on mechanisms besides VRAs (e.g., habitat restoration, wetland creation, reforestation).

- Multi-jurisdictional partnerships for developing stormwater retrofit have been established or are of mutual interest to parties in the vicinity of the project.
- Watershed-scale resource issues such as groundwater balance issues, salt and nutrient management planning, base-flow augmentation, or groundwater source protection/management are present and would be better addressed via a coordinated watershed-scale approach for evaluating VRA feasibility and siting rather than a site-by-site approach.
- Existing water resources have been degraded by prior development, such that providing funding for restoration efforts would have greater watershed protection benefit than mitigating volume of runoff from individual project sites (which may make up a small fraction of total development).
- The local regulatory structure acknowledges pathways for watershed-scale approaches.
- A water agency prefers to manage infiltration or harvest and use in its own facility as part of its mission.
- A watershed-scale pollutant or runoff volume trading program has already been established, such that this framework could be used or adapted for the project.
- Other watershed-scale mitigation programs would potentially allow determination of equivalency.

In general, many of the VRA selection and design considerations presented in this manual can be used to develop watershed-scale approaches for volume reduction. However, depending on the type of approach proposed, various institutional issues may need to be addressed beyond what would be required for on-site controls. NCHRP Project 25-37 (in progress) is addressing watershed approaches. For more information, the user is encouraged to refer to the products of this research when they become available.

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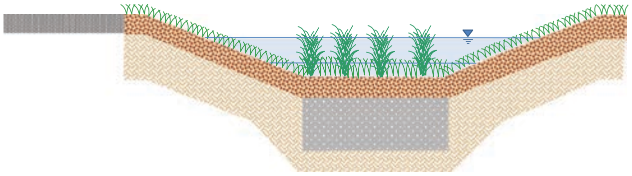
APPENDIX A

Volume Reduction Approach Fact Sheets

Additional information about VRAs is provided in Chapters 4 and 5.

Vegetated Conveyance VRA 01

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



	VOLUME MANAGEMENT POTENTIAL/PROCESSES
◉	Overall volume reduction potential
◉	Infiltration
◉	Evapotranspiration
○	Consumptive use
○	Base-flow–mimicking discharge

Photo credit: Caltrans.

	URBAN HIGHWAY APPLICABILITY
●	Ground-level highways
◉	Ground-level highways with restricted cross-sections
◉	Ground-level highways on steep transverse 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 serve the purpose of conveying stormwater runoff and can also provide significant reduction of 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 VRA 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 VRA for the purpose of design and performance evaluation.

Volume Reduction Processes and Performance Factors

Volume reduction is achieved through infiltration and evapotranspiration. 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 VRA bottom area to tributary area are believed to be the most important 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 water quality treatment benefits and volume reductions of highway runoff. A review of volumetric measurements from swale studies in the International BMP Database (Water Environment Research Foundation, 2011) shows moderate volume reduction on average.

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 avoid the creation of high-velocity flows that will result in erosion. For slopes within the upper end of this range (about 4% or more), better performance can sometimes be achieved through the use of check dams.
- 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.

Geotechnical Considerations

- Vegetated conveyances must be located a sufficient distance from the roadway that infiltration will not compromise its structural integrity.
- Vegetated conveyances are a standard design feature in ground-level highway types and therefore 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 conveyances do 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 (for example, addition of filtration media in the design) or

to be adjusted to enhance treatment and prevent groundwater contamination.

- Where soils allow high rates of infiltration, the use of a 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 ft 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 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 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.
- Salt loadings in cold climates may influence plant selection.
- 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 may have small incremental cost in new projects with sufficient right-of-way 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.

Use in a Treatment Train

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

VRA-Specific Maintenance Considerations *(see Section 4.3.6 for additional maintenance information in common with other VRAs)*

- Generally requires maintenance activities similar to those already needed for maintenance of roadside vegetation and ditches.

- Proper functioning 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 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 VRA may be more appropriately categorized and designed as a linear bioretention area.

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 therefore allow greater volume reduction. Check dams can also help slow and more evenly distribute flow as well as prevent erosion (assuming that downstream of the check dam is protected).

Provide low-flow outlet. Water can be held and released at a slow rate via a low-flow outlet, such as 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 typically their construction relies on impermeable soils and thus evapotranspiration is the primary mechanism for volume removal. Wetland-type systems can also provide areas for vector establishment and reproduction, possibly resulting in the need for abatement measures.

Additional Sources of Design Information

California Stormwater Quality Association. *California Stormwater BMP Handbook: New Development and Redevelopment*. TC-30, Vegetated Swale. 2003. http://www.cabmphandbooks.com/Development.asp.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 3: Grass Channel v.1.9. 2011. 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 to10 ft
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 in. (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 in. (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 in.
Maximum flow depth	The maximum water level above the bottom of the swale under peak storm design conditions	1 to 2 ft
Design infiltration rates	The rate at which water is assumed to infiltrate into the subsurface soils for the purpose of design and benefit evaluation. This should be the rate of infiltration below the amended soil layer or stone reservoir.	Can be used in any soil conditions
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 on higher head values. A 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

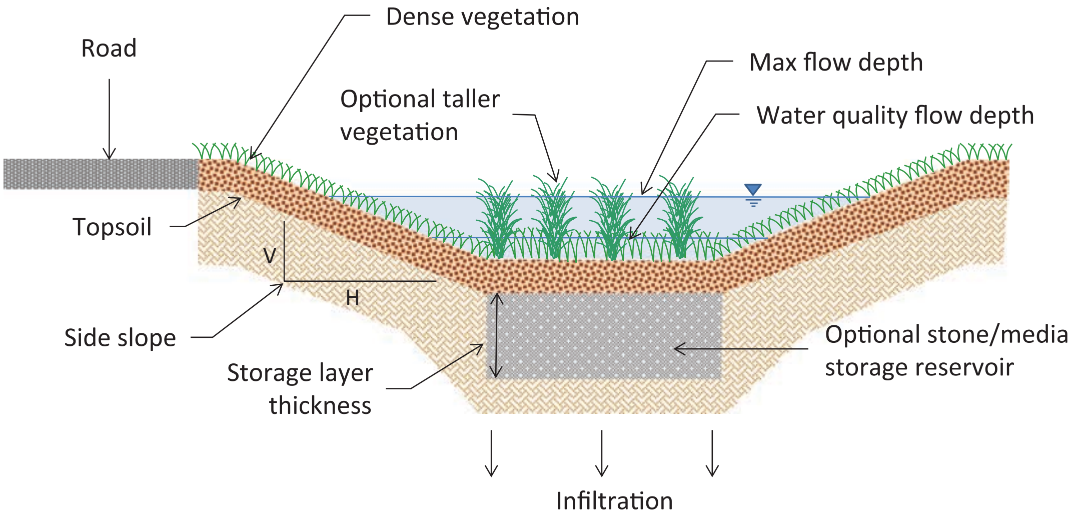


Figure 1. Cross-section view.

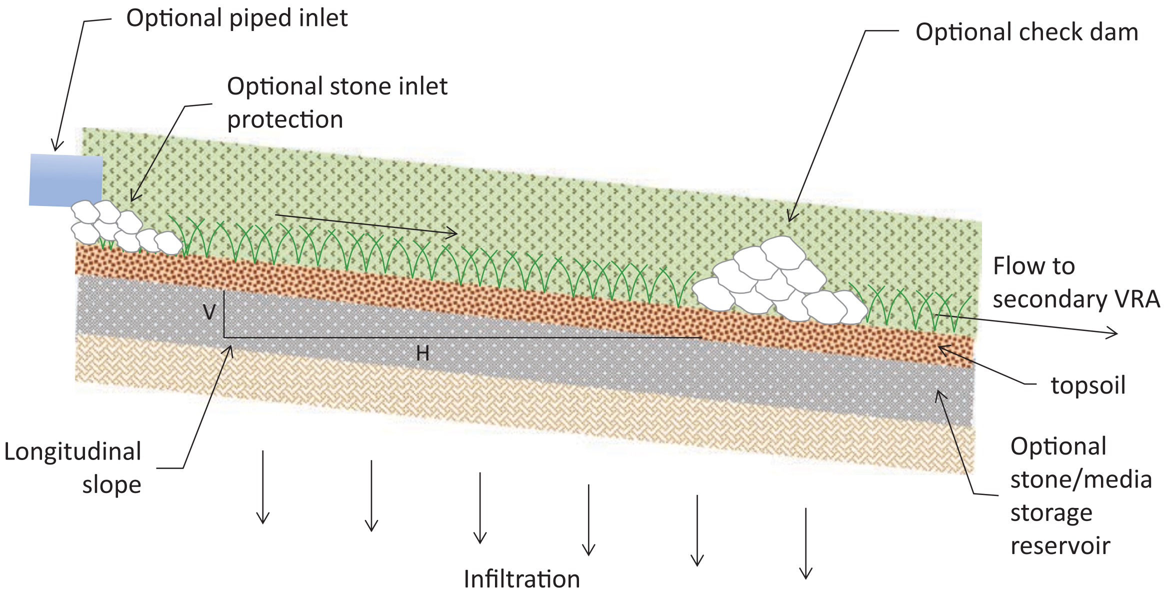


Figure 2. Longitudinal profile.

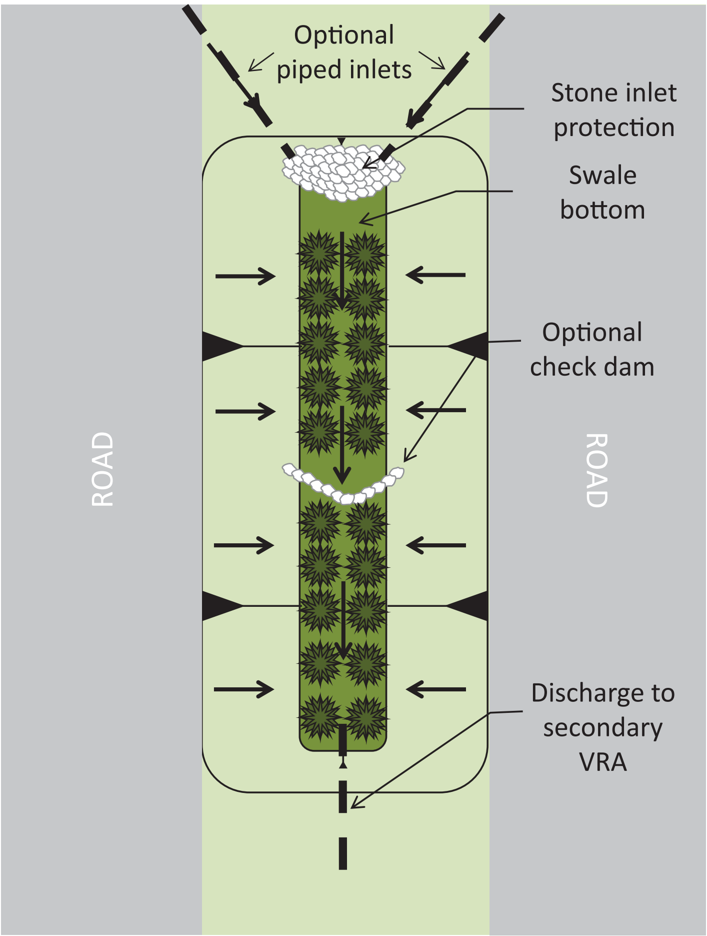
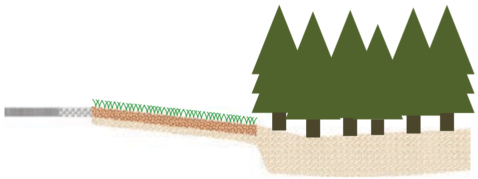


Figure 3. Plan view.

Dispersion VRA 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 urban area (Credit: Google).

VOLUME REDUCTION PROCESSES	
●	Overall volume reduction potential
●	Infiltration
◉	Evapotranspiration
○	Consumptive use
○	Base-flow–mimicking discharge

URBAN HIGHWAY APPLICABILITY	
●	Ground-level highways
◉	Ground-level highways with restricted cross-sections
○	Ground-level highways on steep transverse 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 or restored pervious areas for the purpose of reducing stormwater runoff volumes and achieving incidental treatment. This 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 evapotranspiration. Volume reduction performance can be improved with the use of flow spreaders, soil amendments, and re-vegetation. A critical element of this VRA 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 (i.e., improve uniformity of dispersion) 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 evapotranspiration. The quantity of volume reduction expected is dependent on the site's soils, topography, and hydraulic characteristics (e.g., storage capacity, hydraulic retention time). 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, the ET fraction of the water balance tends to be significant.

General DOT Experience

Dispersion, as a VRA, 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 be otherwise constructed.

The benefits of dispersion for reducing runoff volumes and treating stormwater are increasingly recognized by DOTs. While DOTs have made these land and design investments for transportation and safety purposes, they also provide water quality and volume reduction benefits. Taylor et al. (2014a) conclude: "For swales and filter strips, water quality benefits can effectively be considered free when compared to 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, Reister and Yonge (2005) note that the Washington State Highway Runoff Manual recommends a maximum side-slope of 7:1 for dispersion practices while most roadway embankments fall between 2:1 to 6:1 where space or topography constrains 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 VRA 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 Glick et al. (1993) 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 Database, mostly in California, showed moderate levels of volume reduction (Water Environment Research Foundation, 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, 2013c).

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 ft) to achieve significant volume reduction. They may therefore not be suitable for roads with very restricted rights-of-way.
- 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 (i.e., 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 by the use of a gravel area between the road shoulder and the dispersion area (see schematic design of 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 right-of-way. Therefore, the opportunity for dispersion is dependent on specific site conditions and availability of 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 (i.e., flow spreading, shallow slopes, vegetated cover).
- The most significant geotechnical issue is the potential for rill erosion to form and progress along the roadside shoulder if soil is not stabilized 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

- Due to its extensive nature (i.e., water is dispersed 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 and other obstacles within the clear zone (typically in the range of 22 to 32 ft 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 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 in. should be covered with traversable grates.

Regional Applicability

- Dispersion can be applied across a broad range of climates, but would 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 used, 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 that road shoulder sections will not be hydraulically overloaded and that sheet flow conditions will be maintained to the extent practicable.
- Where adjacent natural land covers are highly erosive (such as in 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 since 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 for more uniform dispersion, or enhancing the dispersion area, such as by amending, decompaction, leveling, 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

- A vegetated conveyance can be used to convey runoff to a dispersion area.
- Dispersion can be used to pretreat and convey stormwater to secondary VRAs.

VRA-Specific Maintenance Considerations *(see Section 4.3.6 for additional maintenance information in common with other VRAs)*

- Typical roadside maintenance activities apply.
- In addition, maintenance activities should seek to maintain dense, robust vegetative cover and correct erosion issues before they progress. The need for corrective maintenance can be reduced by good dispersion design practices.

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 regrading to level 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 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, a 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.

Sources of Additional Information

California Stormwater Quality Association. *California Stormwater BMP Handbook: New Development and Redevelopment.* TC-31, Vegetated Buffer Strip. 2003. http://www.cabmphandbooks.com/Development.asp.

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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. Site-specific analysis of overland flow hydraulics and soil properties should be conducted at the design phase to ensure that potential for erosion and scour have been addressed.

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 ft 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 in.
Effective depth of depression storage	Including pore storage added through soil decompaction/amendment or naturally occurring depressions where ponding is expected; expressed as depth	1 to 6 in.

Example Conceptual Design Schematics

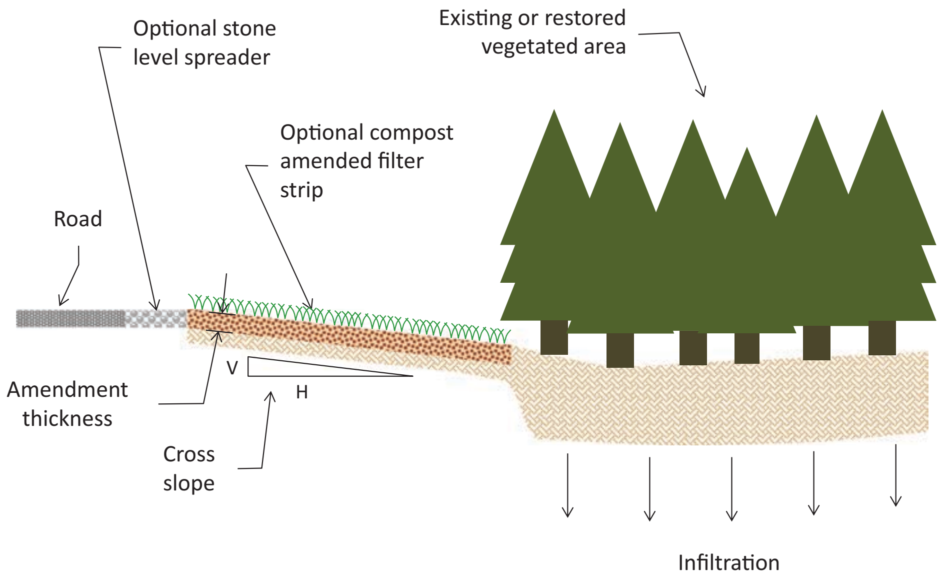


Figure 1. Cross-section view.

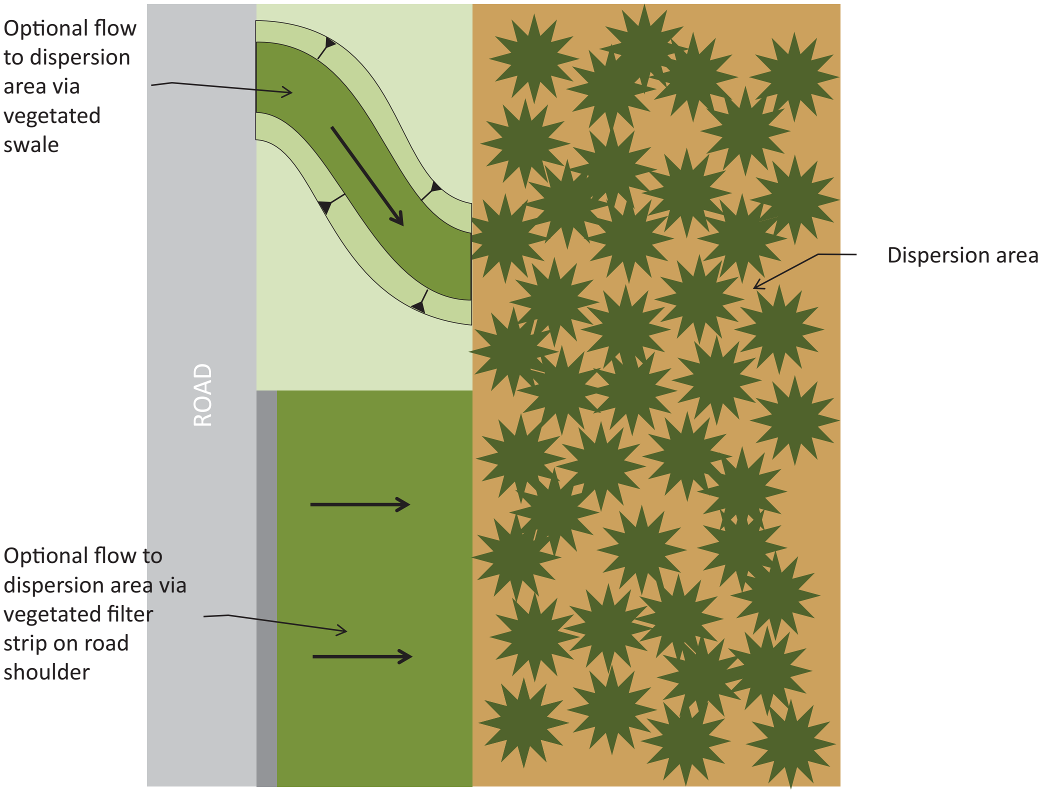
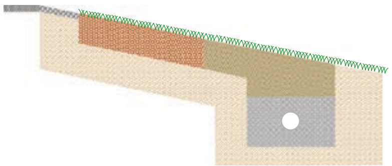


Figure 2. Plan view.

Media Filter Drain

VRA 03

***Alternative names:** formerly known as "ecology embankment"*



Media Filter Drain Along SR 14 in Clark County, WA.
Source: Washington State DOT, 2011.

	VOLUME REDUCTION PROCESSES
●	Overall volume reduction potential
●	Infiltration
◉	Evapotranspiration
○	Consumptive use
○	Base-flow–mimicking discharge

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

● High ◉ Moderate ○ Low

Description

This VRA 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 VRA is typically installed between the road surface and a ditch or other conveyance located downslope. While this approach shares many similarities to VRA 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 evapotranspiration. 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, which may partially mimic base flow in some environments.

General DOT Experience

This VRA is widely used by WSDOT, and was formerly referred to as an "ecology embankment." A technology evaluation report prepared on ecology embankments for WSDOT (Herrera Environmental Consultants, 2006) shows both significant volume and load reductions up to, in some cases, 10%. Other stormwater design manuals have begun to incorporate elements of the media filter drain design; however, widespread application outside of Washington State has not occurred to date. Some design standards for filter strips employed by other DOTs include elements that resemble the media filter drain.

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 VRAs 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 right-of-way.
- Media filter drains work best on low to moderately longitudinal slopes (less than 5%). Greater longitudinal slopes present greater difficulties for evenly spreading water.
- Large drainage areas (i.e., 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 by the use of a dispersion trench or other approach intended to spread and slow flows.
- Media filter drains can be sited in confined rights-of-way, 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 make-up 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 VRA 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 VRA may not be applicable.
- In cold climates where salt is used, vegetation should be selected that is tolerant of elevated salt levels.
- Regional rainfall intensities and characteristic patterns should be considered during the design process to ensure that 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 strips 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 VRAs.

VRA-Specific Maintenance Considerations *(see Section 4.3.6 for additional maintenance information in common with other VRAs)*

- Maintenance consists of routine roadside management.

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 VRA or stormwater outfall.

Increase footprint area at intersections and wider portion of right-of-way. Drainage can be routed to media filter drains with broader footprints in the open space formed by intersections and at wider sections of the right-of-way to help increase the dispersion area that is provided.

Sources of Additional Information

Herrera Environmental Consultants. Technology Evaluation and Engineering Report, WSDOT Ecology Embankment, Prepared for Washington State Department of Transportation. 2006. http://www.wsdot.wa.gov/NR/rdonlyres/3D73CD62-6F99-45DD-B004-D7B7B4796C2E/0/EcologyEmbankmentTEER.pdf.

Washington Department of Ecology. *Stormwater Manual for Western Washington.* BMP RT.07: Media Filter Drain. 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 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 ft
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 ft
Grass strip width	The width of the grass strip used for pretreatment	3 to 5 ft
Media filter depth	The depth of the filter media storage reservoir	12 in.
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

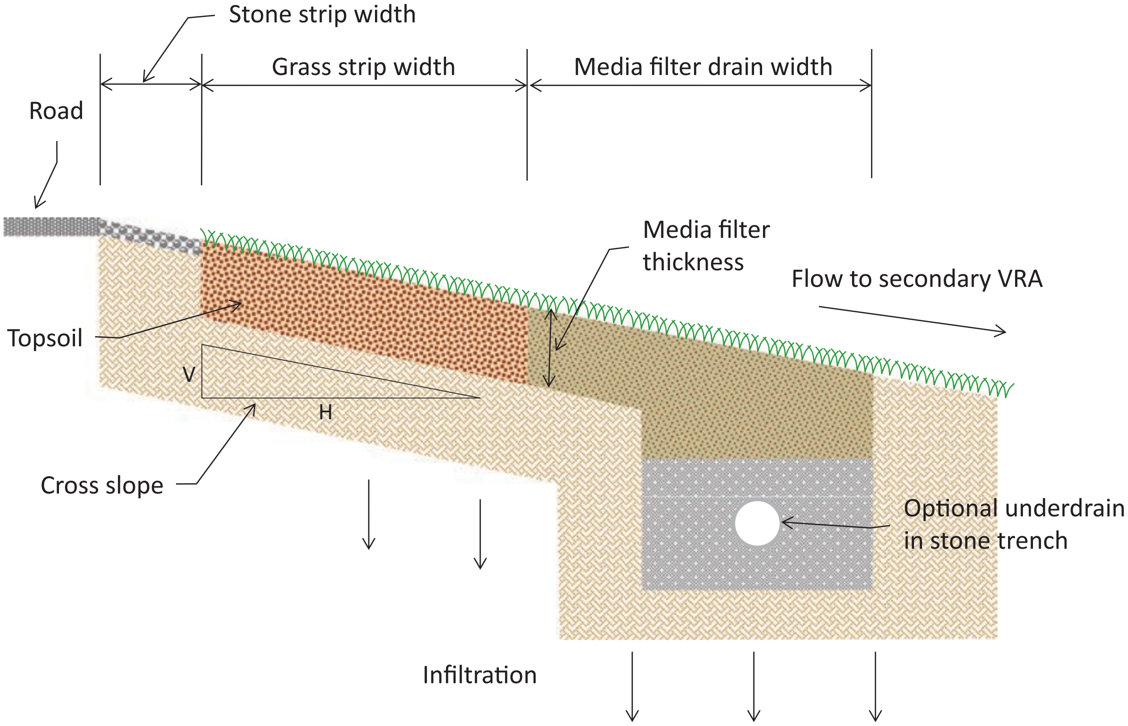


Figure 1. Cross-section view.

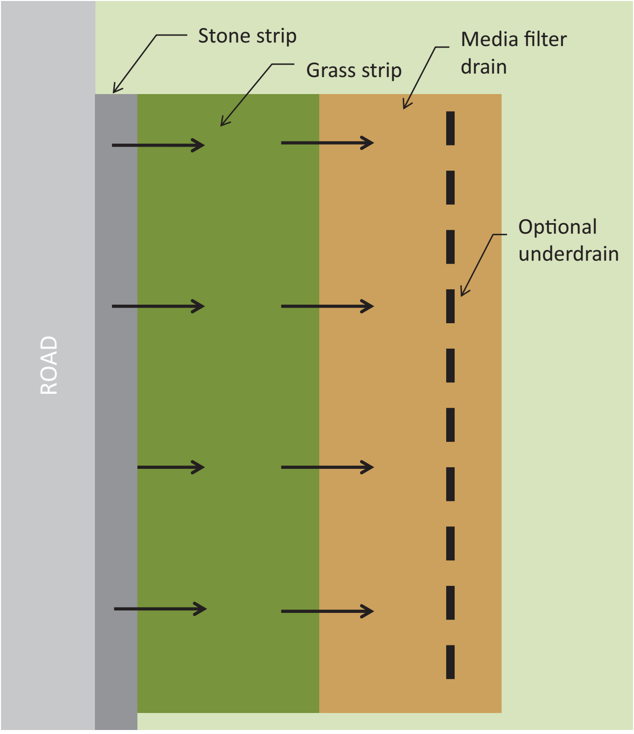


Figure 2. Plan view.

Permeable Shoulders with Stone Reservoirs VRA 04

Alternative names: *permeable shoulders, permeable gutters*

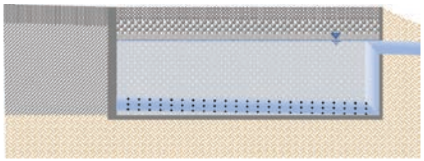


Photo credit: Pike Industries.

VOLUME REDUCTION PROCESSES	
●	Overall volume reduction potential
●	Infiltration
○	Evapotranspiration
○	Consumptive use
◉	Base-flow–mimicking discharge

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

● High ◉ Moderate ○ Low

Description

This VRA 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 the 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 VRA is most effective for volume reduction when soils are suitable for infiltration or where outlet control can be provided to mimic base-flow 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 (i.e., 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.

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 and 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. DOTs have found permeable pavement shoulders to be an effective method to not only improve roadway safety (by reducing surface flow and splash/spray effects) but also to reduce overall stormwater volumes generated from the linear roadway environment. Volume reductions from permeable pavement shoulders are generally moderate to high.

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, although it should be noted that in some studies (Van Seters et al., 2006; Legret and Colandini, 1999; Bean et al., 2007, Collins et al., 2008 and Brattebo and Booth, 2003), volume reductions ranged from 94% to 100%.

Ongoing research with methods including full-depth permeable shoulders is also being conducted with specific applications to the highway environment. The University of California Pavement Research Center concludes that permeable shoulders are technically feasible and economically advantageous compared to other BMPs and can be used where infiltration rates are as low as 0.014 in. per hour (Chai et al., 2012).

Guidance on design, construction, and maintenance of permeable shoulders with stone reservoirs has been developed under NCHRP Project 25-25(82). For information, please go to http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3315. An additional summary of permeable pavement experiences is provided in Appendix F, which is published as part of *NCHRP Web-Only Document 209*.

Applicability and Limitations

Site and Watershed Considerations

- Permeable pavements are especially well 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 most suitable for permeable shoulders because the volume of the storage reservoir is best utilized. Where longitudinal slopes are steeper, cutoff walls and intermediate outlet points are needed at a greater frequency, and there is greater potential for water to flow longitudinally below the roadway.
- 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 VRAs.
- 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

- 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 are 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 (i.e., a separation wall) in order to avoid compromising road integrity from excess infiltration or 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 into 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 are providing an amended soil layer below the storage reservoir and providing 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 predevelopment conditions; the use of underdrains with adaptable outlet elevation can help provide a contingency for water balance impacts.

Safety Considerations

- Permeable shoulders function in the same way as shoulders with standard pavement and do not present any added safety hazards.
- Studies have found that, in cold-weather climates, less salt application is needed to address ice formation than is needed on traditional pavements (see Appendix F).
- Supplemental drainage may be needed in critical cross-sections, such as sags and depressed sections, to ensure that peak flows can be conveyed from the roadway in the event that the permeable surface clogs.

Regional Applicability

- Permeable pavement can be used across a wide range of climates; however, designs must account for differences in climate (specifically precipitation), peak temperatures, freeze/thaw cycles, and solar irradiation.
- 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. Additionally, salting of roadways may pose groundwater quality issues but may have a net benefit if total salt usage can be reduced.
- 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

- It is not typically practicable to provide pretreatment prior to discharge to permeable pavement; however, a sand filter layer within the permeable pavement can serve as pretreatment prior to water entering the subsurface reservoir.
- Permeable pavement can be designed with an underdrain that can be used to convey stored and partially treated runoff to secondary VRAs.
- An amended soil layer below the stone reservoir can be used to improve the level of treatment of infiltrated water before it reaches groundwater.

VRA-Specific Maintenance Considerations *(see Section 4.3.6 for additional maintenance information in common with other VRAs)*

- Permeable shoulders should include regular maintenance procedures to ensure that overall permeability and infiltration are maintained. To reduce surface clogging and help reduce the migration of fines into the subbase, permeable shoulders should be cleaned regularly with a high-efficiency vacuum sweeper.

Enhancements and Variations

Add storage**.** Increasing the depth or porosity of the stone subbase can be done 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 VRAs/BMPs or mimic natural base-flow conditions. It can also help provide adaptability of designs relative to water balance issues.

Consider various materials. Several different surface materials are available for permeable pavement (e.g., permeable concrete, permeable asphalt, permeable pavers). Different materials can be selected to tailor the design to specific applications and requirements.

Sources of Additional Information

AASHTO. Guide for Design of Pavement Structures, Washington, D.C. 1993.

ACI. “Specification for Permeable Concrete Pavements.” 522.1-08, Committee 522, American Concrete Institute. 2008.

ACPA . American Concrete Paving Association, Pervious Pave – Background, Purpose, Assumptions and Equations, Washington, D.C. 2012.

ASCE. Recommended Design Guidelines for Permeable Pavements. Manual of Practice on Recommended Design Guidelines for Permeable Pavements, B. Eisenberg, K. Lindow, and D. Smith, eds., American Society of Civil Engineers, The Permeable Pavements Technical Committee, Low Impact Development Standing Committee, Urban Water Resources Research Council, Environment and Water Resources Institute.

Low Impact Development Center, Inc. Low Impact Development Manual for Southern California: Technical Guidance and Site Planning Strategies. 2010. http://www.casqa.org/LID/SoCalLID/tabid/218/Default.aspx.

NAPA. “Design, Construction, and Maintenance Guide for Permeable Asphalt Pavements.” Information Series 131, National Asphalt Pavement Association. 2008.

NCHRP Project 25-25 (Task 82), “Permeable Shoulders with Stone Reservoirs.” http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3315.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 7: Permeable Pavement v.1.9. 2011. http://chesapeakestormwater.net/category/publications/design-specifications/.

Washington State Department of Transportation. Highway Runoff Manual. BMP IN.06: Permeable Pavement Surfaces. 2011. http://www.wsdot.wa.gov/Environment/WaterQuality/Runoff/HighwayRunoffManual.htm.

See Appendix F for additional references on permeable pavements and shoulders.

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 ft
Porosity	The effective void space within the stone storage layer	Typically 0.35 to 0.45 (unitless)
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 1 ft
Longitudinal Slope	Slope along the axis of the road and associated slope along the bottom of the infiltration bed	Preferably less than 2%; possibly up to 5% 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 that 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)
Subbase 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 possible 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	At least 6 in. below pavement
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

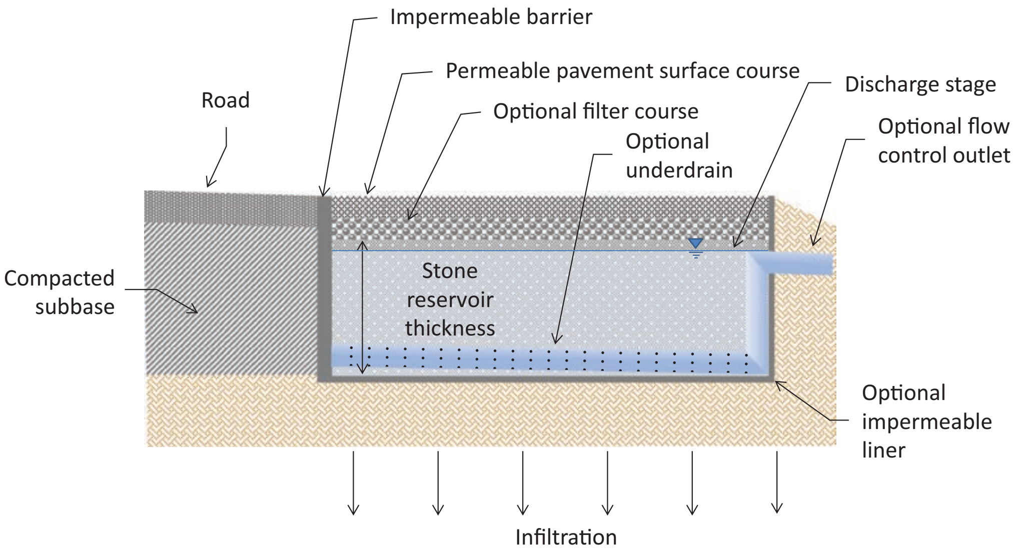


Figure 1. Cross-section view.

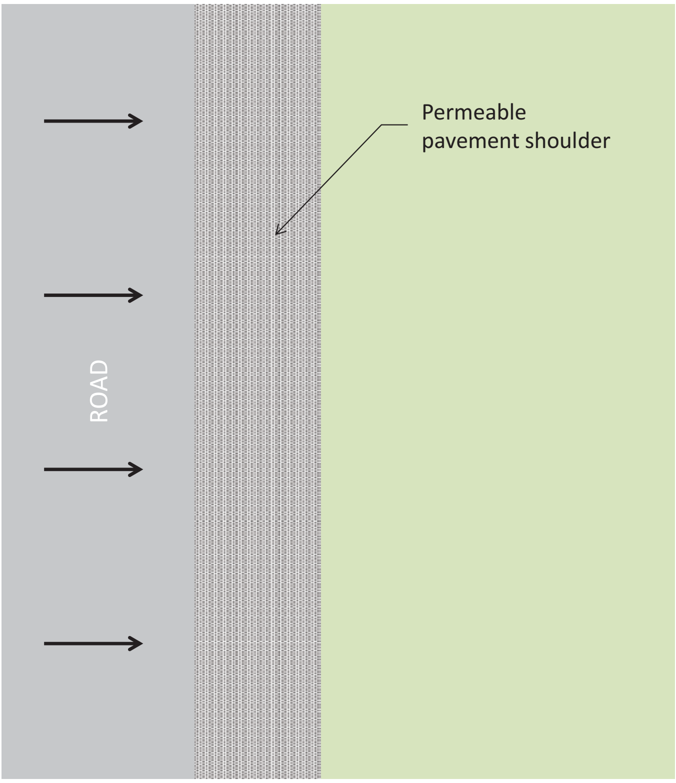


Figure 2. Plan view.

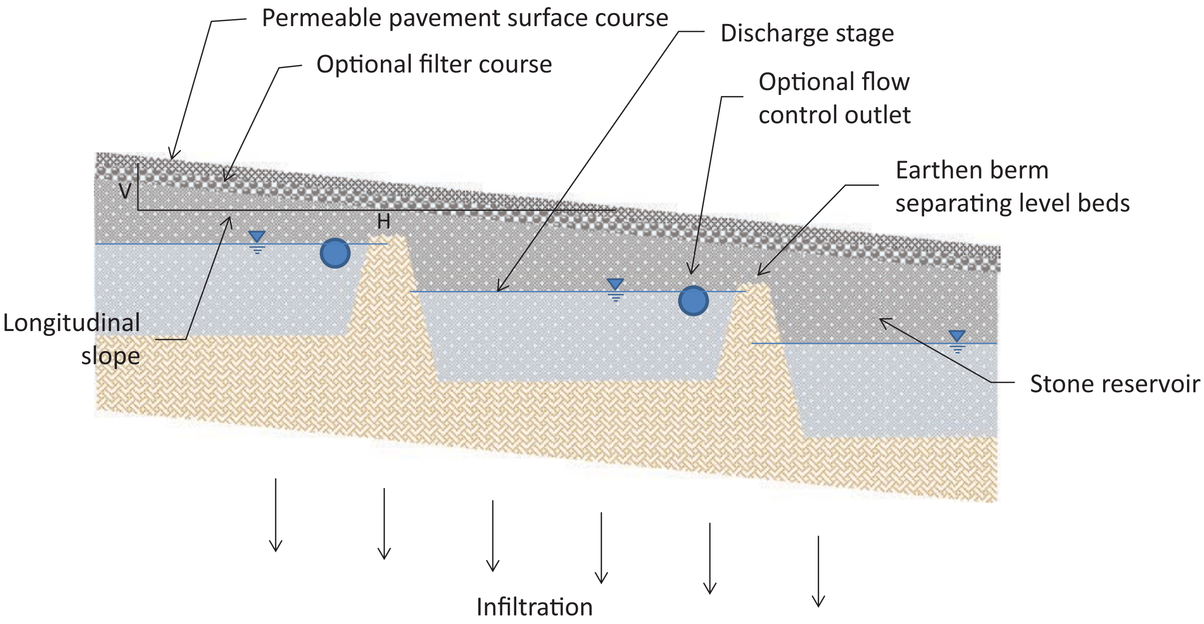


Figure 3. Longitudinal profile of an installation along a mild slope (earthen berms).

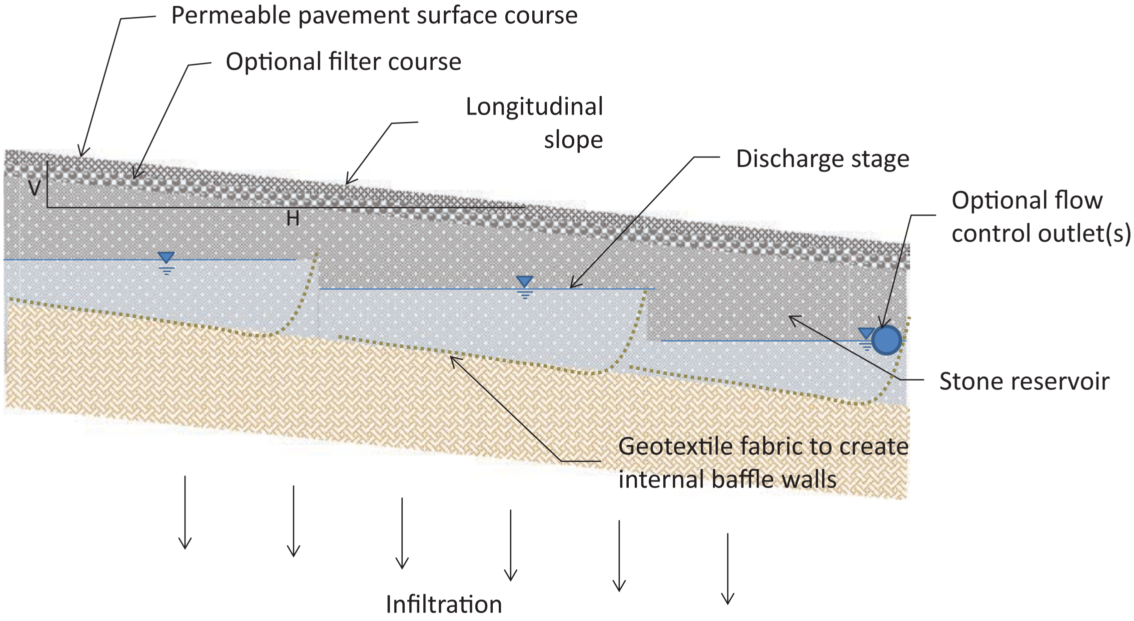
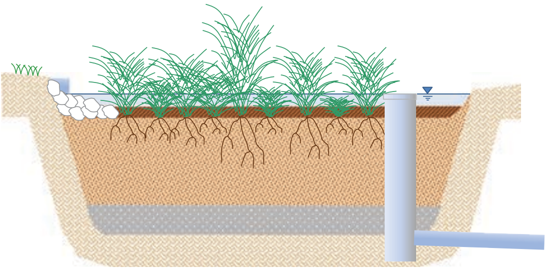


Figure 4. Longitudinal profile of an installation along a mild slope (geotextile cutoff walls).

Bioretention Without Underdrains VRA 05

Alternative names: *rain garden, bioretention, retention swale*



Credit: Geosyntec Consultants
Highway 99E Viaduct, Portland, OR.

VOLUME MANAGEMENT POTENTIAL/PROCESSES	
●	Overall volume reduction potential
◉	Evapotranspiration
●	Infiltration
○	Consumptive use
○	Base-flow–mimicking discharge

URBAN HIGHWAY APPLICABILITY	
●	Ground-level highways
●	Ground-level highways with restricted cross-sections
◉	Ground-level highways on steep transverse 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 are central to bioretention design and typically include a mixture of sand, soils, or 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 characteristic element of bioretention design and typically includes grasses, sedges, and small woody plants and shrubs. 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 depends on infiltration rates and storage capacity, with some losses to evapotranspiration.

Volume Reduction Processes and Performance Factors

Volume reduction in bioretention cells is achieved through infiltration and evapotranspiration. 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 evapotranspiration 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. Edmonston, Maryland, incorporated bioretention facilities were shown to successfully capture 1.33 in. of rainfall (90% of storm events) without overtopping (Low Impact Development Center, 2010) while 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 (Hunt et al., 2010). 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. MnDOT, 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 guardrails, are necessary.
- Terraced bioretention cells can be constructed in areas with steeper longitudinal slopes.
- 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 spaces) may result in premature clogging of the system.

Geotechnical Considerations

- Bioretention without underdrains is primarily an infiltration measure and, therefore, must be cited and designed accordingly. Wide medians, wide shoulders, and interchanges tend to provide the best opportunities for bioretention in the urban highway environment.

- Through the use of underdrains (see VRA 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 and therefore results in a relatively low risk of groundwater quality impacts from these constituents if separation to groundwater is observed.
- Like other infiltration VRAs, bioretention is not generally effective for controlling salts or viruses.
- Media with excessive compost 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 with natural conditions. If water balance issues would potentially result from an increase in groundwater recharge, this can be mitigated by including an underdrain to reduce the amount of infiltrated water (see VRA 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.

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 VRAs by use of overflow controls such as weirs.

VRA-Specific Maintenance Considerations *(see Section 4.3.6 for additional maintenance information in common with other VRAs)*

- Plant types and landscaping techniques may differ from traditional roadside vegetation, but do not require specialized equipment; mowing not appropriate.
- Facilities should be checked periodically for evidence of erosion or excess sediment deposition.
- Remediation of surface clogging may be needed if watershed sediment loading exceeds the assimilative capacity of the bioretention cell.

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 right-of-way, such as:

> *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 features such as a guardrail 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.

Additional Sources of Design Information

Low Impact Development Center, Inc. *Low Impact Development Manual for Southern California: Technical Guidance and Site Planning Strategies.* 2010. http://www.casqa.org/LID/SoCalLID/tabid/218/Default.aspx.

Low Impact Development Center, Inc. Bioretention Specification. 2003. http://www.lowimpactdevelopment.org/epa03/biospec.htm.

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Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 9: Bioretention v.1.9. 2011.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. https://fortress.wa.gov/ecy/publications/summarypages/1210030.html.

Photo credit: Philip Jones.

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 ft^2; potentially to 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 ft; 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 ft
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 ft
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 (unitless)
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

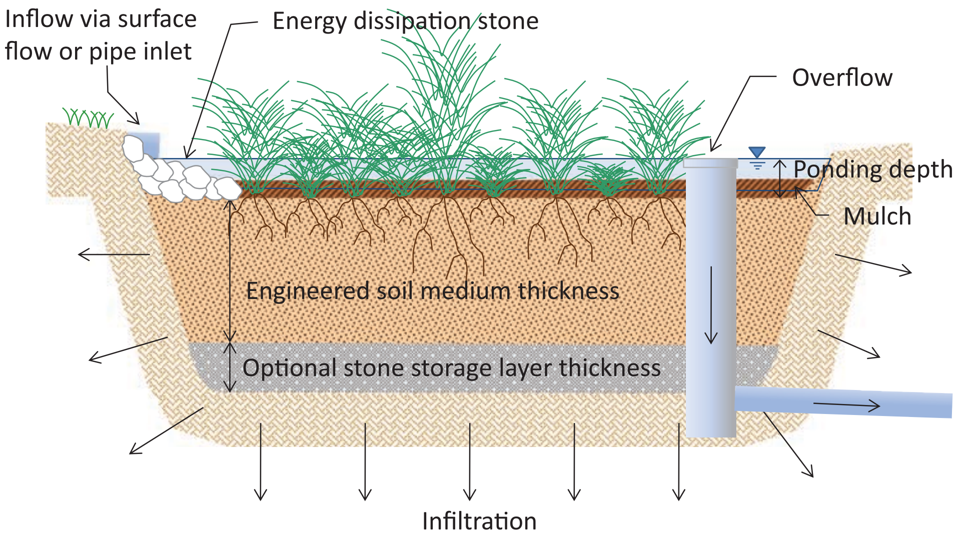


Figure 1. Cross-section view.

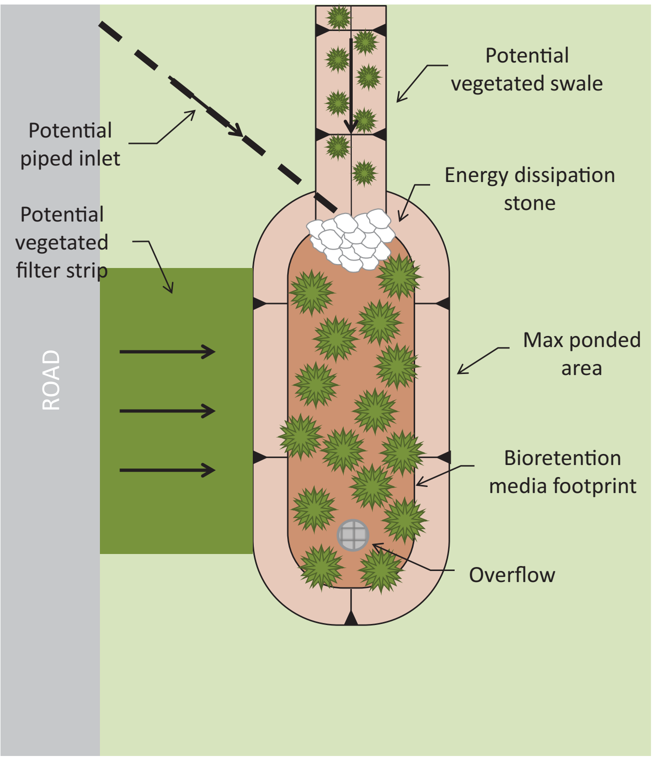


Figure 2. Plan view.

Bioretention with Underdrains

VRA 06

Alternative names: *bioretention, biofiltration, retention swale*

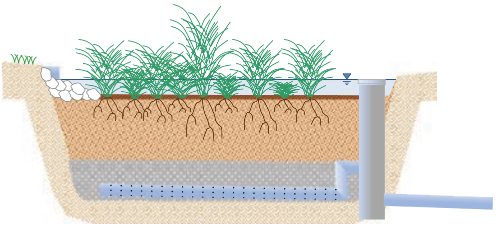


Photo credit: Geosyntec Consultants,
I-5 Exit 298, Portland, OR.

VOLUME REDUCTION PROCESSES	
●	Overall volume reduction potential
●	Infiltration
◉	Evapotranspiration
○	Consumptive use
◉	Base-flow–mimicking discharge

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

● High ◉ Moderate ○ Low

Description

Bioretention with underdrains consists of a shallow surface ponding area underlain by porous soil media storage reservoirs, an underdrain layer, and optional porous stone storage layers below the underdrain layer. 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. 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 VRA is suitable for a wider range of conditions than bioretention without an underdrain and can be used to mimic natural base flows. 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 base flow 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), evapotranspiration, and base-flow–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 evapotranspiration 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 VRA. 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 of 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 (Water Environment Research Foundation, 2011), even when underdrains were present.

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; therefore, bioretention tends to be more flexible to a wide variety of sites than many other VRAs.
- 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.
- 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, were 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.
- Irrigation is typically required for plant establishment.

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 that 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 VRAs by use of overflow controls such as weirs.

VRA-Specific Maintenance Considerations *(see Section 4.3.6 for additional maintenance information in common with other VRAs)*

- Plant types and landscaping techniques may differ from traditional roadside vegetation, but do not require specialized equipment; mowing is not appropriate.
- Facilities should be checked periodically for evidence of erosion or excess sediment deposition.
- Remediation of surface clogging may be needed if watershed sediment loading exceeds the assimilative capacity of the bioretention cell.
- In the event of decline in surface drainage, check underdrains for obstructions.

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 bioretention features.

Adaption to narrow spaces. Bioretention cell geometry is flexible and is easily adapted to the narrow spaces commonly available in the urban highway right-of-way. 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 VRAs/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 maximum 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 help improve the applicability and performance of these systems by making intelligent decisions about when and at what rate to release stored water based on storage conditions and forecasted rainfall.

Sources of Additional Information

Low Impact Development Center, Inc. Bioretention Specification. 2003. http://www.lowimpactdevelopment.org/epa03/biospec.htm.

Low Impact Development Center, Inc. *Low Impact Development Manual for Southern California: Technical Guidance and Site Planning Strategies.* 2010. http://www.casqa.org/LID/SoCalLID/tabid/218/Default.aspx.

North Carolina State University. Bioretention at North Carolina State University BAE. http://www.bae.ncsu.edu/topic/bioretention/index.html.

Prince Georges County Bioretention Manual. 2009. http://www.princegeorgescountymd.gov/Government/AgencyIndex/DER/ESG/Bioretention/pdf/Bioretention%20Manual_2009%20Version.pdf.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 9: Bioretention v.1.9. 2011. 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. 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 covered by the surface of the bioretention cell	Typically 100 to 2,000 ft^2; potentially to 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 ft; can 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 ft
Stone storage layer thickness	The thickness of the optional stone storage layer, if provided	Typically 0 to 2 ft
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 (unitless)

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 ft
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 benefit evaluation. This should be the rate of infiltration below the amended soil layer or stone reservoir.	Any; partial infiltration (upturned elbow design) can 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 ft 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 ft, accounting for porosity of stone below underdrain discharge stage

Example Conceptual Design Schematic

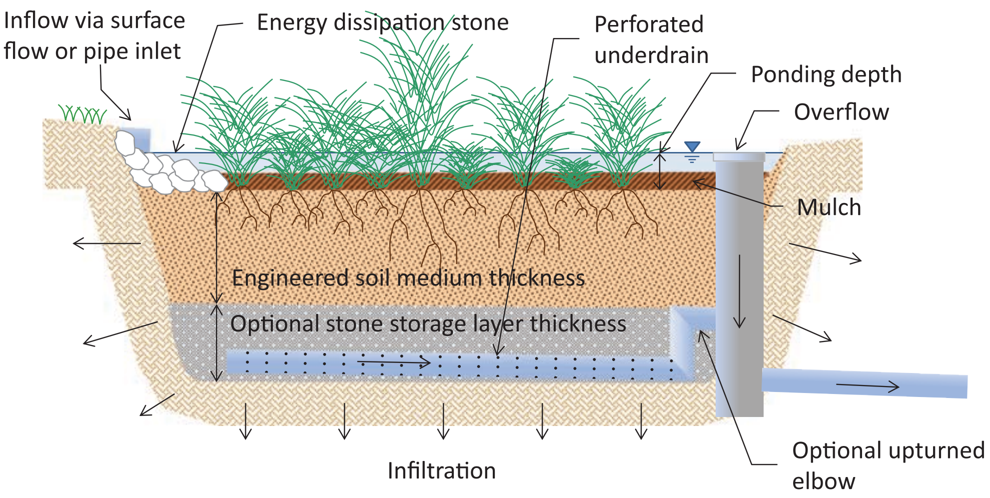


Figure 1. Cross-section view.

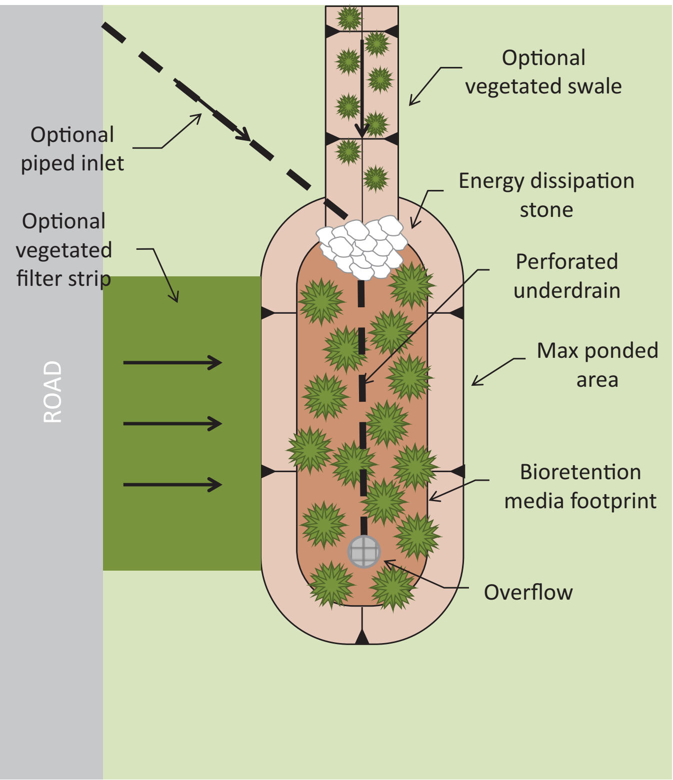
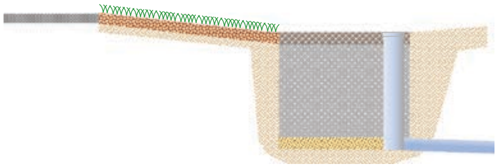


Figure 2. Plan view.

Infiltration Trench

VRA 07

Alternative names: *Exfiltration trench*



Source: Maryland SHA.

VOLUME REDUCTION PROCESSES	
●	Overall volume reduction potential
●	Infiltration
○	Evapotranspiration
○	Consumptive use
○	Base-flow–mimicking discharge

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

● High ◉ Moderate ○ Low

Description

This category of VRA 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 conveyances such as swales or filter strips. Infiltration trenches tend to be well suited to the linear highway environment as they are generally constructed in a linear configuration and their surface tends to be nearly flush to the 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.

Variation of infiltration trenches by including underdrains can provide additional volume reduction performance and operational flexibility in the form of base-flow–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 design storm used to size the features, volume reduction for infiltration trenches was 100%. The Virginia Department of Conservation and Recreation (2011) notes that when designs incorporate less pretreatment and involve soils with lower infiltration rates, volume reduction estimates should be reduced to 50%.

Proper design and maintenance of infiltration trenches is critical to their performance. The 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.

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

- 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 or to be adjusted to enhance treatment and prevent groundwater contamination.
- Use of infiltration trenches to provide more infiltration than was historically present or is 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 in. should be covered with traversable grates.

Regional Applicability

- Infiltration trenches have been applied successfully across a broad range of climates.

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 tight spaces common to urban highways. Pretreatment can be included with a 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 cost 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 since 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 the medium 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 a 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 VRAs/BMPs by the use of overflow controls such as weirs.

VRA-Specific Maintenance Considerations *(see Section 4.3.6 for additional maintenance information in common with other VRAs)*

- Infiltration trenches have been observed to have high potential for failure from clogging.
- Pretreatment swales or filter strips should be maintained per guidelines for those types of VRAs. Scour in pretreatment systems may exacerbate potential for clogging of trenches.
- Check trench periodically for evidence of clogging. If trench becomes clogged, stone may need to be replaced, and infiltrating surface may need to be restored via over-excavation or scarification.

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 basin can significantly improve system performance and reduce the potential for clogging.

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-in. layer of sand on the bottom of the trench will help to avoid compaction as the trench is filled with stone.

Sources of Additional Information

California Stormwater Quality Association. *California Stormwater BMP Handbook: New Development and Redevelopment.* TC-10, Infiltration Trench. 2003.

Lindsey, G., L. Roberts, and W. Page. Storm Water Management Infiltration. Maryland Department of the Environment, Sediment and Storm Water Administration. 1991.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 8: Infiltration Practices v.1.9. 2011. http://chesapeakestormwater.net/category/publications/design-specifications/.

Washington Department of Ecology. *Stormwater Manual for Western Washington*. BMP IN.03: Infiltration Trench. 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 covered by the surface of the infiltration trench	Typically 100 to 2,000 ft^2; can be any size with appropriate flow distribution
Stone storage layer thickness	The thickness of the stone storage layer	Typically 2 to 10 ft
Porosity	The effective void space of the stone storage layer	Typically 0.3 to 0.4 (unitless)

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 ft
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 benefit evaluation. This should be the rate of infiltration below the stone reservoir layer.	Typically require at least 0.3 to 0.5 in. per hour for sufficient drawdown of storage

Example Conceptual Design Schematic

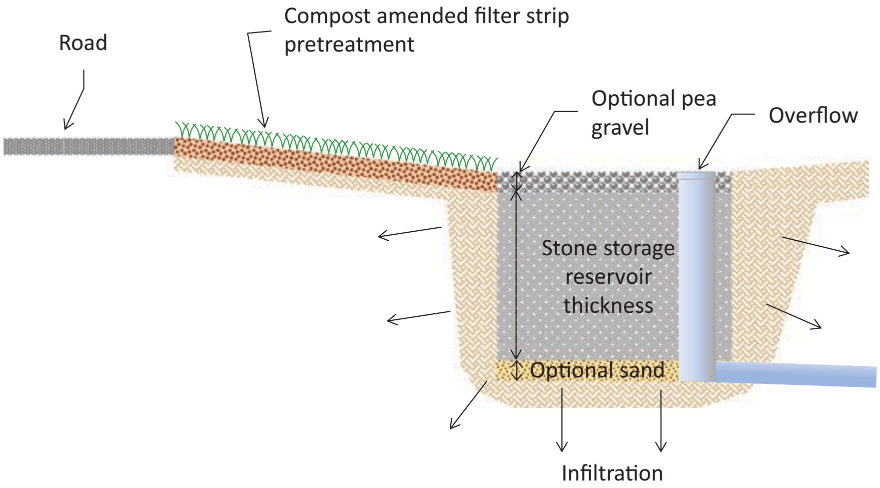


Figure 1. Cross-section view.

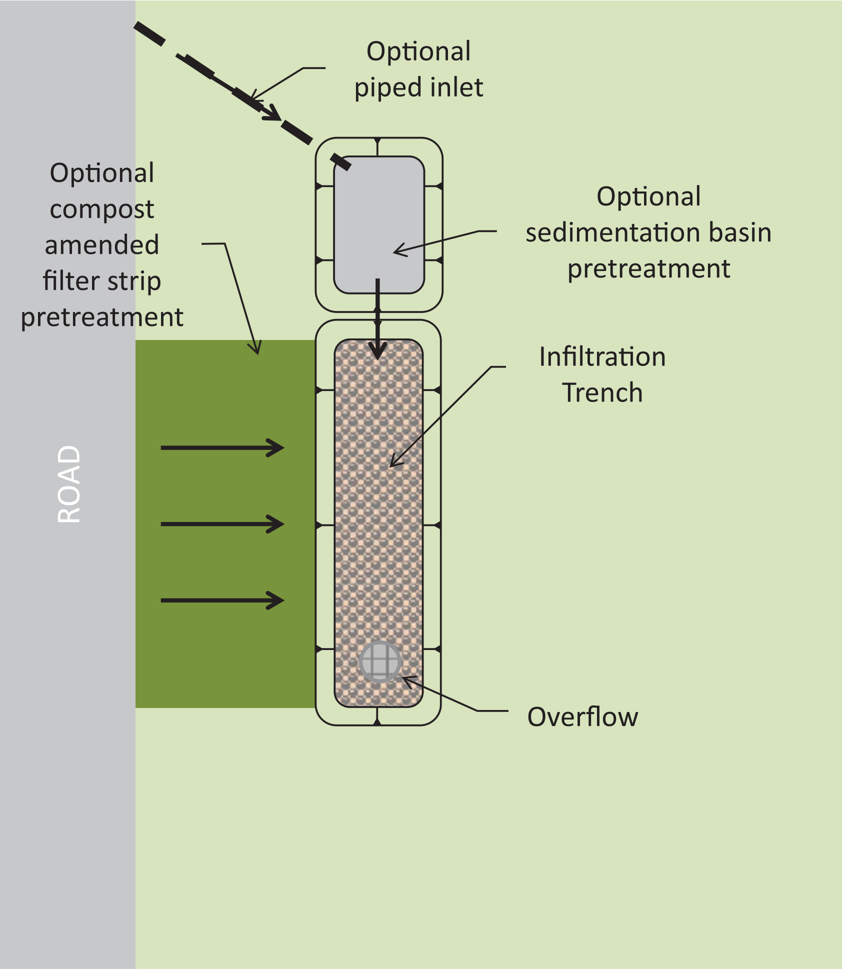
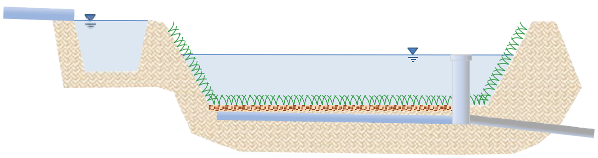


Figure 2. Plan view.

Infiltration Basin

VRA 08

***Alternative names:** percolation basin, recharge basin*



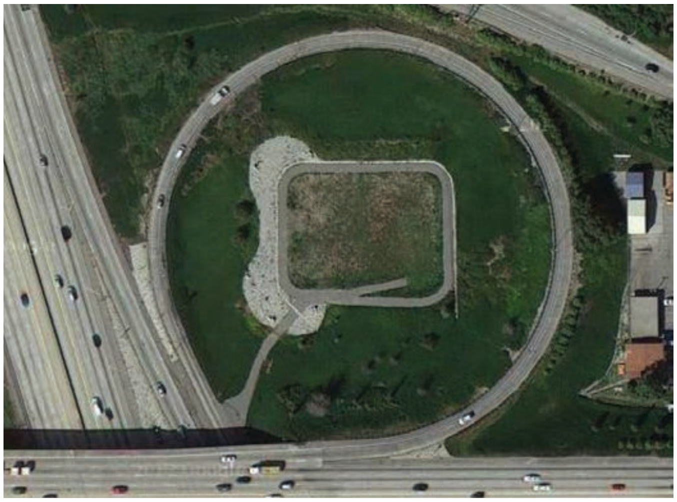


Photo credit: Google Earth.

VOLUME REDUCTION PROCESSES	
●	Overall volume reduction potential
●	Infiltration
◉	Evapotranspiration
○	Consumptive use
○	Base-flow–mimicking discharge

URBAN HIGHWAY APPLICABILITY	
◉	Ground-level highways
○	Ground-level highways with restricted cross-sections
○	Ground-level highways on steep transverse 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 generally have relatively little vegetation. Their contours appear similar to detention basins but 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 differentiated from bioretention basins because 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 evapotranspiration. 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 a vegetated conveyance or a sedimentation forebay. Additional mechanical pretreatment measures exist, including cartridge filtration or centrifugal separation where 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. One of the two basins monitored by Caltrans was observed to not be draining within the design maximum of 72 hours, most likely due to 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.

Geotechnical Considerations

- Infiltration basins must be located a sufficient distance from a roadway to maintain the roadway’s 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

- 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 was historically present or is 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 ft 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 VRA.

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 rights-of-way.

New Projects, Lane Additions, and Retrofits

- Because of their large footprint and setback requirements, infiltration basins are more easily considered for 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 the 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 will reduce required maintenance.
- Pretreatment can be provided as stormwater through a vegetated conveyance to the system, by the use of a sedimentation forebay, or by mechanical devices such as cartridge filtration.
- Stormwater runoff in excess of the infiltration basin's storage capacity can be conveyed to additional VRAs/BMPs by the use of overflow weirs.

VRA-Specific Maintenance Considerations *(see Section 4.3.6 for additional maintenance information in common with other VRAs)*

- Maintenance is generally similar to that of flood control or extended detention basins.
- Check periodically for excess sediment accumulation or scour.
- If vegetated, maintain vegetation to avoid line-of-site issues.
- Check periodically for signs of clogging; periodic maintenance such as tilling or scraping of the surface may be needed to restore surface infiltration rates.

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 it 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 help 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.

Sources of Additional Information

California Stormwater Quality Association. *California Stormwater BMP Handbook: New Development and Redevelopment.* TC-11, Infiltration Basin. 2003.

City of Portland, Oregon. St*ormwater Management Manual.* 2008. http://www.portlandonline.com/bes/index.cfm?c=47953&.

Virginia Department of Conservation and Recreation. Virginia DCR Stormwater Design Specification No. 8: Infiltration Practices v.1.9. 2011. http://chesapeakestormwater.net/category/publications/design-specifications/.

Washington Department of Transportation. *Highway Runoff Manual.* BMP IN.02: Infiltration Pond. 2011. 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 ft; 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 benefit evaluation	At least 0.5 in. per hour; higher infiltration rates needed for higher ponding depths

I-5 Exit 102, Tumwater, Washington. Source: Google Earth.

Example Conceptual Design Schematic

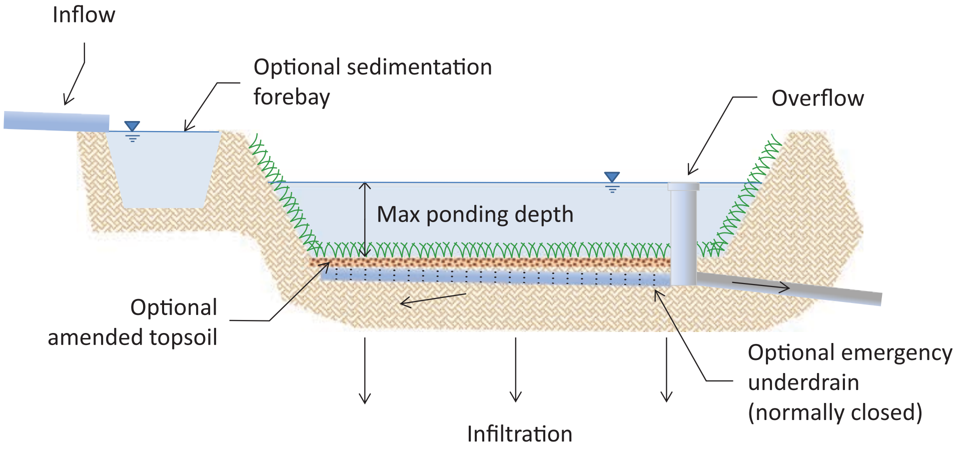


Figure 1. Cross-section view.

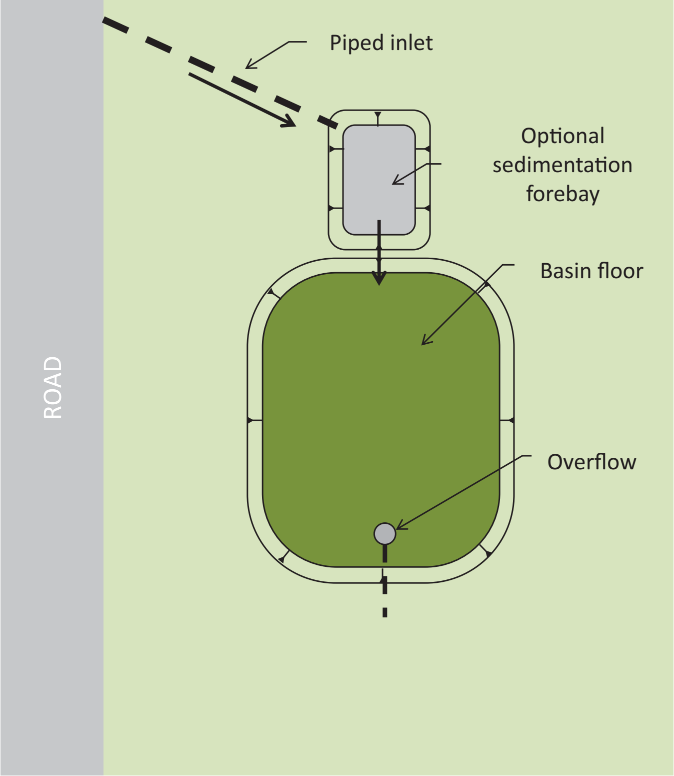


Figure 2. Plan view.

Underground Infiltration Systems VRA 09

Alternative names: *infiltration galleries, infiltration vaults*

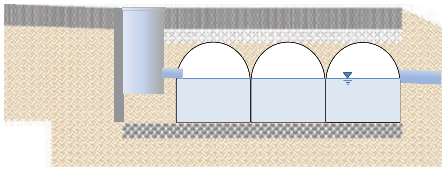


Photo credit: WSDOT.

VOLUME REDUCTION PROCESSES	
●	Overall volume reduction potential
●	Infiltration
○	Evapotranspiration
○	Consumptive use
○	Base-flow–mimicking discharge

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

● High ⦿ Moderate ○ Low

Description

Underground infiltration systems include a broad class of VRAs that consist of storage reservoirs located below ground and preceded by pretreatment systems. Water is pretreated, is 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 underground infiltration systems can be placed, including below parking areas, below access roads, and below travel lanes.

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 subsurface systems, long-term volume reduction is also a function of the level of pretreatment provided.

General DOT Experience

While case studies on the effectiveness of underground infiltration systems in the highway environment are currently limited, their use in some states, such as Minnesota, is increasing. Monitoring studies for several underground infiltration systems around St. Paul, Minnesota (Alms and Carlson, 2012) found that runoff volumes were reduced by 60% to 100% and often by above 90% (including snowmelt). An important point to note is that depending on design, there is a possibility that these facilities meet the U.S. EPA definition for class V injection wells (Minnesota DOT, 2012). It should be taken into account that without adequate pretreatment, underground injection systems have relatively high potential for groundwater contamination (Pitt et al., 1994). If properly designed, underground infiltration systems have the ability to reduce runoff volumes by 98%.

Applicability and Limitations

Site and Watershed Considerations

- Underground infiltration systems are suitable for sites with sufficiently permeable subsoils and where significant amounts of infiltration will not result in water balance or geotechnical issues.
- The subbase must be level for proper functioning and stability while still maintaining permeability. On sloped sites, underground infiltration systems can be constructed as a series of level benches.
- Underground infiltration systems can be used on road shoulders, on medians, and under roadways. They can be favorable in constrained areas where there is insufficient space for vegetated VRAs.

Geotechnical Considerations

- Where underground infiltration is used in areas that supports traffic (e.g., breakdown lanes, travel lanes, parking lots), the system and its associated subgrade preparation must be designed with adequate load-bearing capacity and must not cause 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

- In general, infiltration galleries represent a higher risk of groundwater contamination than do other VRAs, 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 underground systems allows negligible ET; therefore, the use of these systems has the potential to alter the water balance of a site compared to natural conditions (i.e., more infiltration).

Safety Considerations

- Underground infiltration systems 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

- Underground infiltration can be used across a wide range of climates.
- Underground systems will generally continue to function under normal freezing conditions.

New Projects, Lane Additions, and Retrofits

- Because underground infiltration systems are generally large and require significant grading, excavation, and geotechnical/structural requirements, they are more easily incorporated into new construction.
- Retrofit projects will likely incur significant costs since they would essentially contain many of the elements of new construction and additional removal of existing constraints.
- In both new and retrofit situations, designs of underground infiltration systems should take into careful consideration the U.S. 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 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 VRAs/BMPs if sufficient hydraulic grade lines exist or if pumps are included.

VRA-Specific Maintenance Considerations *(see Section 4.3.6 for additional maintenance information in common with other VRAs)*

- Underground vaults require periodic inspection to ensure continued performance.
- Confined-space entry permits may be required to inspect and maintain vaults.
- Accumulated sediment and debris must be regularly removed from pretreatment filters and settling vaults.
- Designs that provide access to the infiltrating surface (i.e., vaults rather than aggregate storage beds) may allow remediation of clogging without significant excavation and replacement costs.

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. Underground infiltration galleries may also pose the highest level of risk of groundwater contamination among stormwater VRAs. Pretreatment to remove sediments and particulate matter prior to it 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, and other advanced filtration systems should be considered.

Storage geometry. Dry wells can be considered as a variation of this VRA. They are typically deeper than wide, such that these systems tend to be deeper than typical infiltration galleries and infiltrate primarily from their walls instead of from their bottoms. 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 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 have a high degree of opportunity in the urban highway environment. This would essentially be a variation on permeable pavement but 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 to 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.

Sources of Additional Information

Massachusetts Highway Department. *The Mass Highway Stormwater Handbook for Highways and Bridges.* 2004.http://www.mhd.state.ma.us/downloads/projDev/2009/MHD_Stormwater_Handbook.pdf.

Washington Department of Transportation. *Highway Runoff Manual.* BMP IN.04: Infiltration Vault. 2011. 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 underground infiltration system	Any
Effective storage depth	The effective depth of water stored within the underground infiltration system. It is a function of the depth and porosity of the storage layer and/or dimensions of the chambered reservoir.	Typically 6 in. to more than 8 ft 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 benefit evaluation. This should be the rate of infiltration below the reservoir layer.	Typically requires at least 0.5 in. per hour
Filter course	A bed of sand or small stone placed at the bottom of the excavation in order to provide bedding and storage and to help reduce the need for compaction of the subsoil during construction.	6 to 12 in.

Example Conceptual Design Schematic

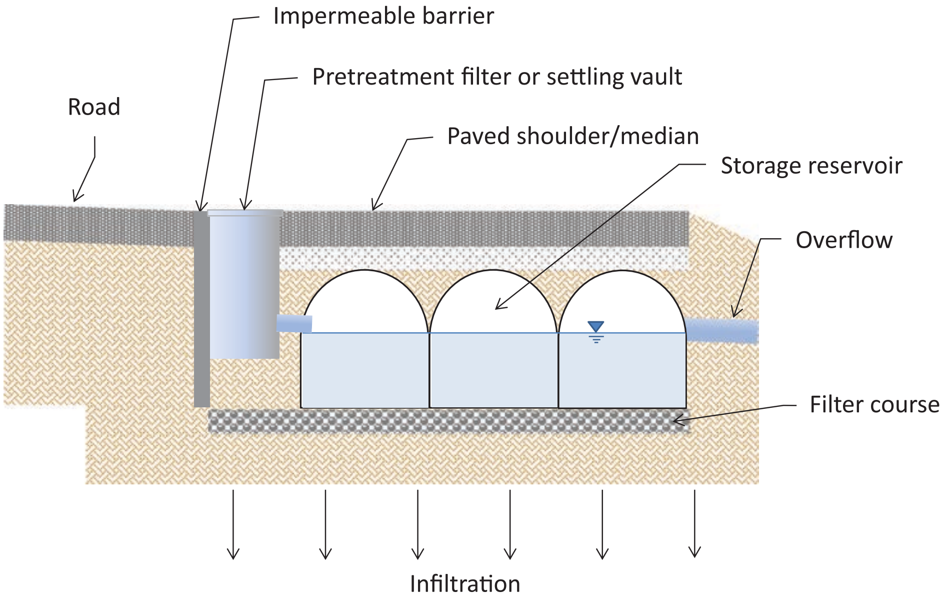


Figure 1. Cross-section view (example of arch gallery sited in breakdown lane).

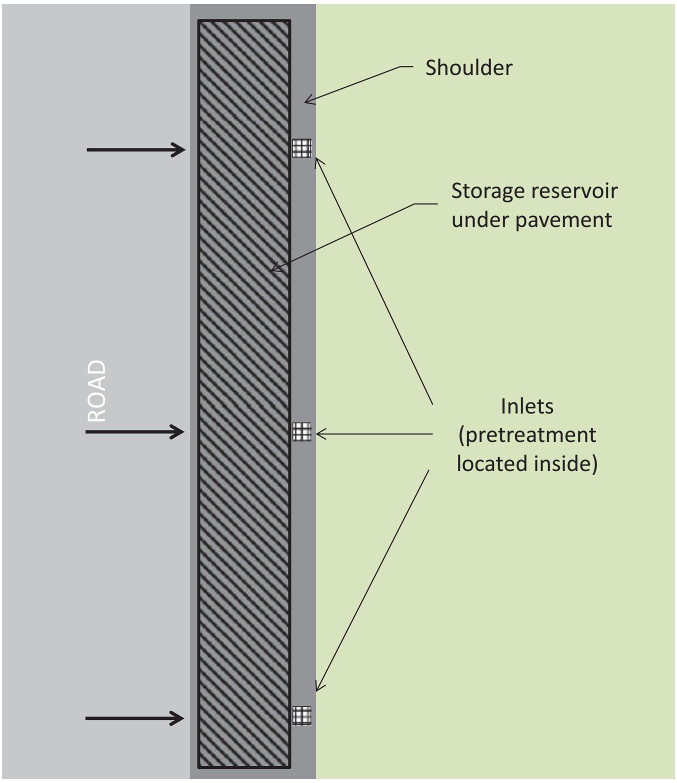


Figure 2. Plan view (example of siting in breakdown lane).

APPENDIX B

User's Guide for the Volume Performance Tool

1 Introduction and Purpose

The performance of volume reduction approaches (VRAs) is a function of many factors, including local climate and hydrology, storage volume, VRA design (i.e., footprint, depth, and discharge rates), and underlying soil properties. The purpose of the Volume Performance Tool is to assist in efficiently estimating the performance of volume reduction approaches and understanding the effects and sensitivity of local climate patterns, design attributes, and site conditions. The tool is a macro-enabled Excel spreadsheet application that calculates an estimate of long-term volume reduction based on user-provided location and planning-level project information. This tool is intended to allow DOT staff and contractors to quickly evaluate the relative benefits of various scenarios and assist in developing sizing criteria.

The purpose of this document is to guide users through the steps and inputs necessary to provide a reliable estimate of volume reduction through BMP treatment for site-specific project requirements. In addition, the steps required to perform a sensitivity analysis and interpret the results are outlined. Additional guidance is also provided within the tool itself in the form of a Readme page and Guidance and Default Values columns.

2 Intended Applications and Functionality

The tool is intended for planning-level analysis and conceptual design-level analysis of VRA designs. It is intended to assist in:

- Estimating the long-term volume reduction performance of VRAs,
- Understanding the effects and sensitivity of local climate patterns, design attributes, and site conditions on volume reduction performance, and
- Utilizing performance feedback to select VRAs and develop sizing and design criteria to be incorporated into a detailed design process.

The following general limitations are inherent in the architecture of the tool:

- Each instance of the tool can be used to analyze a single drainage area (watershed) within the project.
- Up to two VRAs in series (i.e., a treatment train) can be applied to the project drainage area.
- The tool is considered reliable for developing sizing criteria and design parameters (e.g., total storage needed, VRA footprint needed, and drawdown time). However, the tool does not simulate detailed hydraulics of the conveyance system or the VRA outlet structure; therefore, it should be coupled with design-level analysis methods as part of developing detailed project designs. For example, the tool can be used to set a drawdown goal of 12 hours for bioretention ponding storage, but more detailed hydraulic calculations would be needed as part of detailed design to set the orifice size or media specifications needed to achieve this drawdown time.
- The tool does not fully support VRA designs that are well outside of the typical range of VRA design parameters; in these cases, the tool will extrapolate results and may underestimate or overestimate performance. Notes appear in the tool in red text when normal operating bounds are exceeded.

Please review the Readme page for further discussion of limitations and intended uses.

3 General Use of Tool

3.1 System Requirements

- The tool is intended to run in Microsoft Excel 2010 or 2013; macros must be enabled for the tool to run properly. This can be adjusted in Excel settings or by clicking the message board to enable macros when the tool opens.
- Excel must be set to "Automatic" calculation mode rather than "Manual" calculation mode. This can be adjusted from the "Formula" ribbon by selecting "Calculation Options."
- The tool has been tested in a Windows 7 environment; user experience may differ in other operating system environments.
- Each instance of the tool requires approximately 20 MB of storage space.
- The tool involves no traditional installation, and therefore should generally not require administrator privileges to use. For users operating within strict security settings, administrator privileges may be required to enable macros within Excel.

3.2 Preparing the Tool for Use

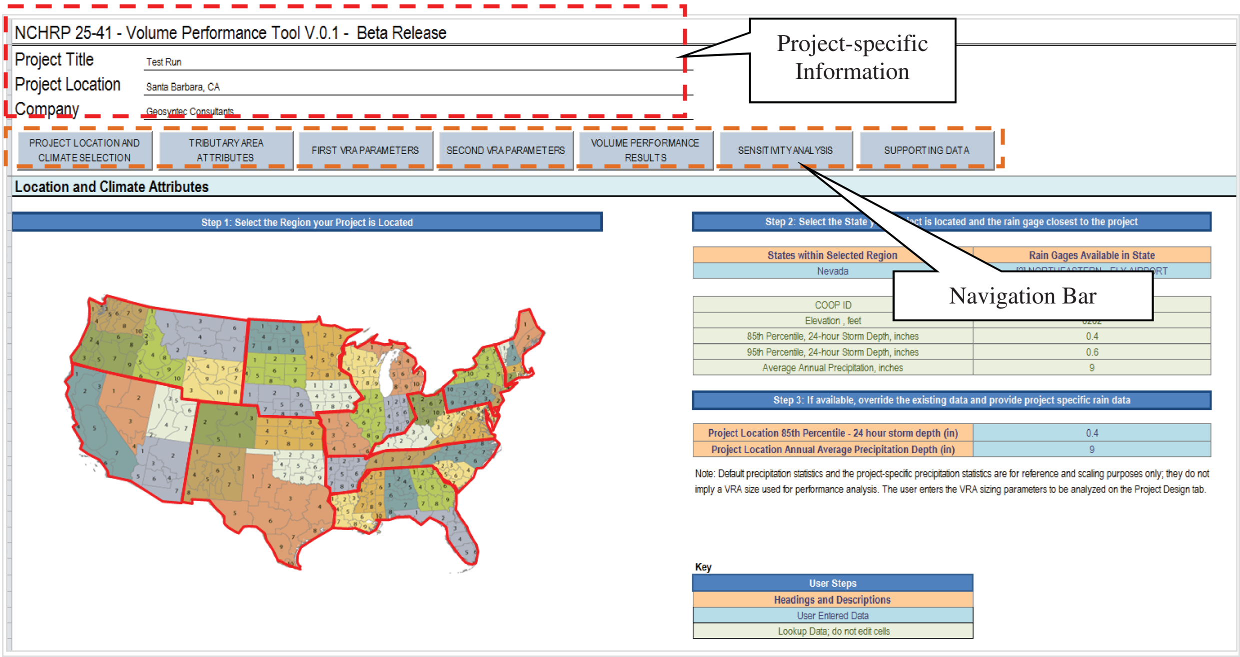
To save the tool files on your computer and prepare them for use, follow these steps:

1. Load the tool by accessing the CD-ROM that accompanies this manual (or the ISO image available for download from the project website) and following the commands within the installation dialogue boxes. The tool may be saved to the directory of the user's choice (local machine or network).
2. The tool consists of one single macro-enabled spreadsheet (.xlsm) that is ready to use once it is installed (i.e., saved) on the directory of user's choice.
3. The original .xlsm tool file is read-only; therefore, each instance of the tool must be saved as a new file name, as discussed in the following section.

3.3 Starting a New Project

To start a new project, follow these steps:

1. Open the original tool spreadsheet by double-clicking the .xlsm file.
2. When the tool opens, it is necessary to enable macros. The process of enabling macros varies depending on local security settings in place. If macros are not enabled, the user should consult Excel support for guidance in enabling macros.
3. Save the project to a directory of the user's choice by using the "Save As" command in Excel. The file must be saved as a macro-enabled workbook (.xlsm) file.
4. The tool will open to the Project Location worksheet. The header provides space to enter project information (see Figure 1).
5. Once the project information is entered into the heading of the Project Location worksheet, the remaining headings on subsequent worksheets will be updated to match.
6. These steps can be followed for each project/scenario being analyzed with the tool.



NCHRP 25-41 - Volume Performance Tool V.0.1 - Beta Release

Project Title Test Run

Project Location Santa Barbara, CA

Company Geosyntec Consultants

Project-specific Information

Navigation Bar

Location and Climate Attributes

Step 1: Select the Region your Project is Located

Step 2: Select the State y… …ect is located and the rain gage closest to the project

States within Selected Region	Rain Gages Available in State
Nevada	[2] NORTHEASTERN - ELY AIRPORT

COOP ID	
Elevation , feet	
85th Percentile, 24-hour Storm Depth, inches	0.4
95th Percentile, 24-hour Storm Depth, inches	0.6
Average Annual Precipitation, inches	9

Step 3: If available, override the existing data and provide project specific rain data

Project Location 85th Percentile - 24 hour storm depth (in)	0.4
Project Location Annual Average Precipitation Depth (in)	9

Note: Default precipitation statistics and the project-specific precipitation statistics are for reference and scaling purposes only; they do not imply a VRA size used for performance analysis. The user enters the VRA sizing parameters to be analyzed on the Project Design tab.

Key

User Steps
Headings and Descriptions
User Entered Data
Lookup Data; do not edit cells

Figure 1. Project information and navigation bar.

3.4 Organization of the Tool

The tool is divided into various input forms that reside on separate worksheets. In some cases, multiple input forms are found on a single worksheet. Table 1 summarizes the organization of the tool.

Each input form contains stepwise instructions and a key to the color of cells that appear in the form. Color coding identifies cells as:

- User Steps (i.e., instructions)
- Headings and Descriptions
- User-Entered Data
- Default Data (editing allowed with rationale)
- Lookup Reference and Calculation Values (not editable)
- Guidance
- Warnings

The user is expected to enter data for each "User-Entered Data" cell at a minimum and should review the default and reference values to verify that they are appropriate. Inputs are intended to be populated sequentially (e.g., Project Location, Project Design—VRA 01, then Project Design—VRA 02). Inputs on previous tabs can later be modified by skipping backward and forward; however, skipping forward as part of the initial tool parameterization will result in an undesirable user experience and potential for calculation errors.

Table 1. Organization of the tool.

Input Form	Worksheet Name	Summary of User Inputs and Results
Project Location and Climate Selection	Project Location	Specify project location View default climate parameters Override default climate parameters as needed
Tributary Area Attributes	Project Design	Specify tributary area characteristics View reference information related to precipitation and runoff volumes
First VRA Parameters	Project Design	Select first VRA type Specify primary VRA design parameters View and edit default and additional design parameters Specify whether the VRA discharges to a second VRA
Second VRA Parameters (optional)	Project Design	Select second VRA type Specify primary VRA design parameters View and edit default and additional design parameters
Volume Performance Results	Volume Performance Results	View summary of performance results in tabular and graphical format
Sensitivity Analysis	Sensitivity Analysis	Specify sensitivity scenarios by selecting sensitivity bounds and identifying sensitivity parameters Run analysis and view sensitivity results
Supporting Data	Supporting Data	View underlying model results data used by the tool to provide performance estimates

3.5 Navigating Within the Tool

The tool provides two options for navigation:

- The navigation bar that is located below the project information on every page (see Figure 1) provides hyperlinks to jump to each input form. These buttons can be clicked to move forward or backward to each input form.
- Traditional Excel navigation methods can also be used, including selecting worksheet tabs, scrolling, and zooming, as the user prefers.

Either of these methods can be used, interchangeably, at any point in use of the tool.

3.6 Saving and Editing Scenarios

Each instance of the tool (i.e., each individual .xlsm file) represents a single scenario. Multiple scenarios can be run using the following general steps:

1. Open a new instance of the tool.
2. Enter inputs to define the first scenario.
3. Save this scenario with a distinct file name (e.g., "File" ➔ "Save As" ➔ "VolumeTool_ScenarioA1 .xlsm").
4. Edit inputs to define a new scenario.
5. Save this scenario with a distinct file name (e.g., "File" ➔ "Save As" ➔ "VolumeTool_ScenarioA2 .xlsm").

Repeat for as many scenarios as desired. Files can be organized into directories to help distinguish different analysis scenarios. After scenarios are generated, any of the instances of the tool can be reopened by double-clicking on the selected .xlsm file to view the scenario inputs and results.

3.7 Printing Summary Results

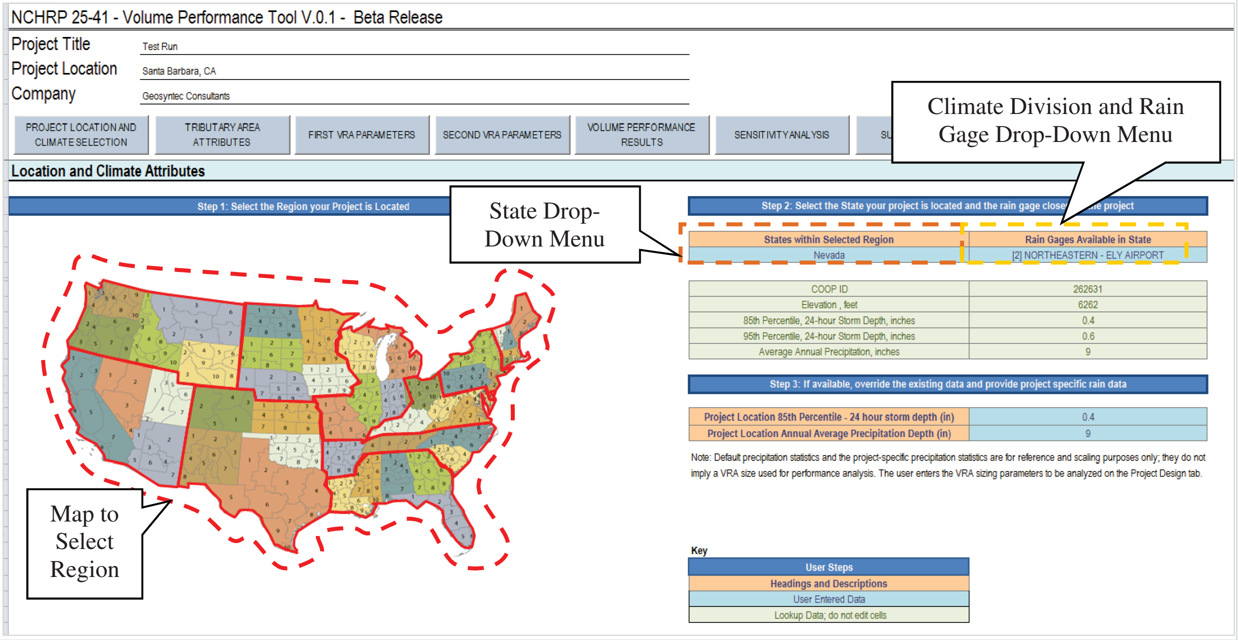
Any sheet within the worksheet can be printed using native Excel print functions. The user can use Excel menus to specify the paper size, printer preferences, and print ranges. By selecting multiple worksheet tables, multiple worksheets can be printed at the same time. Please consult Excel documentation and help files for guidance on printing from Excel.

4 Entering Project Location and Climate Information

4.1 Selecting a Rain Gage

The first step in developing a project scenario is to select the appropriate precipitation gage for your project (see Figure 2):

1. Select your project's region by clicking on the map.
2. Select your project's state by using the drop-down menu under "States within Selected Region."
3. Select the precipitation gage that best represents the project precipitation by using the drop-down menu under "Rain Gages Available in State." Generally, the precipitation gage closest to the project location should be used. Each precipitation gage has associated ET data as well.



NCHRP 25-41 - Volume Performance Tool V.0.1 - Beta Release

Project Title: Test Run
Project Location: Santa Barbara, CA
Company: Geosyntec Consultants

Location and Climate Attributes

Step 1: Select the Region your Project is Located

Map to Select Region

State Drop-Down Menu

Climate Division and Rain Gage Drop-Down Menu

Step 2: Select the State your project is located and the rain gage close e project

States within Selected Region	Rain Gages Available in State
Nevada	[2] NORTHEASTERN - ELY AIRPORT

COOP ID	262631
Elevation , feet	6262
85th Percentile, 24-hour Storm Depth, inches	0.4
95th Percentile, 24-hour Storm Depth, inches	0.6
Average Annual Precipitation, inches	9

Step 3: If available, override the existing data and provide project specific rain data

Project Location 85th Percentile - 24 hour storm depth (in)	0.4
Project Location Annual Average Precipitation Depth (in)	9

Note: Default precipitation statistics and the project-specific precipitation statistics are for reference and scaling purposes only; they do not imply a VRA size used for performance analysis. The user enters the VRA sizing parameters to be analyzed on the Project Design tab.

Key

Key
User Steps
Headings and Descriptions
User Entered Data
Lookup Data; do not edit cells

Figure 2. Project location and climate selection layout.

4.2 Providing Site-Specific Precipitation Statistics

When a gage is selected, the tool provides a number of reference statistics related to the gage, including the 85th- and 95th-percentile, 24-hour storm depths and the average annual precipitation depth.

If more accurate precipitation statistics are available for the project location, these data can be used to improve the estimates provided by the tool. The tool uses the 85th-percentile, 24-hour storm depth and the average annual precipitation depth to localize model estimates. To enter site-specific precipitation statistics, overwrite the "Project Location" values as called out in Figure 3. If a new gage is selected, user-entered numbers will be overwritten and must be entered again if still applicable.

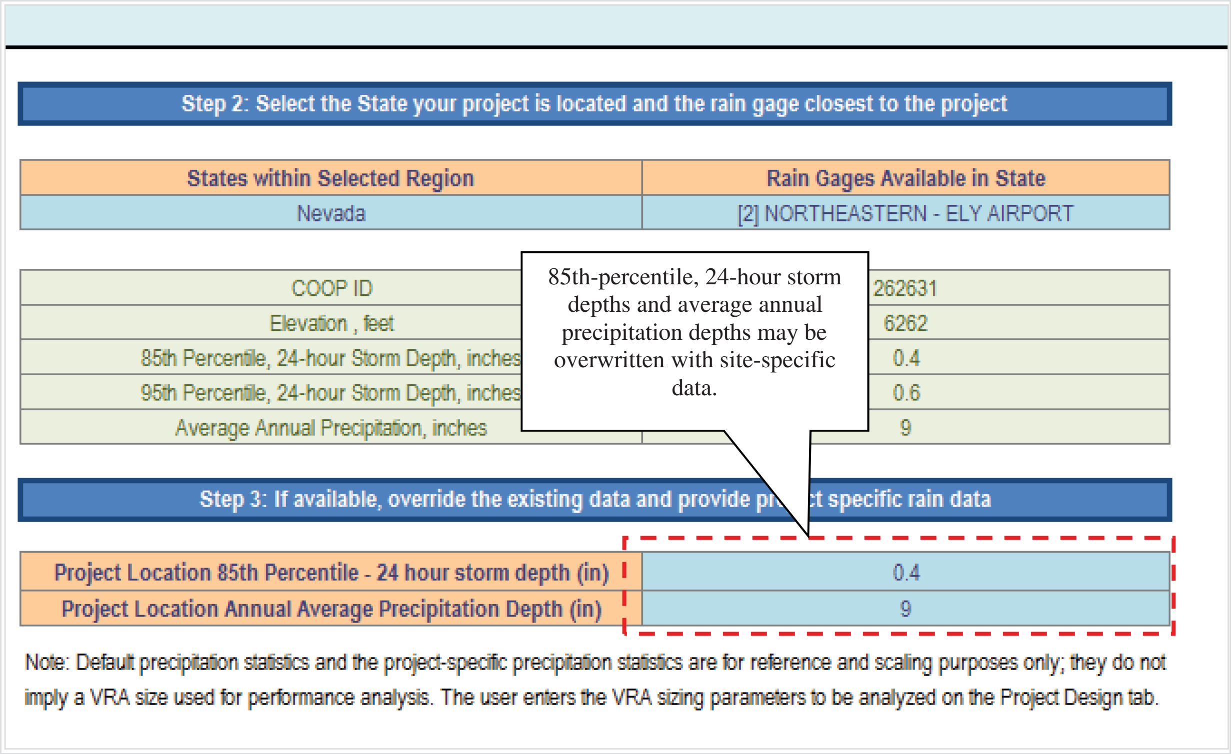
Note that default and project-specific precipitation statistics are for reference and scaling purposes only; they do not imply a VRA size used for performance analysis. The user enters the VRA sizing parameters to be analyzed on the Project Design worksheet.

5 Entering Project Design Information

5.1 Entering Tributary Area Attributes

To determine the quantity of runoff that will drain to the VRAs in the design scenario, it is necessary to provide certain inputs regarding the tributary area watershed. Follow these steps to provide the necessary tributary area information (see Figure 4):

1. Enter the tributary area (in acres) that represents the entire area that will drain to your VRA. Except in the case of permeable pavement, the tributary area should exclude the VRA area itself. In the case of permeable pavement, the VRA should be counted as part of the tributary area with an imperviousness of 100%.
2. Enter the estimate of percent of the tributary area that is impervious (ranging from 0% to 100%), which determines the relationship between impervious and pervious area and whether the rainfall will infiltrate or run off. Permeable pavement area should be entered as 100% impervious in this input to represent the fact that all rainfall on permeable pavement enters the pavement storage reservoir (similar to runoff from 100% impervious area).



Step 2: Select the State your project is located and the rain gage closest to the project

States within Selected Region	Rain Gages Available in State
Nevada	[2] NORTHEASTERN - ELY AIRPORT

COOP ID	262631
Elevation , feet	6262
85th Percentile, 24-hour Storm Depth, inches	0.4
95th Percentile, 24-hour Storm Depth, inches	0.6
Average Annual Precipitation, inches	9

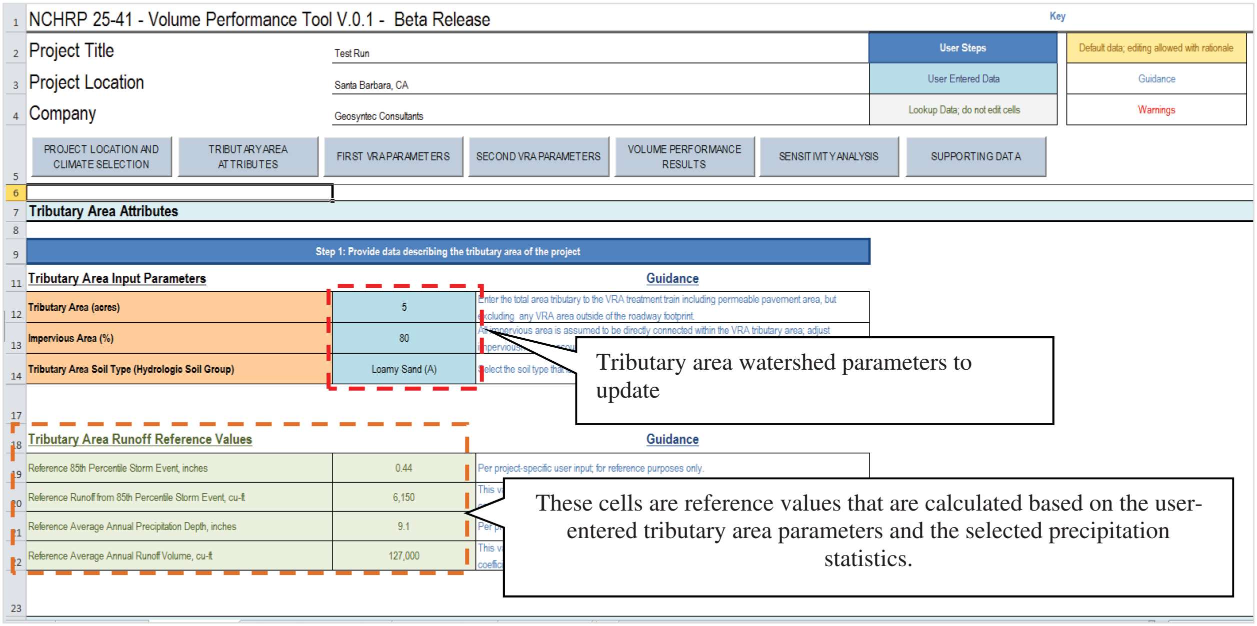
85th-percentile, 24-hour storm depths and average annual precipitation depths may be overwritten with site-specific data.

Step 3: If available, override the existing data and provide project specific rain data

Project Location 85th Percentile - 24 hour storm depth (in)	0.4
Project Location Annual Average Precipitation Depth (in)	9

Note: Default precipitation statistics and the project-specific precipitation statistics are for reference and scaling purposes only; they do not imply a VRA size used for performance analysis. The user enters the VRA sizing parameters to be analyzed on the Project Design tab.

Figure 3. Site-specific precipitation data.



NCHRP 25-41 - Volume Performance Tool V.0.1 - Beta Release

Project Title	Test Run
Project Location	Santa Barbara, CA
Company	Geosyntec Consultants

Key

User Steps	Default data; editing allowed with rationale
User Entered Data	Guidance
Lookup Data; do not edit cells	Warnings

Tributary Area Attributes

Step 1: Provide data describing the tributary area of the project

Tributary Area Input Parameters		Guidance
Tributary Area (acres)	5	Enter the total area tributary to the VRA treatment train including permeable pavement area, but excluding any VRA area outside of the roadway footprint.
Impervious Area (%)	80	All impervious area is assumed to be directly connected within the VRA tributary area; adjust impervious
Tributary Area Soil Type (Hydrologic Soil Group)	Loamy Sand (A)	Select the soil type that

Tributary area watershed parameters to update

Tributary Area Runoff Reference Values		Guidance
Reference 85th Percentile Storm Event, inches	0.44	Per project-specific user input; for reference purposes only.
Reference Runoff from 85th Percentile Storm Event, cu-ft	6,150	This v
Reference Average Annual Precipitation Depth, inches	9.1	Per p
Reference Average Annual Runoff Volume, cu-ft	127,000	This v coeffic

These cells are reference values that are calculated based on the user-entered tributary area parameters and the selected precipitation statistics.

Figure 4. Tributary area attributes layout.

3. Select a tributary area soil type from the drop-down menu provided. These soil types have been chosen to represent the typical hydrologic soil groups (A through D). The soil type selected here should be representative of the soil beneath the tributary area. When this soil type is selected, a representative infiltration rate (based on the literature) is also copied into the "underlying soil infiltration rate" input for your VRAs. However, note that the soil type may vary between the tributary area and the VRA area, and the infiltration rate should be updated to reflect a value that is appropriate within the VRA area. This may occur when different soils are present within the VRA area than the overall tributary area or when better VRA area infiltration rate data are available, such as that obtained from field testing. It is strongly recommended that default infiltration rate values be updated with site-specific information whenever available.
4. Review the default long-term runoff coefficient and enter a user-provided long-term runoff coefficient, if desired.

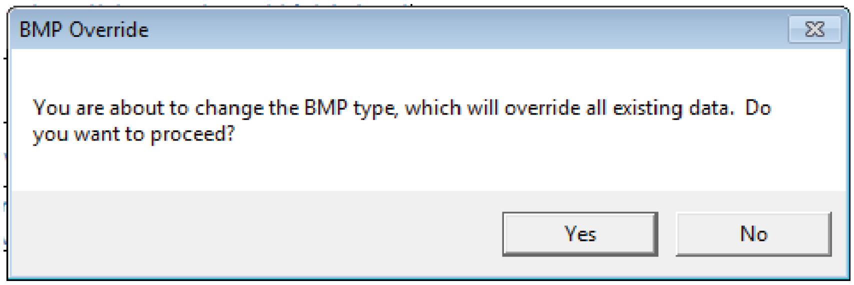
Several tributary area runoff reference values are reported below the user inputs. These are for reference purposes only and are not to be confused with VRA design inputs, which are entered in the next section.

5.2 Selecting VRAs and Entering VRA Design Parameters

5.2.1 Entering First VRA Input Parameters

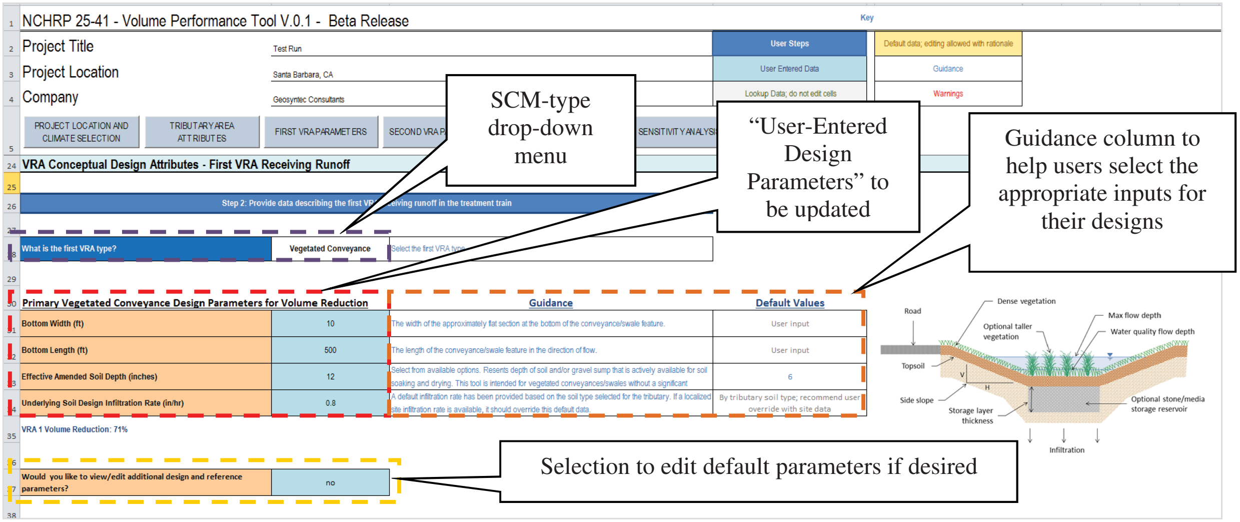
To begin providing the inputs for your first VRA, follow these steps (see Figure 6):

1. In the "What is the first VRA type?" input, select the type of VRA that will be the first (and potentially only) VRA receiving runoff.
2. Once the type of VRA is selected, the "BMP Override" message (Figure 5) will display to remind you that you are selecting a new VRA and that it will override the existing design parameters that have been selected. If you are ready to start over or change your design, click "yes." If you want to keep your original VRA, click "no."
3. After the type of VRA is selected, the design parameters will need to be inputted. The blue cells are project-specific and should be updated. The yellow cells also may be project-specific; however, default values have been provided for these parameters. If the default values do not represent the project design, then they may be overwritten.
4. In addition to the "Primary Design Parameters," some VRAs will also have additional parameters, which are either additional input values or reference calculations (e.g., calculated drawdown time). To view and edit these parameters, select "yes" in the field entitled "Would you like to view/edit additional design and reference parameters?" Default parameters are provided for these parameters; however, these should be reviewed and adjusted, as needed, to match actual project design configurations to provide the most accurate results.
5. If there is only one VRA in your design, proceed to the volume performance results after all the parameters have been updated by clicking the "Volume Performance Results" button or



You are about to change the BMP type, which will override all existing data. Do you want to proceed?

Figure 5. VRA selection message box.



NCHRP 25-41 - Volume Performance Tool V.0.1 - Beta Release

Project Title: Test Run

Project Location: Santa Barbara, CA

Company: Geosyntec Consultants

Key	
User Steps	Default data; editing allowed with rationale
User Entered Data	Guidance
Lookup Data; do not edit cells	Warnings

VRA Conceptual Design Attributes - First VRA Receiving Runoff

Step 2: Provide data describing the first VR… …eiving runoff in the treatment train

What is the first VRA type? Vegetated Conveyance — Select the first VRA type

Primary Vegetated Conveyance Design Parameters for Volume Reduction		Guidance	Default Values
Bottom Width (ft)	10	The width of the approximately flat section at the bottom of the conveyance/swale feature.	User input
Bottom Length (ft)	500	The length of the conveyance/swale feature in the direction of flow.	User input
Effective Amended Soil Depth (inches)	12	Select from available options. Resents depth of soil and/or gravel sump that is actively available for soil soaking and drying. This tool is intended for vegetated conveyances/swales without a significant	6
Underlying Soil Design Infiltration Rate (in/hr)	0.8	A default infiltration rate has been provided based on the soil type selected for the tributary. If a localized site infiltration rate is available, it should override this default data.	By tributary soil type; recommend user override with site data

VRA 1 Volume Reduction: 71%

Would you like to view/edit additional design and reference parameters? no

Figure 6. First VRA parameters input form layout.

worksheet tab. However, if there is a second VRA in your design, refer to the following section for guidance.

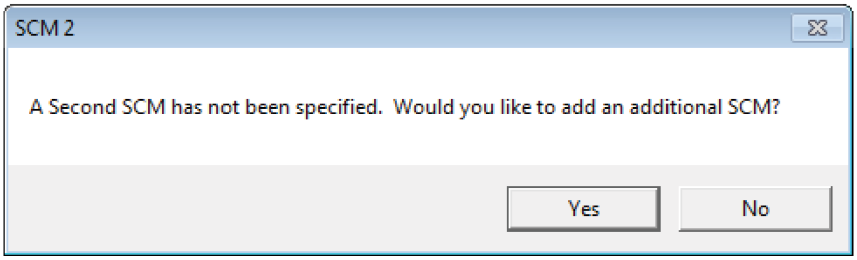
Note: Guidance regarding the individual VRA parameters is not provided in this user's manual. Please refer to the "Guidance" and "Default Value" columns located within the tool that provide guidance for each parameter specific to the VRA selected. Additionally, refer to VRA fact sheets in Appendix A for more information on VRAs and typical ranges of design parameters.

5.2.2 Selecting Two VRAs in a Treatment Train

If there are two VRAs as a treatment train in your design, follow these steps:

1. Select "yes" from the field asking "Is there a second VRA in the treatment train?" or click on the "Second VRA Parameters" button and click "yes" in the window that pops up to confirm that you want to add a second VRA to your design (Figure 7).
2. Selecting "yes" will load the "User-Entered Design Parameters" for the second VRA. Follow the previous steps outlined for the first VRA (Section 5.2.1) to fill in parameters.
3. After all of the parameters are entered for the second VRA, proceed to the volume performance results to evaluate the performance of the design.

Note that volume reduction estimates are provided below the primary design parameters in the "First VRA Parameters" and "Second VRA Parameters" sections for reference. These results are intended to help facilitate rapid evaluation of multiple scenarios.



SCM 2

A Second SCM has not been specified. Would you like to add an additional SCM?

Figure 7. Second VRA message box.

6 Viewing and Interpreting Volume Performance Results

6.1 Viewing Volume Performance Results

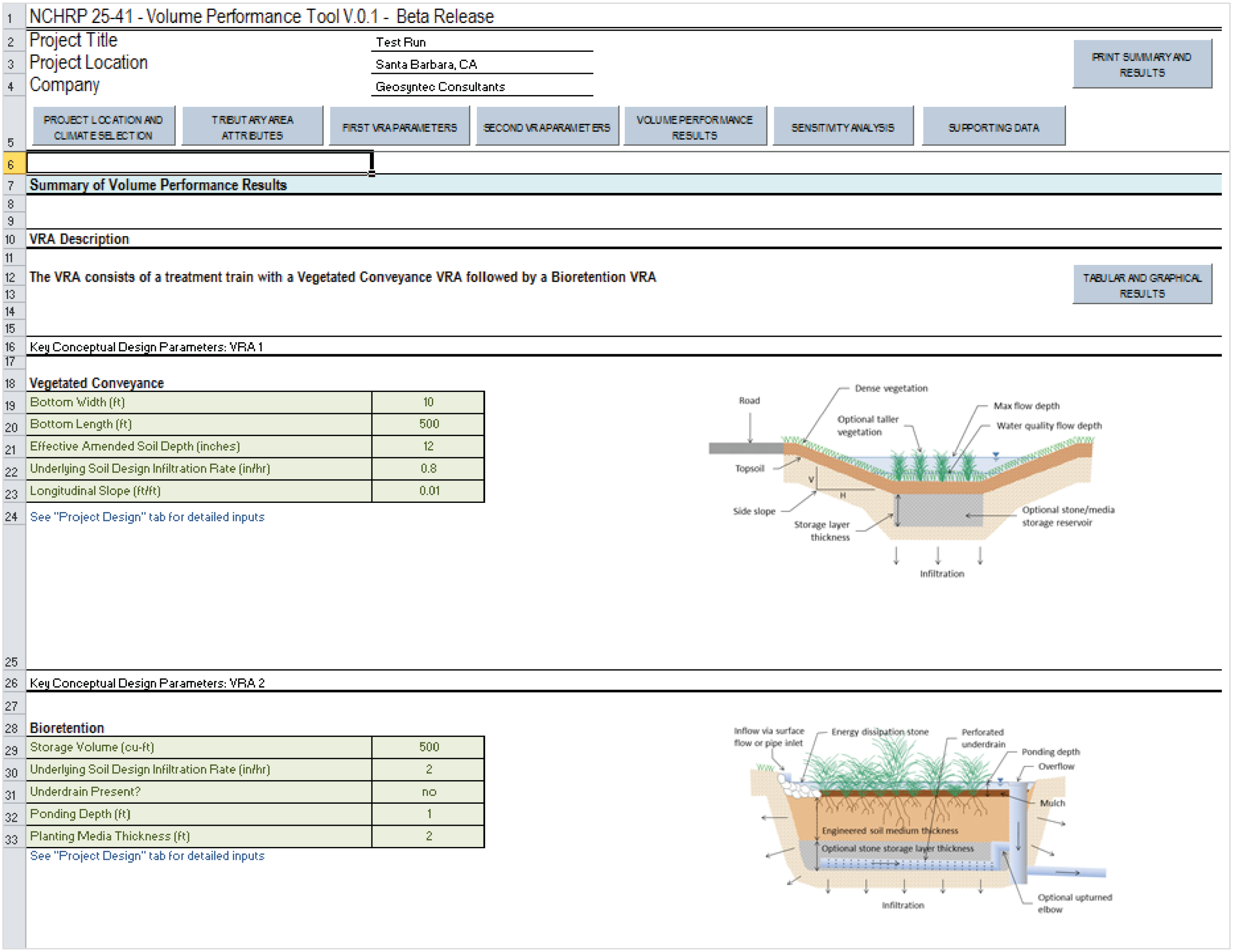
The Volume Performance Results worksheet is updated based on the scenario that has been inputted in previous forms. It is designed to be printed on a single page to document key inputs as well as results. The Volume Performance Results page consists of the following two sections:

1. A summary of your design, and
2. A tabular and graphical volume performance summary for your design.

The first part of the sheet (Figure 8) summary section provides a concise description of your VRA or VRA treatment train and the key conceptual design parameters.

The volume performance summary, located below the input summary on the same worksheet, provides a tabular and graphical representation of the estimated volume reduction achieved by your design. These results are reflective of the cumulative performance provided by the VRA(s) provided in the Project Design worksheet. The following results are provided within this summary:

- **Baseline Average Annual Runoff Volume.** This value represents the estimated average annual volume runoff for the tributary area to the VRA(s), based on climatic region/sub-region, drainage area, imperviousness, and soil type.



NCHRP 25-41 - Volume Performance Tool V.0.1 - Beta Release

Project Title	Test Run
Project Location	Santa Barbara, CA
Company	Geosyntec Consultants

Summary of Volume Performance Results

VRA Description

The VRA consists of a treatment train with a Vegetated Conveyance VRA followed by a Bioretention VRA

Key Conceptual Design Parameters: VRA 1

Vegetated Conveyance

Bottom Width (ft)	10
Bottom Length (ft)	500
Effective Amended Soil Depth (inches)	12
Underlying Soil Design Infiltration Rate (in/hr)	0.8
Longitudinal Slope (ft/ft)	0.01

See "Project Design" tab for detailed inputs

Key Conceptual Design Parameters: VRA 2

Bioretention

Storage Volume (cu-ft)	500
Underlying Soil Design Infiltration Rate (in/hr)	2
Underdrain Present?	no
Ponding Depth (ft)	1
Planting Media Thickness (ft)	2

See "Project Design" tab for detailed inputs

Figure 8. Volume performance summary—echo of scenario inputs.

- **Reduction in Runoff Volume.** This value represents the predicted average annual volume reduction achieved by the VRAs given the inputs provided. This volume represents the total reduction of volume from ET and infiltration, if they are applicable to your chosen design.
- **Captured, Treated, and Released Volume.** This value represents the predicted average annual runoff volume captured by the VRA(s) that is treated and then released back into the environment. This volume is a separate calculation from and does not include the volume that is reduced via ET or infiltration.
- **Runoff Bypassed Volume.** This value represents the estimated annual volume bypassing or overflowing the VRA(s).

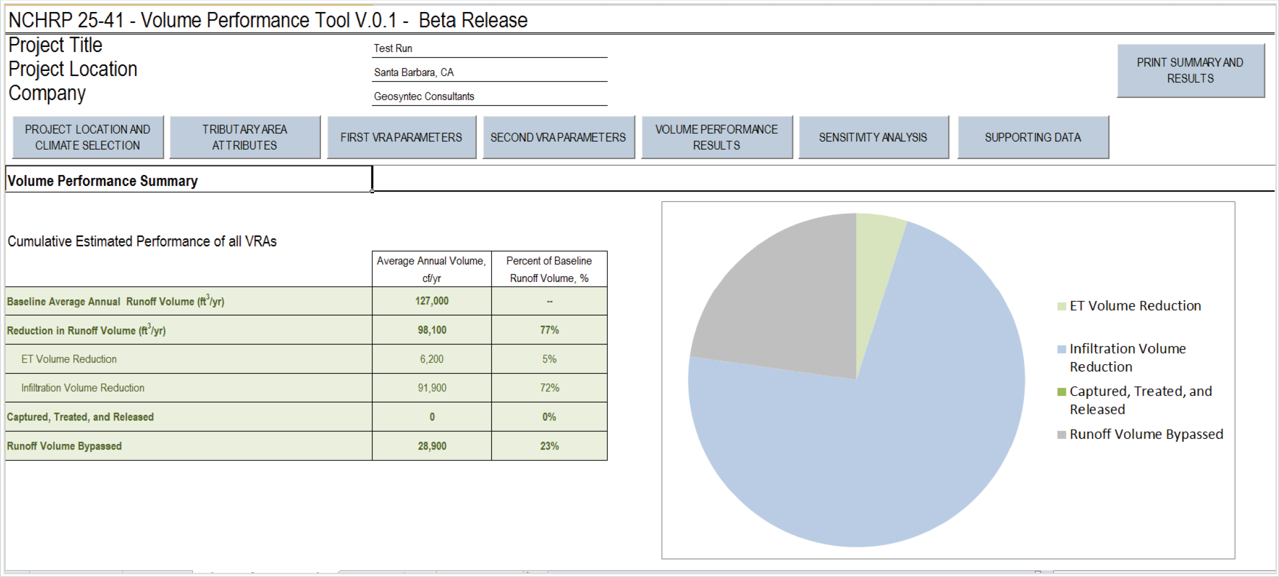
Each value is expressed in terms of an average annual runoff volume (ft^3/year) as well as a percentage of the baseline runoff volume. A pie chart illustrates the relative proportion of each element (Figure 9).

6.2 Running a Sensitivity Analysis

A sensitivity analysis allows the user to vary VRA design parameters and observe how this variation affects the final volume reduction estimates. The user is able to analyze a low and high bound value of design parameters by selecting a low and high multiplier that will adjust the already established design value for each parameter selected.

Navigate to the "Sensitivity Analysis" page by clicking the "Sensitivity Analysis" button or worksheet tab and follow these steps to perform the sensitivity analysis for your design:

1. Enter the value for the "High Multiplier." This value will be multiplied by the design value for each parameter selected for analysis and represents the high bound.
2. Enter the value for the "Low Multiplier." This value will be multiplied by the design value for each parameter selected for analysis and represents the low bound.
3. Select the design parameters to be analyzed for the first VRA from the drop-down menus provided.
4. If your design is a treatment train with two VRAs, select the parameters to be analyzed for the second VRA from the drop-down menus provided. (This will not be shown if two VRAs are not part of your design.) Note: When a new VRA is selected, the user must reselect the



NCHRP 25-41 - Volume Performance Tool V.0.1 - Beta Release

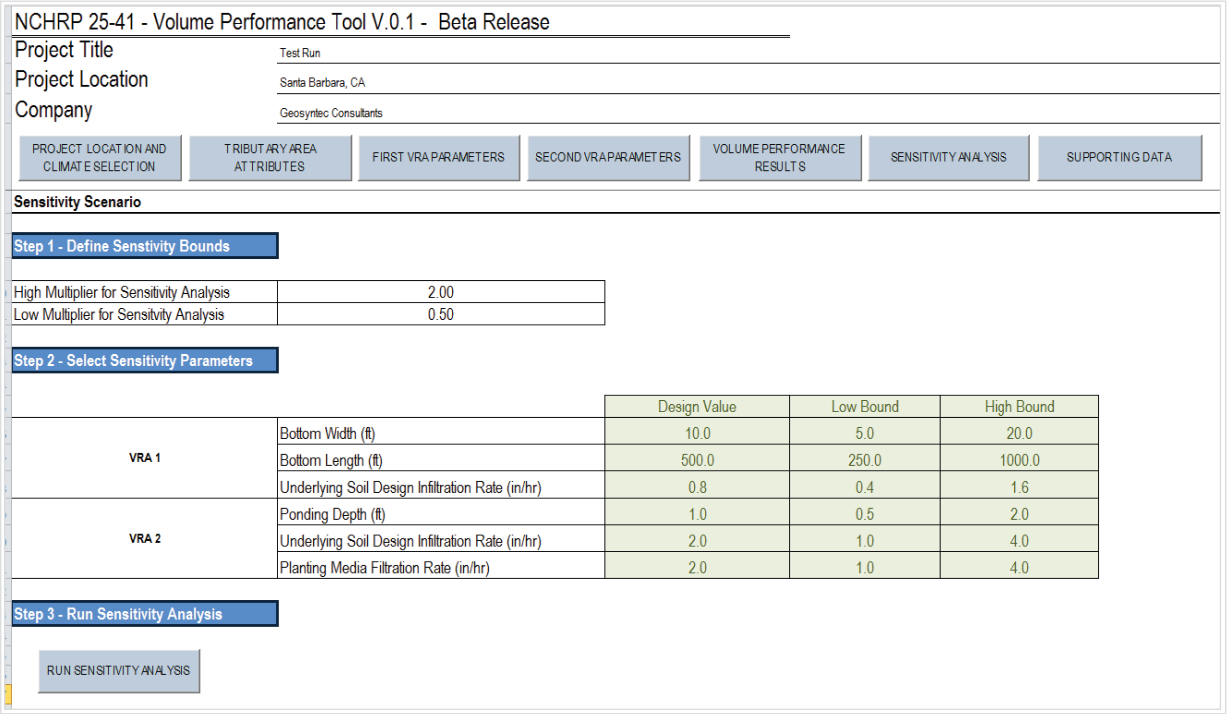
Project Title: Test Run
Project Location: Santa Barbara, CA
Company: Geosyntec Consultants

Volume Performance Summary

Cumulative Estimated Performance of all VRAs

	Average Annual Volume, cf/yr	Percent of Baseline Runoff Volume, %
Baseline Average Annual Runoff Volume (ft^3/yr)	**127,000**	**--**
Reduction in Runoff Volume (ft^3/yr)	**98,100**	**77%**
ET Volume Reduction	6,200	5%
Infiltration Volume Reduction	91,900	72%
Captured, Treated, and Released	**0**	**0%**
Runoff Volume Bypassed	**28,900**	**23%**

Figure 9. Volume performance tabular and graphical results.



NCHRP 25-41 - Volume Performance Tool V.0.1 - Beta Release

Project Title: Test Run
Project Location: Santa Barbara, CA
Company: Geosyntec Consultants

Sensitivity Scenario

Step 1 - Define Senstivity Bounds

High Multiplier for Sensitivity Analysis	2.00
Low Multiplier for Sensitvity Analysis	0.50

Step 2 - Select Sensitivity Parameters

		Design Value	Low Bound	High Bound
VRA 1	Bottom Width (ft)	10.0	5.0	20.0
	Bottom Length (ft)	500.0	250.0	1000.0
	Underlying Soil Design Infiltration Rate (in/hr)	0.8	0.4	1.6
VRA 2	Ponding Depth (ft)	1.0	0.5	2.0
	Underlying Soil Design Infiltration Rate (in/hr)	2.0	1.0	4.0
	Planting Media Filtration Rate (in/hr)	2.0	1.0	4.0

Step 3 - Run Sensitivity Analysis

Figure 10. Sensitivity analysis inputs.

sensitivity parameters from the drop-down menu to ensure that the parameters being analyzed are applicable to the current design and VRA.

5. Click the "Run Sensitivity Analysis" button.

See Figure 10 for an example of inputs to the sensitivity analysis.

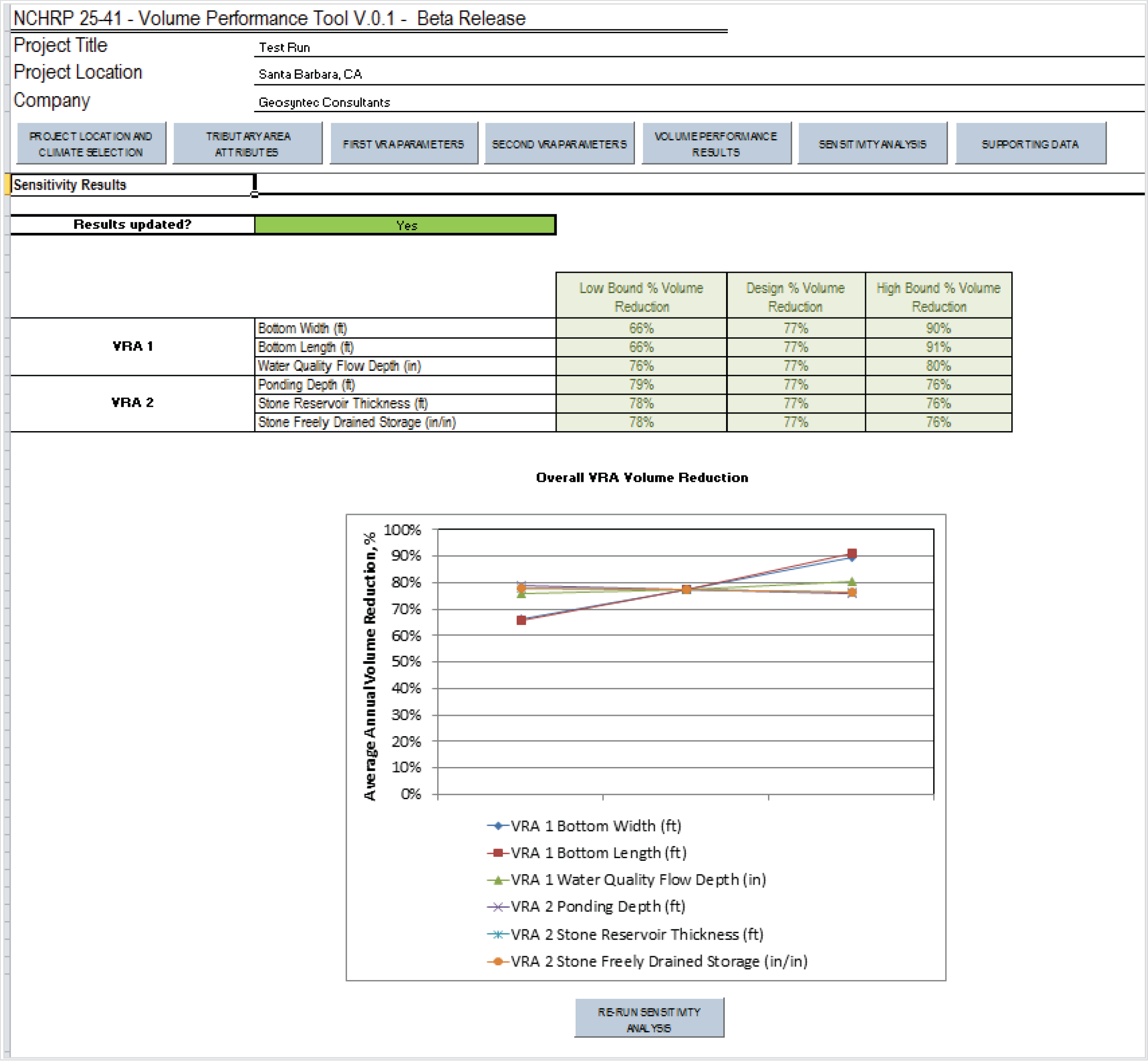
The results of the sensitivity analysis are presented in tabular and graphical form. Each sensitivity scenario represents the resulting performance if all other parameters are held fixed and the selected parameter is varied between the low and high bound. For each parameter analyzed, the low bound, design, and high bound estimates for volume reduction are displayed. If the design consists of a treatment train with two VRAs, the calculated results are representative of the total treatment train performance. An example of sensitivity analysis results is provided in Figure 11.

6.3 Viewing Supporting Data

The Supporting Data worksheet provides selected plots showing the continuous simulation model results that are being referenced by the tool to provide the VRA-specific performance results. The information on this worksheet is not editable and is provided for informational and technical documentation purposes only.

7 Error Messages

The tool provides volume reduction estimates by referencing tens of thousands of hydrologic simulations. Because an individual simulation is not being run for each individual project, the tool has some inherent limitations. When providing inputs, the tool interprets them and returns values based on a specific range of data. If the user-provided data are outside of this range, the tool will override the user input with the minimum and maximum values, respectively. In the event that this occurs, the tool will likely be underestimating performance if forced to use



NCHRP 25-41 - Volume Performance Tool V.0.1 - Beta Release

Project Title: Test Run
Project Location: Santa Barbara, CA
Company: Geosyntec Consultants

Sensitivity Results

Results updated?: Yes

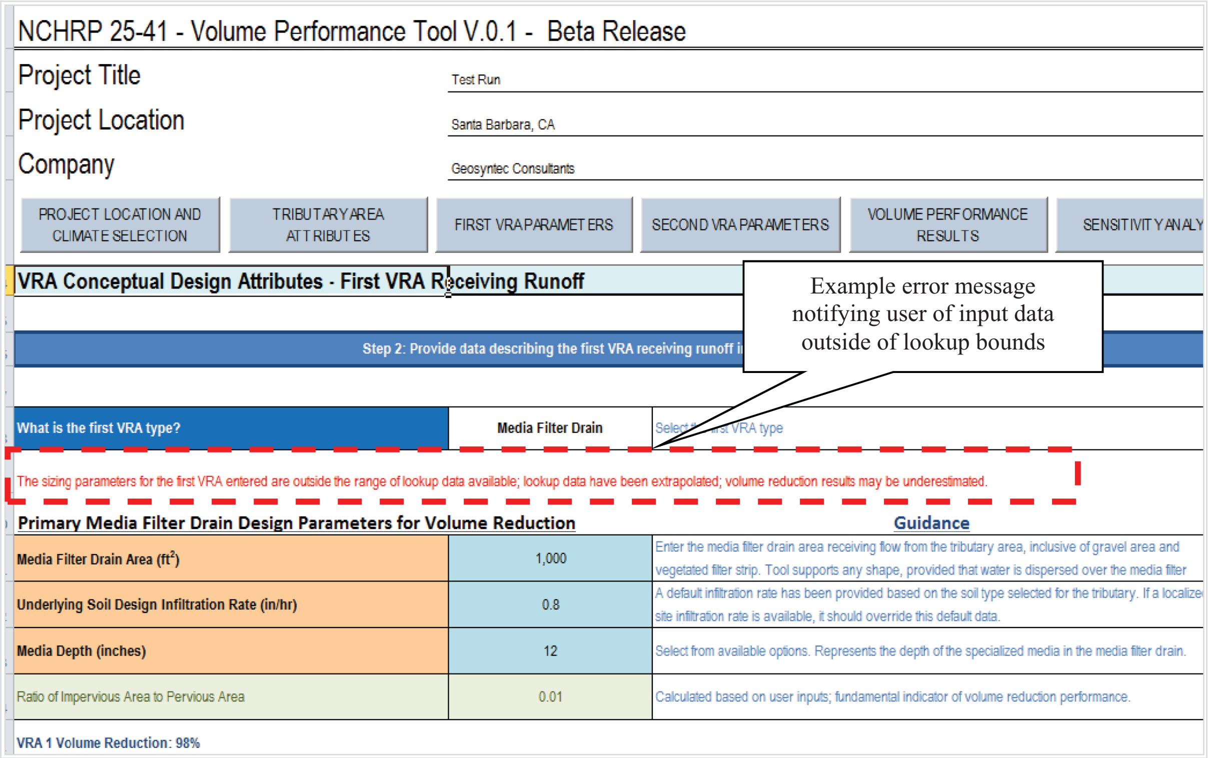
		Low Bound % Volume Reduction	Design % Volume Reduction	High Bound % Volume Reduction
VRA 1	Bottom Width (ft)	66%	77%	90%
	Bottom Length (ft)	66%	77%	91%
	Water Quality Flow Depth (in)	76%	77%	80%
VRA 2	Ponding Depth (ft)	79%	77%	76%
	Stone Reservoir Thickness (ft)	78%	77%	76%
	Stone Freely Drained Storage (in/in)	78%	77%	76%

Figure 11. Sensitivity analysis results.

the maximum value or overestimating performance if forced to use the minimum value. If the input bounds are exceeded and the minimum or maximum is used, an error message will be displayed for the applicable VRA, similar to that shown in Figure 12. The user should review the error message and adjust inputs or interpret results accordingly. A key to help understand error messages is provided in the Readme page of the tool.

8 Tool Theoretical Basis and Technical Assumptions

This tool is based on a number of technical assumptions. These assumptions are not critical for general use of the tool; however, they may be relevant for interpreting results and understanding the limits of the applicability of the tool. For detailed information about the theoretical basis for the tool and the underlying technical assumptions, see Annex A: Technical Documentation of *Volume Reduction of Highway Runoff in Urban Areas: Final Report*, which is part of *NCHRP Web-Only Document 209*.



NCHRP 25-41 - Volume Performance Tool V.0.1 - Beta Release

Project Title	Test Run
Project Location	Santa Barbara, CA
Company	Geosyntec Consultants

VRA Conceptual Design Attributes - First VRA Receiving Runoff

Example error message notifying user of input data outside of lookup bounds

Step 2: Provide data describing the first VRA receiving runoff i

What is the first VRA type?	**Media Filter Drain**	Select the first VRA type

The sizing parameters for the first VRA entered are outside the range of lookup data available; lookup data have been extrapolated; volume reduction results may be underestimated.

Primary Media Filter Drain Design Parameters for Volume Reduction		**Guidance**
Media Filter Drain Area (ft^2)	1,000	Enter the media filter drain area receiving flow from the tributary area, inclusive of gravel area and vegetated filter strip. Tool supports any shape, provided that water is dispersed over the media filter
Underlying Soil Design Infiltration Rate (in/hr)	0.8	A default infiltration rate has been provided based on the soil type selected for the tributary. If a localize site infiltration rate is available, it should override this default data.
Media Depth (inches)	12	Select from available options. Represents the depth of the specialized media in the media filter drain.
Ratio of Impervious Area to Pervious Area	0.01	Calculated based on user inputs; fundamental indicator of volume reduction performance.

VRA 1 Volume Reduction: 98%

Figure 12. Error message (shown in red).

Appendices C–F

The following appendices are not published herein but are included as part of *NCHRP Web-Only Document 209*, which also includes the contractor's final report.

Appendix C	White Paper No. 1—Infiltration Testing and Factors of Safety in Support of the Selection and Design of Volume Reduction Approaches
Appendix D	White Paper No. 2—Potential Impacts of Highway Stormwater Infiltration on Water Balance and Groundwater Quality in Roadway Environments
Appendix E	White Paper No. 3—Geotechnical Considerations in the Incorporation of Stormwater Infiltration Features in Urban Highway Design
Appendix F	White Paper No. 4—Review of Applicability of Permeable Pavement in Urban Highway Environments

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
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
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