Guidelines for Evaluating and Selecting Modifications to Existing Roadway Drainage Infrastructure to Improve Water Quality in Ultra-Urban Areas

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 728

Guidelines for Evaluating and Selecting Modifications to Existing Roadway Drainage Infrastructure to Improve Water Quality in Ultra-Urban Areas

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Christopher Hedges
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NCHRP Report 728 provides guidelines to evaluate and select hydraulic modifications to existing drainage infrastructure that will help mitigate potential impacts of highway runoff on receiving waters. The guidelines are directed specifically at roadway facilities in dense urban areas that can be particularly difficult and costly to retrofit because of space limitations, high pollutant loadings, hydrologic flashiness, hydraulic constraints, legacy contamination, utility conflicts, and other issues. They will assist transportation agencies in meeting regulatory requirements under the Clean Water Act, National Pollutant Discharge Elimination System (NPDES) permits, Total Maximum Daily Load (TMDL) allocations, endangered species protection, and watershed protection initiatives. The guidelines are accompanied by a Microsoft® Excel-based design and sizing tool on a CD-ROM bound into the back of this report. The tool generates best management practice (BMP) performance curves that relate the performance and design criteria for selected BMP controls described in the guidelines for each of the 15 U.S. rain zones. One of the significant features of the tool is that it allows users to explore BMP performance and retrofit sizing and design options based on user-selected design criteria and inputs. The guidelines will be of particular interest to planners, designers, and engineers with a basic understanding of the technical issues of BMP selection and design as applied to ultra-urban retrofit settings.

The transportation community is faced with a need to reduce pollutant loadings from existing facilities to achieve watershed Total Maximum Daily Loads (TMDLs) or to meet other regulatory requirements. Existing infrastructure was designed for efficient drainage and flood control and offers several possibilities for retrofits to enhance water quality. The literature on retrofitting of storm drainage systems to improve effluent water quality is divided into two broad areas. The first assumes the availability of land or right-of-way sufficient to place new or off-line best management practices (BMPs) for treatment; the second is usually referred to as "ultra-urban," meaning that the right-of-way is limited and there is little or no permeable surface. The latter condition is the focus of this work.

Under NCHRP Project 25-31, a research team led by Geosyntec Consultants and including Oregon State University, Venner Consulting, Inc., the Low Impact Development Center, and Wright Water Engineers, Inc. developed guidelines for evaluating and selecting hydraulic modifications to existing drainage infrastructure in order to reduce pollutant loads and concentrations in ultra-urban areas. The research team conducted a thorough review of existing technologies and reviewed available options for BMP retrofitting and methods to evaluate their effectiveness. A methodology for a retrofit strategy process and method was developed, which takes into account not only effectiveness but also installation and longer-term maintenance costs. The report includes seven case studies that illustrate how departments of transportation have successfully met the challenges of ultra-urban retrofits.

The contractor's final report is also available on the NCHRP Project 25-31 page of the TRB website (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=1642).

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Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

SECTION 1

Introduction

1.1 Motivation and Objectives

State departments of transportation (DOTs) and county and city transportation departments routinely design, construct, and maintain highway drainage systems to ensure safe driving conditions and to prevent downstream flooding. Highway runoff that is not treated or flow-managed beyond flood control has been associated with detrimental effects to the water quality and hydrologic characteristics of receiving waters. Accordingly, various federal and state environmental regulations increasingly require DOTs and municipalities to meet water quality and hydrologic discharge requirements for runoff that originates from their jurisdictions.

The federal Clean Water Act (CWA) is the primary regulatory framework for many DOT discharge requirements. Commonly encountered regulations include the National Pollutant Discharge Elimination System (NPDES) permitting requirements, the Section 303(d) water quality impairments designation, and discharge prohibitions established through Total Maximum Daily Loads (TMDLs). Other regulations such as the Endangered Species Act (ESA), legal actions, or local watershed initiatives may also lead to specific discharge requirements for highway runoff. Highway runoff contributions to contaminated sediments is also receiving increasing attention under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA; commonly known as Superfund).

To mitigate potential impacts of highway runoff on receiving waters and to meet discharge requirements, DOTs commonly implement a broad array of measures that collectively are referred to as Best Management Practices (BMPs). BMPs include the following:

- **Education BMPs:** Programs intended to promote environmental awareness and change public behavior. Examples are highway anti-littering campaigns and adopt-a-highway initiatives.
- **Source control BMPs:** Initiatives intended to reduce pollutants before they are entrained in highway runoff. These include programmatic actions such as proper selection and use of herbicides for roadside vegetation control, selection of road building and associated infrastructure materials, or tangible measures such as highway litter cleanup, street sweeping, and catch basin stenciling.
- **Treatment/flow control BMPs:** Structural facilities designed to remove pollutants from stormwater runoff prior to discharge to receiving waters and/or to reduce or control runoff volumes. Common approaches include roadside swales, filter strips, detention basins, infiltration systems, and sumped catch basins. Treatment BMPs are normally required during both the construction and post-construction phases of highway projects. Runoff control is typically completed for post-construction phases.

Post-construction treatment/flow control BMPs are often the focus of DOT stormwater programs and regulatory oversight. Environmental and resource agencies that are mandated to protect water resources are necessarily focused on the effectiveness of treatment BMPs, including factors such as BMP selection, sizing, design, and maintenance. While these criteria are also important to the success of DOT stormwater programs, DOTs are additionally concerned about the cost of constructing and maintaining post-construction treatment BMPs. Costs are particularly important given that DOT budgets are often constrained by their dependence on legislative allocation, which is affected by economic and political circumstances.

The regulatory requirements for treatment BMPs have historically been associated with the construction of new highway facilities. However, environmental regulations continue to evolve. More recently, environmental regulations increasingly require retrofit treatment BMPs for previously constructed highway facilities. Some examples of highway retrofit drivers include:

- NPDES permit requirement (Washington State DOT, North Carolina DOT);
- TMDL loading allocations (California, Maryland, many other state DOTs);
- Endangered species protection (Oregon and Washington DOTs for endangered salmon protection); and
- Watershed initiatives (state DOTs in the Chesapeake Bay Watershed).

Retrofitting highways with treatment BMPs is relatively straightforward when there is adequate space, hydraulic head, and budget. However, highway facilities that are located in dense urban areas or "ultra-urban areas" can be particularly difficult and costly to retrofit due to space limitations, high pollutant loadings, hydrologic flashiness, hydraulic constraints, and utility conflicts. In addition, ultra-urban environments are typically much more challenged in terms of receiving water quality and in some cases stream stability issues. Consequently, DOTs potentially face costly and challenging BMP retrofit requirements in ultra-urban environments.

Recognizing the potentially high costs and difficulty associated with retrofit mandates in ultra-urban areas, the National Cooperative Highway Research Program (NCHRP) initiated NCHRP Project 25-31 with the goal of developing guidance on retrofit procedures for evaluating and selecting modifications to existing drainage infrastructure. This document provides the basis for and details of this guidance. The purpose of this guidance is to provide planners, designers, and engineers with a basic understanding of the technical issues of BMP selection and design as applied to ultra-urban retrofit settings. This guidance is intended as a starting point for retrofit projects. Because the nature of retrofitting is highly site specific, this guidance cannot be a substitute for site-specific planning, permitting, engineering analysis, design, cost estimation, construction, and post-cost operation, maintenance, and monitoring.

1.2 What Is an Ultra-Urban Highway?

An "ultra-urban environment" is a highly urbanized area that has little or no available space for new development and where land costs are typically high. The first use of the term is attributed to city staff in Alexandria, Virginia (Shoemaker et al., 2002). In an ultra-urban environment, the use of traditional treatment BMPs such as detention basins and swales is constrained by the lack of available surface area. Thus, the term "ultra-urban BMP" is associated with the use of proprietary treatment BMPs that have small footprints and are installed underground.

By extension, an "ultra-urban highway" is defined as a highway segment located in a highly urbanized area, with little to no right-of-way (ROW) for expansion of highway infrastructure, and where adjacent land costs are high or essentially unavailable. An ultra-urban highway has one or more of the following characteristics:

- **Limited right-of-way:** The most common and significant feature of the ultra-urban highway is the lack of available surface space in the ROW corridor for locating retrofit BMPs.
- **High land costs:** High land costs associated with highly urbanized areas may constrain the ability to acquire additional ROW or to find potential off-site locations for siting retrofit BMPs.
- **Large traffic volume:** Ultra-urban highways have multiple lanes designed for large average daily traffic (ADT), typically in excess of 30,000 and in many cases in excess of 100,000 or more vehicles per day.
- **Large fraction of impervious cover:** Ultra-urban highway catchments have a high percentage of impervious surfaces, typically 75–100%. The contribution of highway impervious area to total impervious area is small. In a national study (Tilley and Slonecker, 2006), all roads make up about 20–25% of total impervious area (TIA) as TIA increases over 25%, and highways likely make up a small fraction of the total roadways in ultra-urban areas.
- **Potential for utility conflicts:** Highly urbanized areas potentially have numerous existing and abandoned underground utilities.
- **Compacted soils or unknown subsurface conditions:** Soils in dense urban environments may have poor infiltration characteristics and/or are usually compacted and less amenable for infiltration. Older highways may include unknown or unengineered fill.
- **Underground drainage system:** Drainage collection systems typically include curbs and inlets to underground-piped storm sewers due to the lack of ROW for surface conveyances.

1.3 What Is a Highway Water Quality Retrofit?

A highway water quality retrofit (or "BMP retrofit") is defined as the construction and maintenance of engineered treatment BMPs to reduce the water quality and hydrologic impacts of runoff from existing highway facilities. A BMP retrofit can entail:

- Modification and enhancement of existing BMPs and infrastructure;
- Construction of stand-alone treatment/flow control BMPs for existing highway facilities; and
- Construction of retrofit BMPs in association with highway improvement projects, for example, highway-widening projects that include BMPs to treat existing and added travel lanes.

In ultra-urban highway settings, BMP retrofits are most commonly associated with highway improvement projects, as this is usually more cost effective and affords more flexibility in BMP design than stand-alone retrofits. Stand-alone retrofits in highly space-constrained urban highways can be triggered by TMDLs and ESA requirements, but are less often constructed due to high costs, challenges, and localized benefit. In addition, off-site alternatives may be available that are more cost effective and provide greater benefits to receiving waters. In the future, evolving water quality and quantity regulations may increasingly necessitate more stringent and costly stand-alone retrofit projects.

1.4 Characteristics of Retrofitting

Highway BMP retrofitting is more complex and costly than BMP planning and construction for new highways. In retrofitting, the BMPs must be adapted to the existing highway and drainage systems. In contrast, BMP design for new highways is more flexible as there are almost always fewer constraints and more opportunity for coordinated planning and construction of the highway, drainage system, and BMPs. Table 1.1 compares BMP development for highway retrofits and new highway construction projects.

1.5 Challenges of BMP Retrofitting in Ultra-Urban Highway Environments

Designing and constructing BMP retrofits of ultra-urban highways can be difficult and costly. Physical, operational, and budgetary constraints can each limit the ability to implement BMP retrofits. These challenges and constraints are described below and are summarized in Table 1.2.

Finding Adequate Space to Locate Aboveground Retrofit BMPs: The most common and significant constraint, other than funding in general, is the lack of surface area within the

Table 1.1. Project components for BMP retrofitting versus BMPs for new highway construction.

Project Component	Highway BMP Retrofitting	BMPs Integrated with New Highway Construction
Data collection	Significant data collection for characterizing constraints and identifying opportunities.	Less data collection needed for existing infrastructure. Characterization studies required for highway design are usable for BMP design.
BMP siting	Fewer options. Physical obstructions (space, head, connectivity, utilities) are more likely to constrain BMP siting and design.	BMP siting is more flexible. Conflicts with existing infrastructure are less likely and are more easily mitigated through coordinated design.
Stormwater conveyance system	BMPs must conform to the existing storm sewer system, or the existing system must be modified.	Allows for coordinated design and construction of conveyance systems and BMPs.
BMP sizing	Sized to meet treatment objectives. There may be limits on the ability to meet sizing requirements due to physical and economic restrictions.	Sized to meet DOT or local stormwater standards. There is less flexibility for reducing sizing below minimum criteria.
Practicality assessment	Fewer feasible options. Candidate BMPs are more likely to be infeasible due to physical or economic constraints.	Most candidate BMPs are likely to be feasible.
Planning and design costs	Higher costs. More coordination, data collection, and site characterization is needed. Greater likelihood of design changes.	Lower costs. More flexibility in design. Constraints more likely to be identified and mitigated.
Construction cost	1.5 to 4 times greater than new construction sites. Must work around existing infrastructure. Greater likelihood of unexpected conditions and change orders.	Fewer construction constraints. Less likely to encounter unexpected conditions.

Source: Adapted from the Center for Watershed Protection Urban Stormwater Retrofit Practices Manual (Schueler et al., 2007)

Table 1.2. Constraints and challenges of BMP retrofits for ultra-urban highways.

Retrofit Consideration	Retrofit Constraints	Mitigation	Potential Implications
Limited ROW	• ROW too small for aboveground BMPs • Available ROW has planned uses such as future highway expansion • Available ROW has poor configuration or location, limited access • Adjacent land costs are high	• Select alternative locations • Locate BMPs underground • Adapt BMP design or type to fit within available ROW • Use proprietary small-footprint BMPs • Coordinate retrofits with future projects	• Greater design and construction costs • More maintenance requirements and costs for underground BMPs • Reduced treatment performance • Project delays
Obstructions	• Buried utilities • Building foundations • Landfills/contaminated soils • Historic structures • Archeological finds • As-built drawings are not available or unreliable	• Select alternative location • Adapt/change BMP design • Dig additional test pits to identify obstructions • Remove obstruction at additional cost	• Greater design and site characterization costs • Greater construction costs • Project delays and change orders • Longer construction period
Topography	• Below-grade highway sections • Roadway crowned to drain away from candidate locations • Available ROW has steep slopes, rocky, and uneven terrain • Insufficient head in flat terrains	• Select alternative location or retrofit design • Re-grade/excavate/fill as needed • Construct retaining walls • Modify existing drainage system • Modify roadway crown	• Greater design and construction costs • Longer construction period
Soil and groundwater conditions	• Compacted soils with low permeability • Shallow groundwater • Overly wet soils/hydric soils • Unknown or non-engineered fill • Soil or groundwater contamination	• Select alternative location or retrofit design • Amend soils at additional cost • Install dewatering systems • Excavate and dispose unsuitable or contaminated soil	• Increased design and construction costs • Construction delays and change orders to address unexpected conditions • Longer and more complicated construction
Connection to existing drainage system	• Piped and underground systems • Difficult to tie in BMPs due to insufficient head, conveyance capacity, and location	• Select alternative location or retrofit design • Use pumps to compensate for elevation issues at additional cost • Reconfigure existing conveyances	• Greater costs for design, construction, and ongoing operation
Construction	• Space and connectivity constraints • Obstructions, depth, confined-space issues • Limited space for construction staging • Longer distance from import/export sites • Lane closures due to limited space or retrofit design • Traffic delays due to high volume or lane closure	• Select alternative location • Modify BMP design • Develop designs that eliminate required lane closures, minimize connectivity issues, require no proprietary materials • Schedule construction for off-peak hours/seasons • Reuse exports on site	• Greater construction costs • Longer construction periods because of traffic impacts and traffic control • Potential construction delays and change orders to address unexpected conditions • Worker and public safety concerns due to limited space and large traffic volume
BMP treatment performance	• Large flowrates, runoff volumes, and pollutant loadings • Space constraints limit BMP options and capacity • Compacted soils restrict use of infiltration BMPs • Little potential for runoff capture and reuse • Cold climate–related effects on pollutant loadings and BMP sizing	• Select alternative location • Modify BMP design and sizing • Include operational and design enhancements • Provide pretreatment • Use treatment trains	• Greater project costs • Target pollutants not mitigated
Maintenance burden	• Impacts to traffic • High maintenance frequency • Need for specialized equipment or materials • Safety issues for road crews and drivers • Maintenance access requires lane closures or traffic impacts • Vegetation maintenance	• Select alternative location • Select alternative BMP types • Modify BMP design • Schedule maintenance at off-peak hours/seasons at additional cost	• Potentially excessive maintenance requirements and costs • Diminished treatment performance if maintenance needs are not met

Table 1.2. (Continued).

Retrofit Consideration	Retrofit Constraints	Mitigation	Potential Implications
Cost	• High land / implementation cost • High maintenance cost • High replacement cost	• Select alternative location • Select alternative BMP types • Modify BMP design • Seek off-site locations, pollutant trading • Re-evaluate treatment objectives	• Potentially excessive costs needed to meet regulatory requirements • Diminished treatment performance with alternative BMPs
Public acceptance	• Aesthetics • Increased traffic and public hazard from space limitations • Mosquito habitat from standing water in underground BMPs • Odors • Use of sustainable materials	• Install BMPs behind guard rails • Use grates and fences to reduce hazards • Modify design to eliminate or reduce standing water • Maintain regularly for aesthetics, odors, pests	• Greater maintenance costs • Public concerns about vectors, aesthetics, sustainable practices, and safety • Public support when aesthetics can be improved

ROW for siting aboveground retrofit BMPs. The lack of adequate surface area requires retrofit designers to seek alternative locations or to develop designs that can fit within the available ROW including consideration of underground BMPs. Retrofit locations that are underground, off-site, or require extensive site changes are likely to be more costly, have increased maintenance requirements, and may result in selected BMPs with poorer treatment performance than aboveground ones. The search for usable and sufficient surface storage or vegetative filtration is a primary retrofitting task.

Selecting and Designing Retrofit BMPs: Identifying and designing retrofit BMPs that cost effectively achieve treatment objectives can be difficult. Factors that can complicate BMP selection are as follows:

- ***Physical constraints:*** Space limits, topography (steep slopes or flat topography), high groundwater, poorly draining soils, underground infrastructure and obstructions, including existing soil contamination.
- ***High hydraulic loadings:*** Hydrologic flashiness (peaky hydrographs), high flow rates, and large runoff volumes caused by large impervious fractions and small drainage catchments.
- ***High pollutant loadings:*** Comparatively greater pollutant concentrations and pollutant loadings associated with large ADT, surrounding urban land uses, and greater runoff volumes.
- ***Reduced feasibility for infiltration:*** Although infiltration BMPs are among the most effective measures for reducing hydrologic and pollutant loadings, their feasibility in ultra-urban highways is constrained by:
  – Limited surface area;
  – Probative infiltration rates associated with compacted soils and fill;
  – Geotechnical concerns for protection of the roadway subgrade or other adjacent infrastructure;
  – Greater likelihood of conflicts with underground infrastructure; and
  – Greater potential for subsurface contamination.
- ***Limited feasibility for on-site retention:*** Ultra-urban highways have limited potential for on-site retention due to reduced feasibility for infiltration, limited surface area for storage and evaporation of harvested stormwater, and few options for use of stormwater such as irrigation and non-potable water supply.

Project costs generally increase when large, proprietary, and/or complex underground BMPs are used in an effort to meet treatment objectives. Alternatively, BMP designers may consider smaller and more affordable BMPs in an effort to mitigate space and budget constraints and to comply with regulatory requirements. However, treatment performance can be compromised if the BMPs do not include relevant unit processes and/or have extensive maintenance requirements. A key retrofitting task is evaluating and selecting candidate BMPs and treatment trains that include appropriate unit processes.

Developing Retrofit BMPs That Are Adequately Maintained: BMP maintenance is vital to ensuring design-level treatment performance. Treatment effectiveness is compromised when maintenance needs are not identified, are scaled back, and/or are neglected. Without ongoing maintenance, the utility of retrofit BMPs and the investment in retrofitting is questionable. On the other hand, DOT maintenance departments are often under-resourced and may be reluctant to assume additional responsibilities. DOTs have noted disproportionate funding for BMP construction versus BMP maintenance of the nature: "they provide money to construct BMPs, but no money to maintain them."

Consequently, maintenance departments may view BMP maintenance as onerous, especially for small-footprint, underground, and proprietary BMPs that can require frequent maintenance, specialized equipment, significant health and safety measures, and costly proprietary materials. As a result, BMP maintenance requirements and costs can dictate BMP selection. Ongoing BMP maintenance is a principal consideration in retrofitting.

Identifying and Mitigating Utility Conflicts, Obstructions, and Unknown Conditions: Ultra-urban highways potentially have numerous existing and abandoned underground utilities or other obstructions such as foundations, old landfills, or historic structures. As-built drawings may be unreliable or unavailable, particularly in older urban areas. Retrofit costs increase when utilities or obstructions must be relocated or designs must be adapted to accommodate utility constraints and unfavorable or contaminated soils. Retrofit costs also increase when extensive test pits are needed to locate or confirm utility locations, and construction change orders are needed to address unforeseen conditions.

Connecting Retrofit BMPs to the Existing Drainage Systems: Drainage collection systems in ultra-urban highways are typically piped and underground. The existing drainage systems can be poorly defined, include large diameter conduits, include run-on from off-site drainage areas, and have inadequate capacity or insufficient head to accommodate BMP retrofits. As a result, retrofit designers may need to consider system modifications or new facilities such as pumping equipment. Connectivity constraints will increase retrofit costs or can limit retrofit options. The ability to tie into existing drainage systems is a primary consideration in retrofitting.

Constructing BMP Retrofits in Limited-Space, High-Traffic Conditions: Construction in ultra-urban highway environments is affected by space limitations, existing infrastructure, known and unknown obstructions, and high traffic volumes. Construction constraints can significantly increase project costs and construction periods. Traffic flow will also be impacted if lane closures are required and there are safety concerns with construction in high-traffic, space-constrained settings. Retrofit constructability should be considered early in the planning process.

Identifying Cost-Effective Retrofits: Retrofitting ultra-urban highways with BMPs is potentially very costly. DOTs are very concerned about the ability to fund retrofit projects and to meet regulatory obligations or watershed initiatives. Cost is a critical factor throughout the retrofitting process, including BMP planning, design, construction, operation, and maintenance.

1.6 Document Organization

Although the constraints of ultra-urban highways can be daunting, a rational approach to BMP retrofitting follows the same fundamental steps commonly used in water resources planning (Orth and Yoe, 1997). Accordingly, this document is organized about the fundamental steps of rational planning as shown in Figure 1.1.

Ideally, the steps in a rational planning process are sequential. In reality, retrofit planning may begin with any step and steps will be repeated to assess new information. Sections 2 through 8 of this document are organized into topics that separately support the fundamental retrofitting steps, and Sections 9 and 10 integrate the information and guidance provided in the previous sections, as follows:

1. *Define the Problem*
   - **Section 2, Ultra-Urban Highway Characterization:** This section summarizes the characteristics of runoff from ultra-urban highways and the potential impacts on receiving waters. Runoff and receiving water character-

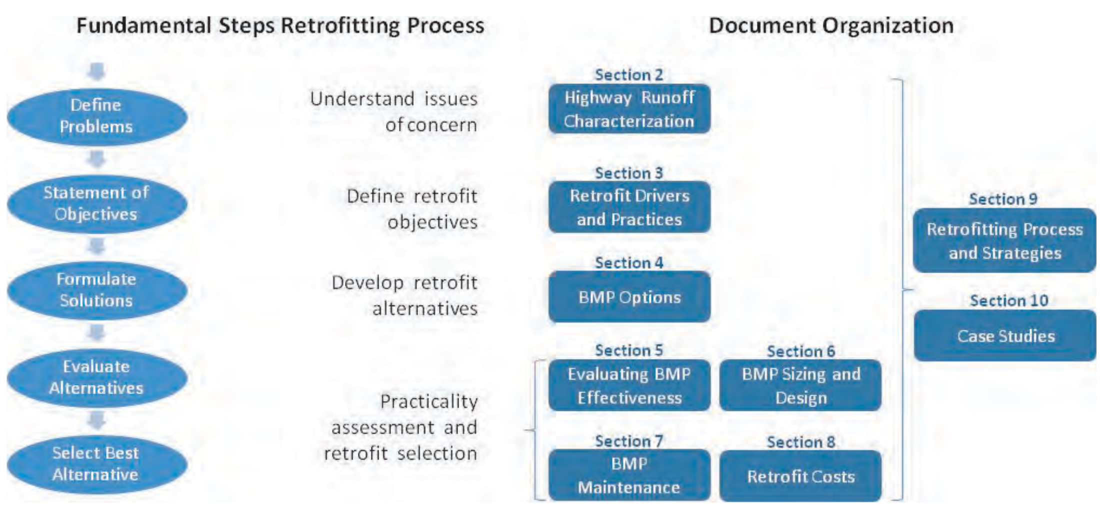


Figure 1.1. Document organization.

ization supports the development of sensible treatment objectives and effective retrofit solutions. A summary of common highway pollutants and conditions of concern and their characteristics is provided in Table 2.1.

2. *Statement of Retrofit Objectives*
   - **Section 3, Retrofit Drivers and Practices:** Regulatory compliance is usually the main retrofit objective. This section describes the regulatory requirements for BMP retrofits and DOT compliance practices.
3. *Formulation of Candidate Retrofits*
   - **Section 4, BMP Options for Ultra-Urban Highway Retrofits:** This section describes treatment BMPs that can potentially be used in retrofitting highways. BMP options are grouped into 10 retrofit categories based upon their design characteristics, target pollutants, and applicability to surface and underground applications. A summary of retrofit categories and general BMP characteristics is provided in Table 4.1. Detailed summary tables are provided throughout Section 4 for each retrofit category.
4. *Practicality Assessment of Candidate Retrofits*
   - **Section 5, Evaluating BMP Effectiveness:** This section describes regulatory criteria and empirical data that are used to assess treatment performance of candidate BMPs. Fundamental unit processes of BMPs are discussed as a primary criterion for the selection of BMPs and treatment trains. Rankings for unit operation effectiveness are listed in Table 5.1 for each retrofit category. A summary of median influent and effluent levels from the BMP Database is provided in Table 5.4.
   - **Section 6, BMP Sizing and Design:** This section discusses regulatory and performance considerations for assessing BMP sizing and design. This section describes a BMP sizing spreadsheet tool that synthesizes continuous simulation modeling results for evaluating detention (volume-based) and media filtration (flow-based) BMPs. The purpose of the tool is to assist stormwater and highway professionals with planning-level sizing and design of detention and media filtration BMPs for ultra-urban highway runoff control.
   - **Section 7, BMP Maintenance and Monitoring:** This section describes post-construction activities, which include ongoing BMP maintenance and monitoring. Maintenance practices are discussed and a summary of common maintenance practices and maintenance indicators is provided in Table 7.1. This is followed by a description of BMP monitoring and performance assessment practices and protocols.
   - **Section 8, Retrofit Costs:** Ultimately, retrofit costs will be the overriding consideration for retrofit assessment. This section describes cost elements, cost factors for ultra-urban settings, and cost reduction strategies. A summary of available retrofit cost data is provided in Table 8.1.
5. *Integration*
   - **Section 9, Retrofitting Strategies and Process:** Only a limited number of retrofit alternatives can be evaluated in detail. This section describes general strategies for identifying promising candidates, including strategies for locating and selecting BMPs and alternatives to retrofitting. A retrofit process is discussed.
   - **Section 10, Case Studies:** This section presents seven BMP retrofitting case studies from DOTs. Case studies include aboveground and underground BMP applications, and pilot studies to assess BMP design, performance, and construction procedures.

SECTION 2

Ultra-Urban Highway Runoff Characterization

Characterizing highway pollutants of concern supports the development of retrofit treatment objectives and selection and design of appropriate BMP strategies.

2.1 Retrofit Benefits of Water Quality Characterization

Water quality characterization provides a basis for planning, evaluation, and design of BMP retrofit projects. Retrofit projects benefit from water quality characterization in the following ways:

- **Appropriate representation of water quality issues:** Many DOTs actively study or sponsor research on stormwater runoff, stormwater BMPs, and receiving water impacts. When water quality conditions and mitigation measures are studied and evaluated from a watershed perspective, DOTs gain a broader perspective of potential impacts from highway runoff, and a more accurate representation of the DOT's contribution to watershed conditions and runoff controls.
- **Basis for sensible retrofit objectives:** Understanding receiving water conditions and highway runoff characteristics provides a basis for evaluation and prioritization of retrofit projects, and supports development of sensible retrofit objectives that (1) address pertinent water issues, (2) attempt to balance costs and benefits, (3) achieve regulatory compliance, and (4) strive for consensus among stakeholders.
- **Basis for effective treatment strategies:** Treatment BMPs are not equal in performance. Treatment effectiveness depends on the fundamental unit processes of the BMP as well as the BMP sizing and design. Defining and characterizing the target pollutants and their forms (e.g., particulate-bound or dissolved) provides a basis for considered selection of retrofit BMPs.

2.2 Pollutants of Concern for Ultra-Urban Highway Retrofits

Table 2.1 summarizes common pollutants of concern (POCs) for ultra-urban highways. Subsequent sections describe the pollutant characteristics, issues of concern in receiving waters, and potential implications for retrofit requirements and BMP design.

Runoff from ultra-urban highways is a component of the regional urban runoff water quality. However, highways usually comprise a small fraction of the total watershed area, and therefore runoff quality from other urban land uses will tend to dominate the regional urban runoff quality. Using information compiled in the National Stormwater Quality Database, Table 2.2 shows median values of selected water quality parameters for various urban land uses (Maestre and Pitt, 2005). Comparisons in Table 2.2 indicate the water quality of highway runoff is generally similar to the runoff from other urban land uses but tends to be somewhat higher in total suspended solids (TSS), oil and grease, and metals, and somewhat lower in nutrients and bacteria.

2.2.1 Runoff Volume and Discharge

Characteristics in Highway Runoff

High impervious cover in ultra-urban highway catchments dramatically increases runoff volumes and peak discharges in comparison to undeveloped conditions. Impervious cover also reduces infiltration and recharge to groundwater, reduces sediment supply to receiving streams, and accelerates the delivery of pollutants. These conditions cause changes to the hydrologic regime of receiving streams, including increased stream flows, increased frequency and number of erosive flow events, increased long-term cumulative duration of flows, and increased peak flows. These effects are referred to as hydromodification.

Table 2.1. Ultra-urban highway conditions and pollutants of concern.

Condition/ Pollutant	Potential Sources in Ultra-Urban Highway Environments	Potential Receiving Water Impacts
Runoff volume and discharge	• High impervious cover	• Hydromodification • Increased erosion and sediment transport • Stream channel adjustment, geomorphic impacts • Loss of habitat and riparian species
Sediment and particulates	• Vehicle abrasion, fall off, and wash off • Pavement wear • Wash off from landscape areas and construction sites • Atmospheric deposition • Sanding for traction control	• High turbidity • Streambed occlusion due to deposition • Loss of aquatic habitat • Stream channel modifications • Exceedance of water quality objectives
Metals (copper, lead, zinc, cadmium, nickel, chromium)	• Tire wear • Lubricating oils • Brake lining wear • Moving engine parts • Fuels and fuel additives • Automobile exhaust • Metal plating and highway structures • Atmospheric deposition	• Toxicity of aquatic organisms • Behavioral effects on salmon • Bioaccumulation in fish with potential health hazards to humans • Contaminated sediments and associated impacts • Exceedance of water quality and sediment quality objectives
Organic compounds (polycyclic aromatic hydrocarbons, oil and grease, petroleum-related products)	• Lubricating oils • Fuels and fuel additives • Automobile exhaust • Atmospheric deposition	• Toxicity and impairment of aquatic life • Persistence in sediments • Reduced diversity and abundance of benthic communities • Exceedance of water quality and sediment quality objectives
Litter and debris	• Intentional or inadvertent littering or dumping • Windblown sources from outside the ROW • Highway landscaping	• Impaired recreational benefits • Loss of aquatic habitat • Increased biochemical oxygen demand and contribution to eutrophication
Nutrients	• Automobile exhaust • Atmospheric deposition • Roadside fertilizer applications • Sediments	• Accelerated growth of vegetation • Changes in algae, benthic, and fish communities • Surface algal scum, water discoloration • Exceedance of water quality objectives
Chlorides	• Highway deicers	• Damaged or killed salt-intolerant vegetation • Reduced plant and invertebrate diversity • Impaired groundwater supplies • Exceedance of water quality objectives
Indicator bacteria	• Bird and wildlife droppings • Road kill • Transport of livestock or manure • Human waste disposal • Re-growth in storm drains	• Indicator of potential human health effects from body contact with receiving waters • Exceedance of water quality objectives

Receiving Water Issues of Concern

Hydromodification together with reduction in sediment supply can significantly intensify the erosion and sediment transport processes in receiving streams and often leads to stream channel adjustment, geomorphic impacts, and loss of habitat and associated riparian species.

Retrofit Implications

Hydromodification impacts to urban receiving streams are a regulatory issue of concern. NPDES permits are increasingly including hydromodification control requirements, particularly through implementation of Low Impact Development (LID) requirements. Retrofit BMPs to address hydromodification entail infiltration BMPs, including LID practices, and flow-duration control basins. These practices are difficult to implement in space-constrained settings and may necessitate evaluation of off-site BMPs or in-stream controls.

2.2.2 Sediments

Characteristics in Highway Runoff

Suspended sediments and solids are prevalent in highway stormwater runoff and urban runoff and are the most widely

Table 2.2. Comparison of highway runoff quality and water quality of other urban land uses.

Water Quality Constituent	Parameter	Residential	Commercial	Industrial	Freeway
TSS (mg/L)	Number of samples	991	458	428	134
	% above detection	98.6	98.3	99.1	99.3
	Median value	49	42	78	99
Total dissolved solids (mg/L)	Number of samples	861	399	413	97
	% above detection	99.2	99.5	99.5	99.0
	Median value	72.0	74	92	77.5
Oil and grease (mg/L)	Number of samples	533	308	327	60
	% above detection	57.8	70.8	65.1	71.7
	Median value	3.9	4.7	5.0	8.0
Fecal coliform (MPN/100 mL)	Number of samples	446	233	297	49
	% above detection	88.3	88.0	87.9	100
	Median value	8345	4300	2500	1700
Nitrate + nitrite (mg/L)	Number of samples	927	425	418	25
	% above detection	97.4	98.1	96.2	96.0
	Median value	0.6	0.6	0.73	0.28
Total phosphorus (mg/L)	Number of samples	963	446	434	128
	% above detection	96.9	95.7	96.3	99.2
	Median value	0.30	0.22	0.26	0.25
Total copper (µg/L)	Number of samples	799	387	416	97
	% above detection	83.6	92.8	89.9	99.0
	Median value	12	17	22	34.7
Dissolved copper (µg/L)	Number of samples	90	48	42	130
	% above detection	63.3	79.2	90.5	99.2
	Median value	7.0	7.6	8.0	10.9
Total zinc (µg/L)	Number of samples	810	392	433	93
	% above detection	96.4	99.0	98.6	96.8
	Median value	73	150	210	200
Dissolved zinc (µg/L)	Number of samples	88	49	42	105
	% above detection	89.6	100	95.2	99.1
	Median value	31.5	59	112	51

Source: National Stormwater Quality Database: http://rpitt.eng.ua.edu/Research/ms4/Paper/Mainms4paper.html

addressed pollutant in urban stormwater. The primary sources of sediments and solids in highway runoff are pavement, tire, and vehicle abrasion (Oregon State University et al., 2006). Abraded pavement is reported to make up between 40–50% of the total particulate mass, and abraded tires account for 20–30% of the total particulate mass (Karamalegos et al., 2005). Other identified sources include salting and sanding, brake pad dust, aerial deposition, off-site tracking, and runoff from highway landscaping and construction sites (USEPA, 2005a).

The particle size distribution (PSD) in highway runoff affects pollutant transport and treatability. There is considerable variability in reported PSDs (Bent et al., 2003; Kim and Sansalone, 2008a), even on different shoulders of the same highway section (Sansalone and Tribouillard, 1999). Variability in measured PSD is due to spatial and temporal variability in runoff, wear of materials, and deposition, as well as differences in the collection and measurement procedures (Bent et al., 2003; Kim and Sansalone, 2008a). Kim and Sansalone (2008a) measured event-based PSDs from paved surfaces and compared results to an extensive review of published PSDs. Measured PSDs were dominated by fine particles (<75 µm), which accounted for 25–80% of the particles on a mass basis. This is generally consistent with published PSDs from urban street surfaces. Other studies have reported a dominance of coarser particle sizes (>250 µm) in PSDs from highway and street runoff (Shaheen, 1975; Sansalone et al., 1998).

Sediment concentration in runoff is commonly measured as TSS. The TSS method requires subsampling of the collected water sample, which has been found to result in the underrepresentation of the true sediment concentration (Bent et al., 2003). Alternatively, the suspended sediment concentration (SSC) method measures the sediment concentration of the entire water sample, which provides a more accurate measurement of the true sediment concentration (Guo, 2006).

Although TSS is more commonly used, it has been suggested that TSS measurements are fundamentally unreliable for measuring sediment loads in runoff (Bent et al., 2003). Guo (2006) concludes that a more precise "measurement methodology would lead to a more reliable performance certification process and greater water quality benefits." Accordingly, some testing and certification organizations of proprietary BMPs do require use of SSC measurements. On the other hand, Lenhart (2007) argues that both TSS and SSC should be used to measure BMP performance. He notes that SSC does not usually work within the framework of regulatory requirements, which often specify TSS. Furthermore, SSC measurements can skew BMP performance by showing high mass load reductions when there is diminished or ineffective treatment of the smaller particles that are more strongly associated with some pollutants and are mobilized by smaller, more frequent storms. Lenhart (2007) suggests SSC measurements to assess BMPs that target heavy sediment loads and TSS measurements to assess filtration-type BMPs. For any online BMP and likely many offline BMPs that effectively remove larger materials, the question of TSS versus SSC is likely a non-issue for effluent quality.

Receiving Water Issues of Concern

Excessive levels of sediments and solids in highway runoff contribute to receiving water impacts from high turbidity, sedimentation, loss of aquatic habitat, and channel modification. Sediments in highway runoff also transport other pollutants that adhere to them, such as trace metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and phosphorus. Particulate-bound pollutants can accumulate in receiving waters and have been associated with impacts on aquatic life near highway discharge points (Buckler and Granato, 2003). Trace metals are of particular concern for highway runoff because they can strongly partition to sediments, contributing to exceedance of water quality objectives in receiving waters:

Retrofit Implications

Almost all highway retrofit projects will consider the effects of sediment loadings and sediment treatability due to one or more of the following issues:

- **Sediment impairments may trigger BMP retrofits.** Water quality impairments caused by sediments or particulate-bound pollutants are common in urban receiving waters. Sediment and turbidity TMDLs make up more than 10% of all approved TMDLs, and TMDLs associated with particulate-bound pollutants such as metals, phosphorus, and organics comprise more than a third of all approved TMDLs (USEPA, 2010a). Highway facilities located in TMDL watersheds are likely to be identified as contributing sources and assigned wasteload allocations for the impairing pollutants. This can potentially necessitate retrofit treatment requirements in order to meet the wasteload allocations.
- **Sediment removal is a common performance metric.** Because sediments are surrogates for other pollutants, sediment removal criteria are often performance measures for BMPs and/or programmatic effectiveness. Retrofit treatment objectives may be based solely on meeting regulatory criteria for sediment removal (e.g., 80% TSS removal). In addition, some states use TSS removal as a criterion for evaluating and certifying proprietary BMPs.
- **Sediments in highway runoff influence BMP design.** Because of the prevalence of sediments in highway runoff, all treatment BMPs must be designed to manage the effects of sediment loadings on BMP performance and maintenance. Design considerations include sedimentation mechanisms, storage, trapping and resuspension, clogging of filtration BMPs, maintenance frequency, and access.

The PSD is also a consideration in assessing candidate retrofit BMPs. Coarser particles (>75 μm) are removed relatively easily in BMPs through gravitational settling. For example, Smith (2002) found the vast majority of sediments retained in deep sumped catch basins and oil and water separators are greater than 62 μm. Finer particles, on the other hand, are more difficult to treat, requiring longer settling times or the use of filtration processes. In addition, some pollutants tend to be more strongly associated with finer particles on a particle mass basis due to larger surface area (Grant et al., 2003; Lau and Stenstrom, 2005; Smith, 2002; Wilson et al., 2007). Consequently, treatment effectiveness of particulate-bound pollutants can be constrained by the ability to capture fine particles. Retrofit BMPs that utilize media filtration processes, such as sand filters, are likely to be more effective at reducing fine particulates than sedimentation BMPs such as extended-detention basins (Karamalegos et al., 2005). In addition, testing organizations and regulatory agencies that certify and approve BMPs sometimes require PSD measurements to address uniformity in evaluation results and representativeness to highway conditions.

2.2.3 Metals

Characteristics in Highway Runoff

Metals are ubiquitous in highway and are common pollutants of concern. Copper, lead, zinc, and cadmium are the most routinely monitored and most prevalent metals in highway and urban runoff (Oregon State University et al., 2006). There are numerous sources of metals in ultra-urban highway runoff, including vehicles, highway infrastructure, and atmospheric deposition.

A key attribute of metals is the form in which they are characterized. Metals in highway runoff and receiving waters are commonly measured as total metals (particulate-bound forms plus soluble forms) or as “dissolved” metals based on an operational definition of filtration through a 0.45-micron filter. The partitioning between particulate and dissolved forms depends on chemical and physical factors including pH, alkalinity, temperature, the amount of particulates available, and dissolved and particulate organic carbon (Breault and Granato, 2003; Oregon State University et al., 2006). Thus, considerable variability in particulate and dissolved concentrations has been reported (Grant et al., 2003; Breault and Granato, 2003). Lead, chromium, and copper generally have the highest particulate phase fractions but reported ranges are large (Grant et al., 2003; Breault and Granato, 2003; Barber et al., 2006). In addition, particulate-bound metals are often associated with small and fine particle sizes (Sutherland, 2003; Grant et al., 2003; Pitt et al., 2004; Lau and Stenstrom, 2005; Wilson et al., 2007).

Receiving Water Issues of Concern

Metals in highway runoff can accumulate in receiving water sediments and can contribute to the exceedance of aquatic life standards. At elevated levels, metals can impact aquatic life and potentially contribute to toxicity of aquatic organisms (Grant et al., 2003; Breault and Granato, 2003). Metals can also bioaccumulate in fish tissues, posing potential health risks to humans. Some dissolved metals have been associated with neurophysiological and behavioral responses in salmon, which may cause them to be more susceptible to predation (Sandahl et al., 2007). Receiving water objectives for aquatic life protection are typically developed for dissolved concentrations, with conservative conversion factors (i.e., translators) included for total concentration measurements. In addition, water quality objectives for some metals are a function of hardness, which varies regionally. Increasingly, stormwater sources of metals are being identified as significant contributors to sediment contamination, which could lead to Superfund implications.

Retrofit Implications

Listed impairments and TMDLs are a significant issue of concern for DOTs. Because of the numerous sources of metals in urban areas, urban streams are susceptible to exceedance of aquatic life protection standards for metals, sediment contamination, and toxicity issues. TMDLs for metals account for more than 17% of all TMDLs (USEPA, 2010a). Highway facilities located in such watersheds are likely to be identified as contributing sources. This can potentially trigger retrofit treatment of highway facilities in order to meet DOT wasteload allocations. In the Pacific Northwest, the potential effects of very low levels of dissolved copper in highway runoff on endangered salmon is a primary concern of resource agencies, which can also trigger BMP retrofit requirements.

A primary consideration in the design of BMP retrofits is the treatability of dissolved and particulate phase metals. Different treatment processes are needed to reduce dissolved and particulate concentrations in highway runoff. Sedimentation BMPs that are effective for metals associated with medium and coarse particles will be largely ineffective for dissolved metals and metals associated with very fine particulates. The latter may require use of infiltration BMPs or BMPs that include sorption and fine filtration processes. These considerations have implications for retrofit treatment objectives, BMP selection, design, maintenance, and overall costs.

2.2.4 Organic Compounds

Characteristics in Highway Runoff

Many organic compounds are used for vehicle operation, including fuels, oils, and lubricants. Consequently, ultra-urban highways, which have high ADT, are potentially significant sources of organic compounds in runoff due to accidental spills and drips of fuels and lubricants, deposition from exhaust, and tire wearing. Other potential sources are atmospheric deposition, leachate from asphalt roads and treated lumber such as utility poles, and pesticides and herbicides from highway landscaping.

A large variety of organic compounds with varying physical, chemical, and toxicological properties are potentially found in highway runoff. Semivolatile organic compounds (SVOCs) and volatile organic compounds (VOCs) are two classes of organic compounds that have been studied in highway runoff (Lopes and Dionne, 2003). SVOCs are more likely to be detected in highway runoff. Commonly reported SVOCs include oil and grease, PAHs, and total petroleum hydrocarbons. As a class of compounds, SVOCs are strongly associated with particulates. VOCs such as toluene, xylene, and benzene are common components of fuels but are less commonly monitored and less frequently detected in highway runoff than SVOCs. In fact, most organic constituents are below laboratory detection limits in samples of highway runoff (Smith, 2002; Smith and Granato, 2010).

Oil and grease are used as vehicle lubricants and are therefore common constituents in highway runoff. Runoff concentrations are variable, but are typically less than 10 mg/L, and sometimes spike to 20 mg/L or more (CalEPA, 2006; Caltrans, 2003a). Highest concentrations have been associated with parking lots, urban highways, and industrial land uses (CalEPA, 2006). Oil and grease are composed of many compounds, which individually have different physical, chemical, and toxicological properties. Many components will tend to adsorb and are associated with sediments. Monitoring of oil and grease is typically accomplished with grab samples due to interactions with tubing and pumps for automated samplers. Stenstrom and Kayhanian (2005) found a high degree of correlation between measured dissolved organic carbon (DOC) and oil and grease in highway runoff. They suggested that DOC, which can be reliably measured by automated samplers, can be used as a surrogate for oil and grease measurements.

Receiving Water Issues of Concern

Toxic SVOCs that strongly partition to particulates can accumulate in receiving water sediments, potentially to levels that can impair aquatic life (Lopes and Dionne, 2003; Buckler and Granato, 2003). PAHs, in particular, are of concern because they are often present in urban runoff, they partition to particulates and can accumulate in sediments, and certain PAHs have a high potential for adverse impacts on aquatic health (Grant et al., 2003). Other potentially toxic organic compounds in ultra-urban runoff are PCBs from atmospheric deposition and older pavement joint compounds, and herbicides and pesticides that are applied to highway landscaping.

VOCs are generally considered to have low environmental toxicity at concentrations found in urban stormwater (Lopes and Dionne, 2003). A significant concern of VOCs on highways is the possibility of large fuel spills that can potentially contaminate drinking water supplies.

Excessive levels of oil and grease in highway stormwater discharges can potentially impair aquatic and recreational beneficial uses. Receiving water objectives for oil and grease are often qualitative, requiring the waters to be free of visible floating oils and grease. Certain components of oil and grease are highway pollutants of concern and may have numeric objectives, metals and PAHs, in particular, which can accumulate in receiving water sediments and potentially contribute to aquatic toxicity.

Retrofit Implications

Receiving water impairments and TMDLs that address organics and toxicity, notably from PAHs and oil and grease, can potentially trigger highway BMP retrofits. Many organics have low solubility and will tend to partition to sediments with high organic content. Effective treatability of organics with retrofit BMPs may require filtration and sorption processes.

2.2.5 Litter and Debris

Characteristics in Highway Runoff

Litter and debris are general waste products on the landscape. Litter is composed of manufactured materials such as paper, plastic, wood, cigarette butts, Styrofoam, metal, and glass. Debris is biodegradable organic material such as leaves, grass cuttings, and food waste. Litter and debris are common on ultra-urban highways from intentional and inadvertent littering or dumping, vegetative litter from highway landscaping, and deposition of windblown trash and debris from adjacent urban areas. Several studies have found the composition of litter and debris in highway runoff is dominated by vegetative debris and includes a high proportion of plastics and cigarette butts (Caltrans, 2000; Smith, 2002).

Caltrans Litter Research Program

Caltrans has an ongoing litter research program to evaluate litter management strategies and the effectiveness of various education and treatment BMPs (Caltrans, 2000).

- Measured annual trash loadings from highway monitoring stations are variable, ranging from about 3 to 7.5 kg/area on an air-dried mass basis, or about 20 to 60 L/acre on a volume basis.
- The composition of litter and debris is dominated by vegetative material, accounting for 75% to 87% by weight of all material collected.
- A high proportion of the litter composition was from smoking- and food-related waste (20% to 30% by weight and volume).

Receiving Water Issues of Concern

The presence of excessive litter and debris in receiving waters can result in the impairment of recreational uses and can increase the biochemical oxygen demand. Litter and debris can also impact aquatic habitat by inhibiting growth of aquatic vegetation, decreasing spawning areas, or directly impacting wildlife that ingest or become entangled in trash.

Retrofit Implications

The USEPA has listed trash impairments in several states, and trash TMDLs are established in California (USEPA, 2010a). In watersheds with established TMDLs, DOTs are required to meet TMDL wasteload allocations for highway facilities. This requirement can potentially necessitate retrofit BMPs. For example, the trash TMDL for the Los Angeles River Watershed has a wasteload allocation of "zero" trash in all municipal separate storm sewer system (MS4) discharges, to be achieved over a 10-year implementation period. Treatability of trash and debris requires screening and capture processes. In watersheds with comparatively large trash loads, effective treatment of trash will require greater BMP storage capacity, and/or more frequent maintenance.

2.2.6 Nutrients

Characteristics in Highway Runoff

Nutrients are inorganic forms of nitrogen (nitrate, nitrite, and ammonia) and phosphorous. Organic forms of nitrogen are associated with vegetative matter such as particulates from sticks and leaves. Total Kjeldahl nitrogen (TKN) is a measure of organic nitrogen plus ammonia.

Phosphorus in runoff occurs in dissolved and particulate forms. Particular matter includes organic debris and phosphorous adsorbed to soil particles. Phosphorus is measured as total phosphorus (TP), orthophosphate (the biologically available form), and soluble phosphate (orthophosphate and organic phosphorus) (Oregon State University et al., 2006).

Nutrients are commonly present in highway runoff and are generally more prevalent in runoff from other urban land uses (Table 2.2). The sources of nutrients include automobile exhaust, atmospheric deposition, and runoff from highway landscaping and cut slopes. Groundwater inflow into storm drains/slope drains has also been identified as a source of phosphorus in areas where phosphorus is naturally high in groundwater or historical uses (e.g., farming) have contributed to elevated phosphorus.

Maryland SHA Nutrient Management

The Maryland State Highway Administration (SHA) is implementing nutrient reduction initiatives to address exceedances in TMDL nutrient objectives. Measures include:

- Detailed geographical information system (GIS) mapping of nutrient and sediment impairments overlaid with SHA impervious surfaces and stormwater BMPs to assist in prioritization and deployment of BMPs
- BMP research and development, including: swale design and effectiveness monitoring studies; optimization of bioretention media for nutrient removal through laboratory measurement of sorption isotherms and vegetated column studies; and wet infiltration basin transitional performance assessment studies
- Reduction in fertilizer use through active nutrient management programs based on soil testing
- Pilot projects on the use of native meadow vegetation that have reduced mowing and fertilizer requirements

Receiving Water Issues of Concern

Nutrients are biostimulatory substances that can cause excessive or accelerated growth of vegetation, such as algae, in receiving waters. Eutrophication due to excessive nutrient input can lead to changes in algae, benthic, and fish communities; extreme eutrophication can cause hypoxia, resulting in fish kills. Surface algal scum, water discoloration, and the release of toxins from sediment can also occur.

Retrofit Implications

Listed impairments and TMDLs for nutrients are a significant issue of concern for DOTs in nutrient-sensitive areas and can potentially initiate retrofit treatment requirements, for example in the Chesapeake Bay watershed. Nutrient TMDLs account for about 10% of all approved TMDLs (USEPA, 2010a). Retrofit treatability of nutrients can be difficult and may require multiple treatment processes. Particulate-bound nutrients including phosphorus and organic nitrogen are removed by sedimentation and filtration processes, whereas soluble nutrients including orthophosphate and nitrate are more difficult to remove requiring sorption and/or biologically mediated processes. Some DOTs are actively studying BMP processes and designs for enhanced treatment of nutrients (SHA, 2009).

2.2.7 Chlorides

Characteristics in Highway Runoff

In many parts of the nation, deicing activities are the primary source of chloride in highway and urban runoff. Deicing activities are routinely conducted in cold weather regions for public safety, and urban areas in particular receive greater and more responsive deicing activities due to large ADT. Sodium chloride is the most commonly used deicer due to low cost of the material. Alternatives to sodium chloride are traction sanding and more costly chemical deicers, including calcium chloride, magnesium chloride, and calcium magnesium acetate.

Sodium chloride readily dissolves into sodium and chloride ions in runoff. Chloride ions are very mobile in the environment and are conservative; they do not degrade, adsorb to solids, or volatilize. Thus, chloride is readily transported with highway runoff to surface receiving waters and can infiltrate and migrate to groundwater (Kunze and Sroka, 2004). Sodium ions are less mobile and will tend to accumulate on sediments but can leach to groundwater supplies (MassHighway, 2006). The concentration of chloride and sodium ions in receiving waters is diminished by mixing and dilution, especially in surface waters.

Receiving Water Issues of Concern

DOT studies have found that road salting is not a widespread environmental threat and that impacts from road salting are site specific with greatest impacts occurring near the place of application where concentrations are greatest (MIDOT, 1993). Other reports have found that chloride concentrations in receiving waters may be diluted to concentrations for which there are little measurable effects (MDT, 2004). However, elevated chloride concentrations in highway runoff and splash zones do cause damage or kill roadside salt-intolerant vegetation, reduce plant and invertebrate diversity, and impair groundwater supplies and surface receiving waters. Road salt may also have impurities such as nitrogen, phosphorus, copper, and cyanide that are discharged to receiving waters with snow melt. The United States Geological Survey (USGS) found that levels of chloride are elevated in many urban streams and groundwater across the northern United States, and that increases in chloride levels in streams during the last two decades are consistent with overall increases in salt use in the United States for deicing (Mullaney et al., 2009). Road salting has been linked to exceedances of drinking water standards for sodium in groundwater supply wells (MassHighway, 2006). Listed impairments and TMDLs for chloride due to deicing activities can potentially trigger changes in snow removal practices.

Retrofit Implications

Chloride is not effectively removed with traditional treatment BMPs. Control of chloride requires reducing sources via snow removal practices, including less frequent deicing, and use of alternative deicers. Many alternative deicers, however, can increase loadings of biochemical oxygen demand (BOD) to BMPs and receiving waters.

2.2.8 Indicator Bacteria

Characteristics in Highway Runoff

Pathogens are viruses, bacteria, and protozoa that can cause gastrointestinal and other illnesses in humans through body contact exposure. Identifying pathogens in water is difficult as the number of pathogens is exceedingly small. Traditionally, water managers and regulatory agencies have relied on measuring "fecal indicator bacteria," such as fecal coliform bacteria, as indirect measures of the presence of human pathogens and, by association, human illness risk. However, indicator bacteria are not reliable markers of actual human pathogens in highway runoff due in part because there are many non-human sources of indicator bacteria in highway runoff including bird and wildlife droppings, roadkill, trucks hauling livestock and livestock waste, and sediments from highway landscaping.

Highway monitoring studies have found variable and elevated levels of indicator bacteria in highway stormwater runoff, often above receiving water objectives (Barrett et al., 1995b; Smith, 2002; Caltrans, 2003a; Herrera Environmental Consultants, 2007). However, in a detailed monitoring study conducted by the California DOT (Caltrans), actual human pathogens were infrequently detected in runoff from exclusive highway drainages and mixed use drainages (Caltrans, 2002b). The Caltrans study supports the common belief that highway facilities are generally not a significant source of human contamination and human pathogens.

Receiving Water Issues of Concern

Although there is ongoing debate on the health effects of exposure to receiving waters of direct and recent stormwater runoff (WERF, 2007), indicator bacteria are ubiquitous in urban runoff and concentrations frequently exceed receiving water objectives. Consequently, receiving water impairments and TMDLs for indicator bacteria are widespread in urban centers. Bacteria TMDLs account for almost 20% of all approved TMDLs (USEPA, 2010a).

Retrofit Implications

Highway facilities in urban centers that discharge into TMDL-listed receiving waters may be assigned waste load allocations that trigger retrofit treatment requirements. Because highways are not common sources of human pathogens, initial retrofit studies should include source identification efforts of indicator bacteria, such as illicit connection testing, identification of off-site contributions, wildlife sources in landscaped areas, and possibly highway sources such as trucks hauling livestock. If specific sources are identified, then source control efforts may be sufficient to meet retrofit objectives. If needed, effective retrofit treatment of indicator bacteria requires media filtration processes or advanced disinfection systems.

2.3 Ultra-Urban Influences on Highway Runoff Quality

2.3.1 ADT and Adjacent Land Use

Pollutant levels in ultra-urban highway runoff are generally greater than in runoff from other highway facilities. Dense urban development and high ADT are primary factors that are associated with higher pollutant levels in urban highway runoff. Their influence, however, is difficult to separate as both are found in dense urban areas (Driscoll et al., 1990; Irish et al., 1995; Smith and Granato, 2010).

Concentrations of contaminants in highway runoff have been found to increase as the adjacent land use becomes increasingly urban (e.g., Driscoll et al., 1990; Kayhanian et al., 2003, 2007), in particular industrial and commercial land uses (Driscoll et al., 1990; Caltrans, 2003a). Recently, Smith and Granato (2010) monitored highways with similar ADT and different total impervious fractions within a 1-mi radius. They found an order of magnitude difference in concentrations at highways with similar ADTs but with imperviousness in the 20–30% and 41% ranges, which suggests that surrounding land use (airborne deposition) may be a major source of constituents found in highway runoff from these areas. The surrounding land use affects the amount of pollution in dustfall deposited on a highway, which affects the ensuing quality of highway runoff (Barrett et al., 1995b).

There is also an association between ADT and increasing levels of pollutants in highway runoff (Driscoll et al., 1990; Barrett et al., 1995a; Caltrans, 2003). Highway monitoring studies have shown greater runoff concentrations at sites with higher ADT, with a consistent pattern for conventional constituents and trace metals with few exceptions (Barrett et al., 1995a; Caltrans, 2003). Caltrans (2003) noted that ADT is an important predictor of pollutant concentration and an important factor in prioritizing management alternatives. Other studies have found that runoff concentrations do not correlate directly with ADT, and there are contributing co-factors (Driscoll et al., 1990; Barrett et al., 1995a; Kayhanian et al., 2003). Pollutant concentrations correlated to ADT only in conjunction with numerous other factors, including total event rainfall, seasonal cumulative precipitation, antecedent dry period, surrounding land use, vegetation, soil characteristics, pervious versus impervious area, and rainfall intensity (Barber et al., 2006).

Greater pollutant concentrations expected in ultra-urban highway runoff pose challenges and constraints as well as opportunities for BMP selection and treatment performance, especially in areas with established loading limits (TMDLs) to receiving waters. Because land use and ADT only partially explain elevated pollutants concentrations, other factors must be considered for the estimation of runoff concentrations when there is an absence of site-specific monitoring data.

2.3.2 First Flush Phenomena

First flush is the concept that the highest pollutant concentrations and loads occur in the first portions of the runoff hydrograph. Many monitoring studies have noted first flush for a variety of constituents and land uses; however, first flush is not always present for all constituents or for all land uses, or may not be significant (e.g., Roseen et al., 2006; Flint, 2004; Strecker et al., 2005; Sansalone and Cristina, 2004). A number of highway monitoring studies have reported first flush in highway runoff (Barrett et al., 1995a; Irish et al., 1995; Sansalone and Buchberger, 1997; Oregon State University et al., 2006; Caltrans, 2003a; Stenstrom and Kayhanian, 2005).

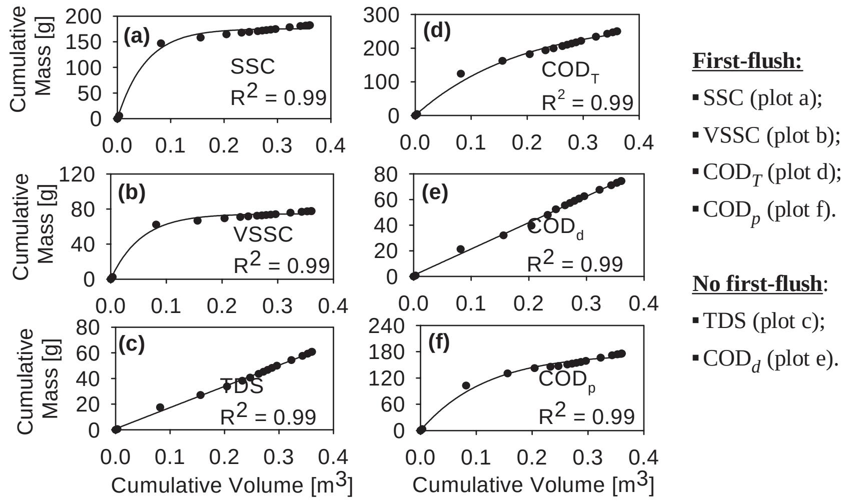
> **Caltrans First Flush Characterization Study**
>
> Caltrans conducted a comprehensive first flush characterization of highway runoff from ultra highway catchments in southern California (Stenstrom and Kayhanian, 2005).
>
> - ADT ranged from 260,000 to 328,000.
> - Monitoring data showed significant and generally consistent first flush behavior for many dissolved and particulate-bound pollutants.
> - Between 30% to 50% of the pollutants in highway runoff from a single storm event were contained in the first 10% to 20% of the runoff volume.

One way to determine first flush is to plot runoff versus mass load for individual storm events and pollutants, as shown in Figure 2.1. First flush is indicated when a large fraction of the total pollutant load occurs disproportionately in the early runoff. Quantitative measures of mass first flush have been developed, for example, 50% of the mass load in the first 25% of runoff (Wanielista and Yousef, 1993) or, more generally, the mass first flush ratio (Stenstrom and Kayhanian, 2005).

Maestre et al. (2004) found that first flush occurs with greater frequency from land uses with high impervious cover and in simple watersheds where the peak intensity is near the beginning of the storm. Such conditions are typical of ultra-urban highway environments. Therefore, first flush is more likely in ultra-urban highway environments than in other land use types due to:

- **Small catchment areas and simple watersheds,** which have been associated with high pollutant concentrations (Caltrans, 2003a; Kang et al., 2008b);
- **High fractions of impervious cover** that can produce rapid runoff response and high flow rates that mobilize pollutants; and
- **Greater and more widely distributed pollutant sources** from tire/road wear, cars, highway infrastructure, run-on from adjacent urban areas, and atmospheric deposition.

First flush in highway runoff affords opportunities for more efficient or effective BMP design (Stenstrom and Kayhanian,



SSC = Suspended sediment concentration
VSSC = Volatile suspended sediment concentration
TDS = Total dissolved solids

COD_T = Chemical oxygen demand - total
COD_p = Chemical oxygen demand - particulate
COD_d = Chemical oxygen demand - dissolved

Source: WERF (2005)

Figure 2.1. Illustration of first flush.

2005; Kayhanian and Stenstrom, 2008; Kang et al., 2006; Tucker, 2007). Some examples of first flush BMP designs are:

- Inlet control devices to limit mixing and dilution with bypass flows,
- Outlet controls to operate detention facilities in batch mode, and
- Two-compartment basin designs.

Using first flush as a basis for BMP design is generally not a reliable practice because first flush is not always present or can be overwhelmed by periods of high rain intensity in the later portions of the storm (Strecker et al., 2005). However, in ultra-urban retrofit situations BMP design options are likely to be limited by space and budget constraints. In this case, first flush as a basis for BMP design is suitable and appropriate provided data support first flush behavior of the primary target constituents, and space and budget constraints justify reduced BMPs sizing.

2.3.3 Climatic and Hydrologic Factors

There is an association between runoff quality and antecedent dry period. In the arid west where there is a distinct wet and dry season, highway monitoring studies have measured greater pollutant concentrations in the early season storms, greater concentrations with increasing duration of antecedent dry period, and decreasing concentration with increasing cumulative rainfall during the wet season (Stenstrom and Kayhanian, 2005; Caltrans, 2003a). This evidence has led to the concept of a "seasonal first flush."

Stenstrom and Kayhanian (2005) suggest seasonal first flush affords opportunities for designing BMPs that target the early season storms, for example, designing and operating infiltration basins that have dried out over the dry season to capture and retain the first few storms of the wet season. Another option is seasonally focused source control efforts to remove accumulated pollutants from surfaces and drainage systems prior to the onset of winter storms.

Storm characteristics (depth, duration, intensity, interevent time, etc.) can also influence retrofit design and performance. Runoff and associated loadings increase with storm depth and impervious fractions that are characteristically large in ultra-urban catchments. Storm duration and rainfall intensity often have an inverse relationship with runoff concentrations—shorter storm durations and lower rainfall intensity produce higher runoff concentrations (Caltrans, 2003a). However, this relationship is not consistent for all parameters. For example, increasing rainfall intensity has been found to significantly increase sediment concentrations in runoff from highway construction sites (Pitt, 2001). It would also be expected to increase sediments arising from landscaped areas when they begin to contribute to runoff. Local storm characteristics will normally be reflected in DOT sizing and design criteria for BMPs. However, in space-constrained retrofit situations, site-specific sizing and design may be warranted.

2.3.4 Cold Climate Factors

In cold climate regions, snow accumulation and snow removal practices affect highway runoff volumes, highway runoff quality, and BMP performance.

During cold weather, treatment systems can experience periods of no runoff followed by large volumes of runoff due to rapid snowmelt and/or rain-on-snow events. In other cases, melts can provide slow steady flows with low TSS. Thawing of accumulated roadside snow packs can lead to significant runoff periods and runoff volumes. Rain-on-snow events can produce extreme runoff volumes. The hydrologic loading from snowmelt, however, is difficult to predict. Snowmelt processes depend on many factors including the volume and nature of the accumulated snow pack, snow removal practices, and environmental factors including temperature, precipitation, and freeze-thaw cycles.

Pollutants from vehicles, vehicle exhaust, and atmospheric deposition partition into and accumulate in snow banks over extended periods. Consequently, snowmelt typically has elevated pollutant concentrations in comparison to rainfall runoff. Snow removal practices such as plowing and removal of snow and use of chemical deicers and traction sand also affect runoff concentrations or are direct sources of pollutants. Pollutants most likely to be elevated in snowmelt are sediment, particulate-bound pollutants particularly metals and PAHs, salts from chemical deicers, chemical oxygen demand (COD), and oil and grease (Driscoll et al., 1990; Sansalone and Buchberger, 1996; Glenn, 2001). pH levels in snow are often low, which can change the portioning of pollutants with particulates.

Cold weather conditions pose challenges for sizing and design of retrofit BMPs in space-constrained settings, including:

- Greater hydrologic and pollutant loading;
- Reduced treatment performance due to reduced infiltration rates, reduced biological activity, and reduced settling velocities;
- Ice cover on permanent pools; and
- Pipe freezing and inlet clogging.

Targeted snow removal may be a method to reduce loadings associated with snowmelt. For example, in Lake Tahoe, snow is moved to specific snowmelt areas that drain to BMPs

Table 2.3. Sources of highway runoff information.

Organization	Topics/Description	References
FHWA	In 1990 FHWA published results of a nationwide highway stormwater monitoring study from 31 highway sites in 11 states. Site event mean concentrations were developed and factors influencing highway pollutant loads were investigated. The database includes a computer program to evaluate highway pollutant loadings and the associated receiving water impacts.	http://ma.water.usgs.gov/fhwa/90Model/ Driscoll et al. (1990)
USGS stormwater database	Comprehensive database of 103 highway-runoff monitoring sites in the conterminous United States, as documented in seven selected highway-runoff data sets. These data include the 1990 FHWA runoff-quality model data compilation and results from six other data sets collected during the period 1993–2005.	http://ma.water.usgs.gov/fhwa/SELDM.htm
NSQD	The National Stormwater Quality Database (NSQD) was developed by the University of Alabama and the Center for Watershed Protection in 2004. The database consists of nearly 10 years of stormwater outfall data collected by MS4 permit holders throughout the United States.	http://rpitt.eng.ua.edu/Research/ms4/mainms4.shtml
Caltrans	Caltrans publications listing for monitoring and applied studies	http://www.dot.ca.gov/hq/env/stormwater/ongoing/index.htm
	Litter research program – publications listing	http://www.dot.ca.gov/hq/env/stormwater/ongoing/litter_management/index.htm
	Statewide runoff characterization for DOT facilities	Caltrans (2003a)
	Toxicity associated with particles in highway runoff	Grant et al. (2003)
	First flush characterization	Stenstrom and Kayhanian (2005)
Texas DOT	Highway runoff characterization in the Austin area	Barrett et al. (1995a)
	Investigation of factors affecting highway runoff	Irish et al. (1995)
	Receiving water impacts of bridge deck runoff	Malina et al. (2005)
Washington State DOT	Publications listing of stormwater research reports	http://www.wsdot.wa.gov/Environment/WaterQuality/Research/Reports.htm
	Heavy metals in highway runoff	Barber et al. (2006)
	Summary of 5-year statewide highway monitoring program	Mar et al. (1982)
Research Organizations	UT Austin - Center for Transportation Research, Searchable library.	http://www.utexas.edu/research/ctr/

versus allowing the snow to stay in areas where it cannot be treated effectively.

2.4 Sources of Water Quality Information to Support Retrofit Planning

Compiling and evaluating existing runoff data is the first step in characterizing highway runoff and receiving water quality. The most common sources of runoff data follow:

- **DOT monitoring data:** DOTs are the best source of highway runoff data. Most DOTs have historical or ongoing stormwater monitoring programs to characterize runoff from their facilities. Ideally, site-specific or regional DOT runoff data will be available that can be used to characterize DOT contributions to receiving waters issues of concern and to support retrofit BMP selection and design. DOTs also sponsor research on highway runoff and receiving water impacts. Table 2.3 includes references to selected DOT runoff data and sponsored research studies.
- **Municipal stormwater programs:** Metropolitan areas adjacent to ultra-urban highways are likely to be permitted under Phase I NPDES rules and in some cases the DOTs may be co-permittees with the municipal programs. Municipal stormwater programs routinely collect water quality monitoring data of MS4 discharges.
- **Regulatory agencies and studies:** State and federal environmental agencies routinely compile runoff monitoring data, often for the Section 303(d) water quality impairments designations and semiannual reports, and for source analysis in TMDL documents.
- **Regional databases:** Regional and national highway runoff quality data that have been subjected to rigorous statistical testing can serve to fill data gaps. Several of these databases are listed in Table 2.3.

SECTION 3

Retrofit Drivers and Practices

Various state and federal regulations are the basis for highway water quality retrofits. However, retrofit mandates vary significantly among individual DOTs. This section describes the regulatory triggers for BMP retrofits and DOT experiences and practices with BMP retrofits. This information is relevant for understanding the regulatory drivers that currently and potentially affect DOTs, and secondly, for drawing on DOT experiences and approaches for addressing retrofit requirements.

3.1 Regulatory Drivers of BMP Retrofits

Regulatory drivers are the main impetus for most BMP retrofits. Historically, water resources regulations affecting highway projects have mainly focused on construction and post-construction BMPs associated with new highway construction. However, there is an increasing trend in environmental regulations for protection and enhancement, and retrofitting requirements are expected to receive greater consideration in future USEPA stormwater rulemaking (USEPA, 2009). A number of federal regulations can provide the basis for retrofit mandates, including the:

- Clean Water Act,
- NPDES Permitting Program,
- Water quality impairments and TMDLs,
- Endangered Species Act,
- Underground injection controls regulations, and
- State and local requirements.

3.1.1 Clean Water Act

The USEPA regulates water quality under the CWA, also known as the Federal Water Pollution Control Act. Enacted by the federal government in 1972, and significantly amended in subsequent years, the CWA is designed to restore and maintain the chemical, physical, and biological integrity of waters of the United States. The CWA provides the legal framework for several water quality regulations that can impose BMP retrofit requirements.

3.1.2 National Pollutant Discharge Elimination System Permit Program

Section 402 of the CWA authorized the NPDES permit program. Under this program, a permit is required for facilities that discharge pollutants from point sources into waters of the United States. Phase I of the program regulated medium and large MS4s that serve areas with a population of 100,000 or greater, and Phase II expanded coverage to small MS4 in urbanized areas. NPDES permits are also required for point discharges from DOT-owned industrial facilities and construction activities.

Most states are authorized to administer the NPDES permit program, but the USEPA remains the permitting authority in a few states and territories. Delegated authorities have a certain amount of discretion in permitting approaches and conditions. As a result, NPDES permit requirements vary among permitting agencies and EPA regions, as well as in response to specific receiving water issues. Thus, a variety of NPDES permitting strategies are applied to state DOTs. Within Phase I and Phase II coverage areas, an NPDES permit may be issued to state DOTs and DOT districts, or DOTs may be co-permittees with local municipalities. In some states, DOTs are issued DOT-specific Phase I NPDES permits with statewide coverage. These permits are tailored to DOT activities, and often are more prescriptive with expanded requirements.

NPDES MS4 permits can explicitly mandate DOTs to implement specific water quality retrofit requirements, such as stand-alone retrofits, retrofits associated with highway improvement projects, or retrofit evaluation studies. Examples include Phase I permits issued to the North Carolina DOT and the Washington State DOT (WSDOT). In the case of WSDOT, recent litigation has expanded retrofit requirements in the Puget Sound region.

Highway BMP retrofit requirements are expected to extend to more DOTs with the increasing trend toward more DOT-specific MS4 permits, as well as greater consideration of retrofitting requirements in the USEPA stormwater rulemaking (USEPA, 2009). In addition, TMDLs and CERCLA contaminated sediment efforts will likely result in retrofit requirements in subsequently issued NPDES permits and/or USEPA- or state-issued orders.

3.1.3 Water Quality Criteria, Impairments, and TMDLs

In accordance with the CWA, the USEPA developed national water quality criteria (National Toxics Rule, or NTR) that are designed to protect the aquatic health of water bodies. The CWA requires state water quality programs to designate uses for all state waters, establish water quality criteria to meet those uses, and institute an antidegradation policy for waters that meet or exceed criteria for existing uses. The state water quality criteria must include both numeric standards for quantifiable chemical properties and narrative criteria or criteria based on biomonitoring. Some states have adopted the NTR criteria, while others adapted the NTR criteria or developed their own criteria (e.g., the California Toxics Rule [CTR]).

Section 303(d) of the CWA requires the states to prepare a list of water bodies that are compromised or "impaired" by water quality based on an assessment and determination of meeting water quality objectives. The 303(d) list is prepared every 2 years and submitted to the USEPA for approval. Once a water body has been deemed impaired, a TMDL must be developed for the impairing pollutant(s). A TMDL is an estimate of the total load of pollutants from point, non-point, and natural sources that a water body may receive without exceeding applicable water quality standards (plus a "margin of safety"). Once established, the TMDL allocates the loads (waste load allocations) among current and future pollutant sources to the water body. The TMDL includes an implementation plan for achieving the waste load allocations.

TMDLs are a major driver of BMP retrofits. Due to their linear nature, urban highways cross numerous watersheds and many of these watersheds will have approved TMDLs, especially in urbanized areas where anthropogenic impacts are more profound. DOTs may literally have hundreds of waste load allocations for numerous pollutants and receiving water bodies, even in cases when highways are not significant sources of impairing pollutants. The waste load allocation can be expressed in terms of loads (e.g., zero trash loads) or in terms of concentration limits. To meet waste load allocations, DOTs may need to implement BMP retrofits to address loadings from existing highway facilities. For example, Caltrans and DCDOT are researching and implementing BMP retrofits to address trash TMDLs. In the Lake Tahoe Basin, BMP retrofits are required as part of the TMDL. Applicable TMDL requirements must be incorporated into NPDES permits as they are renewed.

3.1.4 Section 401 Water Quality Certification and Section 404 Permits

Section 401 of the CWA requires that any applicant for a federal permit that may result in a discharge of pollutants into waters of the United States must obtain a state water quality certification that the activity complies with all applicable water quality standards, limitations, and restrictions. No permit may be issued by a federal agency until certification required by Section 401 has been granted. A state-issued Section 401 water quality certification is needed for DOT projects that require a federal permit, for example, highway improvement projects that require a Section 404 permit (see next paragraph). The certification process differs from state to state, and some states may be involved early in the project's development to affect BMP selection and design. Thus, the water quality certification can potentially impose conditions on the project, including retrofit treatment, which will become a part of the federal permit.

Section 404 of the CWA establishes a program to regulate the discharge of dredge and fill material into waters of the United States, including wetlands. These permits regulate discharges that alter substrate elevation or contours, suspended particulates, water clarity, nutrients and chemical content, current patterns and water circulation, water fluctuations, and salinity gradients. Regulated activities include fills for development, water resource projects, infrastructure development (such as highways and airports), and conversion of wetlands to uplands for farming and forestry. The USEPA and the US Army Corps of Engineers (USACOE) jointly administer the program. The USACOE oversees day-to-day administration of the program, including issuing individual or general permits. DOT projects that result in construction and stormwater management adjacent to or across waters of the United States may be required to obtain a Section 404 permit. The permit may have requirements for stormwater treatment and discharge activities, potentially including retrofit treatment requirements that are developed as part of the water quality certification.

3.1.5 Endangered Species Act

The ESA of 1973 provides a means to protect endangered and threatened species and the ecosystems upon which they depend. The US Fish and Wildlife Service (USFWS) has jurisdiction over terrestrial and native freshwater species, and the

National Marine Fisheries Service (NMFS) is responsible for listings of marine species or anadromous species. The USFWS and NMFS determine the critical habitat for the maintenance and recovery of endangered species, and require that the impacts of human activities on species and habitat be assessed. If the biological assessment finds that the endangered species may be affected by the proposed project, then the DOT must work with the USFWS or NMFS to develop mitigation measures for the project, which can potentially include retrofit treatment of existing highway infrastructure. The mitigation measures may potentially include requirements for retrofit treatment of existing highway facilities associated with the project. This is the case for many DOT projects in the Pacific Northwest, where critical habitat for endangered salmon species occurs in numerous watersheds that are traversed by highways, including watersheds in dense urban centers. Ultimately, the ESA may result in stricter water quality goals than state water quality standards.

3.1.6 Underground Injection Control Program and the Safe Drinking Water Act

Underground injection controls (UICs) are subsurface distribution and fluid disposal systems. There are five types of UICs based on USEPA classification. Class V UICs are for the disposal of non-hazardous fluids, such as on-site waste disposal systems and stormwater disposal systems such as dry wells and soakage trenches. The USEPA defines a Class V well as any bored, drilled, or driven shaft or dug hole that is deeper than its widest surface dimension, or an improved sinkhole, or a subsurface fluid distribution system (an infiltration system with piping to enhance infiltration capabilities). Stormwater disposal in dry wells is the most common stormwater management practice in regions with favorable geology. Thousands of dry wells are in operation throughout the country, including DOT-operated facilities.

The UIC program is a federal program under the Safe Drinking Water Act (SDWA) and Title 40 of the Code of Federal Regulations (CFR) Parts 144-148, designed to prevent groundwater contamination from injection wells. The UIC program is administered by the USEPA, but many states are delegated permitting authorities. Because of the potential to contaminate drinking water supplies, the USEPA implemented new rules for Class V injection wells in 1999. The UIC rules include a number of prohibitions on the use of UICs and require all Class V UICs to be registered and regulated through rule-authorization or area-wide permits. Depending on the location and number of UICs and applicable permit requirements, UIC owners can be required to develop and implement stormwater management programs, conduct UIC evaluation studies, and conduct UIC monitoring programs. In addition, UIC owners, including DOTs, can be required to construct pretreatment retrofits of existing UICs to ensure compliance with drinking water standards prior to injection.

3.1.7 Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), commonly referred to as Superfund, is a federal law that provides broad authority to clean up sites that are contaminated with hazardous substances such as contaminated groundwater and contaminated sediments. Remedial actions under CERCLA require the control of potential upstream sources of recontamination, for example, groundwater flows, overland flow, and riverbank erosion. Contaminants in stormwater are also a potential source of contamination and recontamination, but NPDES-permitted stormwater dischargers have not historically been subject to CERCLA liability under the federally permitted releases exemption. A recent ruling, however, found that WSDOT was liable for CERCLA cleanup costs because WSDOT "arranged for the disposal" of stormwater by designing drainage systems for the three highways that discharge to a Superfund contaminated sediments site. Although the ruling is under appeal, it has implications for implementing effective treatment of highway stormwater discharges to Superfund sites, potentially through BMP retrofitting of highway facilities.

3.2 DOT Retrofit Experiences

There is a range of retrofit practices and policies among state DOTs reflecting differences in regional water quality issues and regulatory requirements by permitting agencies. DOT retrofit practices and policies fall into three general categories:

- **No documented retrofit policies.** Many DOTs have not developed formal retrofit practices in their stormwater manuals, hydraulic design manuals, or management plans, but retrofit projects may be implemented on an individual project basis.
- **Developing retrofit policies.** Some DOTs have initiated retrofit evaluation studies and development of retrofit prioritization procedures.
- **Established retrofit program and requirements.** A few DOTs have established stormwater retrofit practices that are documented and formalized through policy and programmatic procedures.

Washington State DOT: WSDOT has an established stormwater retrofit program. WSDOT's Phase I NPDES permit requires three categories of stormwater retrofits: (1) capital improvements funding for stand-alone stormwater retrofits; (2) project-triggered stormwater retrofits, implemented in conjunction with highway improvement projects; and (3) opportunity-based retrofits. Recent modifications to the NPDES permit resulting from a settlement agreement will expand stormwater project-triggered retrofit requirements in the Puget Sound region. WSDOT has implemented more than 65 stand-alone stormwater retrofit projects since 1995, and project-triggered retrofit requirements are routinely implemented on highway projects (WSDOT, 2008b).

WSDOT has established programmatic retrofit procedures that are integrated into the state's Highway Runoff Manual (WSDOT, 2008a). The procedures are used to determine minimum cost-effective retrofit requirements associated with project-triggered highway projects, including assessment of off-site retrofits. For stand-alone and opportunity-based retrofits, WSDOT initially developed an outfall prioritization scheme based on numeric scoring procedures (WSDOT, 1996; Barber et al., 1997). The highest priority outfalls were found to be concentrated in urban areas that discharge to small streams. To achieve more consensus on the procedures, WSDOT updated the outfall prioritization procedure based on collaboration with the Washington State Department of Ecology, National Oceanic and Atmospheric Administration (NOAA) Fisheries, and the USFWS. A tiered approach is used. The first screen uses geographical information systems (GIS) and existing information to identify high scoring areas. The second stage is based on field assessment and coordination with local area biologists to identify problem areas and recovery strategies. Coordination and upfront buy-in with the regulatory and resource agencies was a programmatic breakthrough for retrofit prioritization.

North Carolina DOT: The North Carolina DOT (NCDOT) Phase I NPDES permit requires implementation of 14 stand-alone stormwater retrofits per year, and development of a prioritization process. Retrofit prioritization is based on assessment of high ADT roads and sensitive waters, and on field assessments to identify constraints and opportunities. NCDOT has identified retrofit opportunities at rest areas, which tended to be hotspots; at interchanges near shellfish waters; and in watersheds with TMDL waters. It has also partnered with municipalities in developing off-site retrofits. NCDOT has constructed 43 stand-alone retrofit projects, with another 23 in the planning stages (NCDOT, 2008a). They have implemented a variety of conventional BMPs including dry and wet ponds, bioretention, sand filters, infiltration basins, swales wetlands, and catch basin inserts.

NCDOT actively coordinates with researchers, contractors, and maintenance personnel to assess and improve retrofit activities. NCDOT has a strong partnership with North Carolina State University and sponsors research on BMP development and evaluation, including bioretention, biofiltration, and permeable friction overlays. They coordinate with contractors to work out design issues and seek feedback from maintenance crews on BMP maintenance practices and issues. Ongoing coordination advances NCDOT's retrofit program by expanding the knowledge base on effective BMP selection, efficient BMP design and construction, and practical BMP maintenance.

Caltrans: The California Department of Transportation (Caltrans) routinely implements stormwater retrofits in conjunction with major redevelopment projects (Caltrans, 2008). In addition, Caltrans implements stand-alone stormwater retrofits to comply with NPDES permit requirements, to comply with court orders or state water resources board orders, or to meet watershed-specific requirements [e.g., TMDLs, Lake Tahoe Environmental Improvement Program (EIP), Areas of Special Biological Significance (ASBS), and the California Ocean Plan (COP)].

Caltrans also has an active retrofit pilot test program for evaluating alternative BMPs. The program is designed to study and evaluate all aspects of stormwater retrofits for highway facilities, including design and construction, capital and maintenance costs, treatment effectiveness, and operations and maintenance (O&M) requirements. The program is also used to support BMP certification. The ongoing program has produced a number of pilot test data reports on a wide variety of BMP types.

Caltrans conducted a comprehensive BMP retrofit pilot study for highway infrastructure (Caltrans, 2004). This study evaluated a wide range of BMPs that were installed as retrofit applications along freeways and in Caltrans facilities. The study included cost information tracking, performance monitoring assessments, and information about maintenance practices (Currier and Moeller, 2000; Currier et al., 2001).

SECTION 4

BMP Options for Ultra-Urban Highway Retrofits

This section describes BMP options for ultra-urban highway retrofit applications. The available approaches include traditional non-proprietary BMPs such as detention basins, and a variety of proprietary BMPs that have been developed and adapted specifically for space-constrained environments.

4.1 Overview of BMP Options

Table 4.1 summarizes the BMP options for highway retrofits. In this report, BMP options are grouped into 10 retrofit categories based upon their design characteristics, target pollutants, and applicability to surface and underground applications. The subsequent sections describe specific BMP types and configurations within each of the 10 retrofit categories and provide sources for more information on BMPs.

4.2 Catch Basin Retrofits

4.2.1 Options

Incorporating BMPs into existing stormwater collection and conveyance systems is a rational approach for minimizing site disturbances and costs of retrofitting. Existing catch basins are a logical target for BMP retrofits. The options for catch basins retrofits include:

- Installing catch basin inserts;
- Modifying/retrofitting catch basins to increase sediment storage and capture, for example using deep sumped catch basins or sediment traps;
- Incorporating proprietary BMPs into catch basins; and
- Installing a "water quality" catch basin just upgradient of existing inlets to intercept water quality flows for treatment.

The main concerns of catch basin retrofits are: (1) can the BMP retrofit provide adequate performance and (2) can the BMP be adequately maintained? Table 4.2 summarizes the BMP options for catch basin retrofits and the following subsections further describe the catch basin retrofit options.

4.2.2 Catch Basin Inserts

Types of Devices: A large number of proprietary low-cost catch basin inserts with a variety of designs are available. These systems are typically designed for easy drop-in installation in existing catch basins (Figure 4.1); however, they could also be included in new retrofitted catch basins. Most inserts target removal of gross solids and particulates through course screens and sediment traps. Some include oil-adsorbent media to target removal of oil and grease. A number of devices have undergone independent testing and have received use approval from local jurisdictions.

Area and Head Requirements: Catch basin inserts require no additional space. There is little to no head requirement, provided there is adequate bypass capability in the event of clogging.

Performance: Performance of catch basin inserts is device dependent. Evaluation of inserts by DOTs and other organizations has found variability in testing results, with generally low to moderate treatment performance for sediment, gross solids, and organics in systems that use oil absorbents (Caltrans, 2004; Walch et al., 2004; CSU, 2005; EC&T, 2005). Noted issues include poor capture, bypassing of filled or clogged storage compartments, and poor removals. Hydraulic performance is also a potential concern as clogging of inserts has been reported, causing surface ponding, safety concerns, and frequent maintenance requirements (Caltrans, 2004).

Maintenance Requirements: Maintenance of inserts is device dependent but the physical maintenance requirements are generally minimal, which mainly entail cleaning and disposal of accumulated solids. However, due to their small storage capacity, catch basin inserts may require frequent inspection to assess maintenance needs, or to assess clogging and potential safety hazards, particularly in high

Table 4.1. BMP options and characteristics for highway retrofits.

Retrofit Category	BMPs for Surface Retrofits	BMPs for Underground Retrofits	Characteristics
Catch Basin Retrofits	Not applicable	• Catch basin inserts • Deep sumped basins • Proprietary catch basin treatment systems	Modification of existing catch basins or installation of additional catch basins for water quality treatment.
Gross Solids Removal Device (GSRD) Retrofits	• Public works practices (screens, racks) • Trash capture systems • Non-proprietary GSRDs	• Proprietary and non-proprietary GSRDs	Screening systems targeting trash & debris.
Hydrodynamic Retrofits	Not applicable	• Proprietary hydrodynamic devices	Small-footprint BMP for underground applications. Small wet vaults and use of vortex and centrifugal forces for capture of gross solids and course sediment.
Oil-Water Separator Retrofits	Typically installed underground	• Proprietary oil-water separator devices	Small-footprint underground vaults. Targets floatables by density separation, especially separate-phase oils that are buoyant. They also include baffled wet vaults to trap coarse sediment.
Detention Retrofits	• Extended-detention basins • Wet basins • Constructed wetlands	• Detention tanks/vaults • Detention pipes	Stormwater detention for sedimentation, peak shaving, and volume attenuation. Includes dry basins and basins with permanent wet pools.
Media Filtration Retrofits	• Sand filters • Non-proprietary media filters	• Proprietary media filtration systems • Non-proprietary sand filters	Filtration through sands, soils, and engineered media. Targets fine sediments and dissolved pollutants.
Vegetative Filtration Retrofits	• Filter strips • Vegetated swales and wetland channels • Bioretention with under drains (stormwater planters)	Not applicable	Filtration through vegetated BMPs. Provides volume reduction.
Infiltration Retrofits	• Infiltration basins • Infiltration trenches • Bioretention	• Drywells • Proprietary infiltration systems	Volume reduction through infiltration. Provides volume attenuation and effective load reduction.
Pavement Retrofits	• Porous pavement • Permeable overlays	Not applicable	Uses roadbed and paved shoulders for treatment.
Advanced Treatment and Non-traditional Retrofits	• Proprietary systems • Disinfection facilities • Package plants • Flocculation systems • Capture and use facilities	Not applicable	Active treatment facilities and non-traditional controls targeting specific pollutants of concern (e.g. bacteria, turbidity).

traffic areas. Frequent inspection, if required, can be costly to the point that they are cost prohibitive (Caltrans, 2004).

Applicability for Ultra-Urban Highway Retrofits: Catch basin inserts are attractive retrofit BMPs because they are low cost and easy to install. However, as a broad generalization catch basin inserts have limited applicability in dense highway environments due to low effectiveness, frequent maintenance requirements, and potential safety concerns. Catch basin inserts are not recommended for ultra-urban highway retrofits. Retrofits using inserts could be applicable in DOT facilities where there is frequent monitoring and maintenance capability and public safety is not an issue, such as DOT maintenance yards. This recommendation does not preclude the potential for certain designs to provide effective and low-cost practical performance, but such systems should be evaluated on a case-by-case basis. Considerations should include:

- Potential loading rates of gross solids and larger particulates,
- Sediment and storage capacity,
- Anticipated cleaning frequency,
- Location and access safety,
- Hydraulic performance and public safety, and
- Performance testing information.

Table 4.2. Summary of catch basin retrofits.

Consideration	Attributes
Target Constituents	• Predominately gross solids, course sediment • Proprietary units may target oil & grease, metals, and other highway pollutants of concern (POCs)
Types of Devices	• Catch basin inserts • Deep sumped catch basins, sediment traps • Proprietary catch basin filtration devices
Unit Operations	• Predominately sedimentation and screening • Proprietary units may include filtration and sorption processes
Area Requirement	• Surface facilities: not applicable • Subsurface facilities: minimal, small-footprint BMP
Head Requirement	• Low, < 1 ft
Online/Offline	• Online; overflow protection should be included and evaluated; can be offline if new catch basin is installed upgradient of existing inlet/catch basin.
Maintenance Requirements	• Regular inspection, possibly frequent • Routine sediment and trash removal • Proprietary units may require additional maintenance such as filter change-out
Performance	• Large variability in testing performance; device dependent • Generally low to moderate performance for gross solids and course sediment; systems generally provide good trapping efficiency but ongoing effectiveness likely depends on frequency of cleaning • Generally poor performance for fine sediments and dissolved POCs, i.e., little to no reduction • No flow attenuation
Relative Cost	• Low, ~< \$100 per m^3 of design storm treated
Treatment Train Considerations	• Applicable as pretreatment to other BMPs such as infiltration and media filtration BMPs
Benefits for Ultra-Urban Retrofits	• BMP is integrated into existing infrastructure • Minimal space requirement and less site disturbance; reduced potential for utility conflicts • Low operating head; easier to tie into existing conveyances in retrofit applications • Low cost
Limitations for Ultra-Urban Retrofits	• May require frequent inspection and cleaning • Limited effectiveness for fine-grained sediments and dissolved POCs • Catch basin clogging and flooding if bypass design is not adequate • Potential vector issues in systems with standing water
Applicability for Ultra-Urban Retrofits	• When coarse sediment & gross solids are the target constituent • Hot spot areas for trash & debris, sediments • When used as pretreatment for other BMPs • When space constraints are restrictive • When there is adequate maintenance capability and safe maintenance access
Design Enhancements	• Proprietary systems that are integrated into catch basins • Use of oil adsorbents

4.2.3 Sumped Inlet Structures

Types of Devices: Deep sumped catch basins are inlet structures with enlarged sediment storage capacity. The outlets may include inverted elbows or hoods to help trap floatables. The potential benefits of retrofitting existing catch basins with deeper sumped structures include:

- Greater sediment storage capacity, reducing clean-out frequency;
- Improved sedimentation performance; and
- Reduced potential for sediment resuspension and washout.

Examples of sumped inlet structures are (1) deep sumped catch basins used by Massachusetts Highway and (2) the Caltrans traction sand traps (Figure 4.2).

Area and Head Requirements: Catch basin modifications require little to no additional space. There is little to no head requirement. In some cases it may be more effective to add new sumped catch basins upgradient from existing inlets/

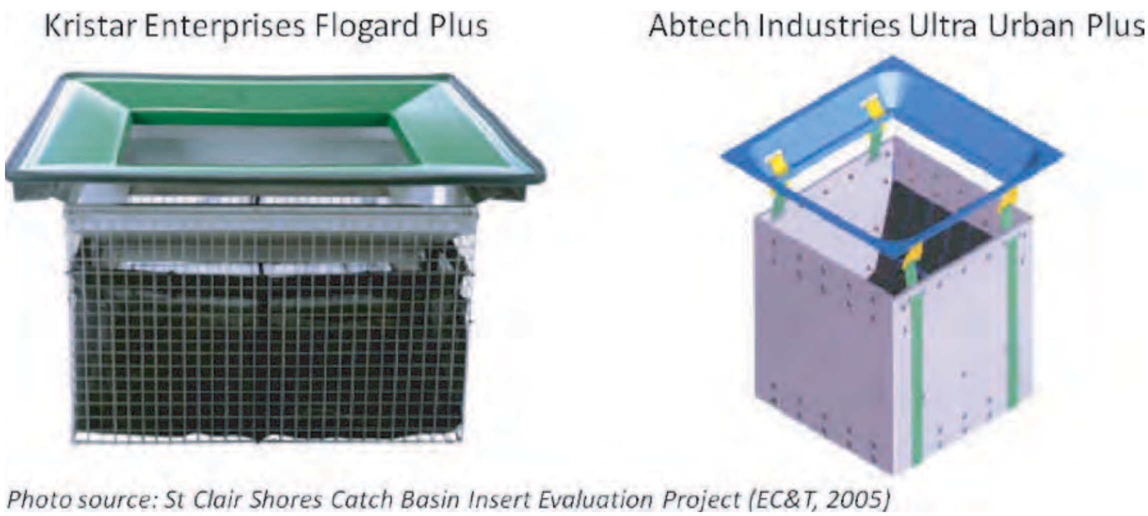


Figure 4.1. Two examples of catch basin inserts.

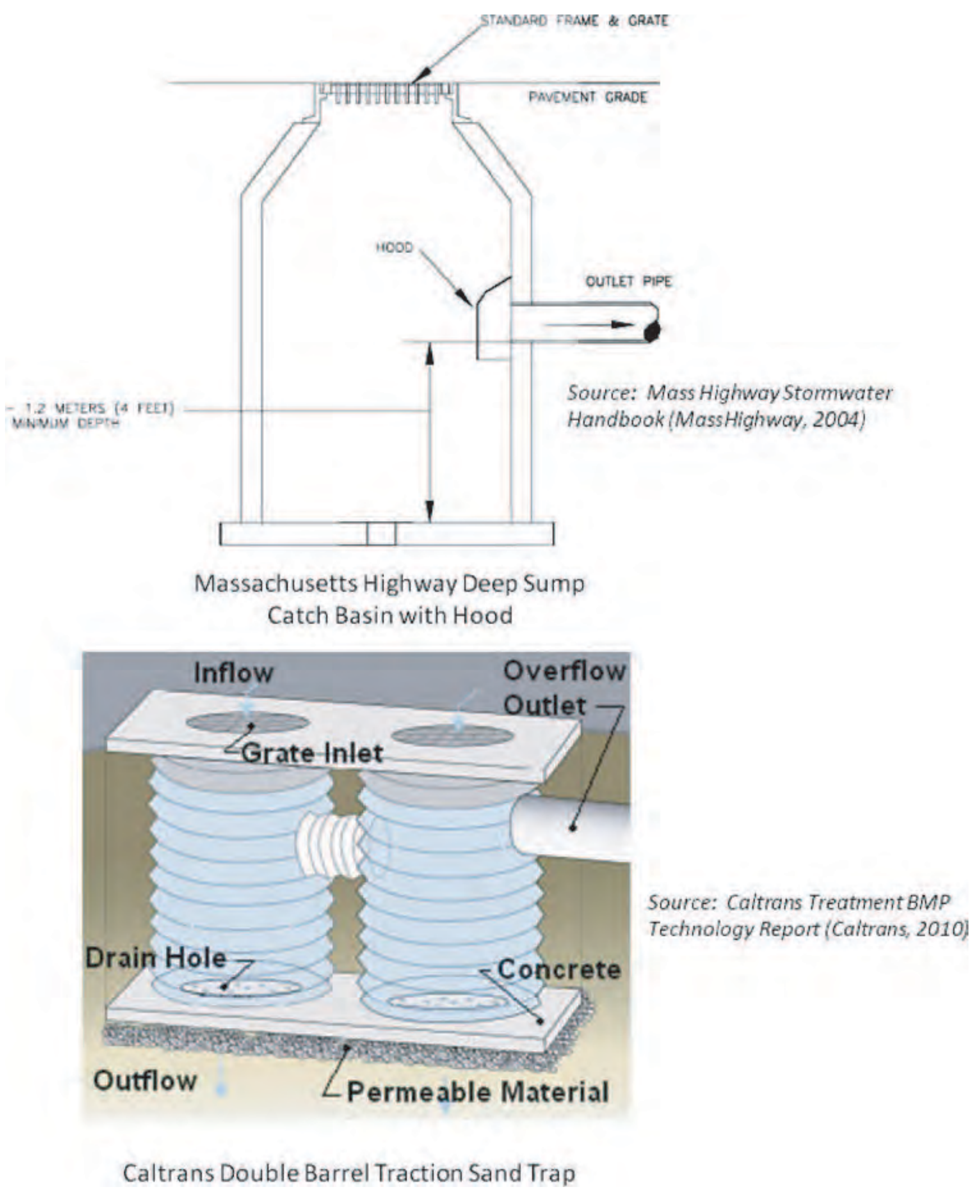


Figure 4.2. Two examples of sumped catch basins.

Sumped Catch Basin Evaluation Study

The USGS in conjunction with the Massachusetts Highway Department monitored the performance of deep sumped hooded catch basins along the Southeast Expressway, Boston, a highly urbanized area with large ADT (Smith, 2002):

- More than half of suspended sediments in runoff were particles less than 0.062 mm. But sediments retained in the catch basins were predominantly greater than 0.25 mm.
- The average sediment removal efficiency was 39%.
- Resuspension and washout occurred during high-intensity storms, even when accumulated sediments were less than 25% of the sump volume.
- Sediment cleaning prior to the summer high-intensity thunderstorms may reduce washout.
- Catch basins did not effectively remove floatables.
- Capture of inorganic and organic pollutants was low because they are associated with smaller particles sizes that are not effectively retained in the basins.
- The average retention time in the catch basins was 1 h, but was as short as 37 s during brief periods. Retention time is the primary factor controlling sediment removal efficiency.

catch basins provided there are no space and connectivity restrictions.

Performance: Sumped catch basins target removal of easily settleable coarse solids. Removal effectiveness is generally low to moderate. Reported removal efficiencies range from a 25% to 45% (Smith, 2002; MassHighway, 2004). Performance can also be influenced by cleaning frequency as basins with greater accumulated sediment may be more susceptible to sediment washout.

Maintenance Requirements: Regular inspection is required to assess sediment storage capacity. Cleaning using standard vactor equipment or manual removal is required when a threshold sediment accumulation is reached, for example 50% of the sump capacity or within 2 ft of the outlet.

Applicability for Ultra-Urban Highway Retrofits: Deep sumped catch basins have limited effectiveness as stand-alone retrofits and are most useful when integrated with other BMPs. Catch basin modifications with deep sumps are applicable for ultra-urban highway retrofits when:

- Space constraints are restrictive and alternative surface locations for other BMPs are not feasible or cost effective;
- Coarse sediment and gross solids are the primary target pollutants, such as areas where traction sand is routinely applied;
- Sumped catch basins are intended for pretreatment to other BMPs as part of a treatment train; and
- There are adequate maintenance capabilities and safe maintenance access.

4.2.4 Proprietary Catch Basin Devices

Types of Devices: Manufacturers have developed a variety of filtration-based treatment devices that are integrated into new catch basins, and in some cases can be retrofit into existing catch basins. Figure 4.3 shows example devices. The advantages of these systems are (1) they can be retrofit into the existing conveyance systems, or as part of a new retrofitted catch basin upstream of existing inlets/catch basins; (2) they potentially provide better treatment performance than the screening and sedimentation-based catch basin retrofits; and (3) they are generally low cost.

Area and Head Requirements: Catch basin modifications require little to no additional space. There are low to moderate head requirements to drive flow through the media, and head requirements will increase with gradual crusting and clogging if maintenance needs are not met. These systems are typically designed with bypass capability for high flows or in the event that filter units become clogged.

Performance: Like all proprietary devices, treatment performance is device dependent and should be evaluated through independent testing and/or DOT pilot testing. Independent organizations have evaluated systems in Figure 4.3 and have generally found moderate to good treatment performance for sediments and particulate-bound pollutants (Pitt and Khambhammettu, 2006; USEPA, 2005b; Yu and Stanford, 2007). They are generally less effective for dissolved pollutants, although media can be tailored for dissolved constituents. Performance was found to degrade over time, possibly due to partial clogging of the media and/or due to the presence of accumulated sediments. In general, these systems are expected to provide better overall treatment than inserts or deep sumped catch basins, provided they are adequately maintained.

Maintenance Requirements: Proprietary catch basin systems will require routine inspection and cleaning of sumps. They also require periodic change-out of media beds and filter cartridges, with frequency being device dependent. Regular inspection and maintenance is required to ensure design-level performance. Frequent inspection and cleaning of the sump is required due to the limited capacity of most systems. Maintenance requirements and capabilities should be a key consideration in system selection.

Hydro International Up-Flo Filter

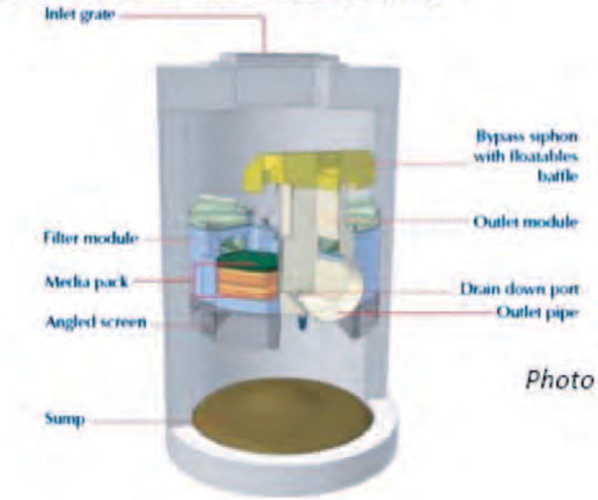
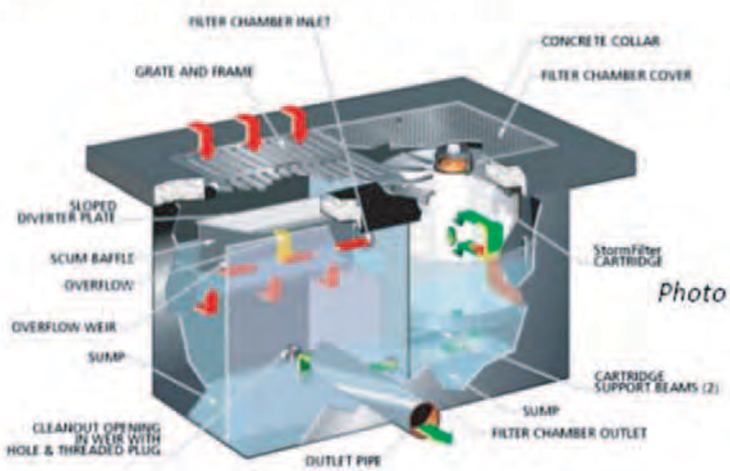


Photo source: http://www.hydro-international.biz

Contech CatchBasin StormFilter



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Filterra Bioretention System

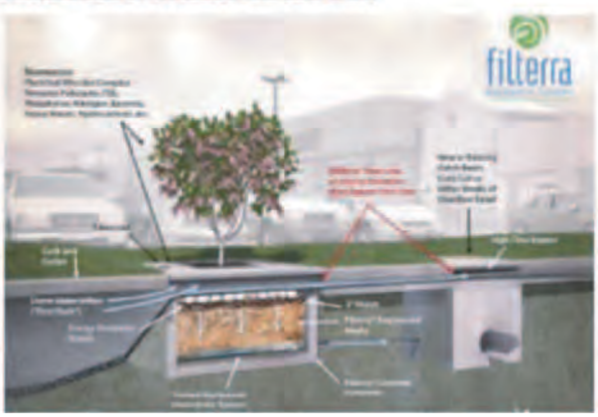


Photo source: http://www.filterra.com/

Figure 4.3. Three examples of proprietary catch basin devices.

Applicability for Ultra-Urban Highway Retrofits: Catch basin filtration BMPs are applicable for ultra-urban highway retrofits when:

- Space and/or budgetary constraints are restrictive and alternative retrofit options are not practical or cost effective;
- Sediment and particulate-bound POCs are the primary target pollutants; and
- There are adequate maintenance capabilities and safe maintenance access.

4.3 Gross Solids Removal Device Retrofits

Urban centers and urban highways are sources of trash and debris. Receiving water impairments and TMDLs due to excessive discharge of trash and debris are increasingly impacting DOTs, potentially imposing retrofit treatment. Gross solids removal devices (GSRDs) are structural BMPs that specifically target removal of trash and debris, particles typically greater than 0.25 in. in diameter. GSRDs include trash capture devices using racks and screens, and outfall devices such as trash nets. GSRDs differ from other retrofit BMP categories that may also provide moderate to good removal of gross solids in that GSRDs only target trash and debris and they typically are designed to provide higher removal efficiency. Table 4.3 summarizes the BMP options for GSRD retrofits.

Types of Devices: GSRDs have been developed using a variety of designs. There is a number of proprietary trash capture devices including disposable trash net systems that can be installed inline or at outfalls. Caltrans has developed and tested a variety of non-proprietary GSRDs. These include a linear radial screen design that uses louvered well screens to trap trash & debris, and an inclined screen design (Figure 4.4).

Table 4.3. Summary of GSRD retrofits.

Consideration	Attributes
Target Constituents	Gross solids, course sediment. Typically larger than 0.25 in.
Types of Devices	• Non-proprietary screening systems • Trash nets (inline and outfall installations) • Inlet screening devices
Unit Operations	• Screening
Area Requirement	• Minimal, small-footprint BMP • Design dependent
Head Requirement	• Low to moderate, < 1 to 2 ft
Online/Offline	• Online
Maintenance Requirements	• Regular inspection and cleaning • Frequency of cleaning depends on design, storage capacity
Performance	• Good to excellent performance for gross solids • Does not target sediments and dissolved POCs • No flow attenuation
Relative Cost	• Low to moderate, ~ \$100 to \$1000 per m^3 of design storm treated; costs are strongly device and location dependent
Treatment Train Considerations	• Pretreatment to other BMPs
Benefits for Ultra-Urban Retrofits	• Small-footprint BMP • Effective stand-alone treatment for trash and debris • Can be retrofit into existing inlets, conveyances, and outfalls • Low operating head • Low cost
Limitations for Ultra-Urban Retrofits	• Designs may require frequent inspection and cleaning • Some design can have clogging issues
Applicability for Highway Retrofits	• When gross solids are the target constituent • As pretreatment to other BMPs • Space constraints are restrictive • Adequate maintenance capability
Design Enhancements	• Non-proprietary designs using well casings (linear radial model) • Non-proprietary inclined screen configurations to reduce clogging, achieve full-capture of trash, provide storage to capture annual trash loads, and reduce maintenance requirements to annual cleaning and periodic inspections.

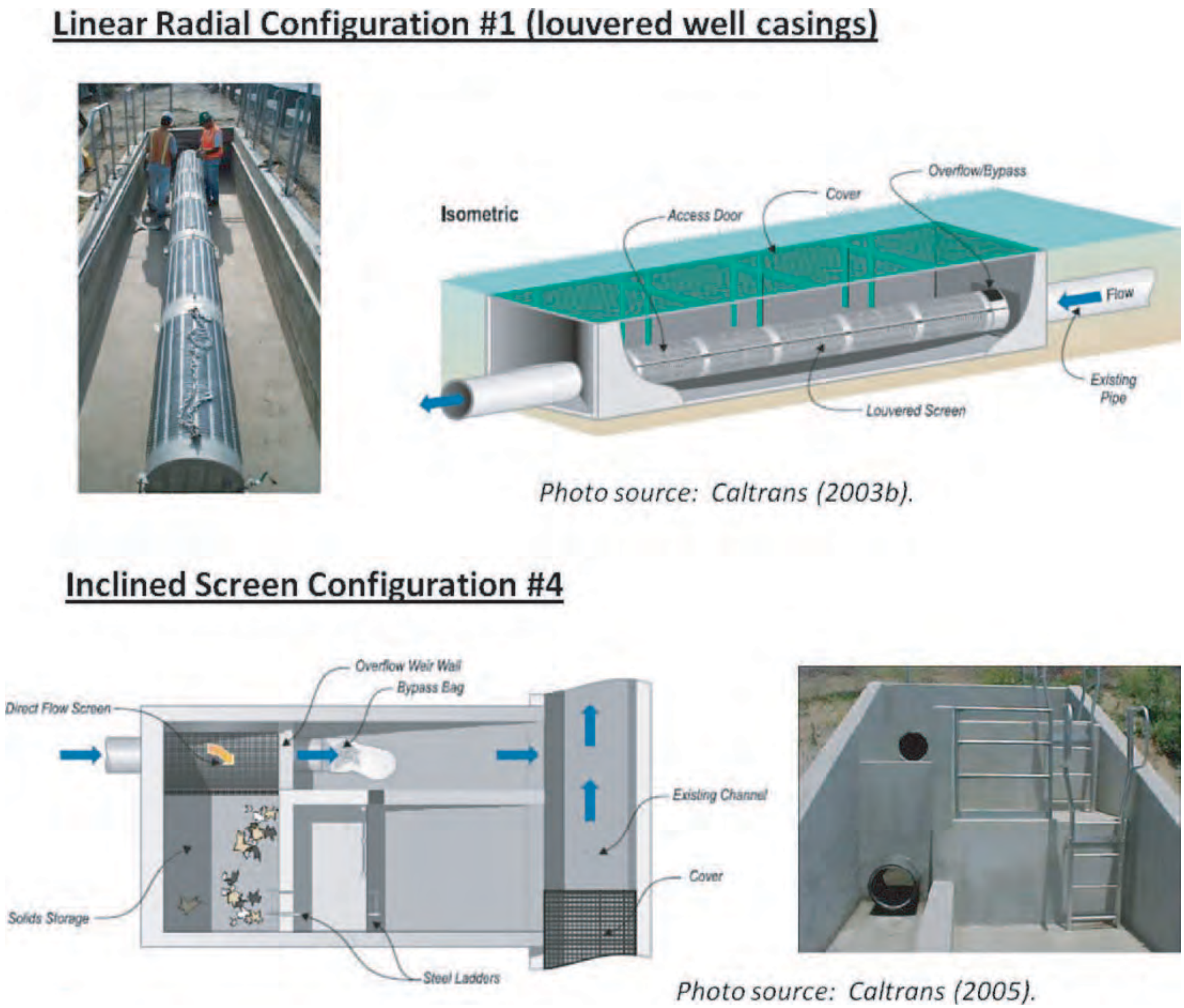


Figure 4.4. Two examples of non-proprietary GSRDs developed by Caltrans.

Area and Head Requirements: Footprint requirements for GSRDs are design dependent but, in general, space requirement are small. Some designs can be retrofit into existing inlets and outlets with no added space requirements. End-of-pipe designs may require construction of frame supports or screen vaults. Head loss through screens depends on flow velocity, screen size, and clogging potential. Some designs are self-cleaning to reduce clogging potential (i.e., inclined screens). In general, head requirements are low to moderate.

Unit Operations: GSRDs primarily use screening processes. Clogging of screens is a concern, and bypass or overflow capabilities should be incorporated in the design.

Performance: GSRDs generally provide good to excellent removal of trash and debris, but performance is design dependent. Factors that can influence performance are (1) clogging of screens causing bypass and (2) excessive velocities on screens that can force debris through openings. Some of the Caltrans designs provide excellent removals of gross solids with 90% to 100% efficiency (Caltrans, 2003b, 2005). GSRDs are not intended for treatment of other highway POCs, nor flow attenuation and volume reduction.

Maintenance: GSRDs require routine cleaning and collection of accumulated trash and debris. The frequency of cleaning depends on storage capacity and loading rates. For example, Caltrans devices are typically designed with a 1-year storage capacity based on trash and debris characterization studies. Regular inspection of devices is required, especially for devices with limited storage capacity, devices that are subject to clogging, and devices in high loading areas. Maintenance practices may include hand removal of accumulated debris, vactoring of accumulated sediments in sumped facilities, and replacement of trash nets with truck-mounted cranes.

Applicability for Ultra-Urban Highway Retrofits: GSRDs are applicable in ultra-urban highway retrofits when:

- Trash and debris are the primary target pollutant;
- GSRDs are used as pretreatment for other BMPs; and
- There are adequate maintenance capabilities including maintenance access.

4.4 Hydrodynamic Device Retrofits

Hydrodynamic devices are proprietary flow-based BMPs that use hydrodynamic controls (swirl action, deflection, and/or screening) to promote removal of sediment and gross solids. They are typically online structures, housed in underground reinforced concrete vaults.

Hydrodynamic devices are relatively low-cost prefabricated structures that are easy to install, have small-footprint areas, provide effective removal of coarse sediments and gross solids, and can treat high discharge rates. For these reasons, DOTs and municipalities have used hydrodynamic separators as stand-alone BMPs or for pretreatment to other BMPs. Several proprietary models are certified by various testing organizations and approved for use by DOTs. Other DOTs do not allow their use, primarily due to maintenance concerns. Table 4.4 summarizes hydrodynamic device retrofits.

Types of Devices: There are a large variety of commercially available hydrodynamic devices using a wide range of designs, configurations, and sizing. Figure 4.5 shows selected

Table 4.4. Summary of hydrodynamic device retrofits.

Consideration	Attributes
Target Constituents	• Predominately coarse solids, sediment, trash and debris
Types of Devices	• Wide variety of commercially available proprietary systems
Unit Operations	• Sedimentation, screening, swirl action separation
Area Requirement	• Surface facilities: not applicable • Subsurface facilities: minimal, small-footprint BMP
Head Requirement	• Low to moderate, < 1 to 2 ft
Online/Offline	• Online
Maintenance Requirements	• Regular (potentially frequent) inspection • Routine (potentially frequent) sediment and trash removal • Vector control
Performance	• Moderate to good treatment for gross solids, coarse sediment, and associated POCs • Effectiveness may be diminished in cold climates • Poor to moderate treatment performance for fine sediments and dissolved POCs • No flow attenuation
Relative Cost	• Low to moderate, ~ $500 per m^3 of design storm treated; costs are strongly device and location dependent
Treatment Train Considerations	• Applicable as pretreatment to other BMPs such as infiltration and media filtration BMPs
Benefits for Ultra-Urban Retrofits	• Small-footprint underground BMP • Low to moderate operating head • Low cost • Prefabricated units are relatively easy and inexpensive to install • High treatment capacity and can handle high flow rates • Effective performance for coarse sediment and gross solids
Limitations for Ultra-Urban Retrofits	• Limited effectiveness for fine-grained sediments and dissolved pollutants • Limited sediment storage capacity • Frequent inspection and maintenance • Potential vector issues
Applicability for Ultra-Urban Retrofits	• Coarse sediment and gross solids removal • Pretreatment to other BMPs • Space constraints are restrictive • Adequate maintenance capability
Design Enhancements	• Integrate into catch basins • Include oil absorbent pads

Continuous Deflective Separation (CDS) System

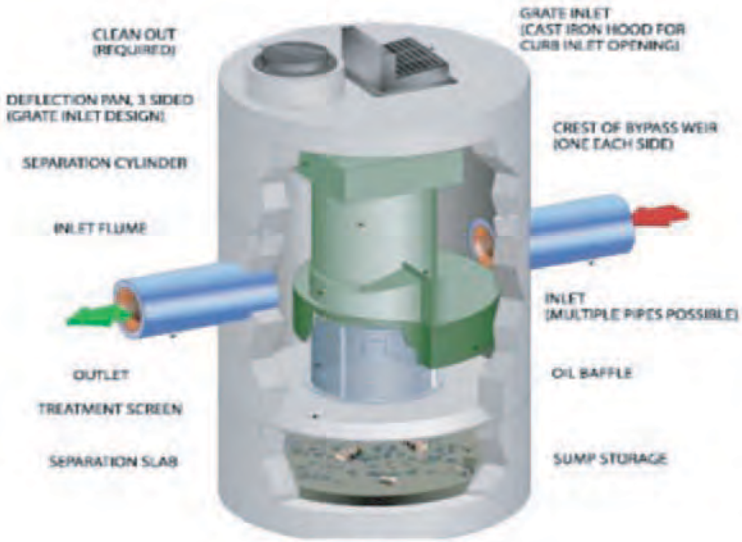


Photo source: http://www.contech-cpi.com/

Stormceptor

Photo source: http://www.wateronline.com/article.mvc/Stormceptor-Assists-The-Port-Of-Los-Angeles-B-0001

Photo source: http://www.stormceptor.com/

Figure 4.5. Two examples of hydrodynamic devices.

example devices, which represent a small cross section of available systems.

Area and Head Requirements: Hydrodynamic systems are small-footprint, underground structures with minimal space requirements. They are housed in reinforced concrete vaults of various sizes and shapes that are manufacturer specific and depend on flow capacity. Typical sizes range from 4 to 8 ft circular or rectangular vaults to larger elongated vaults on the order of 10 by 20 ft. Head requirements are generally low. Small footprints and low head requirements are advantageous to retrofit applications because there is less potential for utility conflicts and tying into existing conveyances is easier.

Unit Operations: Hydrodynamic devices leverage density differences between pollutants and stormwater and the centrifugal forces that result from the circular motion of the influent to separate solids from stormwater. Density separation is the primary pollutant removal process in hydrodynamic devices. Sedimentation, screening, and filtration are additional treatment processes that may be present depending on the design of the specific brand of hydrodynamic device.

Performance: Hydrodynamic devices are effective at removing coarse particulates and gross solids (Caltrans, 2004; USEPA, 1999a; Kim and Sansalone, 2008b). In general, hydrodynamic devices have limited effectiveness for finer

Caltrans Retrofit Evaluation

Caltrans monitored the effectiveness of continuous deflective separation (CDS) units in highway retrofits as part of its Retrofit Pilot Program (Caltrans, 2004).

- CDS units were effective at removing coarse sediments and trash and debris.
- Influent sediment concentrations were low.
- The majority of captured gross solids were vegetative debris and trash.
- Standing water in tested units created vector issue concerns.

MassHighway Evaluation Study

The Massachusetts Highway Department evaluated the suitability of hydrodynamic separators for highway applications (Barbaro and Kurison, 2005). Study conclusions included:

- Selection and use of hydrodynamic systems as primary treatment systems should be based on scientifically supportable data on the field performance.
- Limitations of hydrodynamic systems should be considered, including low effectiveness for fine particles and soluble pollutants; potential vector breeding; and potential trapping of hazardous materials (may enhance spill response/capture).
- Hydrodynamic separators may be appropriate for pretreatment and retrofit applications where sand is the target contaminant and where the operator has adequate maintenance capabilities.

particulates and little to no effectiveness for dissolved pollutants and flow attenuation (USEPA, 1999a; Barbaro and Kurison, 2005; Roseen et al., 2006). Treatment performance for sediments is also affected by maintenance frequency, particularly if the system design is susceptible to washout of accumulated sediment (Kim et al., 2007).

Cold Climates: Cold weather conditions have also been found to reduce treatment effectiveness for sediments due to increased viscosity and increased chloride, both of which affect particle settling velocity (UNH, 2009a). Hydrodynamic devices that rely on particle settling and are installed in prolonged cold climate regions should be oversized to account for diminished cold weather performance (UNH, 2009a). Design should also consider the effect of freezing conditions on conveyance capacity, such as burying pipes below the frost line, increasing minimum size and slopes on pipes, and other conveyance modifications (Caraco and Claytor, 1997).

Maintenance: Hydrodynamic devices require regular monitoring of sediment accumulation and regular removal of accumulated sediment, typically with vactor trucks. Treatment performance generally diminishes as sediment storage increases. Depending on sediment chamber design, significant washout of accumulated sediments can occur (Andoh et al., 2007). Consequently, frequent inspection and cleaning may be required, particularly for highways with high sediment loads (cold weather sanding areas) or highways with significant sources of trash and vegetative debris such as slopes that are sparsely vegetated (Caltrans, 2004). Excessive maintenance requirements can be a concern for retrofit design, if frequent inspections and cleaning are anticipated, or if there are access restrictions from highway constraints or confined access issues.

Special Features and Enhancements: Enhancements to hydrodynamic retrofits include efforts to improve capture sediment, reduce resuspension, and improve treatment of oil and grease.

- ***Screens:*** Screens facilitate the removal of solids. Screen sizes can be tailored to target particle sizes. Screens can also be designed to direct sediment into sumps or secure areas within a hydrodynamic device to prevent resuspension of captured pollutants.
- ***Hydrodynamics:*** A variety of hydrodynamic design features including baffles, staked plates, and multi-compartments are marketed as improving sediment and floatable capture, improving capture of fine sediments, and reducing resuspension and washout.
- ***Catch Basin Design:*** Some systems are integrated into standard catchment basins that may be advantageous for retrofit applications.
- ***Adsorbents:*** Adsorbent pads have been added to hydrodynamic devices to facilitate the removal of floatable pollutants such as oil and grease as well as dissolved constituents. Sorbent pads come in a variety of shapes and sizes and can be selected based on target pollutants at the site.

Applicability for Ultra-Urban Highway Retrofits: Hydrodynamic devices are most applicable for ultra-urban highway retrofits when:

- Space constraints are restrictive and alternative surface locations are not feasible or cost effective;
- Coarse sediment and gross solids are the primary target pollutants;
- They are used as pretreatment for other BMPs; and
- There are adequate maintenance capabilities and maintenance access.

4.5 Oil-Water Separation Retrofits

Oil-water or oil-grit separators are chambered tanks that are designed to remove gross pollutants and solids by sedimentation and to trap floatables, specifically including free-phase oils and grease. They are suited to ultra-urban highway retrofits because they are typically underground and have small space requirements. However, the storage volume in oil-water separators is smaller than in underground detention facilities, and consequently the effectiveness of oil-water separators is limited by short retention times. Some DOTs employ oil-water separators as pretreatment systems, while other DOTs have found that runoff concentrations of free oil are not sufficiently high to warrant use of oil-water separators. Table 4.5 summarizes oil-water separator retrofits.

Types of Devices: Oil-water separators are available commercially from a large number of vendors. There are two common designs: the American Petroleum Institute (API) separator and the Coalescing Plate Separator (CPS) (Figure 4.6). The API separator consists of three chambers divided by baffles. The first chamber acts as an equalization chamber where grit and larger solids settle and flow energy is dissipated. The second chamber is the main chamber where finer sediments and floatables are trapped, and the third chamber contains the outlet. The CPS design is generally smaller than the API separator and uses a single baffle and a

Table 4.5. Summary of oil-water separator retrofits.

Consideration	Attributes
Target Constituents	• Gross solids, sediment, free oil and grease
Types of Devices	• Three chambered baffled tanks (American Petroleum Institute design) • Coalescing Plate Separator (CPS)
Unit Operations	• Sedimentation, density separation of floatables
Area Requirement	• Various sizes ranging from 50 to 20,000 or more gallons • Small space requirement for underground installation
Head Requirement	• Low to moderate, 1 to 4 ft
Online/Offline	• Either. Systems that are offline may be less susceptible to washout
Maintenance Requirement	• Regular inspection and cleaning, potentially frequent (multiple times per year) • Cleaning frequency depends on design, storage capacity
Performance	• Poor to moderate for sediment • Poor to moderate for floatables • Good for heavy oil and grease loads, poor for low loads • No treatment for dissolved POCs
Relative Cost	• Moderate to high, ~ >$1000 per m^3 of design storm treated; costs are strongly device and location dependent
Treatment Train Considerations	• Applicable for pretreatment
Benefits for Ultra-Urban Retrofits	• Small-footprint BMP • Designed to trap free-phase oils • Low operating head
Limitations for Ultra-Urban Retrofits	• Designs may require frequent inspection and cleaning • Can be prone to sediment resuspension and washout • Limited effectiveness, other pretreatment options may be more cost effective
Applicability for Ultra-Urban Retrofits	• When oil and grease are the target constituent and there is sufficiently high oil concentrations to warrant the use of oil-water separation • Used as pretreatment to other BMPs • Space constraints are restrictive • There is adequate maintenance capability and access
Design Enhancements	• Modular designs that enable features as necessary, such as skimmers

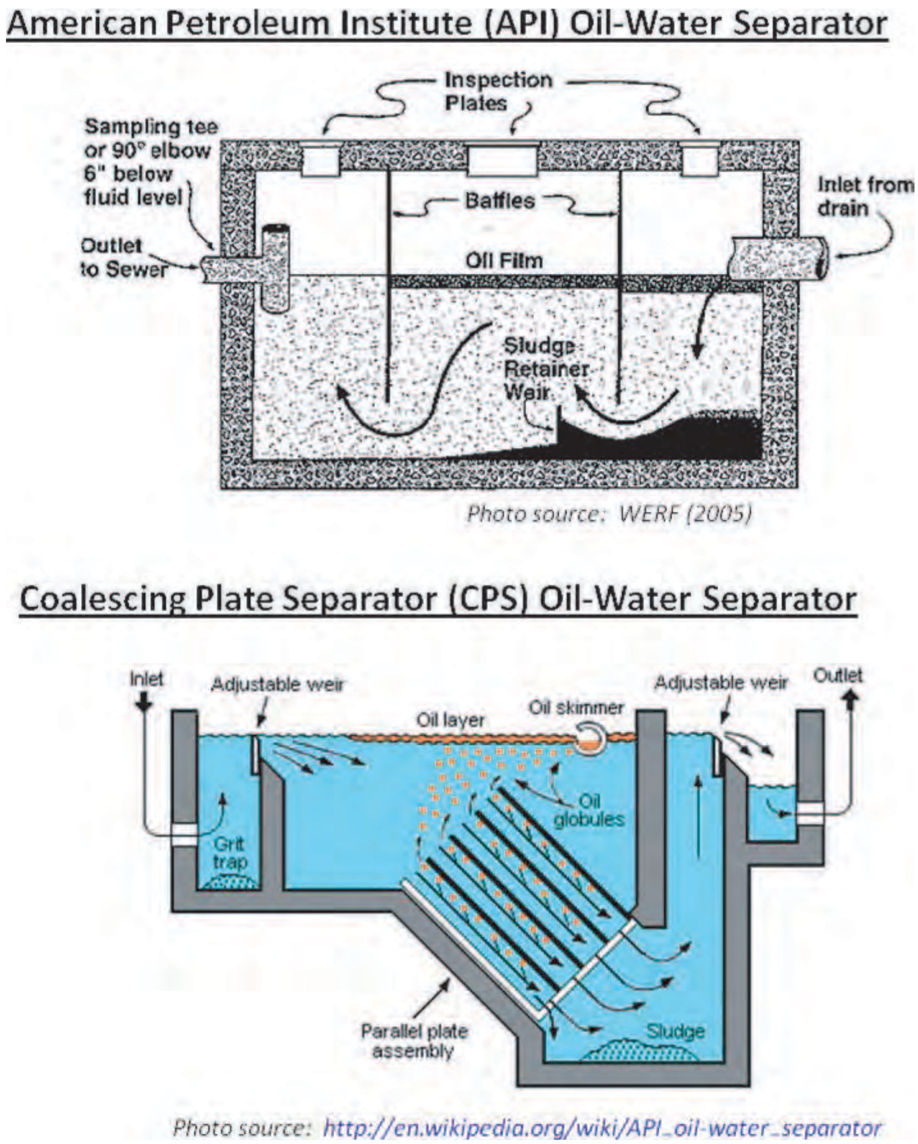


Figure 4.6. Common oil-water separator designs.

series of oil-attracting coalescing plates in the main chamber. Larger oil-water separators contain a sludge scraper that continually removes the captured settled solids into a sludge pit. An oil-skimming operation on the water surface also removes the oil.

Area Requirements: Oil-grit separators come in a variety of size ranges from 50 to 20,000 or more gallons. Underground installations have minimal space requirements, but should be located in areas with good maintenance access.

Head Requirements: Operation head requirements are low to moderate. Connectivity with gravity drainage to outlet points is an issue with underground structures in flat terrains.

Performance: Treatment performance for oil and grease and petroleum hydrocarbons is variable. Reduction of free-phase oil concentration by gravity separation is evident when concentrations are high, but is limited when influent concentrations are low and when oils are emulsified or present as fine droplets. CPS designs may be more effective for these situations. Typical concentrations of free oil in highway runoff do not warrant use of oil-water separators, and other technologies may be more effective at removing oil and grease (Caltrans, 2004). Oil-water separators are not effective for dissolved organic constituents. The removal of particulate-bound organics is limited by the sedimentation efficiency for the associated particle sizes.

Oil-water separators provide poor to moderate treatment for sediments, with reported efficiencies in the range of 25% to 35% (Smith, 2002). The main factor limiting the removal of sediments is the small volume and short retention times in these systems (Smith, 2002; Schueler, 2000; Yu and Stopinski, 2001). Due to the small storage volume, they are susceptible to sediment resuspension and washout, even when they are constructed offline (Smith, 2002). The systems are effective at removing floatable trash, provided they are cleaned regularly.

Cold Climates: Underground oil-water separators can be subject to freezing in cold weather and may have reduced performance in cold weather due to greater runoff from snowmelt and lower sedimentation effectiveness. Systems can be oversized to improve cold weather performance and to accommodate greater runoff from snowmelt events. Conveyance modifications to mitigate freezing conditions should also be considered.

Maintenance: Oil-water separators should be frequently inspected for levels of accumulated sediments and organics. Regular cleaning of accumulated solids and organics with a vactor truck is required to ensure design-level performance and to minimize washout. Depending on storage capacity and loading, frequent cleaning could be needed (quarterly). Permanent pools in these devices are a potential mosquito habitat vector that may necessitate vector control measures.

Applicability for Ultra-Urban Highway Retrofits: Oil-water separators are applicable for ultra-urban highway retrofits when:

- They are located in areas with significant loadings of free-phase oils (e.g., as spill protection measures) or are intended as hazardous materials traps;
- Space constraints are restrictive;
- They are used as pretreatment for other BMPs; and
- There are adequate maintenance capabilities and maintenance access.

In the absence of significant free-phase oils, other BMP options may be more suitable for treatment of coarse particles and gross solids (e.g., hydrodynamic systems, deep sump catch basins).

4.6 Detention Retrofits

Detention facilities are volume-based BMPs that temporarily store stormwater runoff to promote sedimentation, reduce peak discharges, and attenuate flows. They have advantages in flexible design and simple construction, basic maintenance requirements, multi-function performance, and relatively low cost. For these reasons, detention facilities are likely the most widely used and widely accepted treatment BMP. Detention retrofits include surface detention retrofits and underground detention retrofits that are applicable in space-constrained settings. Table 4.6 summarizes detention retrofits.

4.6.1 Surface Detention Retrofits

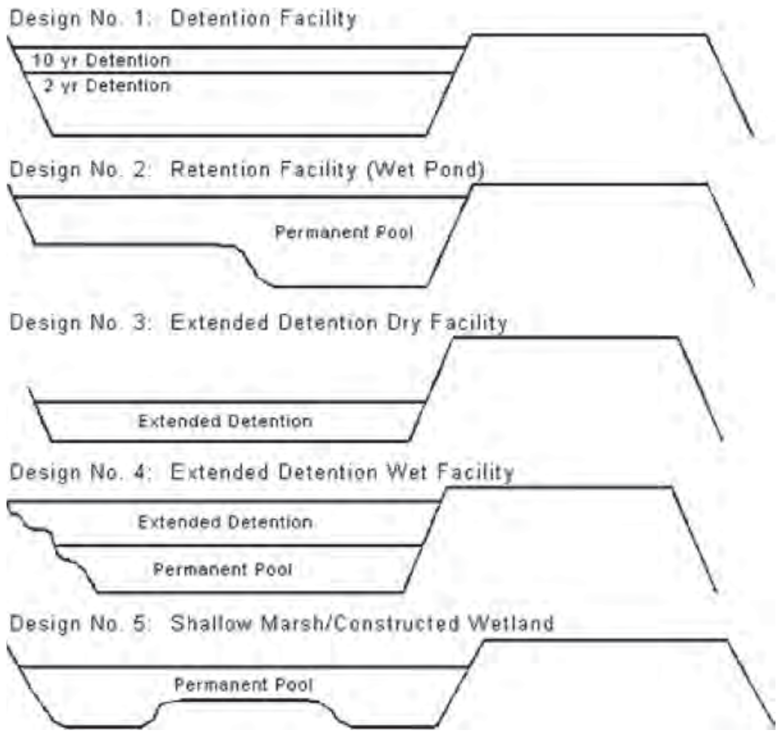
Types of Surface Detention Retrofits: Surface detention retrofits are configured on the basis of design objectives for flow attenuation, water quality treatment, or some combination thereof. Shoemaker et al. (2002) categorized surface detention facilities into five basic types as shown in Figure 4.7 and summarized in Table 4.7:

1. **Detention Basin:** Flow attenuation is the primary design basis for detention basins. The basin storage volume and drawdown rates are designed on the basis of flow attenuation criteria. They are typically dry between storms.
2. **Retention/Wet Basins:** Wet basins are the reverse of detention basins in that (1) they are designed for water quality treatment, (2) they include a permanent wet pool that is large in comparison to the water quality design event, and (3) they have minimal live storage for flow attenuation. Wet basins provide long retention times for flows that are retained in the basin between storm events. This enhances sedimentation and other removal processes, especially for finer sediments and dissolved pollutants that are not effectively removed in detention basins.
3. **Dry Extended-Detention Basins:** Extended-detention basins are similar to detention basins, except they additionally consider sedimentation processes in the design of the basin volume and drawdown rates. The outflows from extended-detention basins are more restricted in comparison to detention basins in order to increase detention time and promote sedimentation and contact time with soils and vegetation. The basins are typically dry between storms.
4. **Wet Extended-Detention Basins:** Wet extended-detention basins are multi-objective facilities that are designed for enhanced water quality treatment and flow attenuation. They incorporate a permanent pool for water quality treatment and they have significant live storage capacity for flow attenuation.
5. **Constructed Wetlands:** Wetlands, like wet basins, are designed for water quality treatment. Wetlands use shallow detention to promote flow through emergent vegetation, and detention times are long, on the order of days to weeks. Some wetlands are designed with a live storage component, similar to wet extended-detention basins.

Unit Operations: Detention facilities target sediment, suspended solids, trash and debris, and particulate-bound pollutants such as metals. The dominant unit processes are sedimentation and gravity separation. Screening of gross solids occurs with screens, racks, GSRDs and pre-settling areas. Surface detention facilities can provide volume reduction through infiltration, filtration through vegetation, evaporation, and sorption and microbial transformations in basin soils. Wet systems also target dissolved constituents by increased opportunities for sorption and biological update.

Table 4.6. Summary of detention retrofits.

Consideration	Attributes
Target Constituents	• Flow attenuation, trash and debris, sediment and associated pollutants
Types of Facilities	• Surface detention basins, multiple configurations • Underground vaults, pipes, cisterns
Unit Operations	• Primary processes: sedimentation and screening • Minor processes: infiltration, filtration, sorption, degradation, transformations
Area Requirement	• Surface facilities: 2% to 4% of the tributary watershed, larger for wet basin and wetlands • Subsurface facilities: 0.5% to 1% of the tributary watershed
Head Requirement	• Low to moderate; ~ 1 to 4 ft
Online/Offline	• Usually online, offline designs may improve sediment capture
Maintenance Requirement	• Regular inspection • Routine sediment and trash removal • Vector control • Vegetation management
Performance	• Generally effective treatment for gross solids, sediment, and particulate-bound POCs. Many design factors influence treatment effectiveness including storage volume, detention time, hydrodynamic characteristics, permanent wet pool volume, infiltration pathways, inclusion of vegetation • Generally less effective treatment performance for dissolved POCs. Wet basins and wetlands that are designed to promote long detention times (days to weeks) and include vegetation generally provide improved treatment performance for some dissolved constituents • Excellent flow attenuation (better for dry ponds than wet)
Relative Cost	• Surface detention facilities: Moderate, ~ \$400 to >\$1000 per m^3 of design storm treated • Underground detention facilities: High, >\$1000 per m^3 of design storm treated; costs depend strongly on design and location
Treatment Train Considerations	• Pretreatment facilities are commonly integrated or coupled with detention facilities (e.g., sedimentation forebays, trash racks, GSRDs) • Enhanced treatment processes can be integrated or coupled with detention facilities (wet basins and vegetated wetlands targeting dissolved constituents, downstream polishing processes such as filtration and disinfection)
Benefits for Ultra-Urban Retrofits	• Widely used; DOTs are familiar with requirements and performance • Many design options and configurations • Low to moderate head requirements • Relatively simple and low maintenance requirements, particularly for surface facilities • Low to moderate construction and maintenance cost • Moderate to good performance • Longevity of facilities with proper maintenance
Limitations for Ultra-Urban Retrofits	• Area requirements for surface facilities can be prohibitive • Limited effectiveness for dissolved POC • Sediment resuspension and discharge in smaller systems • Underground structures are more challenging to connect existing conveyance system in flat terrains • Stagnant pools in underground structures may potentially promote mosquitoes and vector concerns • Harder to maintain underground systems • Wet basins and wetlands require a source of water to maintain permanent pools
Applicability for Highway Retrofits	• Where there is adequate space and maintenance access • When treatment of general highway POCs is suitable • When flow attenuation is required
Design Enhancements	• Batch mode operation • Outlet design



Source: FHWA (2002)

Figure 4.7. Design variations for surface detention facilities.

Area Requirements: The space requirements for surface detention ranges from 2% to 10% of the tributary area, which is the primary drawback for ultra-urban applications. Space requirements are smallest for detention facilities and largest for wet basins and wetlands (Table 4.7). Space requirements can be reduced with the use of vertical retaining walls, but this will increase costs.

Head Requirements: Surface detention facilities have low hydraulic head requirements (typically about 1 to 4 ft), which is advantageous for retrofitting in flat terrains.

Performance: Detention facilities provide good performance for sediments and particulate-bound POCs. Removal of fine particulates is variable and is influenced by the system design and operation. Sediment resuspension and washout potentially diminishes effectiveness for fine particulates, especially in smaller underground systems.

Impervious detention facilities (tanks and lined facilities) generally provide poor treatment for dissolved pollutants. Detention facilities that have longer settling periods such as wet basins, wet vaults, and constructed wetlands, and/or include vegetation and contact with soils generally have better overall treatment performance, including better treatment of dissolved pollutants. Resuspension of captured pollutants and washout is less likely in basins with a permanent wet pool.

Detention facilities with infiltration pathways can provide significant volume reduction and associated pollutant load reductions for all pollutants. Infiltration is more likely in dry basins. Where feasible, detention facilities should include vegetation and infiltration pathways. Vegetation can also increase evapotranspiration losses and further volume reduction.

Detention facilities provide excellent flow attenuation, which is often a primary design objective. Volume reduction through infiltration will also help to attenuate flows.

Cold Weather: Dry extended-detention basins can perform well in cold climates because they provide effective treatment, they provide snow storage, and design modifications can mitigate cold weather problems. Design modifications include over-sizing basins to accommodate greater runoff and snow storage, burying pipes below the frost line, increasing minimum size and slopes on pipes, and other conveyance modification (Caraco and Claytor, 1997). Salt-tolerant vegetation and potential impacts to groundwater should be considered in areas of heavy salting.

Wet basins, wetlands, and basins with permanent pools have greater cold weather challenges due to freezing conditions and resulting smaller live storage. Design modifications to mitigate impacts include increasing live storage volumes, incorporating extended-detention storage into forebays, or designing the facilities to be operated with seasonal pools (i.e., drain facilities prior to winter freeze periods). In addition, conveyance modifications and consideration of vegetation and groundwater impacts should be addressed.

Maintenance: An advantage of surface detention facilities is that they have fairly routine and infrequent maintenance

Table 4.7. Design goals and attributes of surface detention retrofit options.

Type	Main Design Goals & Processes	Effectiveness		Attributes	Space Required (% of tributary area)
		Water Quality*	Flow Control**		
Detention Basin	• Flow attenuation • Some gross sediment and gross solids removal • Some volume reduction	Low	High	• Dry between storms • Basin volume and drawdown rates based on flow attenuation criteria	1% to 2%
Retention Basin/ Wet Ponds	• Pollutant removal • Long retention times to enhance removals • Limited flow attenuation	High	Low	• Permanent pool • Permanent pool volume is large, and live storage is small • Outlet weirs have limited flow restrictions • Water source required to maintain the permanent pool	About 5%
Dry Extended-Detention Basins	• Enhanced sedimentation via extended detention times • Flow attenuation • Volume reduction via infiltration	Low to Moderate	Moderate to High	• Similar in design to detention facilities except outflows are more restricted • Outlet design based on detention time (12 to 48 h), and on flow attenuation criteria	About 2%
Wet Extended-Detention Basins	• Enhanced pollutant removal by including a permanent pool • Flow attenuation • Volume reduction via infiltration	Moderate to High	Moderate	• Similar to dry extended-detention facilities except includes a permanent pool • Live storage volume above the permanent pool • Outlet design based on detention time criteria (12 to 48 h)	2% to 4%
Shallow Marsh/ Constructed Wetlands	• Water quality treatment by flow through emergent vegetation and long retention • Flow attenuation • Volume reduction	High	Moderate to High	• Shallow permanent pools with emergent vegetation • Long average retention times, on the order of days • Requires permanent water source to maintain wetland vegetation	5% to 10%

Source: Adapted from Shoemaker et al. (2002)
* Qualitative scale based on general treatment performance for settable solids (>50 μm). A poor rating indicates treatment is not intended for settable solids or is only effective for coarse solids. A high rating indicates treatment is generally effective for finer settable solids.
** Qualitative scale gauging the live or active storage volume designed for flow attenuation.

requirements. Routine requirements are inspection, trash and litter pickup, removal of obstructions at inlets and outlet, vector control, and vegetation management if applicable. The major requirement will be periodic removal of accumulated sediments.

General Design Considerations: The main design criteria are detention volume and configuration, outlet design and drawdown time, and pretreatment and screening facilities.

In space-constrained settings, detention volume is a key design variable and tradeoffs with performance are expected. Small or undersized basins can still provide beneficial treatment for smaller, more frequent storms and for first flush discharges. Smaller basins should be considered, even in highly space-limited areas (see Section 7 regarding the useful effectiveness of "underdesigned" basins).

Outlet design and sizing significantly affects performance and sediment trapping. For a fixed basin volume, there is a tradeoff between volume capture (greater with short detention time) and sediment capture (greater with longer detention time). Sediment trapping and sediment resuspension are also influenced by the system and outlet design.

Detention facilities typically have pretreatment facilities such as grates, GSRDs, and initial settling area for removal of gross solids, trash and debris.

Siting Considerations: Space requirements are the main constraint limiting surface detention retrofits in ultra-urban environments. However, the configuration of surface detention facilities is somewhat flexible, which provides opportunity for adapting designs to fit within available space and contours. Potential opportunities for siting surface detention retrofits are discussed in Section 9.

Applicability to Ultra-Urban Retrofits: Surface detention facilities are a primary and attractive retrofit option based on the following benefits: (1) they are non-proprietary systems that are accepted and widely used by DOTs; (2) they provide good flow attenuation and general water quality treatment performance; (3) they have relatively low cost; and (4) they do not have excessive maintenance requirements. Surface detention retrofits are applicable for ultra-urban highway retrofits when:

- Adequate space and maintenance access can be located;
- Treatment of general highway POCs is suitable; and
- Flow attenuation is required.

4.6.2 Underground Detention Retrofits

Underground detention retrofits are options for meeting flow attenuation and water quality treatment goals in space-limited situations where there are no aboveground alternatives. Underground detention retrofits are usually secondary options to aboveground facilities due to cost and maintenance considerations.

Underground Detention for Flow Attenuation: Underground detention facilities are designed principally for flow attenuation. Underground detention facilities by themselves do not provide significant water quality treatment and are generally not intended for this purpose.

Table 4.8 shows construction options for underground detention. Oversized conveyances using standard construction materials such as concrete and corrugated metal pipes are commonly used for underground detention. Many vendors of underground storage systems also market a variety of material and approaches. Products may be modular in design providing great flexibility and adaptability, which can be very advantageous for retrofitting situations. These systems are pre-engineered, which simplifies design and installation requirements, and can lower costs. The primary factors in the selection and design of storage systems are (Brzozowski, 2003):

- Space and configuration,
- Head requirements and tolerances,
- Cost, and
- Durability.

Underground Detention for Water Quality Treatment: Various design enhancements have been incorporated into underground detention systems to promote sediment capture. Many are proprietary vault systems that use baffles, energy dissipaters, and/or permanent wet pools to promote sedimentation and capture and to reduce resuspension. Some are modular detention vaults that provide flexible design options, including layout and configuration, use of weir walls to isolate sedimentation chambers, and maintenance access locations. Figure 4.8 shows example proprietary systems.

Commercially available precast concrete vaults provide a non-proprietary alternative for underground detention and sediment capture (Figure 4.9). Precast vaults are prefabricated, available from many vendors, and low cost. Sediment resuspension and washout is a concern with these vaults, and design and operational modifications may be needed to obtain effective sediment capture (see box adjacent to Figure 4.9).

Space Requirements: Space requirements for underground detention facilities are approximately 0.5% to 1% of the tributary area and can be located below vehicular or non-vehicular areas (Shoemaker et al., 2002).

Head Requirements: Head requirements to operate the underground detention facilities are small. Connectivity with gravity drainage to outlet points can be an issue for underground installations in flat terrains and can potentially necessitate pumping to discharge locations.

Performance: Underground detention retrofits provide excellent flow attenuation performance. Underground detention retrofits that are also designed for sediment capture have variable performance. Sediment resuspension and flushing is the primary issue of concern. Good sediment capture performance is reported in systems that have baffles, dissipaters, wet pools, and batch operation conditions (NJCAT, 2007; Li et al., 2008a).

Underground detention retrofits provide poor treatment performance for dissolved POCs such as nutrients and dissolved metals. They also do not allow infiltration and associated volume reduction.

Cold Weather: Underground detention facilities can be designed to operate effectively in cold weather. Modifications may include larger sizing to accommodate increased runoff, conveyance design modifications to mitigate pipe freezing, locating the vault at a depth that is below the freezing layer, and greater pretreatment storage.

Maintenance: Underground flow attenuation facilities have minimal maintenance requirements. They require periodic inspection for sediment accumulation and sediment clearing as needed and may require adherence to confined-space protocols during maintenance episodes.

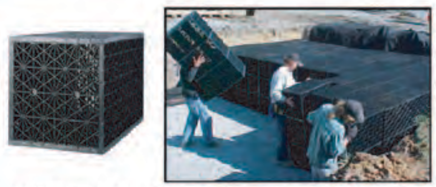
Underground detention facilities designed for water quality treatment require more regular inspection, at least annually or more frequently depending on size and loadings. Sediment clearing should be conducted as necessary to maintain adequate sump capacity and to reduce the potential of washout.

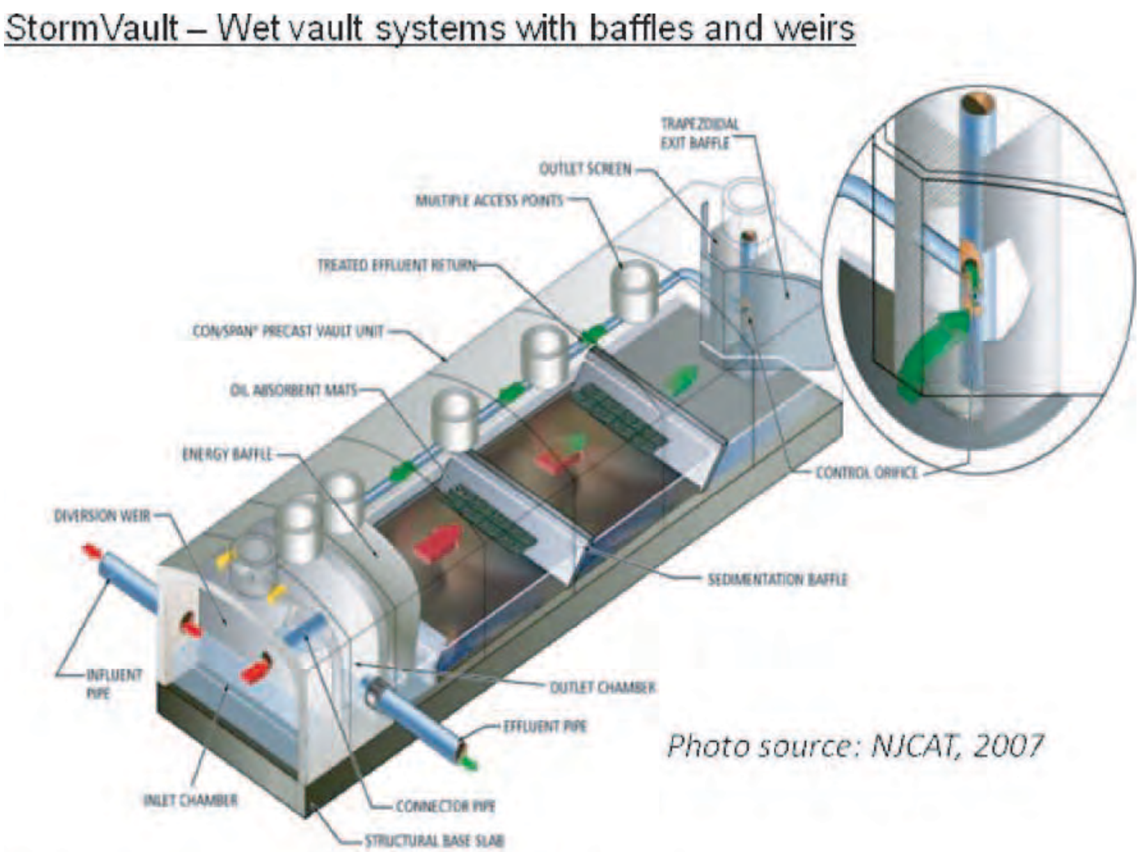
Applicability to Ultra-Urban Retrofits: Underground detention facilities are applicable for ultra-urban highway retrofits when:

- There are no feasible locations for surface detention;
- Flow attenuation is required; and

Table 4.8. Construction options for underground detention.

Material	Example	Advantages	Disadvantages
Concrete Pipe	 Photo source: http://www.concrete-pipe.org	• Standard materials, widespread availability • Many sizes and shapes • High strength, high load-bearing capacity • Very rigid, fill not required to maintain rigidity • Requires minimal fill above structures • Will not float • Good corrosion resistance • Long-term durability and less chance of failure • Reduced repair and replacement needs promote sustainability • Flexible design, adaptable to site configurations and connectivity to existing conveyances • Many vendors with a variety of modular systems and very flexible design; they are pre-engineered and easy to install • Suitable for linear highway environments with small catchments	• Requires more excavation than rectangular-shaped vaults • Heavy, requires moving equipment. More difficult to work with than alterative materials • More costly than alternative materials
Prefabricated Concrete Vaults	 Photo source: http://www.stormtrap.com/	• Similar advantages to concrete pipes • Potentially, less excavation than circular pipes • More compact than pipes; may be more suitable for highly constrained highway environments • More adaptable to irregular-shaped spaces and depths • Vendors have developed a variety of modular designs that are adaptable to site conditions; pre-engineered, easy to install	• Heavy, requires moving equipment • More costly than alternative materials

Corrugated Metal Pipes	 Photo source: Contech Construction Products	• Standard materials, widespread availability • Many sizes and shapes • Lightweight and longer lengths than concrete pipes; easier to work with and less costly to install • Lower cost compared to concrete • Good durability, but less than concrete • Rigid, can withstand some shifting without breaking • Requires minimal fill above structures • Vendors have developed modular systems with flexible designs; they are pre-engineered and easy to install • Good alternative to concrete pipes in linear, space-constrained highway environments.	• Susceptible to corrosion; may require coatings • Concerns about deformation if improperly installed • Requires fill to maintain rigidity
Corrugated High-Density Polyethylene Pipe & Tanks	 Photo source: http://prinsco.com/	• Extremely lightweight and easy to work with; can reduce installation costs • Durable and corrosion resistant • Plastic tanks are available in a variety of sizes • Some are made with recycled material supporting sustainability goals • Vendors have developed modular systems with flexible designs; they are pre-engineered and easy to install • Good alternative to concrete/metal pipes in linear, space-constrained highway environments.	• Requires fill to maintain rigidity • Buoyancy concerns in high groundwater • Strength concerns with corrugated pipes
Modular Plastic Stormwater Storage Systems	 Photo source: http://www.acfenvironmental.com/	• High-porosity stackable plastic units • Lightweight, easy to work with and install • Easily configured to a variety of shapes and sizes, amenable to retrofit applications in space-constrained settings • Durable materials	• Requires pretreatment • No access for maintenance • Newer technology, less long-term performance information • Potentially susceptible to clogging



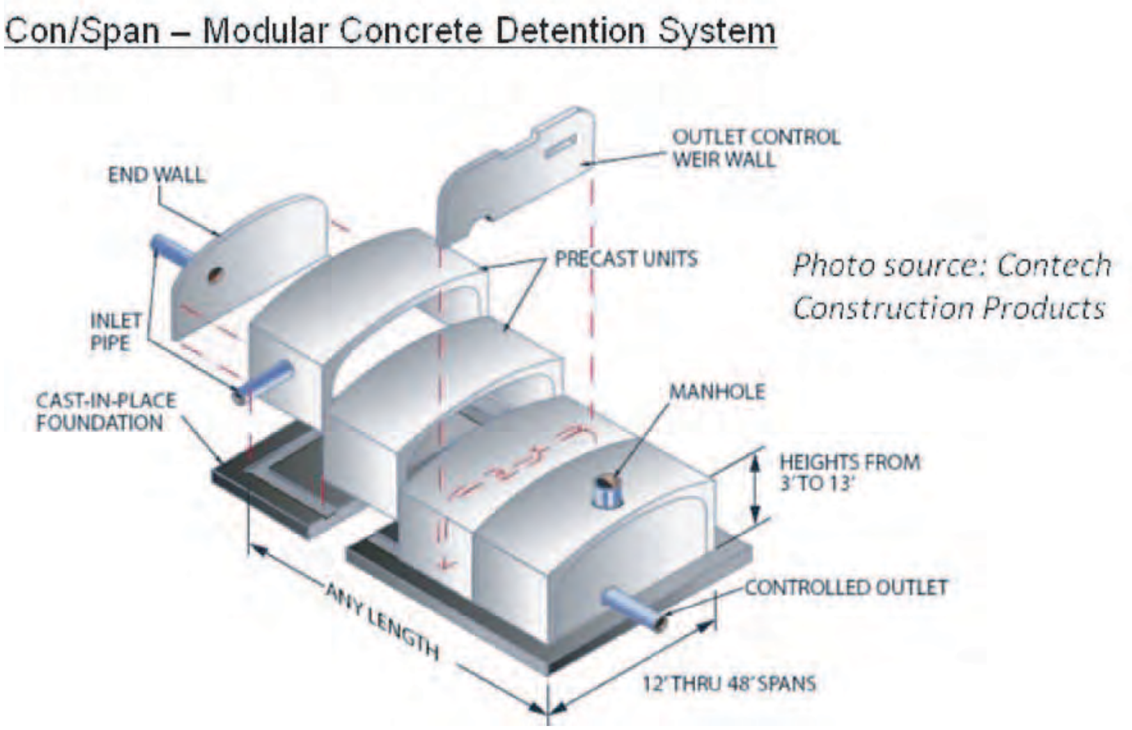


Figure 4.8. Two examples of proprietary underground detention systems.

Figure 4.9. Non-proprietary precast concrete vault used in the Texas Transportation Institute to study sediment capture in prefabricated vaults.

Texas Study on the Sediment Capture Effectiveness in Non-proprietary Vaults

The Texas Transportation Institute tested non-proprietary vaults for reducing TSS and associated pollutants from highway runoff (Landphair et al., 2007; Li et al., 2008a). It assessed the effect of outlet type, location, and operation on sediment capture. Study findings included the following:

- Sediment resuspension is a significant problem when the tank is filling and is magnified when sediment-laden waters enter the tank.
- Sediment trapping is improved in dry vaults with outlet locations near the inlet, and when skimmer (floating) outlets are used.
- Batch operation with standard outlet designs (i.e., a fill, hold, and release strategy) improves sediment trapping as well as reduces resuspension. A detention period (hold time) of 3 hours diminished the problems of resuspension and improved sediment capture above 80% capture.

- Sediments and associated pollutants are the primary target pollutant.

4.6.3 Enhancements for Detention Retrofits

Retrofit designers may consider several structural and operational enhancements to increase performance of detention retrofits.

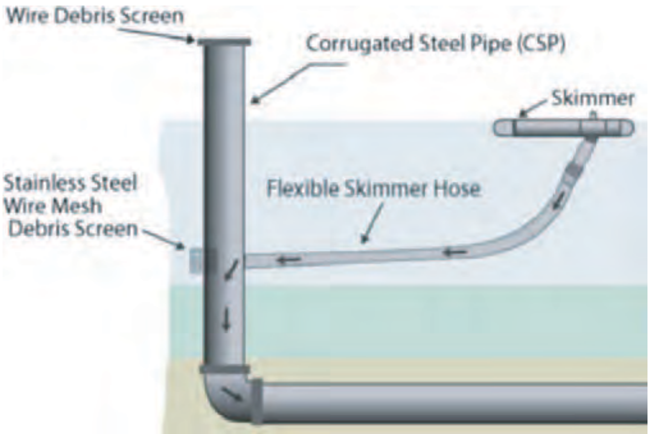
Outlet Design

Traditional outlet designs use orifice plates or pipes near the basin invert that are sized to limit peak flows and/or to provide specified detention times. Such outlets are designed on the basis of brim full capacity and will therefore provide shorter detention and less effective sediment capture for smaller more frequently occurring storms that do not fill the basin.

Stormvault Performance Evaluations

Stormvaults are proprietary underground detention vaults that include a permanent wet pool and other pollutant capture features such as energy dissipaters, sediment trapping baffles, and oil adsorption mats. A typical design includes a 3 ft wet pool, sufficient live storage for the WQ design event, and a 6 h brim full drawdown time. Results from independent field assessments at multiple sites and studies (Wright Water, 2002; Fassman, 2006; NJCAT, 2007) show:

- Average influent TSS concentrations at study sites ranged between 50 to 100 mg/L reflecting field site conditions.
- Effluent TSS concentrations were frequently low, typically < 20 mg/L. The sediment removal efficiency was high, typically greater than 80% to 90%.
- Sediment scour tests showed no obvious sediment resuspension based on effluent TSS concentrations at 100% to 125% of the design peak flow rate, and when accumulated sediments were more than 100% of the required maintenance depth (NJCAT, 2007).
- Good removals were measured for particulate-bound pollutants including TKN, phosphorus, and metals.
- An average peak flow attenuation of 80% was reported (NJCAT, 2007).



Source: Caltrans (2010)

Figure 4.10. Skimmer outlet design.

Perforated riser outlets improve sediment capture by permitting multiple drawdown rates over different stages of the basin. This allows for slower drawdown rates for the lower portion of the basin, providing more effective sediment capture for smaller storms. Perforated risers also provide drawdown over the full depth of the water column.

Skimmer outlets, or floating outlet structures, are specifically designed to improve sediment capture by draining water from the surface where suspended sediment concentration is smaller due to gravitational settling (Figure 4.10). Laboratory studies and studies in underground detention vaults have found skimmer outlets provide better sediment capture than perforated riser structures (Hoechst, 1997; Li et al., 2008a). Skimmer outlets also provide better performance with shorter retention times, which is significant for small detention systems. Despite promising results, skimmer outlets are not widely used in detention facilities, in part because researchers and DOTs are concerned about the long-term maintenance of moving (passive) components in the outlet structure.

Batch Operation

The concept of batch operation (hold-and-release) is to increase sedimentation time in detention facilities by modifying the outlet with a dynamic controller. The controller is programmed to close the outlet at the beginning of a storm (at a predetermined water level) and to open the outlet after a predetermined settling time (e.g., a few hours for small vaults, up to 24 to 48 h for large basins). This provides the full design detention time for distinct storms with runoff volumes that do not exceed the design capacity of the basin.

Batch operation was field tested on retrofitted detention basins in Austin, Texas (Middleton et al., 2006). Effluent concentrations for TSS, particulate metals, COD, TKN, and nitrogen were lower in the retrofitted basins than the pre-retrofit basins, and improvement was statistically significant. The effluent quality from the retrofitted basins was comparable to the treatment performance of Austin sand filters, but with smaller footprint and hydraulic head requirements.

Batch operation of detention facilities may have several benefits in ultra-urban highway environments:

- **Improve sediment trapping in small underground vaults.** Batch operation has been found to improve sedimentation and to reduce effects from resuspension in small-footprint precast underground vaults (Li et al., 2008a). In these systems, hold times of 3 h resulted in greater than 80% TSS removal. Shorter hold times as low as 1 h can be used for areas with high-frequency short-duration storms.
- **Target first flush.** Batch operation can be designed to target treatment of the initial "first flush" portions of the runoff hydrograph. For example, a two-chamber detention vault can be designed with controllers that hold and treat the first flush runoff volume in the primary detention unit, while runoff in excess of the first flush volume is bypassed to the secondary detention unit with shorter detention times (see Section 6.2.2). In small watersheds, such as highly impervious highway environments, first flush of pollutants has been observed (Stenstrom and Kayhanian, 2005).
- **Trap hazardous materials.** Batch operation can allow surface and underground detention facilities to function as a hazardous materials trap by manually overriding the opening of the outlet after a spill event.

4.7 Media Filtration Retrofits

4.7.1 Overview

Media filtration retrofits are structural BMPs designed to capture and filter stormwater through a media filter bed. Media filtration retrofits are distinguished from infiltration retrofits by collection systems that discharge to surface outfalls. Media filtration systems are designed with little or no vegetation. The typical components are stormwater collection and distribution structures, pretreatment areas to remove gross solids, media filtration beds, collection systems such as underdrains, and discharge structures to surface outfalls.

Media filtration systems are very suitable and applicable to ultra-urban retrofit applications because they can deliver good to effective treatment of sediments, particulate-bound pollutants (metals, phosphorus) and organics (oil and grease), and they include designs that are amenable to ultra-urban constraints such as linear configurations and underground installations. The options for media filtration retrofits can be divided into three broad categories:

- Standard sand filter systems,
- Non-proprietary media filter drains with engineered media mixtures, and
- Proprietary underground stormwater filtration systems.

DOTs commonly use and allow the media filtration systems above, and several DOTs have researched and developed media filtration systems that are applicable to highway infrastructure. Table 4.9 summarizes media filtration retrofits. The following subsections detail the three media filtration categories.

4.7.2 Sand Filters

Types of Devices: Common sand filter configurations are shown in Figure 4.11 and include the following:

- **Austin sand filters.** Surface filtration systems, typically contained in concrete shells and sometimes within earthen berms. They are two-stage sedimentation and filtration systems. Sand beds are usually 18 to 24 in.
- **Underground sand filters.** The "DC filter" design is similar in concept to the Austin sand filter but is designed for underground installation in space-limited areas. DC filter designs can be installed in concrete vaults or corrugated metal pipe. The DC filter design has a permanent wet pool.

Table 4.9. Summary of media filtration retrofits.

Consideration	Attributes
Target Constituents	Fine sediments, particulate-bound pollutants, dissolved pollutants
Types of Devices	• Surface and underground sand filters • Non-proprietary media filters • Proprietary stormwater filtration systems
Unit Operations	• Sedimentation, filtration, sorption
Area Requirement	• 2% to 3% of the tributary watershed
Head Requirement	• Moderate to high, 2 to 8 ft or more
Online/Offline	• Usually offline. Can be online with overflow protection.
Maintenance Requirements	• Regular inspection of pretreatment areas and media beds for crusting and caking • Regular cleaning of pretreatment sumps • Regular scraping and replacement of top layers of the media bed
Performance	• Moderate to excellent performance for gross solids, sediments, particulate-bound sediments, and organics, bacteria • Sand filters have poor to moderate performance for dissolved pollutants • Little to no flow attenuation and volume reduction
Relative Cost	• High, ~ \$1000 to >\$2000 per m^3 of design storm treated; costs depend strongly on design and location
Treatment Train Considerations	• To reduce the onset of filter clogging, pretreatment is required to remove gross solids and settable solids
Benefits for Ultra-Urban Retrofits	• High treatment effectiveness for highway POCs • Use commonly available or native materials for media • Many configurations amenable to ultra-urban constraints
Limitations for Ultra-Urban Retrofits	• High cost compared to detention facilities • High head requirements • Ongoing routine maintenance required to ensure performance • Some designs with permanent wet pools can have mosquito issues • Some designs can have clogging issues • Not suitable for areas with high water tables or where infiltration rates are too low, e.g., less than about 0.25 in./h
Applicability for Highway Retrofits	• High level of treatment performance is needed • There is adequate head • There is adequate maintenance capability
Design Enhancements	• Media amendments and engineered media mixtures • Outlet control

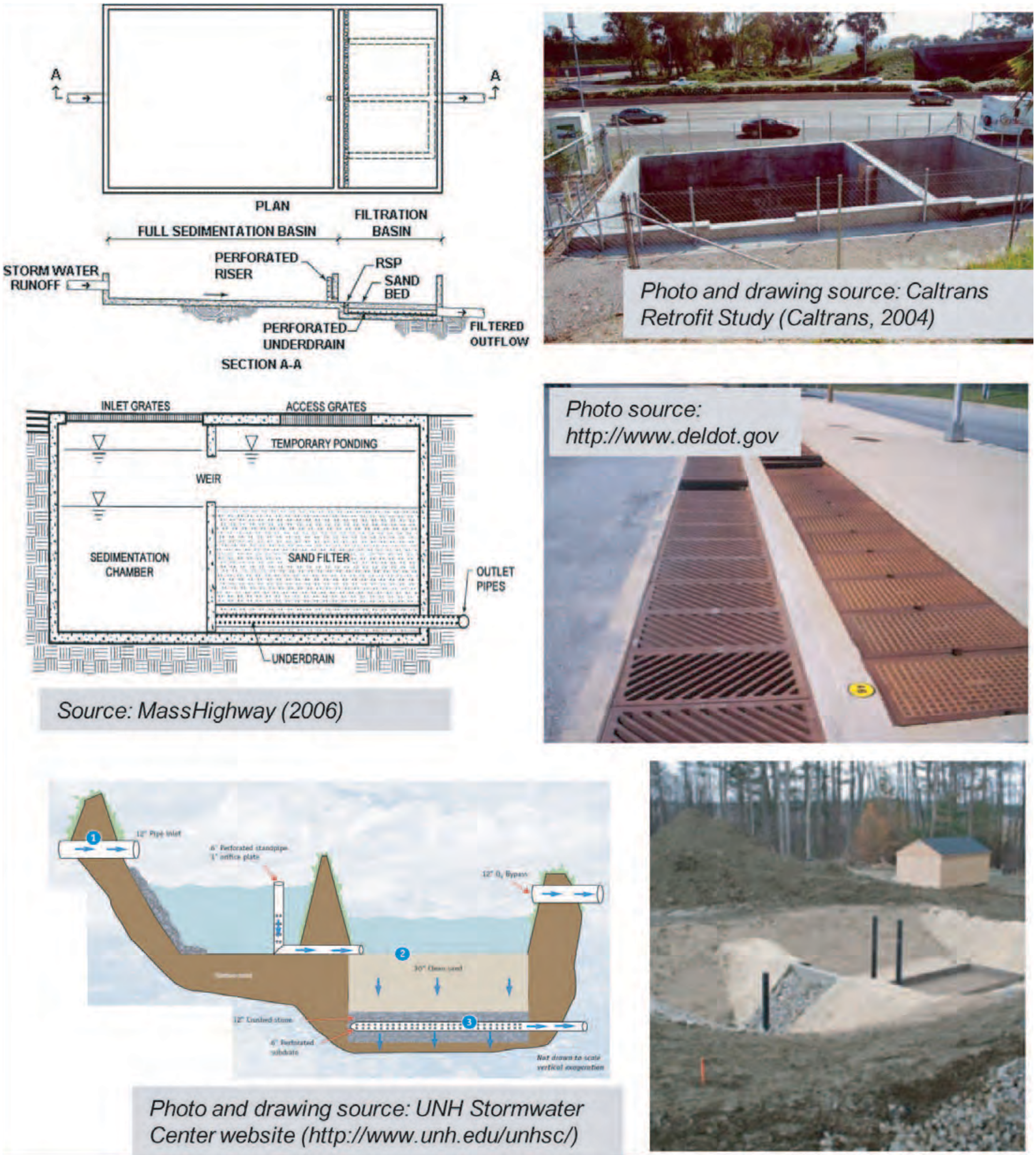


Figure 4.11. Three examples of sand filter configurations: Austin sand filter (top); Delaware sand filter (middle); pocket sand filter (bottom).

- **Delaware sand filters.** Delaware sand filters are underground filter systems with long narrow configurations that are suitable as perimeter filters along parking lots and highway shoulders. They are designed with a double trench, the first trench serving as the inlet, sedimentation, and flow distribution chamber with a permanent wet pool, and the second trench containing the sand media bed.
- **Pocket sand filters.** Pocket sand filters are surface sand filters similar in concept to Austin sand filters but are designed as low-cost systems serving small drainage areas.

Unit Operations: Media filtration systems use pretreatment facilities to remove coarse sediment and gross solids that can clog the media beds. Pretreatment is usually achieved by screening and a sedimentation/settling process, but filtration with vegetated filter strips or porous pavements can also be used. Filtration and sorption processes are the primary pollutant removal process in the media bed. Biofilms that promote microbially mediated transformations of pollutants may develop in the media bed depending on design and operating conditions.

Area and Head Requirements: Area requirements for sand filters are approximately 2% to 3% of the tributary drainage area (Claytor and Schueler, 1996). Head requirements for sand filters can be high. Minimum head requirements for Austin sand filters, underground filters, and pocket sand filters are about 5 to 8 ft. Delaware filters have lower head requirements of about 2 to 3 ft (Claytor and Schueler, 1996). Head requirements are a significant siting constraint for ultra-urban retrofits, especially in flat terrains.

Performance: Sand filters provide good to excellent treatment performance for many highway POCs. They provide excellent treatment of sediment; moderate to good treatment of particulate-bound constituents including metals, phosphorus, and TKN; and moderate to good removals of bacteria and organics (Caltrans, 2004; Claytor and Schueler, 1996). Reported performance for soluble nutrients is poor and systems have shown release of nitrate (Caltrans, 2004; Clark and Pitt, 2009). The main issue affecting performance is clogging and crusting of the media bed, which reduces the hydraulic performance and increases bypass flows (Hatt et al., 2008; Keblin et al., 1997). Sand filters may provide some flow attenuation but are mainly designed for water quality treatment. Because hydraulic conductivity is inversely proportional to viscosity, infiltration rates will be lower as temperature decreases. Capture of organic and/or clay materials may enhance performance for dissolved metals over time, provided they do not clog the filter.

Maintenance Requirements: Maintenance to control clogging and to maintain the infiltration capacity of the media bed is critical for treatment performance. Roseen et al. (2006) observed poor performance of sand filters due to installation and maintenance issues. Routine maintenance activities are sediment removal from the pretreatment areas and rehabilitation of the media bed (scraping and replacing of the top few inches) when drawdown rates are significantly below design criteria. The routine practices depend on the system design and site-specific sediment-loading rates but may be as often as every 6 to 12 months. Underground systems require more frequent inspection and can be more difficult to access and maintain. Caltrans (2004) noted that maintenance to alleviate clogging was not excessive and that siting requirements are compatible with small impervious watersheds. The entire media bed must be replaced periodically, about every 3 to 5 years (USEPA, 1999b). Media testing could be required to determine appropriate disposal methods; however, disposal procedures for hazardous material is not typically required. Systems with permanent wet pools may require vector control.

Cold Weather: Surface media filtration systems will not be effective in freezing conditions during winter months. Cold climate modifications for surface filtration systems include (Caraco and Claytor, 1997):

- Increase the size of pretreatment facilities to handle increased loadings and improve performance;
- Improve underground drainage by increasing the depth of the gravel base, increasing the size of underdrain pipes, and increasing the slope of underdrains;
- Modify design of conveyances to prevent damage from freezing;
- Replace perforated riser pipes from pretreatment forebays with weir outlets;
- Increase inspection during winter months as needed; and
- Consider shutting infiltration facilities in areas with prolonged cold weather.

Underground media filtration systems sited below the frost line should be operable during cold weather. Conveyance and design modifications may be required, and performance will be hindered.

Applicability for Ultra-Urban Highway Retrofits: Sand filters are applicable and appealing retrofit options because they provide effective treatment for many highway POCs, they have a variety of design configurations that address ultra-urban constraints, and they use commonly available or native material for media. They do not have excessive maintenance requirements, but require regular and ongoing maintenance to ensure effectiveness. The main drawbacks are cost and head requirements. Sand filters are applicable for ultra-urban highway retrofits when:

- A high level of treatment performance for highway POCs is required, particularly for sediment and particulate-bound pollutants;
- Systems using engineered media are not cost effective or warranted;
- There is sufficient head available; and
- There is sufficient maintenance access and capability.

4.7.3 Non-Proprietary Media Filters with Amended Soils

Use of Soil Amendments. Media amendments to sand filters or specially designed media mixtures are used to improve treatment performance over sand media alone. Commonly used low-cost amendments to sand filters are peat and compost, which are sometimes called organic filters (Claytor and Schueler, 1996). Peat and compost amendments to sand filters have been found to improve removals of metals and organics, but they can also cause reduction of effluent quality including increases in color, turbidity, and soluble nutrients (nitrate), particularly when the filters dry out (Claytor and Schueler, 1996; Clark and Pitt, 1999; Shoemaker et al., 2002).

Laboratory and field treatability tests are conducted to develop and evaluate media mixtures for improved treatment performance or to target removal of specific pollutants (e.g., Clark and Pitt, 1999; Koob and Barber, 1999; Pitt et al., 2009). A wide variety of amendments and media mixtures have been tested and are used in media filtration systems, including activated carbon, zeolite, perlite, iron-oxide coated sands, dolomite, gypsum, pumice, and many others. Media mixtures that perform well for a range of pollutants are sand/granular activated carbon (GAC) mixtures and sand/peat mixtures (Woelkers et al., 2006). Other mixes target specific pollutants, for example, the WSDOT media mix targets dissolved metal (WSDOT, 2008a). Media mixes have also been developed that target phosphorus (Ma et al., 2009), nitrate (Kim et al., 2003), organics (Milesi et al., 2006), and metals and dioxins (Pitt and Clark, 2010).

Types of Devices: In principle, soil amendments and engineered media mixtures can be used in any type of surface or proprietary media filtration system, as well as vegetated filtration systems and infiltration systems. Highlighted here are two non-proprietary surface media filtration systems that incorporate amended media and are applicable to highway retrofits: (1) the WSDOT media filter drain, and (2) the multi-chambered treatment train.

WSDOT Media Filter Drain

Media Filter Drain Design: The WSDOT media filter drain (MFD) is a roadside media filtration system that is designed to provide enhanced removal of metals, notably dissolved copper (WSDOT, 2008a). Figure 4.12 shows the MFD concept. The MFD is a narrow linear filtration system designed for downslope embankments adjacent to highway, preferably between 4H:1V and 3H:1V. The design includes three treatment components: (1) a gravel base that provides pretreatment of sediments and acts as a level spreader for sheet flow, (2) a vegetated area that acts as a physical biofilter and promotes infiltration, and (3) the media filtration component that promotes removal through filtration and sorption and collection in an underdrain system. The WSDOT media mix includes crushed stone, dolomite and gypsum for alkalinity and ion exchange capacity to promote the precipitation and exchange of heavy metals, and perlite for moisture retention.

Various design configurations are used by WSDOT, including systems with and without underdrains, dual MFDs designed for roadway medians, and a modified MFD in which highway runoff is collected and diverted to a centralized filtration system built in available space within the ROW.

WSDOT does not recommend installation of the MFD near wetlands or in the presence of a high groundwater table, both because of the likelihood of insufficient vertical filtration distance and because soft soil may affect vehicular safety should a vehicle veer onto the filter area. WSDOT is currently experimenting with different media to try to maintain MFD performance while also reducing the risk of stuck tire wheels in the grass strip section.

Area and Head Requirements: The MFD area is sized to provide enough area for full infiltration of runoff using a design infiltration capacity of 10 in./h. The specified minimum widths are 2 ft for a pavement width of 20 ft or less, and 4 ft for a roadbed width greater than 35 ft. Head requirements are minimal for the MFD, which relies on gravity drainage. The modified MFD requires enough head to convey runoff from the collection system through the inlet and outlet points of the media bed, a minimum of 2 to 3 ft or more.

Performance: Monitoring studies have found excellent treatment performance with the WSDOT MFD for a wide range of highway POCs (Herrera Environmental Consultants, 2006). They have observed high removal efficiencies and excellent effluent quality for sediments, total phosphorus, total and dissolved metals, and oils.

Maintenance Requirements: Routine operation and maintenance requirements are minimal. The MFD design requires only standard highway maintenance practices such as vegetation management and litter pickup. Periodic replacement of the media is required. The media design life is 10 years, but longer operation is anticipated.

Applicability for Ultra-Urban Highway Retrofits: The WSDOT MFD and the modified MFD are appealing retrofit options because they provide effective treatment for a wide range of highway POCs, they have a variety of design configurations that are suitable for highways, and they have minimal maintenance requirements. The WSDOT MFDs are applicable for ultra-urban highway retrofits when:

- A high level of treatment performance for highway POCs is required, particularly for sediment, particulate-bound pollutants, and dissolved metals.
- There is adequate and suitable vacant shoulder space down gradient for retrofits with the standard MFD.
- There is suitable ROW area and sufficient head for modified MFD installations.

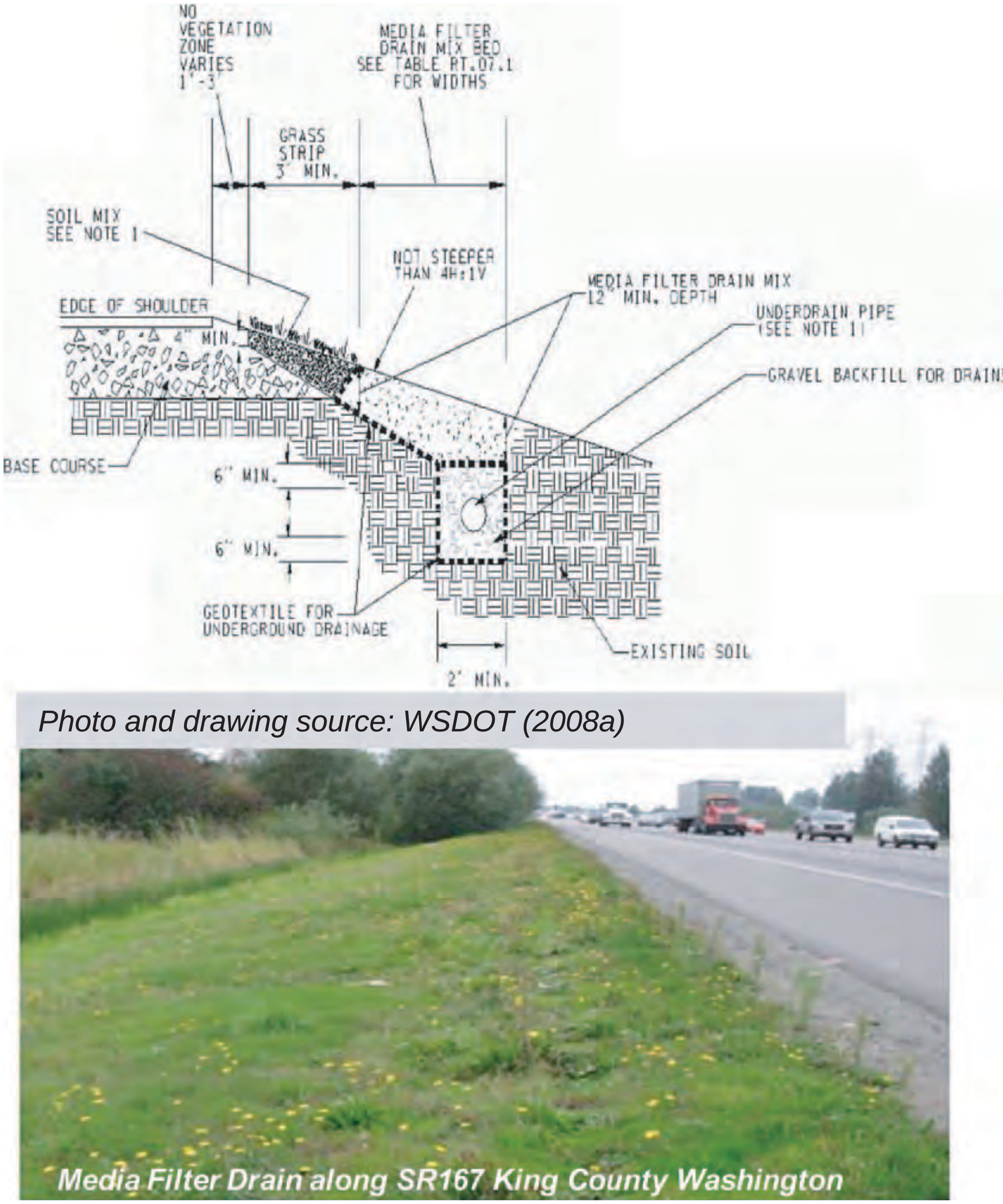


Figure 4.12. WSDOT media filter drain.

Multi-Chambered Treatment Train

Multi-Chambered Treatment Train Design: The Multi-Chambered Treatment Train (MCTT) is a three-stage treatment system. The MCTT is specifically designed to provide a high level of treatment effectiveness for small (0.25 to 2.5 acres) critical source areas in order to reduce toxicity in receiving waters. Figure 4.13 shows the MCTT concept. The MCTT includes three treatment compartments housed in an open concrete shell or constructed underground (Pitt et al., 1999a):

- An initial grit chamber for trapping the largest sediment and packed column aerators for release of volatile organics;
- A main settling chamber with aeration (including power and operation and maintenance requirements) and sorbent pillows for the trapping of fine sediment, associated toxicants, and floating hydrocarbons; and
- A sand and peat mixed media filter (sorption-ion exchange) for the reduction of filterable toxicants.

Area and Head Requirements: The MCTT area requirements are about 1% to 2% of the tributary drainage area

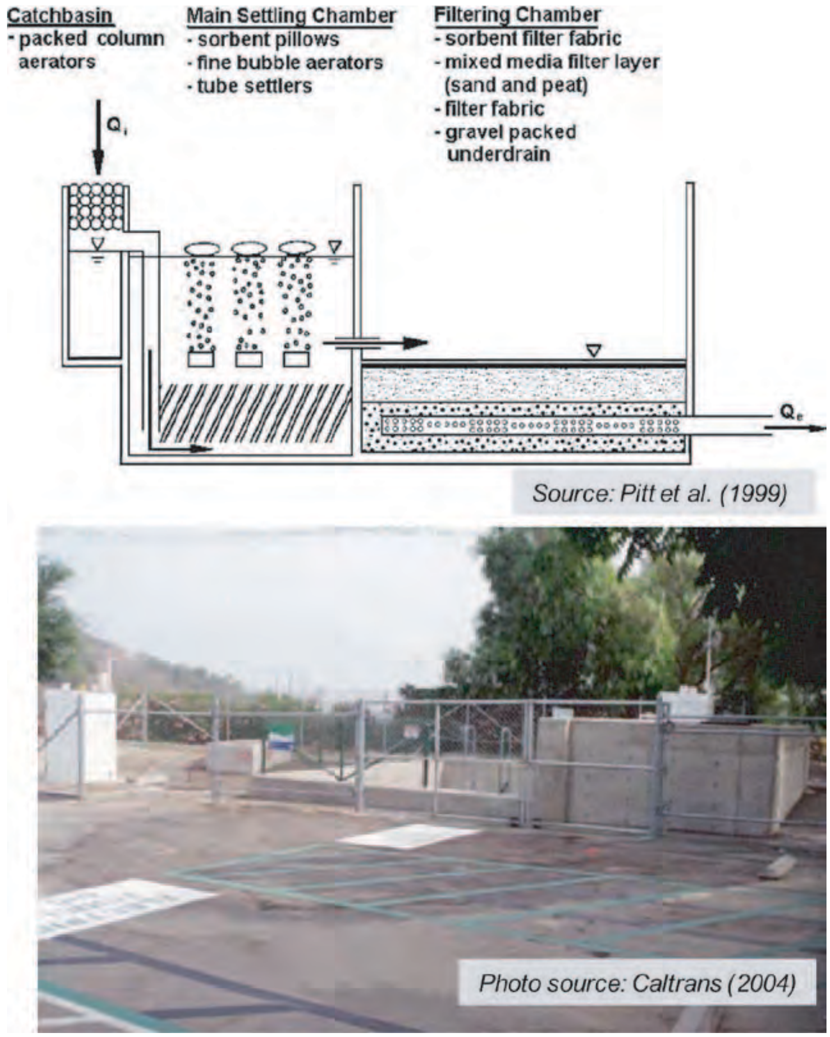


Figure 4.13. Multi-chambered treat train.

depending on site conditions and performance requirements. Hydraulic head requirements can be high with a minimum of about 3 to 10 ft or more depending on design.

Performance: Monitoring studies have found high to very high removal efficiency for toxicity, sediments, total metals, total phosphorus, and many organics, and good removal for dissolved metals (Pitt et al., 1999a). Caltrans (2004) noted that the MCTT had performance similar to the Delaware filter but life-cycle costs were higher.

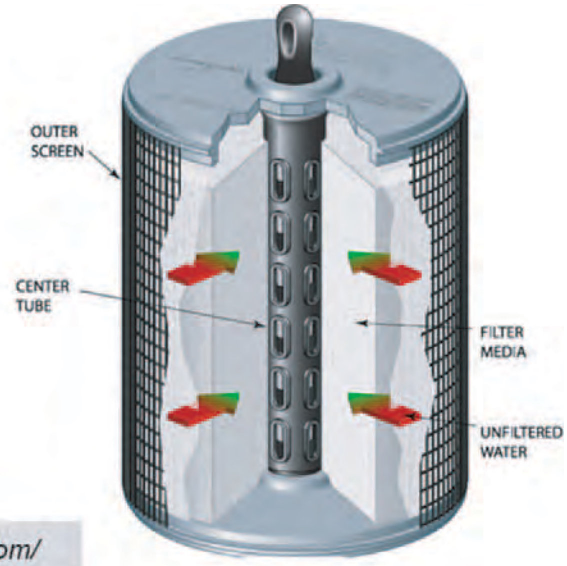
Maintenance Requirements: Maintenance requirements are similar to sand filters. Routine maintenance includes inspection and cleaning of pretreatment and settling areas, and periodic scraping of the media bed to maintain infiltration capacity. Major maintenance to replace the media bed is required every 3 to 5 years (Pitt et al., 1999). The MCTT has a permanent wet pool, which can necessitate mosquito control.

Applicability for Ultra-Urban Highway Retrofits: The MCTT is applicable for ultra-urban highway retrofits when:

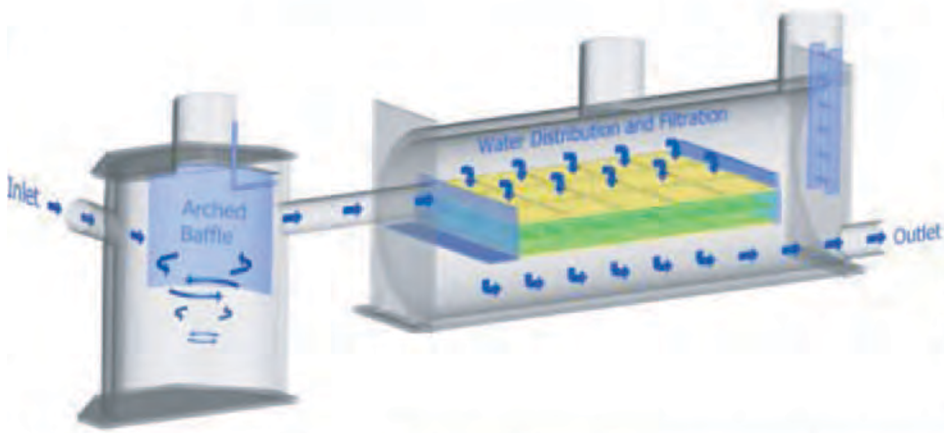
- A high level of treatment performance for highway POCs is required, particularly to address toxicity issues in receiving waters;
- There is adequate roadside space and sufficient head; and
- There is sufficient maintenance access and capability.

4.7.4 Proprietary Underground Media Filter

Types of Devices: There is a wide variety of commercially available proprietary media filtration systems with a range of designs, configurations, and sizing. Figure 4.14 shows selected example devices. Many proprietary systems are designed for small-footprint underground installations using prefabricated systems for easy installation in space-constrained settings. Cast-in-place systems are also marketed, as are self-contained aboveground systems. The designs include variations of standard media bed systems housed in underground vaults or circular conduits or integrated into modular underground detention systems. Media cartridge systems housed in



Source: Contech - http://www.contech-cpi.com/



Source: Aquashield - http://www.aquashieldinc.com/

Figure 4.14. Two examples of proprietary underground filtration systems: media cartridge system (top); integrated hydrodynamic and media filtration systems (bottom).

underground vaults are also widely used. Most systems incorporate sedimentation for pretreatment, but some designs integrate hydrodynamic separators for pretreatment. Most manufacturers provide a variety of media mixes for different applications and target pollutants, and some market proprietary media mixes.

Area Requirements: Proprietary underground filtration systems come in a range of sizes to match site conditions and design requirements. Most are designed for small-footprint underground applications with minimal space requirements. The systems must be located in areas with good maintenance access, sufficient head, and connectivity to existing conveyances.

Head Requirements: Head requirements are system dependent but can be moderate to high. There must be enough vertical clearance for gravity drainage between inlets and outlets, and for discharge to existing conveyances. This can be a siting constraint in flat terrains.

Performance: Treatment performance of proprietary systems depends on the system design and site-specific conditions. Performance assessments of a limited number of devices suggest, as a broad generalization, that proprietary underground filtration systems provide moderate to good removal of sediments, organics, and particulate-bound metals, and they provide poor to moderate performance for dissolved metals and nutrients. A comparison of underground filtration systems to surface sand filters in the Caltrans (2004) retrofit study showed that underground systems did not perform as well as the surface sand filters. In general, the performance of underground proprietary systems may be limited by size and capacity of the systems. However, this does not preclude some designs and media mixes from providing better or very good performance, as for example, some systems have received enhanced treatment certification by the Washington State Department of Ecology. Underground systems, like the surface systems, are not designed to provide flow attenuation or volume reduction.

Maintenance Requirements: Underground proprietary filtration systems have greater maintenance requirements than surface applications. They can require frequent inspection and cleaning of sediment sumps, refurbishment of media beds, and replacement of media cartridges. Increased costs can also be incurred from working in space-constrained underground structures and for replacement of proprietary components. Annualized O&M costs for storm filters were reported at more than twice that of sand filters in the Caltrans retrofit study (Caltrans, 2004).

Applicability for Ultra-Urban Highway Retrofits: Proprietary underground filtration systems are applicable for ultra-urban highway retrofits when:

- Space constraints are restrictive and there are no surface options;
- When target pollutants are primarily sediment and particulate-bound pollutants, and there is sufficient pretreatment; and
- There are adequate maintenance capabilities and maintenance access.

4.7.5 Enhancements for Media Filter Retrofits

Outlet Control

Media filtration systems with amended soils are designed for enhanced removal of dissolved pollutants through sorption and degradation processes. The effectiveness of these systems depends on two factors: (1) the chemical and microbiological properties and interactions of the media and water matrices and (2) the system hydraulics and flow-through rates, which affects the media contact time, as well as the filtering ability of the media.

In conventional gravity drainage filtration systems, the system flow-through rates are controlled by the media properties, principally the hydraulic conductivity, porosity, and thickness. The problem with using the media to dictate hydraulic design is that gravity drainage and flow-though rates can vary both spatially and temporally due to preferential flow paths and clogging over time. An upflow filter design is one approach for controlling the feed rate through the media bed to provide more uniform flow and improve media contact time, but upflow systems are not free draining systems, unless they are modified to do so (i.e., automated draining post event).

The concept of outlet control is to use an orifice outlet to regulate flows through the gravity drainage filtration system, rather than using the media properties to control the hydraulic design. Media with very high saturated conductivities are selected for the media (greater than 60 in./h). As shown in Figure 4.15, a primary discharge orifice is located near the top of the media bed and a low-flow (or trickle) orifice is located below the media bottom. The primary outlet control is sized and configured to pass the design storm flows under saturated media conditions. The low-flow outlet is sized and configured to restrict flows and encourage filling for small storm event flows and allow for complete drainage of the media bed within a specified drain time (e.g., 48 h) following a storm event. The emergency overflow is an open-ended riser pipe sized to pass flood flows without overtopping the filter structure.

An advantage of this type of outlet control is that it can easily be adjusted or calibrated after installation if hydrologic and hydraulic conditions differ from those modeled, or if an alternate hydraulic regime for the filter is desired. The elevations of orifices can be changed by lengthening or shortening the riser pipes. Orifice sizes can be altered by changing out restrictor plates and fittings, or adding inserts. If needed, additional orifices can be added to increase outlet sensitivity to flow conditions.

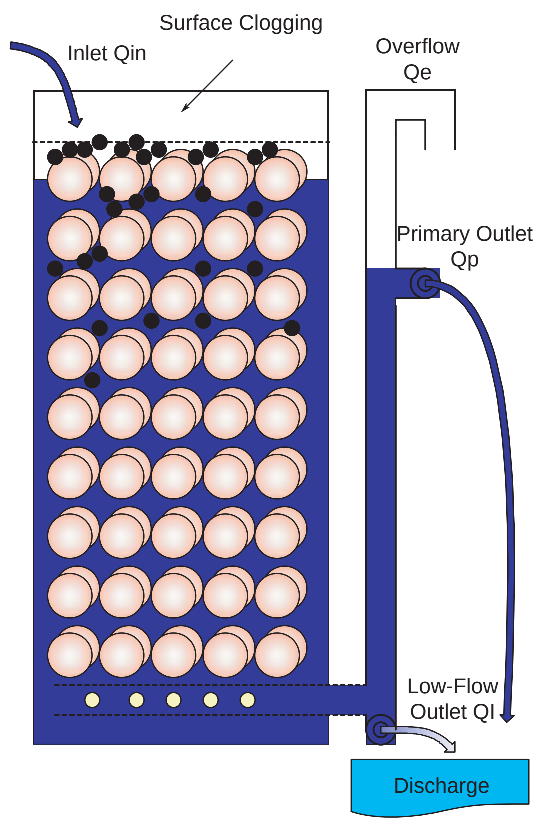


Figure 4.15. Outlet control concept for gravity drainage filtration systems.

Filter Fabric

Use of filter fabric in sand traps has shown effective filtration for sediments without significant clogging and loss of permeability (Caltrans, 2006). Filter fabric can be integrated into media filters near the surface of the filter if pretreatment is not provided. Filter fabric can also be wrapped around underdrains to restrict migration of sediments into effluent discharges.

Vegetation

The root structure of vegetation planted in media filters can help to retain infiltration capacity in media filters (e.g., bioremediation systems, media filter drains). Vegetation can also enhance the aesthetic value of the filtration system.

4.8 Vegetative Filtration/ Media Retrofits

4.8.1 Summary of Options

Vegetative filtration retrofits are a class of surface BMPs that incorporate vegetation into the BMP design to remove highway POCs. Vegetated filtration BMPs such as swales and filter strips are widely used by DOTs because they are compatible with highway design and maintenance practices, they have low capital and maintenance costs, and they provide effective treatment for highway POCs. Ideal conditions for vegetative filtration retrofits are landscape strips along the margins of highway ROWs where there is sheet flow from the roadbed, shallow flow depths, and/or low flow velocities. Limited space is the main siting constraint for ultra-urban retrofits. Table 4.10 summarizes vegetative filtration retrofits.

Vegetative filtration and media facilities are closely allied with low impact development and green stormwater infrastructure (GSI) concepts, and information about those concepts may be applied to ultra-urban installations. See, for example, references in Table 4.13.

Types of Devices: Vegetative filtration retrofits include swales, filter strips, and bioretention (Figure 4.16).

- **Vegetated swales:** Swales are engineered vegetated conveyances that are designed for shallow flow depths of the water quality flow rate to promote treatment by filtration and sedimentation. There are many design variations of swales including dry swales (Figure 4.16A), wet swales with permanent pools or marshy conditions, swales with underdrains, and swales that incorporate soil amendments (e.g., compost) or engineered media.
- **Filter strips:** Filter strips are moderately sloped vegetated embankments that are designed to treat sheet flow from adjacent impervious areas. Filter strips are well suited for treating highway runoff and compatible with highway designs.
- **Bioretention:** Bioretention facilities are vegetation retention areas designed to treat runoff by filtration, infiltration, sorption, and evaporation. Design variations include use of underdrains, overflow protection (Figure 4.16B), and amended or engineered soils. Underdrains are often incorporated into bioretention facilities for areas with poorly draining soils, or in specific landscaping applications such as stormwater planter boxes.

Unit Operations: Vegetative filtration retrofits remove highway pollutants through filtration, shallow settling, sorption, and biological processes. Infiltration into underlying soils also provides significant runoff volume reduction and pollutant load reduction.

Space and Head Requirements: Vegetative filtration systems have large space requirements, on the order of 10% to 20% of the tributary drainage area. Space requirements are likely the main constraint in ultra-urban applications. On the other hand, small units can often be placed between the sidewalk and roadway of ultra-urban downtown settings, providing some runoff attenuation, infiltration, and vegetative filtering. Vegetated BMPs typically have low operating head, on the order of 0.5 to 4 ft.

Performance: Many DOTs' studies have found significant water quality benefits of vegetated filtration BMPs and buffers (Newberry and Yonge, 1996; Biesboer and Elfering, 2003; Kearfott et al., 2005; Ebihara et al., 2009). Vegetated filtration BMPs provide good to excellent treatment performance for sediment and particulate metals, and moderate to good effectiveness for dissolved metals. They provide poor to moderate treatment of nutrients, with reported export of phosphorus and nitrogen compounds. However, some researchers are evaluating ways to improve nutrient performance, including more careful media selection and including long-term saturated conditions in the bottom portions of biofiltration systems. Vegetated filtration systems will also promote significant volume reduction via infiltration and evaporation, which results in associated pollutant reduction even when there is no change in concentration. Results from the Caltrans retrofit study found that swales and filter strips were among the least expensive devices evaluated and among the best performers in reducing sediment and heavy metals (Caltrans, 2004).

Cold Weather: Swales and filter strips can be used in cold weather for snow storage and treatment. Cold climate modifications for swales and strips are minimal (Caraco and Claytor, 1997) and include:

- Increasing sizing to accommodate snow storage and large runoff during snow melt;
- Using salt-tolerant vegetation in areas of salting; and
- Considering potential impacts to groundwater in salting areas.

Table 4.10. Summary of vegetative filtration retrofits.

Consideration	Attributes
Target Constituents	Particulate-bound pollutants primarily metals, dissolved pollutants
Types of Devices	• Swales • Filter strips • Bioretention
Unit Operations	• Sedimentation, filtration, sorption, biological processes, infiltration
Area Requirement	• 10% to 20% of the tributary watershed • Small bioretention/biofilters can often be placed between the sidewalk and the roadway in central business district
Head Requirement	• Low to moderate, 0.5 to 4 ft
Online/Offline	• Typically online
Maintenance Requirements	• Standard highway maintenance practices for vegetation management and litter pickup • Periodic vegetation thinning/planting and sediment removal • Regular scraping and replacement of top layers of the media bed
Performance	• Moderate to excellent performance for gross solids, sediments, particulate-bound pollutants, and organics, bacteria • Low to moderate treatment for nutrients • Can provide significant volume reduction and flow attenuation, depending on design
Relative Cost	• Low to moderate, ~ \$300 to >\$1000 per m^3 of design storm treated; costs depend on design and location
Treatment Train Considerations	• Incorporate pretreatment facilities to reduce clogging, and grates and racks at inlets and outlet as feasible
Benefits for Ultra-Urban Retrofits	• Low capital and O&M costs • Compatible with highway design and maintenance • Small installations practical in crowded, ultra-urban setting • Effective treatment for many highway POCs • Can provide conveyance functions in addition to water quality treatment • Volume reduction and flow attenuation benefits • Potential aesthetic benefits
Limitations for Ultra-Urban Retrofits	• Relatively high space requirements • Low treatment effectiveness for nutrients • Not suitable for large drainage areas • Limit peak attenuation in comparison to detention facilities
Applicability for Highway Retrofits	• Very applicable given compatibility with highway practices • There is available space within or adjacent to the ROW • Topography and drainage patterns are suitable • There is adequate maintenance access
Design Enhancements	• Check dams to promote ponding, sedimentation, and infiltration • Soil amendments targeting specific constituents such as dissolved metals and nutrients

Studies suggest bioretention facilities can perform well in cold climates when properly designed (UNH, 2009b).

Maintenance Requirements: A benefit of vegetated filtration controls is that routine inspection and maintenance requires only standard highway maintenance practices. Vegetation management includes routine mowing, routine trash removal, and occasional thinning or replanting of vegetation. Periodic maintenance may include removal of accumulated sediments, and media maintenance such as tilling or replacement.

Applicability for Ultra-Urban Highway Retrofits: Vegetated filtration systems are applicable and appealing retrofit options due to their low cost, effective treatment performance, and compatibility with highway design and maintenance practices. They are most applicable for treating sediments and metals. With suitable site conditions, they can provide significant volume reduction or can be designed with amended soils to enhance treatment of dissolved constituents. The main drawback is finding suitable space within or adjacent to the ROW. Vegetated filtration facilities are applicable for ultra-urban highway retrofits when:

- Sediments and metals are the main target constituents;
- There is adequate space along the highway shoulder, along ramps, between sidewalk and roadway, and other landscaped areas;

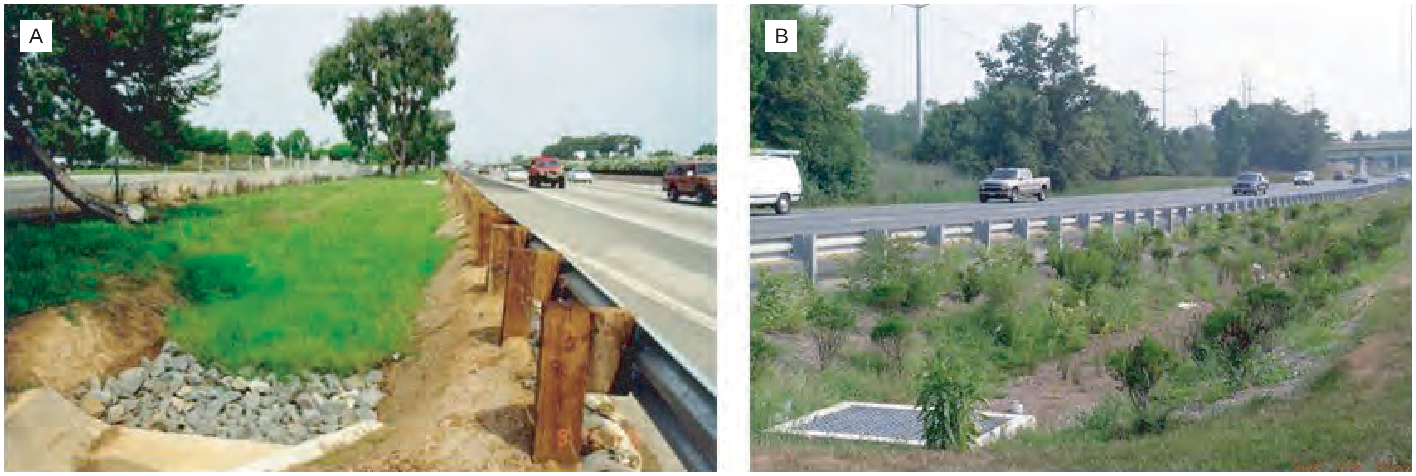


Figure 4.16. Two examples of vegetated filtration BMPs: (A) Caltrans grass-lined swale; (B) DelDOT bioretention area. Notice siting along narrow landscape strips behind guardrails.

- Drainage patterns and topography are suitable; and
- There is safe maintenance access.

4.8.2 Potential Enhancements for Vegetative Filtration Retrofits

Check Dams

Check dams are used in swales to promote ponding and infiltration when the longitudinal slopes are large (> 3% to 5%). Biesboer and Elfering (2003) found that retrofitting existing roadside ditches with check dams provided significant water quality benefits. In areas where vegetated surface conveyances are present, such practices may provide a simple, low-cost, and effective retrofitting approach.

Compost Amendment

Compost added to the soils of vegetated filtration systems can provide a number of benefits. Compost amendments increase the organic content of soils, which increases sorption sites; it lowers the bulk density, which provides conditions conducive to healthy soil microbes; and it has been found to promote growth and increased density of vegetation (Maurer, 2009). The most significant benefit of compost amendments is an increase in the retention and infiltration capacity of soils, which correspondingly increases pollutant load reductions (Pitt et al., 1999b; Herrera Environmental Consultants, 2007). However, compost selection requires careful consideration, as compost-amended soils have been shown to result in the export of nutrients, primarily nitrate (Pitt et al., 1999b; Kirchhoff et al., 2003). From a safety viewpoint, caution is advised, since amended soil inlays constructed close to the edge of the roadway could be a safety hazard for vehicles that go off the road and sink in.

4.9 Infiltration Retrofits

Infiltration retrofits are designed to substantially reduce or eliminate surface water discharge of highway runoff. Associated pollutant loads are also substantially reduced or eliminated, providing highly effective treatment and benefits to surface receiving waters. Most DOTs are familiar with and allow the use of infiltration BMPs where there are suitable soil conditions. Siting constraints and maintenance requirements are the main drawbacks for ultra-urban highway retrofits. Table 4.11 summarizes attributes of infiltration retrofits.

Types of Devices: Infiltration retrofits include infiltration basins and trenches, dry wells, and proprietary underground infiltration systems.

- **Infiltration Basin:** Infiltration basins (Figure 4.17A) are shallow impoundments with flat bottoms. They can be designed with bare soils or include vegetation which can help to maintain infiltration capacity. Pretreatment to remove coarse sediment is important for limiting clogging and associated reduction of infiltration rates.
- **Infiltration Trenches:** An infiltration trench (Figure 4.17B) is a narrow rock-filled trench that receives stormwater runoff, typically via surface runoff. An infiltration trench has no underground outlet (e.g., underdrain), but bypass capabilities can be incorporated into the design in the event of clogging. An exfiltration trench is similar in concept to an infiltration trench, except a perforated pipe embedded in the rock or gravel aggregate is used to deliver stormwater to the trench. In both approaches, pretreatment is required to reduce clogging and maintenance. In addition, designers should be aware that some infiltration trenches can technically meet the definition of Class V injection wells, which are defined by the USEPA as any bored, drilled, or driven shaft or dug hole that is deeper than its widest

Table 4.11. Summary of infiltration retrofits.

Consideration	Attributes
Target Constituents	All highway POCs
Types of Devices	• Infiltration basins • Infiltration trenches • Dry wells • Proprietary underground infiltration devices
Unit Operations	• Settling, infiltration, filtration, sorption
Area Requirement	• 2% to 4% of the tributary watershed for basins and trenches
Head Requirement	• Low to moderate, 2 to 4 ft
Online/Offline	• Typically online, can be designed as offline
Maintenance Requirements	• Strict maintenance practices to protect against clogging and to rehabilitate infiltration capacity • Regular inspection, cleaning of pretreatment areas, and vegetation management • Periodic scraping and tilling of upper soil layers • Replacement of clogged media
Performance	• High level of treatment performance for all highway POCs associated with volume from infiltration • High level of flow attenuation and volume reduction
Relative Cost	• Moderate to high, ~ \$500 to more than \$1000 per m^3 of design storm treated; lower costs for simple basins or trenches, higher costs for areas with site or space constraints
Treatment Train Considerations	• Pretreatment facilities are typically included to prolong infiltration capacity and reduce the frequency of maintenance for rehabilitation infiltration capacity
Benefits for Ultra-Urban Retrofits	• Very high level of surface runoff pollution reduction effectiveness • High level of flow and runoff volume reduction • Very effective for addressing hydromodification requirements
Limitations for Ultra-Urban Retrofits	• Difficult siting constraints in ultra-urban areas • Requires high permeable soils that are free of obstruction, adequate space and topography, and adequate separation from groundwater, supply wells, and structures • Systems have a relatively high rate of failure due to clogging • May require significant maintenance to ensure performance • Possible additional permitting if BMP is a UIC
Applicability for Highway Retrofits	• Applicable when a high level of treatment of flow reduction is required • When difficult siting constraints are fully addressed (space, location, soil conditions) • There is safe maintenance access and adequate maintenance capability
Design Enhancements	• Proprietary underground devices for use in space-constrained settings

surface dimension; an improved sinkhole; or a subsurface fluid distribution system (an infiltration system with piping to enhance infiltration capabilities). Because UICs have additional permitting and pretreatment requirements, designers should investigate applicable state and federal UIC regulations and avoid designs that fall under the UIC authority.

- **Dry Wells:** Dry wells (Figure 4.17C) are perforated wells that are completed above the water table, and are the most common Class V UICs. Dry wells are designed for disposing of stormwater runoff by passive (gravity) drainage, infiltration, and percolation to the underlying groundwater system. The wells are dry when not actively discharging between storms. As discussed in Section 3.1.6, UICs are regulated under the SDWA, which imposes siting restrictions and pretreatment requirements to meet drinking water standards prior to injection.
- **Proprietary Underground Infiltration Devices:** Manufacturers have developed a variety of low-cost underground leaching chambers that are simple to install and are traffic rated. Such systems are well suited for space-constrained settings (Figure 4.17D).

Unit Operations: Infiltration retrofits remove highway pollutants through settling in pretreatment facilities, filtration, sorption, and infiltration.

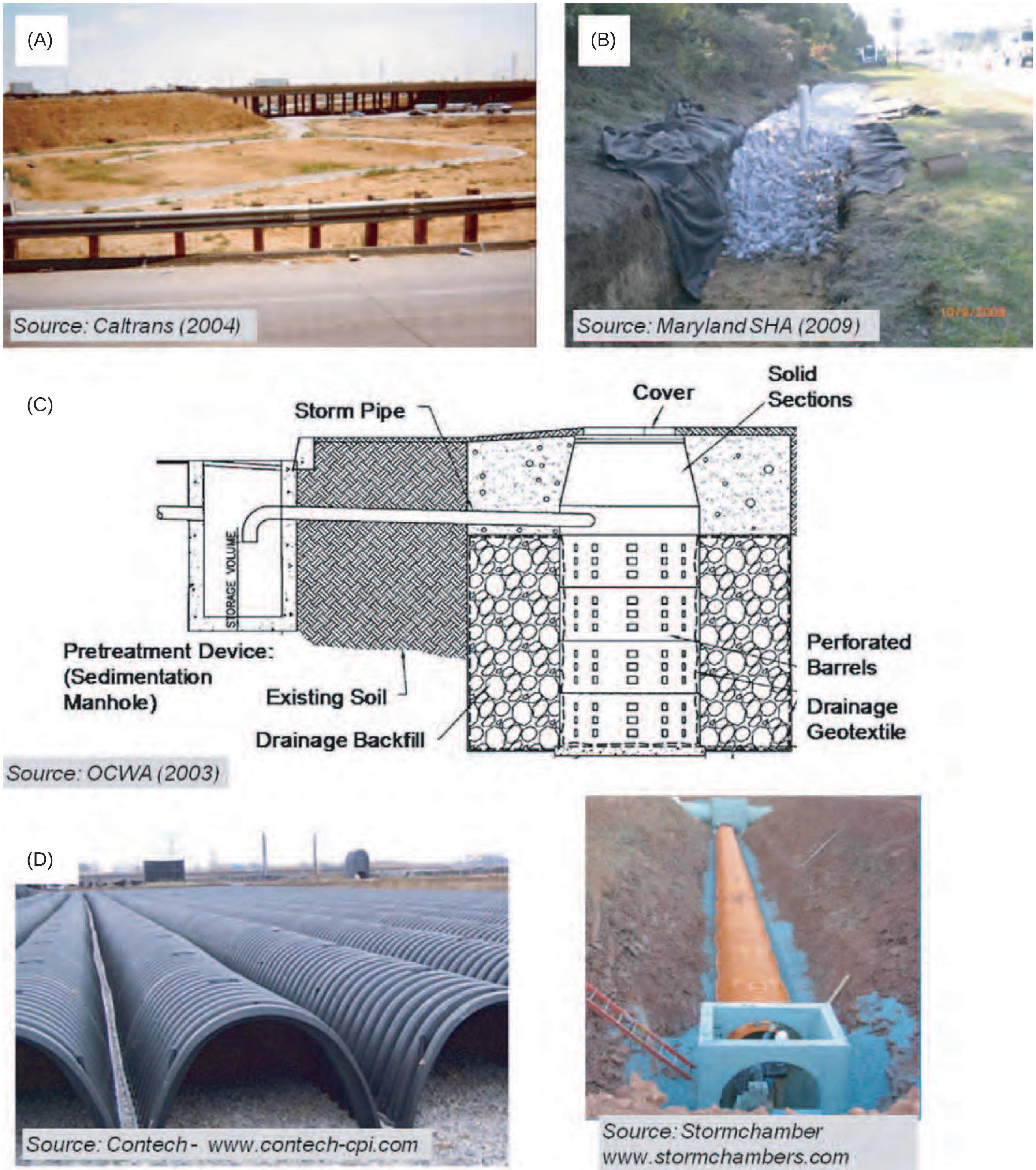


Figure 4.17. Examples of infiltration retrofits: (A) infiltration basin; (B) infiltration trench; (C) dry well; (D) proprietary underground infiltration systems.

Space and Head Requirements: Space requirements for infiltration basins and infiltration trenches are about 2% to 4% of the tributary drainage areas. Basins are suited for vacant areas in interchanges with flat topography, and linear trenches can be located in vacant ROW along shoulders and ramps. Dry wells and underground infiltration systems have minimal space requirements but must consider space requirements for pretreatment facilities and maintenance access. Hydraulic head requirements are low to moderate, about 2 to 4 ft.

Siting Considerations: Siting infiltration facilities in dense urban settings is challenging and difficult.

- ***Native soils:*** The principal siting issue is the suitability of subsurface soils. Native soils must have sufficiently large hydraulic conductivity to permit complete infiltration within the design drawdown period (e.g., 24 to 48 hours). Soils in ultra-urban areas are subject to a high degree of compaction, which reduces infiltration capacity (Pitt et al., 1999b; Schueler et al., 2007). Also, infiltration facilities are not suitable in karst formations where they have the potential to create sinkholes or to intersect low-resistance pathways to groundwater. Identifying suitable soils requires comprehensive field studies using surface and/or downhole infiltration tests. Caltrans (2004) concluded in its retrofit pilot study that siting infiltration devices under marginal soil and subsurface conditions entails a substantial risk of early failure due to clogging.
- ***Underground Constraints:*** Ultra-urban highways have a high potential for underground constraints, including underground infrastructure, unmapped and unsuitable fill, and the presence of contaminated soils and/or groundwater.
- ***Groundwater:*** There must be sufficient separation from the seasonally high groundwater table and water supply wells to reduce the potential for contamination. Typical separation distances are 2 to 10 ft above groundwater and 100 to 150 ft from wells. Because of the potential for hazardous material spills on ultra-urban highways, it is prudent to restrict infiltration practices in areas with a potential to contaminate high-quality groundwater resources.
- ***Structure and Foundations:*** Siting must also consider potential impacts to structures such as footing, foundations, and roadbeds.

Performance: Infiltration facilities provide highly effective treatment for a broad range of pollutants, primarily through runoff and load reduction. Pollutant discharges to surface waters mainly occur when there are bypass flows in excess of the capacity of the infiltration facility. Caltrans (2004) observed 100% treatment effectiveness for the water quality volume in surface infiltration basins and trenches, but did note occasional bypass flows.

Temperature effects on infiltration have been documented by Braga et al. (2007) and Emerson and Traver (2008), who report reductions in the infiltration rate of up to a factor of 2 over a temperature range of 20°C to 0°C. This reduction is directly attributable to a corresponding increase in kinematic viscosity of about the same magnitude, to which the hydraulic conductivity is inversely proportional. However, with sufficient hydraulic conductivity, infiltration facilities can be effective in cold temperatures but not frozen conditions. UNH (2009b) observed very high treatment performance for proprietary underground infiltration systems, including cold weather periods.

Studies have found that most highway POCs (sediment, metals, and organics) are retained in the upper few inches to few feet of the soil column below infiltration facilities (Dierkes and Geiger, 1999; Barraud et al., 1999; Caltrans, 2004). However, soluble pollutants such as nitrate and chloride are easily transported in the subsurface and can potentially impact groundwater quality. Overall, infiltration facilities can safely deliver large fractions of stormwater surface flows to groundwater (Pitt et al., 1994).

Infiltration facilities provide significant benefits for flow attenuation and runoff volume reduction. Therefore, infiltration facilities are a primary strategy for addressing hydromodification impacts.

Cold Climates: Surface infiltration facilities are not suitable in extremely cold climates with permafrost. They are feasible in cold climates but are not operable for portions of the year when the ground is frozen. In cold climates, infiltration facilities may need to be oversized to accommodate snowmelt events, and conveyance modifications are required to protect against freezing (Caraco and Claytor, 1997).

Maintenance Requirements: Maintenance is critical for ensuring effective operation and reducing the potential for frequent clogging and failure. Maintenance practices of surface facilities are similar to media filtration systems. Routine maintenance activities include regular inspection, sediment removal from the pretreatment areas, and vegetation maintenance if applicable. Facilities sited in areas with marginal or poor soils may be susceptible to frequent clogging, which requires major rehabilitation efforts. This could include scraping and tilling of soils, replacement of gravel media in trenches, and refurbishment of pretreatment facilities. Generally, active surface vegetation tends to maintain infiltration capacity.

Dry wells and underground infiltration require regular inspection and cleaning of pretreatment facilities. If the dry well becomes clogged, a compressed air jet can be used to clean and remove sediment or debris (OCWA, 2003). If underground infiltration facilities are clogged, a hydraulic jetting system is used to flush sediments to a sump where they are removed by vactoring.

Applicability for Ultra-Urban Highway Retrofits: Infiltration retrofits potentially deliver appealing receiving water benefits including highly effective treatment, flow attenuation, and volume reduction. However, siting constraints in ultra-urban environments are very restrictive, and there can be high costs and maintenance requirements. Infiltration facilities are applicable for ultra-urban highway retrofits when:

- A high level of treatment performance and/or volume reduction is required;
- The site soils have excellent infiltration characteristics and are free from obstructions;
- There is adequate separation from groundwater and water supply wells, and there is limited potential for hazardous material spills to contaminate high-quality groundwater resources;
- There is sufficient space and suitable topography;
- There is sufficient head and connectivity to existing conveyances; and
- There are safe maintenance access and adequate maintenance capability.

Retrofitting UICs with Pretreatment: UICs for stormwater disposal require pretreatment facilities to meet drinking water standards prior to injection. Many existing UICs used by DOTs may not have pretreatment and will require retrofitting to come into compliance. Pretreatment facilities can include (1) vegetative filtration practices where there is sufficient space or (2) underground sedimentation facilities such as sumped catch basins, hydrodynamic facilities, small tanks, and possibly permeable pavement overlays. However, media filtration practices may be required if POCs include organic compounds for which there are stringent drinking water standards. Yonge and Roelen (2003) investigated non-proprietary high-permeability media filtration barriers as an approach for meeting UIC pretreatment requirements for WSDOT. High-capacity proprietary media filtration systems in underground vaults are another option (Figure 4.14). Some venders have developed media filtration systems that can be easily retrofitted within the dry well and require no additional space (Figure 4.18).

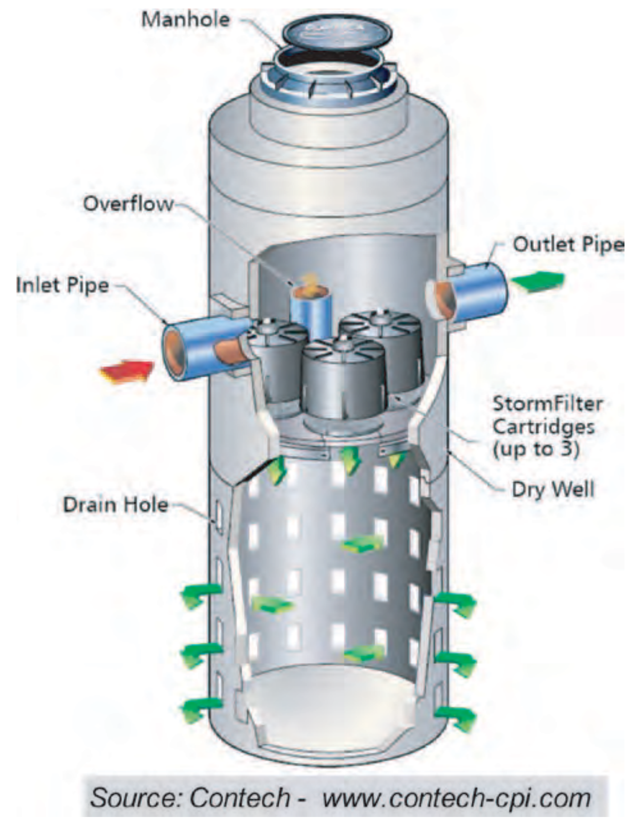


Figure 4.18. Proprietary media filtration system for UIC retrofits.

4.10 Pavement Retrofits

Pavement retrofits refer to the use of permeable pavement for retrofit treatment of highway runoff, either as the main paving layer with underlying infiltration or as overlays. Many studies have documented water quality and hydrologic benefits of permeable pavements (Collins et al., 2007; USEPA, 2010b). Because porous pavements do not require additional space for application, they are attractive candidates for BMP retrofit. However, permeable pavements are not widely used as water quality BMPs or for BMP retrofits in highway settings. DOT concerns may include durability and strength of materials, cost, clogging potential, and maintenance requirements. Table 4.12 summarizes pavement retrofits.

Types of Devices: There are various types of permeable pavements including permeable interlocking pavers, concrete grid pavers, plastic grid pavers, permeable asphalt, permeable concrete, and permeable asphalt overlays:

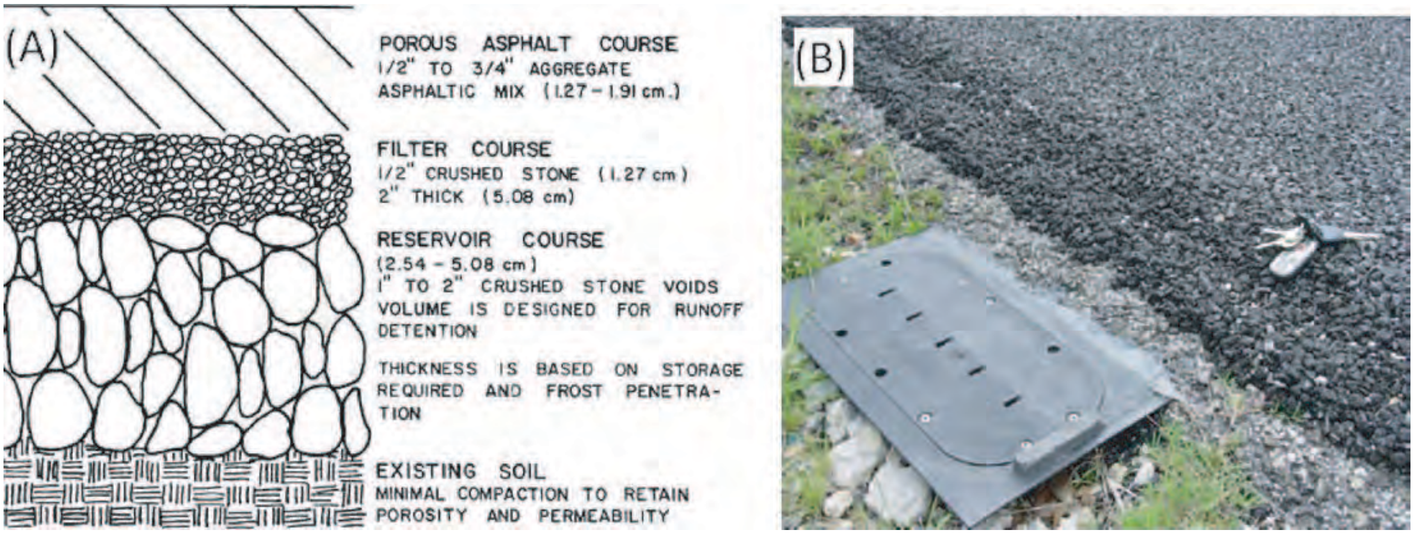
- ***Pavers:*** Pavers are typically installed in lower traffic areas, such as walkways, driveways, hardscaping, parking lots, and low-traffic streets. Pavers are not suitable for highway applications.
- ***Permeable concrete:*** Permeable concrete is a concrete mixture with reduced sand or fines, resulting in increased void space ratio (15% to 35%) and high permeability. Permeable concrete installed over a permeable base delivers substantial runoff reduction and water quality benefits (Collins et al., 2007). However, it has significant limitations for highway applications, including low strength and low freeze-thaw durability (Schaefer et al., 2006; Joung and Grasley, 2008). Surface abrasion can cause deterioration of permeable concrete in high-traffic areas. Studies have found that the addition of a small amount of sand to

Table 4.12. Summary of pavement retrofits.

Consideration	Attributes
Types of Devices	• Permeable asphalt shoulders • Permeable asphalt overlays
Target Constituents	• All highway POCs for infiltration designs • Sediment and particulate-bound pollutants for overlays
Unit Operations	• Filtration, infiltration, sorption
Area Requirement	• Little to no added space required
Head Requirement	• None
Online/Offline	• Online
Maintenance Requirements	• Routine inspection to evaluate clogging issues and structural problems • Control and reduce sources of sediment and debris in upslope landscaping • Routine sweeping of porous pavements • Periodic repaving on the order of typical paving
Performance	• Very good hydrologic and water quality treatment performance with infiltration from full-depth permeable asphalt • Permeable asphalt overlays deliver moderate to excellent treatment for sediments and total metals; low performance for dissolved pollutants; and little to no hydrologic benefits
Relative Cost	• Low to moderate
Treatment Train Considerations	• Permeable asphalt overlays should be used as pretreatment for other BMPs such as filtration and infiltration BMPs
Benefits for Ultra-Urban Retrofits	• No additional space requirement—uses existing travel lanes and shoulders • High level of treatment effectiveness • Low to moderate costs • Highway safety benefits during wet weather
Limitations for Ultra-Urban Retrofits	• Relatively untested on high ADT for water quality treatment • Little long-term performance information • Uncertain cleaning and sweeping requirements; could require extensive sweeping and cleaning practices to maintain long-term reliability • Siting constraints with full-depth permeable asphalt
Applicability for Highway Retrofits	• Permeable asphalt overlays are broadly applicable; full-depth permeable asphalt has limited applicability along shoulders; other permeable pavement types are not applicable • When there are severe space constraints • When integrated into a treatment train • There is safe maintenance access and adequate maintenance capability
Design Enhancements	• Tailor design including thickness and selection of aggregate gradation, fillers, and binders to improve porosity, permeability, and water quality performance for local climate and highway pavement performance standards • Two-layer permeable asphalt overlay system with coarser aggregate in the bottom layer to improve drainage characteristics

the mix can improve strength and durability without substantially reducing permeability; however. this approach requires additional research/testing. Permeable concrete is most applicable for low-traffic applications and is not suitable for high-volume/high-speed roadways that are characteristic of ultra-urban highway retrofit applications (Kuennen, 2003; USEPA, 2010b).

- ***Permeable asphalt:*** Permeable asphalt is similar to permeable concrete in that it is a standard hot-mix asphalt with reduced sand or fines, which results in increased pore space and permeability. Permeable asphalt is typically designed and installed as an infiltration system over an aggregate base (Figure 4.19). Such systems deliver substantial hydrologic and water quality benefits, even in cold weather climates (Gunderson, 2008; USEPA, 2010b) and with reported long-term reliability (Adams, 2003). Permeable asphalt is most applicable in low-traffic areas such as parking and low-volume roads with flat topography. Although full-depth permeable asphalt has been used for highway applications, it is generally recommended only for low-volume and low-speed applications (USEPA, 2010b) or road shoulders (see below). There is not sufficient research to support the use of full-depth permeable asphalt for retrofitting travel lanes of high-ADT ultra-urban highways. Moreover,



Source: (A) USEPA (1980); (B) Barrett (2006)

Figure 4.19. (A) Cross section of full-depth permeable asphalt; (B) permeable asphalt overlay.

such applications would be difficult due to irregular slopes, underground obstructions and utilities, and irregular and compacted soils in ultra-urban settings that would challenge the feasibility of this approach.

- ***Permeable asphalt shoulders:*** As an alternative to using permeable asphalt across the entire roadbed, WSDOT (1997) investigated the benefits of permeable asphalt applied only as a shoulder pavement on a busy two-lane highway. Monitoring studies observed excellent hydrologic and water quality performance. Based on this study, full-depth permeable asphalt shoulder treatments are potentially applicable for retrofit applications. However, there remain a number of siting constraints for applications in dense highway settings and studies are limited to support this approach.
- ***Permeable asphalt overlay:*** A permeable asphalt overlay (PAO) is a permeable asphalt that is placed on top of impervious roadway such as concrete or a conventional asphalt base (Figure 4.19). PAOs are also referred to as permeable friction course or open-graded friction course. PAOs have been used by DOTs for many years to reduce noise, reduce splash, and improve highway safety in wet conditions (USEPA, 2010b). PAOs do not significantly change drainage patterns. Precipitation that falls on the PAO percolates downward through the permeable asphalt, and then percolates laterally over the impermeable road base to the pavement edge. There is no infiltration into the underlying soils and no substantial change in runoff volume (there are some minor evapotranspiration losses or a reduction in losses due to reduced spray). Flow through the permeable asphalt has been shown to reduce levels of sediment and particulate-bound pollutants in runoff, as well as reducing roadway splash that may wash pollutants from vehicles. Potential limitations of permeable asphalt overlays are greater installation cost, shorter life compared to conventional pavement, and increased maintenance (Stanard et al., 2008).

Permeable asphalt overlays are the most broadly feasible option for ultra-urban highway retrofits. Full-depth permeable asphalt shoulder applications are potentially feasible under ideal conditions. Other permeable pavement options are not applicable for ultra-urban highway retrofits for reasons discussed in the foregoing bullet list.

Unit Operations: Permeable asphalt removes pollutants by filtration, sorption, and infiltration. Asphalt overlays primarily use filtration processes to remove particulates. Microbial degradation processes potentially occur in the porous structure and they may also reduce pollutant sources by decreasing splash and pollutant washing from vehicles (Pagotto et al., 2000).

Space and Head Requirements: Permeable asphalt and asphalt overlays require no additional space or head. This is a principal benefit for space-constrained applications.

Performance and Siting: Full-depth permeable asphalt with an underlying aggregate are reported to provide hydrologic and water quality benefits for low-traffic applications (Collins et al., 2007; Gunderson, 2008). Corresponding studies for dense highway applications are limited. WSDOT evaluated permeable asphalt as shoulder treatment, finding that it reduced runoff volumes by 85% for typical storms and reduced solids loadings by 90% or more (WSDOT, 1997). The potential impacts to groundwater resources should be considered when evaluating full-depth permeable asphalt. Similar to infiltration systems, there should be adequate separation from groundwater and water supply wells, and the use of permeable asphalt should be restricted if there is a potential to contaminate high-quality groundwater resources from hazardous material spills.

Studies and reports on PAOs indicate good treatment performance. Studies have found that PAOs reduce TSS concentration by about one order of magnitude, provide moderate to good removals of total metals, and provide poor or little treatment of dissolved pollutants (Berbee et al., 1999; Pagotto et al., 2000; Barrett, 2006; Stanard et al., 2008). Kearfott et al. (2005) found that water quality improvement with PAOs was on the same order or better than vegetated filter strips. Hydrologic monitoring of PAOs indicate they reduce the response time of runoff by about a factor of 2, and there is some indication that they slightly increase the volume of runoff, possibly due to the decrease of water spray resulting in less evaporation and wind losses.

Clogging and long-term effectiveness of permeable pavements are significant concerns given that there are limited long-term performance data. Adams (2003) reports that porous pavement applications have been functioning for up to 20 years. However, other data indicate that the functional durations are substantially shorter. WSDOT (1997) found no reduction in infiltration capacity of porous pavements in only 1 year of monitoring, and Stanard et al. (2008) did not observe significant decrease in performance of PAOs after more than 4 years of monitoring. Moreover, some studies indicate that turbulence from high-speed traffic keeps the void spaces in the asphalt of the driving lanes open, and that the more quiescent shoulders are sink areas that are more susceptible to clogging (Berbee et al., 1999). Thus, Stanard et al. (2008) recommend that PAOs be used in the travel lanes of high-speed roadways, and Berbee et al. (1999) recommend that sweeping and cleaning be focused on the shoulder areas.

The longevity of water quality performance of PAOs is not established and reductions are likely over time (Barrett, 2006; Stanard et al., 2008). Sweeping and cleaning may potentially reduce or delay clogging (Gunderson, 2008, FHWA, 2005). Barrett (2006) states the performance of PAOs is sustained with aggressive cleaning using specially designed vehicles that combine pressure washing and vacuuming. Thus, some degree of cleaning and sweeping is likely required to maintain performance, but the appropriate maintenance levels and practices are not established.

Cleanup of hazardous material spills on full-depth permeable asphalts and PAOs could potentially require the removal and replacement of the asphalt. However, this is not commonly addressed as a siting criterion or issue of concern for PAOs. Permeable asphalts that are limited to shoulder areas would reduce disruption of travel lanes if replacement is needed for cleanup of spills.

Cold Climates: Limited studies suggest that permeable pavements can be used in cold climates, possibly with addi-

Texas Monitoring Studies of Permeable Asphalt Overlays

Two studies sponsored by TXDOT evaluated the water quality benefits of permeable asphalt overlays (PAO) on Austin area highways.

In the first study Barrett (2006) measured water quality in runoff from a two-lane highway with an ADT of 43,000. Monitoring was conducted before and after installation of a PAO that covered the travel lanes and shoulder:

- Water quality comparisons show the PAO substantially reduced TSS concentration (91% efficiency).
- Total metal concentrations were significantly reduced but not to extent of TSS.
- The PAO did not significantly affect dissolved pollutants.

A second follow-on study (Stanard et al., 2008) continued to monitor the first PAO site, and additionally installed a second monitoring site with side-by-side monitoring of adjacent PAO and non-PAO shoulders. Results from using flow weighted composite monitoring include the following:

- Monitoring of the first PAO site continued to show reductions in sediments and pollutants associated with sediments up to 4 years after initial installation.
- Monitoring of the second side-by-side site corroborated findings at the first site. The PAO reduced TSS concentrations by an order of magnitude, significantly reduced particulate-bound pollutants, and did not significantly affect concentrations of dissolved constituents.
- Hydrologic monitoring showed the PAO delayed the response time by up to a factor of 2. Mixed results were found on the effect of PAO on total runoff volume—both increases and decreases have been reported.
- No significant decrease in performance of PAOs was observed after more than 4 years of monitoring.

tional maintenance requirements. Gunderson (2008) conducted cold weather performance assessments of permeable asphalt parking lots, finding that the permeability was actually highest in winter months because the pores were readily drained during thaw periods and remained open during freezing periods. Gunderson (2008) also found porous asphalt parking lots had reduced salting requirements for snow and ice control. Furthermore, Gunderson (2008) notes that porous asphalt parking lots that incorporate significant pavement depth will have a longer life cycle from reduced freeze-thaw susceptibility and greater load-bearing capacity than conventional parking lot pavements.

European countries have successfully used PAOs in cold weather applications, but a number of countries note that porous asphalts require more salting for ice control than conventional pavement (Pagotto et al., 2000; FHWA, 2005; Cooley et al., 2009). Porous pavements exhibit faster and greater temperature drop than dense asphalt pavements, which can lead to icing conditions (FHWA, 2005; Cooley et al., 2009). Also, the voids in the porous pavements may not hold the salt as long as conventional pavements.

If traction sanding is used, there is an increased clogging potential and more frequent sweeping would be required (Cooley et al., 2009). Permeable pavements may not be suitable in areas with significant traction sanding.

Maintenance Requirements: Maintenance requirements include (1) routine inspection to evaluate performance (percolation) and to look for clogging and structural damage and (2) activities to control and reduce sediments on the porous pavements. These activities may include controlling sources of debris in upslope landscaping, and routine sweeping to ensure that the pavement is free of debris. Avoidance of inadvertent sealing and resurfacing with an impermeable surface is a major concern in private development areas. DOTs should be aware of this potential and include safeguards in environmental management protocols.

Aggressive sweeping and cleaning is potentially needed to maintain longevity, as discussed in the previous section. However, the functional life of permeable pavements and the appropriate maintenance levels and practices to preserve performance are not well established. Gunderson (2008) recommends routine sweeping two to four times per year, but this is mainly directed towards porous pavement applications in low-traffic areas. In the Netherlands, it is advised that unused portions of the highways (shoulders) with PAOs be cleaned twice per year with high-pressure washing and vacuuming trucks (Berbee et al., 1999). The travel lanes of the highways with PAOs may not require extensive sweeping due to the pumping and cleaning effect of turbulence from high-speed traffic. An FHWA study on European practices notes there is no consensus on the effectiveness of pavement cleaning (FHWA, 2005). Additional research to establish required sweeping and cleaning practices for permeable pavement in high-ADT highways is needed. Maintenance standards for PAOs are included in Cooley et al. (2009).

Applicability for Ultra-Urban Highway Retrofits: Pavement retrofits, particularly permeable pavement overlays, are potentially suitable and attractive ultra-urban retrofit options because they do not require additional surface area and because available performance information indicates promising and significant water quality benefits. Full-depth porous asphalt shoulders that promote infiltration are also potential retrofit options, but due to stringent siting constraints and limited testing data, such approaches should be considered only for ideal topographic and subsurface conditions.

Porous asphalt overlays are the most feasible permeable pavement retrofit option for ultra-urban highways. In principle, PAOs are feasible as stand-alone retrofits. However, they are more likely to be accepted as part of a treatment train given the lack of long-term performance data, and because they are not commonly accepted as stand-alone BMPs. Ultra-urban highway retrofits with permeable asphalt overlays are applicable when:

- Space constraints are restrictive;
- They are implemented as part of a treatment train;
- They are sited in areas with appropriate groundwater conditions; and
- There is adequate maintenance capability.

4.11 Advanced Treatment Retrofits

Advanced treatment retrofits use non-traditional, innovative, or advanced treatment processes to treat specific pollutants that are not effectively treated with traditional BMPs. Advanced treatment retrofits are often motivated by site-specific requirements, such as TMDLs or other regulatory initiatives with stringent discharge requirements. The selection and design of advanced treatment systems may require specialized knowledge of treatment processes for the target pollutants.

Examples of pollutants and conditions that could require advanced or non-traditional treatment are turbidity, pathogens, PCBs, and on-site retention requirements. Advanced and non-traditional treatment approaches include the following.

Chemical Dosing/Flocculation

Turbidity in stormwater discharges is a pollutant of concern for construction sites and some watersheds have turbidity discharge limits (or TMDLs); for example, the Lake Tahoe watershed has turbidity discharge limitations to address lake clarity. In addition, fine particulates that include attached pollutants, dioxin is an example, may also be of concern to the extent that advanced treatment is required.

Treatment approaches that use chemical dosing to promote flocculation have been studied and tested by DOTs for enhanced treatment of fine particulates (Li and Kegley, 2005; Bachand et al., 2006; McGowen et al., 2009). Stormwater is dosed with flocculants such as alum (liquid aluminum sulfate), expanded shale, and chitosan, followed by sedimentation or filtration treatment to remove suspended sediments and floc. Effective treatment of fine particulates is reported with these systems (Hauser et al., 2005; Bachand et al., 2006).

Drawbacks of flocculation approaches, however, limit their applicability for ultra-urban retrofits. These systems can have high capital, operation, and maintenance costs; may require significant space for detention or filtration systems; and have more frequent maintenance requirements compared to traditional approaches. In general, they are not well suited for small ultra-urban catchments. They are likely to be most practical for off-site retrofits in regional treatment facilities.

Disinfection

Indicator bacteria are ubiquitous in urban stormwater and dry weather discharge, frequently exceeding standards. In areas with stringent regulatory enforcement, advanced disinfection technologies can be applied to stormwater. The primary types of disinfection systems for managing pathogens in stormwater use ozone or UV light. Despite the effectiveness of chlorine compounds, stormwater disinfection using chlorine and chlorine compounds is not as common due to the risks of chemical storage and the potential for formation of disinfection byproducts (Strecker et al., 2005). Disinfection systems require pretreatment, typically media filtration, to remove particulates that can interfere with disinfection. Advanced stormwater disinfection systems are best suited to off-site regional retrofits and would be difficult to implement, operate, and maintain in retrofits to individual urban highway catchments.

Harvest and Use Systems

MS4 permits are increasingly mandating the consideration of on-site stormwater harvesting and use for new/redevelopment, and such requirements could eventually find their way into DOT permits for reconstruction of highways in ultra-urban areas. Stormwater harvesting and use is a general description referring to the capture and storage of runoff and subsequent reuse of that water. Such systems can take a variety of forms. In the case of ultra-urban environments, the typical storage component consists of some form of an enclosed tank or "cistern" that accepts runoff from storm drains. Some level of pretreatment (e.g., screening, filtration, etc.) is typically required upstream of the cistern to prevent the introduction of debris into the system. In addition, some form of treatment would be required, depending on the planned use.

The effectiveness of harvest and use systems primarily depends on the ability to identify sufficient demand (use) for captured runoff relatively soon after storm events. Potential reuse demands in residential neighborhoods are generally limited to irrigation of lawns and landscaped areas and/or to meet non-potable demands in homes such as toilet/urinal flushing (USEPA, 2008). In highway environments, irrigation of highway landscaping is the most likely reuse demand. Researchers at University of Central Florida are studying applications of stormwater harvesting for highway environments, including the use of cisterns, pond storage systems, and pumping to augment storage supplies to meet agronomic rates (about 0.75 in. per week for Florida vegetation) (McGowen et al., 2009). In ultra-urban highway environments landscaped areas would not likely be sufficient to meet on-site reuse requirements. It is likely that off-site use in adjacent areas would need to be identified, such as landscape or golf course irrigation or non-potable water supply. In some climates, irrigation use is limited by cold weather and/or weather patterns with storms arriving back-to-back that limit irrigation use. A final issue is availability of storage in ultra-urban areas.

4.12 Information Sources for Treatment BMPs

There are many information sources on treatment BMPs that can provide useful information for identifying, evaluating, and designing BMPs for retrofit applications. General information sources are listed in the following list and selected sources are compiled in Table 4.13.

- **DOT handbooks:** DOT handbooks and BMP manuals are specific to highway applications. Manuals can include innovative BMP designs and insights on selection and design of BMPs for highway environments.
- **DOT research:** DOTs around the country have researched and addressed BMP planning and design, developed and tested innovative BMPs, and compiled and documented BMP design criteria and effectiveness information.
- **Other guidance manuals:** There are a number of guidance manuals that address BMP evaluation and selection, ultra-urban applications, retrofitting practices, and BMP performance assessment.

Table 4.13. Selected information sources for treatment BMPs.

Source	Description	Reference/Link
Caltrans	Retrofit Pilot Study—a multi-year study of stand-alone BMP retrofits of highway facilities	• Caltrans (2004) • http://www.dot.ca.gov/hq/env/stormwater/special/newsetup/_pdfs/new_technology/index.htm
	Statewide Stormwater Program—conducts a wide variety of BMP research and assessments	http://www.dot.ca.gov/hq/env/stormwater/
	BMP technology report—a biannual report on BMP technologies and assessment of new technologies	Caltrans (2010)
	BMP Pilot Study Guidance Manual—a planning document for developing, implementing, and evaluating BMP pilot tests	• Caltrans (2009) • http://www.dot.ca.gov/hq/env/stormwater/pdf/CTSW-RT-06-171-02-1.pdf
Maryland SHA	Conducts research on BMP design and effectiveness including design of assessment of grass swales, wet infiltration basins, and soil media mixes for nutrient removal	SHA (2009)
MassHighway	Storm Water Handbook for Highways and Bridges	• MassHighway (2004) • http://www.mhd.state.ma.us/downloads/projDev/swbook.pdf
North Carolina DOT	Comprehensive BMP manual Sponsors a variety of BMP research	NCDOT (2008b)
Texas DOT	Sponsors broad range of BMP assessment studies through the Texas Transportation Institute and the Center for Transportation Research at the University of Austin.	• http://tti.tamu.edu/ • http://www.utexas.edu/research/ctr/ • Charbeneau et al. (2004) • Barrett (2006) • Li et al. (2008a)
Washington State DOT	WSDOT Highway Runoff Manual—a comprehensive description of approved treatment BMPs and detailed design criteria	http://www.wsdot.wa.gov/Environment/WaterQuality/Runoff/HighwayRunoffManual.htm#2008revision
	Sponsors and conducts BMP research. Also developed an ultra-urban BMP testing center	• http://www.wsdot.wa.gov/Environment/WaterQuality/Research/default.htm • http://www.wsdot.wa.gov/Environment/WaterQuality/Research/Facility.htm
Washington State Department of Ecology	The Washington State Technology Assessment Protocol–Ecology (TAPE) provides independent information on proprietary BMPs and their effectiveness.	• http://www.ecy.wa.gov/programs/wq/stormwater/newtech/technologies.html
Guidance Manuals	*NCHRP Report 565*—evaluation and selection of highway BMPs	Oregon State University (2006)
	WERF: Critical assessment of stormwater BMPs	Strecker et al. (2005)
	FHWA: Selection and monitoring of BMPs in an ultra-urban setting	Shoemaker et al. (2002)
	Center for Watershed Protection: Urban stormwater retrofit practices manual, and an assortment of BMP studies and guidance	• Schueler et al. (2007) • http://www.cwp.org/
	International Stormwater BMP Database—urban stormwater BMP performance monitoring guidance and data	• Geosyntec and Wright Water (2009). • http://www.bmpdatabase.org/

(continued on next page)

Table 4.13. (Continued).

Source	Description	Reference/Link
Street Sweeping Studies for Source Control and Maintenance	USGS study evaluating the effectiveness of different sweeping strategies	http://wi.water.usgs.gov/non-point/bqy26/index.html
	USGS study presenting street sweeping data including mass and particle size distribution	http://wi.water.usgs.gov/pubs/ofr-03-93/ofr-03-93.pdf
	Wisconsin Department of Transportation study on the effectiveness of high efficiency sweepers	http://wisdotresearch.wi.gov/wp-content/uploads/04-04sweeperstudy-b.pdf
	Metro Washington report on the state of practice of street sweeping and policy directions and implications regarding street sweeping for water quality improvement	http://www.pca.state.mn.us/index.php/view-document.html?gid=13933
Low Impact Development, Green Streets	USEPA summaries of Green Street and Low Impact Development initiatives	• http://www.epa.gov/owow_keep/podcasts/greenstreetsusa.html • http://water.epa.gov/polwaste/green/
	Low Impact Development Center, Green Streets	• http://www.lowimpactdevelopment.org/ • http://www.lowimpactdevelopment.org/greenstreets/
	Selected municipalities	• http://www.portlandonline.com/bes/index.cfm?c=52501& • http://www.seattle.gov/util/About_SPU/Drainage_&_Sewer_System/GreenStormwaterInfrastructure/LowImpactDevelopment/index.htm

SECTION 5

Evaluating BMP Effectiveness

Section 4 describes the available BMP options from which retrofit planners must identify, adapt, and ultimately select BMPs that can meet the retrofit goals and constraints. The initial screening of BMP options should be based primarily on the treatment capabilities of the BMPs using the following criteria:

1. Does the BMP include relevant treatment processes that address the target pollutants and conditions of concern; and
2. Does the BMP provide an acceptable level of treatment performance?

This section describes approaches for evaluating the treatment effectiveness of BMPs and presents general BMP effectiveness information and ratings that can be used for initial screening of the BMP options and identification of candidate BMPs.

5.1 Evaluating the Relevant BMP Treatment Processes

5.1.1 Fundamental Unit Operations to Guide BMP Selection

A common criterion for BMP selection is the ability to meet stipulated BMP performance criteria for pollutants of concern or surrogate pollutants, for example 80% TSS removal. However, a more fundamental approach is to base BMP selection on the unit operations (UOPs) or processes that will be effective for the highway POCs (Strecker et al., 2005). The basic steps are:

1. Characterize the form of the pollutants and conditions of concern (e.g., particulate, dissolved, immiscible, chemical species, particle size, specific gravity, volume, and discharge);
2. Identify the fundamental unit operations that are effective for the pollutant forms and conditions of concern; and
3. Select BMPs that include the appropriate unit operations.

Characterizing retrofit BMPs by their unit operations allows stormwater managers to first identify which treatment processes are needed to achieve retrofit treatment objectives and then to select the BMPs that can feasibly and/or effectively provide those processes. Table 5.1 summarizes the unit operations that are inherent in the retrofit categories. The four fundamental unit operations categories—hydrological, physical, biological, and chemical—are described in the following paragraphs (for additional details, see the WERF Guidance Manual on Critical Assessment of Stormwater Treatment and Control Selection Issues).

Hydrological Operations: Hydrologic operations are common and significant unit operations for stormwater treatment, where the goals include reducing peak flows, reducing runoff volumes, and mitigating hydromodification. Hydrologic operations alter the discharge hydrographs, which affects water quality through direct changes in pollutant loadings and/or concentrations.

- ***Flow attenuation:*** Flow attenuation is the reduction of peak discharge events (peak shaving) by detention, conveyance, and interception. Stormwater detention and gradual release of runoff is the most common approach. Flow attenuation occurs during conveyance by extending the travel time and by infiltration where it occurs. Interception is a form of detention storage that occurs on vegetation, and to a lesser extent on pavement, especially porous and open-graded pavements. Detention retrofits, infiltration retrofits, and capture and use retrofits are the most effective approaches for flow attenuation.
- ***Flow reduction:*** Flow reduction is a decrease in total runoff volume to storm sewers and receiving waters through infiltration, evaporation, retention, and use. Detention

Table 5.1. Ranking of BMP retrofit categories according to unit operation effective level.

Fundamental Process Category	Unit Operations or Processes	Targets	Catch Basin Retrofit	GSRD Retrofit	Hydrodynamic Retrofit	Oil-Water Separator	Vegetated Filter Retrofit	Media Filter Retrofit	Detention Retrofits	Infiltration Retrofits	Pavement Retrofits	Capture & Use Retrofits
Typical Location in Treatment Train			P	P	P	P	P/S	S	S	S	P	S
Hydrology / Hydraulics	Flow attenuation (hydrograph matching)	Peak shaving	0	0	0	1	1	0	4 to 5	3 to 5	1	3 to 5
	Reduce total volume of runoff	Volume reduction	0	0	0	0	3 to 5	0	1 to 2 (A) 0 (U)	5	1 to 2	3 to 5
	Flow-duration control and design	Volume attenuation	0	0	0	1	1	0	3 to 5	4 to 5	0	3 to 4
Physical Operations	Screening	Trash, debris, coarse sediment	1 to 5	4 to 5	3 to 5	0	1 to 3	0 to 3	0	0	0	0
	Flotation and skimming	Trash, debris, oil & grease	0	0	3 to 5	3	0	0	0	0	0	0
	Sedimentation/Settling	Sediment, debris, sorbed metals and nutrients	0 to 2	0	2 to 3	2 to 3	3 to 5	0	3 to 5	2	0	2
	Filtration	Sediment, sorbed metals and nutrients	0 to 3	0	0	0	3 to 5	5	0	4 to 5	3 to 4	0
	Sorption processes (absorption)	Dissolved metals, nutrients, organics	0	0	0	0	3 to 5	3 to 5	0	3 to 5	0	0
	Volatilization/Aeration	Oxygen demand, VOCs, PAHs	0	0	1	0	1 to 3	0	3 (A) 0 (U)	0	0	0
	Physical disinfection (heat and UV radiation)	Pathogens	0	0	0	0	1	0	2 (A) 0 (U)	1 (A) 0 (U)	2	1
Biological Processes	Microbially mediated transformations	Dissolved nutrients, organics, metals	0	0	0	0	0 to 2	2	2 to 4 (A) 0 (U)	2	0	0
	Uptake and storage	Nutrients, organics, metals	0	0	0	0	0 to 2	1	2 (A) 0 (U)	1	0	0
Chemical Processes	Sorption processes	Nutrients, organics, metals	0	0	0	0	3	4 to 5	1 to 2 (A) 0 (U)	4	0	0
	Flocculation / Precipitation	Fine sediment, nutrients	0	0	0	0	0	0	0 to 2 (A) 0 (U)	0	0	0
	Chemical disinfection (ozone, chlorine)	Pathogens	0	0	0	0	0	0	0	0	0	0

P – Primary treatment, S – Secondary treatment; (A) Aboveground application; (U) Underground application
0 - BMP does not include unit process OR is not recommended for that process due to operations and maintenance issues (e.g., a filter should not be used to screen)
1 - BMP includes unit process, but likely provides poor effectiveness.
2 - BMP includes process, but likely provides marginal effectiveness.
3 - BMP designed to include unit process, but other BMPs may be more effective.
4 - BMP is specifically designed to include unit process, but the design is not optimal.
5 - BMP is specifically designed to include unit process and is among the best alternatives available.

Adapted from Strecker et al. (2005)

facilities, infiltration BMPs, and vegetated BMPs provide significant infiltration and evaporation losses. Retention basins and cisterns permanently capture stormwater, where it is reduced through infiltration and evaporation, or used for irrigation or other activities. Infiltration retrofits, vegetated filtration retrofits, and capture and use retrofits are the most effective flow reduction approaches.

- ***Hydromodification control:*** The goal of hydromodification control is to mitigate alterations to the runoff hydrograph by reducing flows and volume to better match predevelopment discharge conditions, usually through attempts to replicate the predevelopment flow-duration relationship. One approach is through volume attenuation, which requires both flow attenuation and flow reduction. For example, LID practices that reduce runoff volume may be combined with detention facilities to control discharges. Flow-duration control is a more accurate sizing and flow control approach that seeks to match the full range of pre- and post-development flows over the long-term, rather than controlling individual design events. Detention retrofits and infiltration retrofits are the most effective approaches for mitigating modifications to the predevelopment hydrograph.

Physical Operations: Physical operations are treatment processes based on physical mechanisms such as screening and sedimentation. Physical unit operations are the dominant forms of treatment in most stormwater BMPs.

- ***Screening:*** Screens are intended to physically exclude solids (including trash, particles, debris, and organisms) that have a dimension larger than a selected screen opening (Strecker et al., 2005). Coarse screening is used to remove larger trash and debris in a way that will not clog stormwater control facilities and will be easy to maintain. Typical applications are upstream trash racks for pretreatment (e.g., upstream of detention or media filtration retrofits). Other retrofits specifically target trash and debris using a variety of screening devices such as bags, socks, nets, or screens located at stormwater inlets, within stormwater conveyances, or at the outfalls.
- ***Floatation and skimming:*** Floatation processes utilize the net buoyancy of some pollutants or pollutants attached to floatable materials by trapping particles, debris, or fluids with a specific gravity of less than 1. The floating pollutants are subsequently removed by skimming (Strecker et al., 2005). Targeted highway POCs are typically trash and debris and separate-phase oils and grease. BMPs that include floatation processes are oil-water separators, baffled tanks, hydrodynamic systems, and inverted elbows used in catch basins (water quality inlets).
- ***Sedimentation:*** Sedimentation is the settling of particles due to density differences. Under quiescent conditions, particle removal is a function of particle density, particle size, and fluid viscosity, the latter being affected by temperature. Under turbulent conditions, removal is dependent upon surface hydraulic loading, particle settling velocity, and shear stress (Urbonas and Stahre, 1993). Sedimentation is most effective for higher pollutant concentrations (> 400 mg/L) and larger particle sizes (> 50 μm) (Urbonas and Stahre, 1993). However, the efficiency of any settling system is generally a function of residence time, which depends on the size and design of the system (Huber et al., 2005). Therefore, small-footprint BMPs such as oil-grit separators, small baffled tanks, and hydrodynamic separators that have small volumes and short retention times will often have reduced sedimentation performance. More effective sediment removal occurs with detention retrofits that have longer detention times.
- ***Filtration:*** Filtration is the physical straining of particles through porous media such as sand, gravel, and permeable asphalt. Filtration processes target removal of particulates and highway POCs that adhere to particulates including metals, organics, and nutrients. Particulates are lodged and trapped in the pore space of the media, which over time can cause clogging and crusting of the porous media, reducing performance and necessitating maintenance. However, with proper pretreatment and maintenance, filtration processes are very effective for particulates, particularly fine particulates that can be difficult to remove by sedimentation processes. Filtration processes are incorporated into proprietary and non-proprietary media filters, infiltration facilities, bioretention BMPs, and porous asphalts.
- ***Volatilization/Aeration:*** Volatilization and aeration refer to mass-transfer across air-fluid interface. Volatilization is the process whereby pollutants that are dissolved in water or present in an immiscible phase (oils) vaporize and escape to the atmosphere. Pollutants of concern that are susceptible to volatilization are VOCs and SVOCs. Volatilization processes are most prominent in BMPs such as surface detention facilities that have large air-water interfaces and good airflow and wind action, and are exposed to elevated temperature or direct sunlight.

  Aeration is the process of entraining air in the water column, primarily to increase dissolved oxygen and to decrease the BOD. Aeration would be applicable for discharges and receiving waters with an excessive oxygen demand, for example to promote nitrification of ammonia. Stormwater BMPs typically do not include active aeration processes (in some cases, wet ponds have included active aeration systems). Passive aeration is most effective in BMPs with large air-water interfaces and good airflow and wind action, such as surface detention facilities.
- ***Physical agent disinfection:*** Physical agent disinfection is the destruction of stormwater-borne pathogens (and

indicators) through non-chemical agents including sunlight, ultraviolet (UV) light, and heat. Physical disinfection is suitable for BMP applications where the influent has low turbidity; otherwise pretreatment is required, e.g., media filtration followed by UV disinfection. Heat and UV from sunlight also promote disinfection. Shallow detention facilities that allow penetration of sunlight and promote heating will be a less friendly environment for pathogens.

Biological Operations: Biological operations use living organisms (plants, algae, and microbes) to transform or remove organic and inorganic pollutants.

- ***Microbially mediated transformations:*** Microbially mediated transformations are chemical transformations by bacteria, algae, and fungi, for example, the degradation of organic compounds and the denitrification of nitrate. Microbial processes are most significant for converting dissolved nutrients (nitrogen), metals, and some organic compounds. The transformations occur slowly, on the order of days, and are greatly affected by temperature. Thus, the most effective BMPs are wet detention facilities with long detention times (wet basins and constructed wetlands), located in warm weather climates. Bioretention with an intentional saturated condition has also been examined for nitrate reduction.
- ***Uptake and storage:*** Uptake and storage refers to the assimilation of organic and inorganic pollutants by plants and microbes. Uptake and storage can be used to remove dissolved metals, nutrients (phosphorus and nitrogen), and organic compounds. The processes occur where soil properties and water quality are adequate to support vegetative and microbial growth, and residence times are adequate. BMPs that include uptake and storage processes include constructed wetlands, wet basins, and bioretention.

Chemical Operations: Chemical operations are treatment processes based on chemical interactions. Chemical operations used in stormwater treatment include sorption, coagulation and flocculation, and chemical agent disinfection.

- ***Sorption:*** Sorption refers to both absorption and adsorption. Absorption is a physical process wherein a substance of one state is incorporated into the structure of another substance of a different state. Adsorption is the physiochemical adherence or bonding of ions and molecules (ion exchange) onto the surface of another molecule. Sorption is a key process for the removal of dissolved highway pollutants of concern including dissolved metals, soluble nutrients, and soluble organics. Sorption processes are integrated with media filtration and infiltration BMPs, and media are often selected on the basis of their sorption capacity. For example, sorption media used in BMPs include perlite, compost, zeolite, and activated carbon. Engineered media may also use iron, manganese oxide, ion exchange media, and media coatings. The effectiveness of sorption processes in BMPs varies greatly and depends on the chemical properties of the media, the surface area of the media, and the system design. BMPs that are designed to enhance sorptive processes are proprietary and non-proprietary media filters; bioretention BMPs; and compost-amended filters, swales and filter strips. Sorption processes can be combined with sedimentation to sequester pollutants.
- ***Precipitation, coagulation, and flocculation:*** These individual processes occur rapidly and are accelerated through chemical additions. Precipitation is the transformation of a pollutant from a dissolved state to a solid state. Coagulation is the destabilization of colloidal particles so that particle growth can occur, and flocculation is the process by which fine particles collide to form larger particles that can be removed through filtration and/or settling. Precipitation, coagulation, and flocculation processes are used in advanced stormwater BMPs for treatment of fine and colloidal particulates, dissolved metals, and phosphorus. The effectiveness of these processes depends on the chemicals being used, pH, temperature, and hardness. These processes can potentially generate significant quantities of sludge, which must be properly handled and disposed.
- ***Chemical agent disinfection:*** Chemical disinfection refers to the destruction of stormwater-borne pathogens through the use of chemical agents such as chlorine and ozone. The effectiveness of chemical disinfection depends on the dose, mixing, contact time, chemical characteristics of the influent, particles in the influent, and the characteristics of the target organisms.

5.1.2 Treatment Train Sequence to Maximize Effectiveness

BMP rankings in Table 5.1 can assist with the identification and selection of retrofit BMPs that provide the fundamental unit operations for meeting water quality and/or quantity objectives. However, Table 5.1 also shows that BMPs may supply multiple unit operations, and some unit operations may occur more effectively in some BMPs than others. As such, the placement or order of one or more BMPs within a treatment system should be considered to maximize the effectiveness of the retrofit design. The recommended approach is to base BMP selection and configuration on the concept of the treatment train. The treatment train targets the most easily treated pollutant first and progressively targets smaller particles and pollutants that are more difficult to treat (Strecker et al., 2005):

1. **Reduce flows from the drainage area (hydrological control).** Runoff volume reduction is a principal stormwater control strategy because it directly reduces pollutant loads and treatment structure requirements. Along rural highways, volume reduction can be achieved by dispersion to the natural landscape. However, runoff dispersion is almost never practical in dense urban highway settings. Porous pavements and porous overlays can contribute to volume reduction to varying extent within the highway catchment, but these are not yet widely accepted practices for dense highways. Similarly, capture and use systems using cisterns are also a potential volume reduction strategy, but these too have limited feasibility due to the lack of sufficient demand for harvested water, particularly within the right-of-way/DOT control. Volume reduction for ultra-urban highways is most likely to be achieved in conjunction with downstream treatment BMPs such as infiltration practices, vegetated BMPs, and surface detention facilities, in situations where these BMPs are feasible.
2. **Remove bulk or gross solids (pretreatment: > 5 mm).** Pretreatment to remove bulk pollutants such as litter, debris, and other large solids (often termed "gross solids") is implemented early in the treatment process to reduce the potential for clogging and/or obstruction of downstream treatment system components. Effective pretreatment can be achieved with screens and racks, GSRD systems, some types of catch basin retrofits, and hydrodynamic systems where underground retrofits are required or where the grade allows.
3. **Remove settleable solids and liquid floatables (primary/secondary treatment: >50 μm):** Easily settleable solids and floatables are addressed by most common and core treatment BMPs that provide primary and/or secondary levels of stormwater treatment. Primary treatment removes the coarser settleable solids and floatables and includes catch basin retrofits, hydrodynamic retrofits, small vaults and settling areas, oil-grit separators, and pavement retrofits. Detention retrofits and vegetated treatment retrofits provide secondary levels of treatment that are more effective for finer settleable solids. In addition, they can provide volume reduction through infiltration where feasible, which can reduce all surface discharge loads of all pollutants.
4. **Remove fine particulates (secondary conventional treatment: <50 μm):** Secondary treatment BMPs that address fine sediments involve filtration processes. BMPs in this category include infiltration practices, sand filters, bioretention systems, and proprietary and non-proprietary media filtration systems. Infiltration and bioretention BMPs that include volume reduction are preferred where feasible.
5. **Remove dissolved, colloidal, and pathogenic constituents (enhanced treatment):** Enhanced treatment practices address pollutants that are not effectively removed in conventional BMPs. Dissolved metals and dissolved nutrients (nitrate, soluble phosphorus) can be addressed by media filtration BMPs where the media is engineered and tailored to enhance sorption processes. BMPs that include biological processes may also be considered, such as wetlands. Coagulation/flocculation processes address the removal of colloidal particles, and disinfection processes address pathogenic pollutants.

BMP selection and configuration for retrofit applications are obviously affected by site constraints, DOT policies, and maintenance requirements. But within the context of site-specific conditions, more effective retrofit treatment systems are obtained when BMPs are selected on the basis of unit operations for specific targeted pollutants, and the configuration of BMPs is based on a treatment train approach.

5.2 Evaluating BMP Performance

When comparing treatment performance of candidate BMPs, the design engineer should consider the various metrics that establish BMP performance as well as regulatory and certification requirements that may establish acceptable BMP types. BMP performance metrics include hydraulic performance metrics and treatment performance metrics described in the following subsections.

5.2.1 Capture Efficiency

Capture efficiency (or "percent capture") is a BMP hydraulic performance metric. For online BMPs, the capture efficiency is the fraction of total runoff that is processed and treated/managed by the BMP. Runoff volumes or flows that exceed the design capacity of the BMPs are considered untreated and are referred to as bypass or overflow. For example, detention basins typically have a water quality outlet at the bottom for treated outflows and an overflow outlet at the top of the basin for bypass flows. Some of the flows may also leave the basin through infiltration and evaporation, which are also considered treated/managed outflows. The percent capture for the detention basin is calculated by:

$$\text{Percent Capture} = 100\left[1 - \left(V_{by}/V_t\right)\right]$$

where V_t is the total influent volume and V_{by} is the total bypass volume leaving the basin through the overflow outlet. This is typically evaluated by conducting a long-term simulation of the performance of the system.

Flow-based BMPs such as swales and media filtration systems are sized on the basis of maximum discharge rate that is managed for water quality. The percent capture of flow-based BMPs is calculated with the same equation above, where flows in excess of the design discharge are considered untreated bypass discharges. To calculate the percent capture, the inflow hydrograph is integrated to determine the total inflow volume and bypass/overflow volume for flows above the design discharge.

A properly designed BMP should generally result in capture efficiencies of about 70% to 90% of the long-term flows from the watershed. However, in severely space-constrained or otherwise constrained situations, lower capture efficiencies may still be appropriate in some locations as part of watershed-wide solutions.

5.2.2 Volume Reduction

Volume reduction is simply the volume loss occurring in the BMP due to infiltration and to a minor extent, by evaporation. Volume reduction is both a hydraulic and treatment metric. Volume loss directly reduces the discharge volume to receiving waters, which is a key process for meeting hydromodification goals. Volume loss also directly reduces the pollutant mass discharged to receiving waters, providing water quality benefits. Pollutant mass reduction is particularly relevant to meeting TMDL objectives where there are mass load allocations but also for reducing the frequency of discharges in some cases.

The volume reduction capacity of BMPs is controlled by the long-term infiltration rate of the underlying soils or by demand drawdown of captured stormwater. Infiltration facilities, which are designed to achieve high levels of volume reduction, must therefore be sited in areas with good infiltration capacity. As noted earlier, finding a demand for harvested stormwater in the highway environment is difficult, but in some cases may be possible.

Other BMPs that are not sited on the basis of infiltration capacity can provide significant volume reduction (Table 5.2). Table 5.2 is based on all reported events; generally higher percent volume reductions will occur for smaller storms. In particular, unlined surface detention facilities (dry extended-detention basins) and biofiltration BMPs have potential volume reductions of 30% or more. BMPs with permanent pools (e.g., wet basins and wetland basins) are generally observed to have lower levels of volume reduction in the range of about 10%. Fine sediments that collect in these facilities may partially seal and impede infiltration losses. BMPs that are lined or contained in vault structures, such as hydrodynamic devices and proprietary media filters, provide no volume reduction (Strecker et al. 2004a,b).

Volume reduction can provide significant hydrologic and water quality benefits to receiving waters. Designers should consider these benefits during BMP selection, when surface detention and biofiltration BMPs are feasible options.

5.2.3 Pollutant Levels

Retrofit planners can use various approaches to quantify pollutant levels in BMP influent and effluent discharges. These approaches include actual monitoring and use of available/appropriate runoff concentrations for highways and other contributing land uses (e.g., Driscoll et al., 1990; Granato et al., 2003a,b).

Concentration: For most highway pollutants of concern, the average concentration of pollutants in BMP influent and effluent discharges is most accurately determined through automated composite samplers. Composite samplers allow for the calculation of an event mean concentration (EMC), which is the flow-proportional average concentration of a given parameter during a storm event. An EMC is the total constituent mass divided by the total runoff volume. The EMC is frequently the most useful means of quantifying the pollutant levels in runoff events and BMP discharges.

Some highway POCs are not amenable to automated sampling and are more commonly measured by individual grab samples. Oil and grease and coliform bacteria are parameters that are not routinely measured with automated samplers. Oil and grease tends to adsorb to tubing in samplers, and bacteria analyses require a short holding time, typically less than the storm duration. Trash and debris are also not amenable to common measurement methods and are usually quantified on a mass load basis.

Sediment: Because of the regulatory emphasis on sediment, designers should be aware of the challenges and approaches of characterizing particulate mass. Sediment is commonly measured as TSS concentration, and most regulations are based

Table 5.2. Average BMP volume losses of media filtration retrofits.

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

Relative volume reduction = (Study Total Inflow Volume & Study Total Outflow Volume)/(Study Total Inflow Volume)
Source: Geosyntec & Wright Water (2010)

on TSS standards. However, as discussed in Section 2.2.2, TSS measurement may under-represent particulate mass, and SSC may be a more appropriate measure. Also, a more complete picture of BMP effectiveness is gained when turbidity and PSD measurements are included as part of the BMP assessment.

Pollutographs: Concentration measurements at individual points in time can be useful for BMP efficiency evaluations. Concentrations resulting from samples collected at specific times during an event allow for the generation of a pollutograph, a plot of the pollutant concentration versus time. Pollutographs are useful for analyzing intra-event temporal variations, for example to determine the presence or absence of first flush by pollutant type and form.

Pollutant Loads: Pollutant load is the mass of pollutant discharged over a specified duration (e.g., lbs per year). Pollutant loads are typically calculated by using an average concentration multiplied by the total volume of flow over the averaging period. Thus, the load calculation depends on the method used to calculate total flow and average concentration. Pollutant loads are useful for assessing the impact to receiving waters where long-term loadings can cause water quality problems outside of discrete storm events. Determining pollutant load reductions in BMPs is relevant to assessing compliance with load-based TMDLs. For example, the Stochastic Empirical Loading and Dilution Model (SELDM), developed by the USGS and FHWA as a highway runoff quality model, can be used to estimate storm flows, concentrations, and pollutant loads from highway facilities, as well as the resulting risk of exceeding water quality criteria in the receiving waters with and without user-defined BMPs (see http://ma.water.usgs.gov/FHWA/SELDM.htm).

5.2.4 Percent Removal

Percent removal (or reduction) is a widely used BMP performance metric. Percent removal (or efficiency ratio) is simply the percentage difference in influent and effluent pollutant levels, expressed on a concentration (e.g., influent and effluent EMC on a storm-by-storm basis) or mass load basis. Regulatory agencies frequently use percent removal standards for BMP performance objectives and certification of proprietary devices. For example, 80% TSS reduction or 60% total phosphorus removal are common BMP performance standards.

The use of percent removal methods should (but often do not) include an appropriate non-parametric (or parametric, if applicable) statistical test to establish if differences in influent and effluent pollutant levels are statistically significant. Note that it is better to show the actual level of significance found, rather than just noting if the result was significant (assuming a 0.05 level). Parametric tests usually require transformation of the data so that tests are carried out on data with normal distributions. The most commonly observed data distribution is log-normal, so computing the mean and standard deviation of log transformations of the sample EMC data and then converting them to arithmetic estimates often results in a better estimate of the mean of the population due to these more typical distributional characteristics (Geosyntec and Wright Water, 2009). However, the geometric mean (the retransformed mean of the logarithms of data) may cause a negative bias in load estimates because the geometric mean gives more weight to low outliers and less weight to high outliers, thereby under-representing the storms that may carry the bulk of the annual load. Because of such difficulties associated with data transformations, non-parametric tests are commonly used to analyze hydrologic and water quality data because these tests do not depend on the assumption that data are from a specific probability distribution (Helsel and Hirsch, 2002).

Percent removal, by itself, is not a fully adequate BMP treatment performance metric because it does not take into account the magnitude of the influent and effluent concentrations (Strecker et al., 2004b; Jones et al., 2008). For example, when influent pollutant levels are large, BMPs can achieve a high percent removal but often with poor effluent quality that would not meet overall water quality goals. Conversely, when influent pollutant levels are small, BMPs may achieve a low percent removal but often with good effluent quality. For example, a BMP with an influent and effluent TSS concentration of 1000 mg/L and 100 mg/L, respectively, achieves a 90 percent removal, but an effluent TSS concentration of 100 mg/L is poor. Conversely, a BMP with an influent and effluent TSS concentration of 50 mg/L and 25 mg/L achieves a 50% reduction, but with good effluent quality in terms of TSS. To counter these limitations, some regulatory agencies and testing organizations consider the magnitude of the influent concentrations by bracketing the allowable TSS influent concentrations in the calculation of percent removal effectiveness (e.g., NJDEP, 2009a; Ecology, 2008).

Percent removal is an important criterion for comparison with regulatory criteria, but percent removal should not be used as a primary treatment performance metric, or should be used in conjunction with appropriate consideration of influent and effluent quality.

5.2.5 Effluent Quality and Effluent Probability Method

Strecker et al. (2004a) recommend BMP effluent quality as the most appropriate treatment performance metric. Effluent quality as a performance metric does not have the problems associated with percent removal metrics, and effluent quality is directly comparable to other BMPs, receiving water conditions, and water quality objectives (Strecker et al., 2001).

Geosyntec and Wright Water (2009) advocate the effluent probability method as the most useful approach for quantifying BMP efficiency. The effluent probability method is a technique that provides a statistical view of influent and effluent quality (Oregon State University et al., 2006). The approach is to first determine if the BMP is providing treatment by applying appropriate non-parametric (or parametric, if applicable) statistical tests to indicate if any perceived differences in the influent and effluent mean of the EMCs are statistically significant.

Next, the cumulative distribution function of influent and effluent quality or a standard parallel probability plot is prepared and examined. For example, Figure 5.1 shows standard parallel probability plots for BMP influent and effluent data. A normal probability plot should be generated showing the log-transformed data of both inflow and outflow EMCs for all storms for the BMP. Equivalently, a normal probability plot can be constructed with a logarithmic concentration axis. In either case, lognormality can be evaluated by seeing if the data points can be approximated using a straight line. If the log-transformed data deviate significantly from normality, other transformations can be explored to determine if a better distributional fit exists (Geosyntec and Wright Water, 2009).

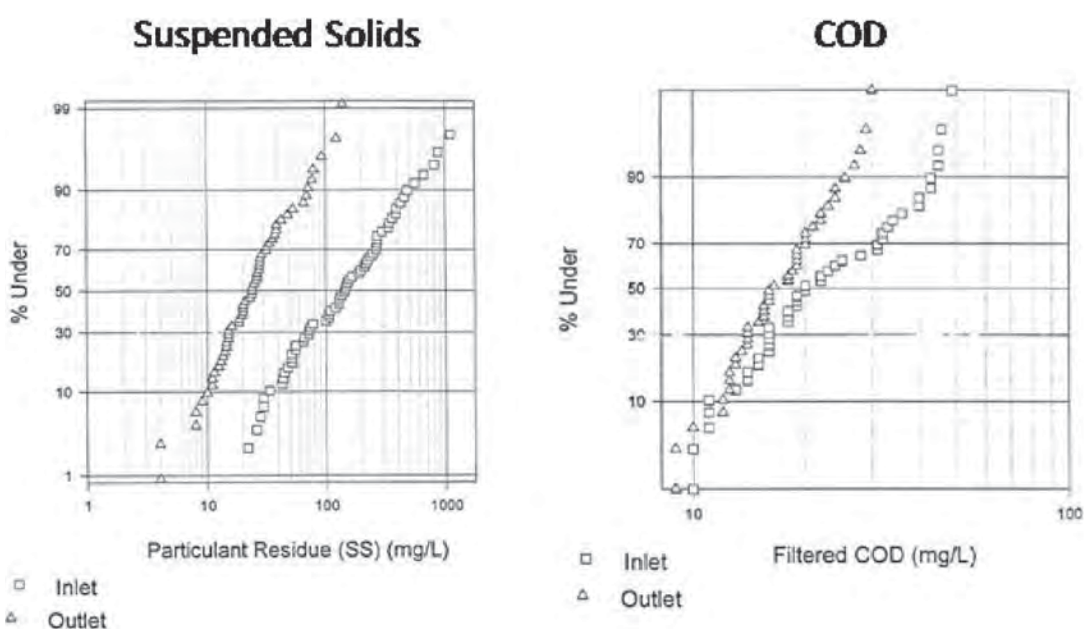
In Figure 5.1, the plot for suspended solids (SS) shows the BMP is effective at reducing SS across the entire range of the influent distribution. The plot for COD shows the BMP provides poor removal at low concentrations (less than about 30 mg/L) but increasing levels of removal at higher concentrations. The effluent probability method provides a clearer picture of the ultimate measure of BMP effectiveness over the full range of the influent quality. However, there is not a one-to-one correlation between the percentiles in the influent data and the percentiles in the effluent data. For example, the median influent concentration and the median effluent concentrations may not occur in the EMC samples collected during the same storm. Although the influent and effluent concentrations in a probability plot are not paired values, the relative position and slope of the two populations are a good indication of the effectiveness of the BMP.

5.2.6 Scour Tests

Sediment resuspension and washout caused by high discharge diminishes the effectiveness of BMPs. Washout is of particular concern for small-footprint BMPs with limited sediment storage capacity. Some laboratory testing protocols of manufactured devices require scour tests (NJDEP, 2009b). For example, the NJDEP protocols require scour tests to determine the maximum treatment flow rate that can be conveyed through the device without causing excessive scouring (i.e., less than 10% washout at 125% of the maximum treatment flow rate). When evaluating small-footprint BMPs with limited sediment storage capacity, designers should strongly consider the potential for sediment flushing and should actively investigate the availability of scour test data or evaluation procedures.

5.2.7 Scaling and Performance Functions

Studies have found the effectiveness of small-footprint proprietary BMPs (hydrodynamic separators, small vault sedimentation systems) for sediment removal is largely a function of the size of the device (Yu and Stopinski, 2001;



Note: Data are ranked for both the inlet and outlet series and are not necessarily paired.
Source: Geosyntec and Wright Water (2009)

Figure 5.1. Probability plots for TSS and COD.

Charbeneau et al., 2004). Accordingly, researchers have applied scaling theory as a means to estimate the performance of proprietary BMPs, particularly for hydrodynamic devices, as a function of the size device.

Wilson et al. (2007) used controlled testing of proprietary BMP devices to develop performance curves (see Figure 5.2). These curves relate the sediment removal efficiency to a dimensionless Peclet number that captures the relevant processes and dimensions of the device. The Peclet number is defined as:

$$Pe = V_s hd/Q$$

where V_s is the particle settling velocity, h is the settling length scale of the device, d is the horizontal diameter of the device, and Q is the discharge.

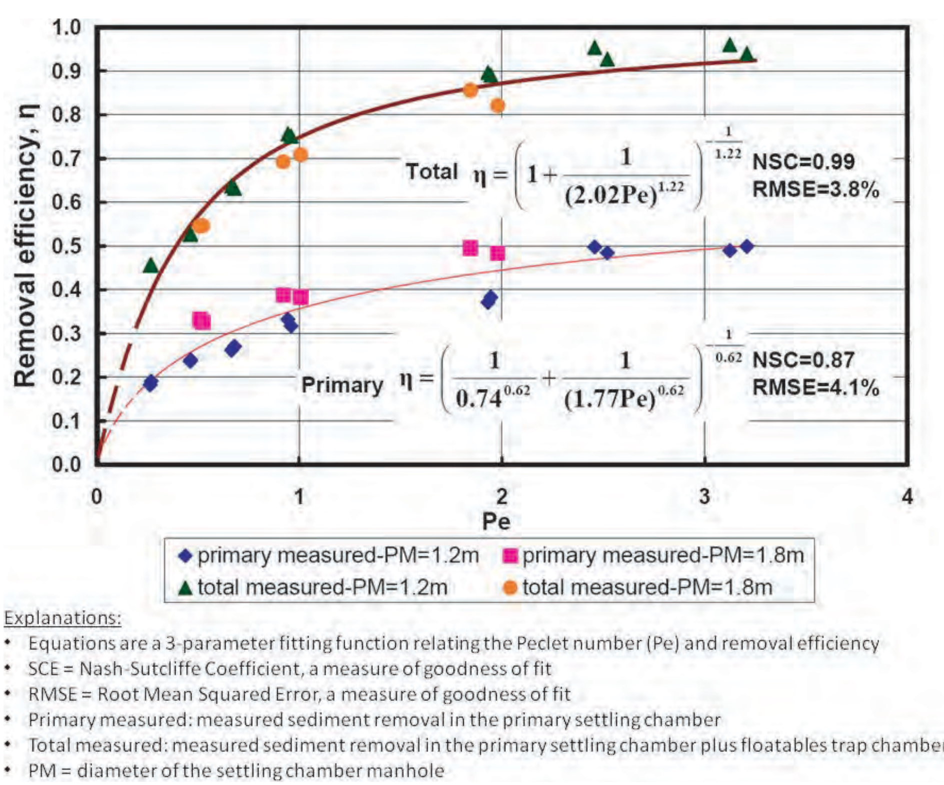
The performance curves can, in principal, be applied in several ways (Gulliver et al., 2009). First, the curves can be used to scale the performance of devices that are measured at one size to another size. Thus, laboratory tests that are performed on small-scale devices can be scaled to full-scale devices. Secondly, the performance curves can potentially be used for BMP sizing, assuming the particle size distributions used to develop the performance curves are representative of actual field conditions. For example, a BMP planner with design discharge and an average sediment particulate diameter (e.g., 100 μm) can use the performance curves to calculate the required device dimensions to achieve a target sediment removal efficiency (e.g., 80%).

The application of scaling theory to proprietary BMPs is still a developing field. Future studies are needed to verify the predictive capabilities of performance curves in actual field installations. If the approach is found to be practical, the ability to scale the performance of manufactured devices can potentially help DOTs design and size manufactured devices.

5.3 BMP Testing Protocols and DOT Certification

One of the greatest limitations of small-footprint proprietary BMPs is the lack of independent verifiable performance information (NRC, 2008). Available testing data are often inconsistent in monitoring protocols and reporting. In response to this limitation, a number of states and DOTs regulate the allowable use of proprietary BMPs through formal testing and certification procedures. However, testing protocols and testing programs to evaluate and/or certify proprietary BMP performance are not uniform. Various testing and certification programs are established, including the following:

- **The Technology and Reciprocity Partnership:** The Technology Acceptance Reciprocity Partnership (TARP) is an



Source: Wilson et al. (2007)

Figure 5.2. Performance curves for the BaySaver Model 1k.

interstate agreement on the reciprocal evaluation, acceptance, and approval of innovative energy and environmental technologies. The TARP agreement resulted in the development of minimum sampling and testing protocols (TARP Tier II Protocol) for evaluating BMP performance and verifying manufacturer claims (TARP, 2003). The TARP II Protocols are a common benchmark for field evaluation of proprietary BMPs.

- **Environmental Technology Verification Program:** The USEPA Environmental Technology Verification Program (ETV) develops testing protocols and verifies the performance of innovative environmental technologies. ETV is a voluntary program that makes objective performance information available to support decision making. ETV does not endorse, certify, or approve technologies. ETV has developed testing protocols for stormwater BMPs (ETV, 2002), and verification reports and statements for a number of propriety BMPs are published on the ETV website.
- **New Jersey Department of Environmental Protection:** The New Jersey Department of Environmental Protection (NJDEP) has established both laboratory and field test protocols for proprietary BMPs. NJDEP actively certifies BMPs based on a TSS removal standard. Laboratory testing of BMPs is conducted by the New Jersey Corporation for Advanced Technology (NJCAT), a non-profit public/private partnership created to provide third-party credible and independent verification of vendors' technology performance claims. Notable testing criteria include limits on influent TSS concentrations, requirements for PSD measurements, limits on maximum particle sizes, and sediment scour tests.
- **Washington State Department of Ecology's Technology Assessment Protocol:** Washington's Technology Assessment Protocol–Ecology (TAPE) is a field test protocol for certifying proprietary BMPs (Ecology, 2008). TAPE certifies and approves proprietary BMPs in accordance with treatment performance goals as shown in Table 5.3. For TSS performance goals, PSD measurements are required to demonstrate representativeness to typical runoff conditions. Evaluation of field monitoring data must include a statistical analysis to show statistical significance of performance results. The status of various proprietary devices is given at http://www.ecy.wa.gov/programs/wq/stormwater/newtech/technologies.html.
- **BMP monitoring protocols from the International BMP Database:** The International Stormwater Best Management Practices Database Project (BMP Database) is a cooperative effort between the American Society of Civil Engineers (ASCE) and the USEPA to develop a repository of scientifically sound BMP performance monitoring data. A detailed BMP performance monitoring guidance document (Geosyntec and Wright Water, 2009) was developed to provide a basis for consistent monitoring and reporting protocols for studies that are adopted into the database. The monitoring guidance document provides detailed protocols for BMP monitoring, data evaluation, and interpretation of BMP performance. No BMP "acceptance" or "approvals" are provided. The purpose of the database was solely to develop a database of rigorous and consistent monitoring and reporting protocols to improve information available for analysis and decision making.

The BMP evaluation protocols and testing programs above demonstrate a continuing and increasing effort to evaluate and certify the performance of proprietary BMPs. There is also an ongoing effort within the ASCE to unify evaluation and certification protocols (Guo et al., 2008). Similarly, the NRC (2008) study *Urban Stormwater Management in the United States* also advocated for a national testing program that would include common protocols to verify the performance of proprietary BMPs. Despite these efforts, however, current testing and certification protocols are disjointed

Table 5.3. TAPE performance goals for proprietary BMP approval.

Performance Goal	Influent Requirements	Effluent Requirements
Pretreatment	TSS = 100 to 200 mg/L	50% TSS reduction
	TSS < 100 mg/L	TSS = 50 mg/L
Basic Treatment	TSS = 100 to 200 mg/L	80% TSS reduction
	TSS < 100 mg/L	TSS = 20 mg/L
Enhanced Treatment	Dissolved copper: 0.003 to 0.02 mg/L Dissolved zinc: 0.02 to 0.3 mg/L	Meet basic treatment condition for TSS
		Exceed basic treatment for dissolved copper and zinc. A numeric target is not specified. It is suggested that available data from vendors and the BMP Database be used to help determine if the device demonstrates significantly higher removal rates (Ecology, 2008).
Phosphorus Treatment	TP = 0.1 to 0.5 mg/L	50% TP Reduction
Oil Treatment		No recurring visible sheen Avg. daily TPH < 10 mg/L Max. discreet TPH < 15 mg/L

across the country. Consequently, DOTs face a range of regulatory policies regarding the use of proprietary BMPs. The flexibility to use or test non-approved BMPs in retrofit applications is a key consideration in BMP selection.

5.4 BMP Performance Data

The most informative BMP performance information is data collected through DOT monitoring studies and pilot testing programs or through local/regional BMP performance assessments. In the absence of local data, the most robust BMP performance monitoring data are compiled in the International BMP Database (http://www.bmpdatabase.org/) because all monitoring studies included in the BMP Database are evaluated for consistency with monitoring and reporting protocols. The BMP Database includes more than 400 BMP studies (and continues to grow), performance analysis results, tools for use in BMP performance studies, monitoring guidance, and other study-related publications. The authors recommend engineers and designers conduct a search of the BMP Database to obtain performance data for specific regions and BMPs of interest.

Table 5.4 shows median influent and effluent concentrations for various BMPs and common highway POCs from the BMP Database as of June 2008. The degree of pollutant removal depends on the pollutant species/form and the level of treatment provided by the BMP. Design features such as pond surface area, length-to-width ratio, vegetation and soil types, and the use of a forebay or other enhancements may affect the type and level of treatment provided. In some instances, effluent medians may exceed influent medians, such as for some nutrients and dissolved constituents. This may suggest that the BMP provides no effective treatment, or possibly the BMP is exporting pollutants from internal sources within the BMP (e.g., nutrients released from biofilters) or due to washout of previously captured materials.

BMP performance data for specific types of proprietary BMP devices and innovative BMP technologies are available from the following sources:

- **Manufacturers:** Many manufacturers will supply independent performance test reports that have been conducted for certification purposes.
- **Certification agencies:** Regulatory agencies that certify proprietary BMPs provide test reports through their websites, for example, the NJDEP: http://www.nj.gov/dep/stormwater/treatment.html.
- **Massachusetts Stormwater Technology Evaluation Project:** The Massachusetts Stormwater Technology Evaluation Project (MASTEP) is a web-based stormwater technologies clearinghouse (http://www.mastep.net/). The website includes a searchable database of proprietary technologies including performance data summaries and reports. The database also provides scoring (0 to 4) of BMP technologies indicating whether there are sufficient TARP-compliant or similar reliable field or laboratory data to be able to evaluate pollutant removal efficiency claims.
- **Independent research studies:** Independent studies have compiled and evaluated available performance data of proprietary BMPs (Brueske, 2000; Yu and Stopinski, 2001; Charbeneau et al., 2004).
- **DOT pilot studies and research programs:** The most applicable BMP assessments are studies conducted in highway settings. DOTs across the country regularly conduct and sponsor a variety of BMP technology assessments, including retrofit pilot studies and pilot studies of innovative BMPs and manufactured devices. Table 4.13 lists potential DOT resources.

5.5 BMP Evaluation Guidance

The recommended criteria for evaluating the effectiveness of BMPs include the following:

- **The amount of runoff that receives treatment or is bypassed.** The capture efficiency of the BMP affects the quantity of pollutant load reduction, as bypass discharges are untreated. BMPs are ideally sized to maximize capture efficiency to an optimal point at which further increases in size provide diminishing returns in terms of treatment and cost. In space-limited settings, the optimized capture efficiency may be highly constrained, and capture efficiencies below the design storm standard may be warranted.
- **The BMP's ability to reduce runoff volumes via infiltration and evapotranspiration.** Reducing runoff volume helps to attenuate flows, mitigate hydromodification impacts, and directly decreases pollutant loads to receiving waters, which can benefit compliance with TMDL allocations.
- **The effluent quality of treated runoff.** The ability of the BMP to achieve acceptable effluent quality for target POCs is the most direct measure of BMP effectiveness. Effective BMPs are those with effluent quality that meet regulatory water quality objectives and effluent quality that is protective of receiving water quality. Estimates of expected effluent quality are ideally based on local pilot tests or BMP effectiveness studies that are representative of anticipated conditions. In the absence of such data, general BMP effectiveness ratings shown in Table 5.5 can be used for comparative guidance. The ratings are based on published BMP performance data and the unit operating processes utilized in the BMP that are expected to reduce runoff volumes and/or contaminant levels.

Table 5.4. Median of average BMP influent and effluent concentration with 95% confidence interval about the median.

Constituent	Point of Discharge	Dry Detention Basin (n = 25)[1]	Wet Pond (n = 46)[1]	Wetland Basin (n = 19)[1]	Biofilter (n = 57)[1,2]	Media Filter (n = 38)[1,3]	Hydrodynamic Devices (n = 32)[1,4]	Porous Pavement (n = 6)[1]
Total Suspended Solids (mg/L)	Influent	72.65 (42–104)	34.13 (19–49)	37.76 (18–53)	52.15 (41–63)	43.27 (27–60)	39.61 (22–76)	xx
	Effluent	31.0 (16–46)	13.37 (7.3–19)	17.77 (9.3–26)	23.92 (15–33)	15.86 (9.7–22)	37.67 (21–54)	16.96 (5.9–49)
Total Copper (µg/L)	Influent	20.14 (8.4–32)	8.91 (5.3–12.5)	5.65 (2.7–39)	31.93 (25–39)	14.57 (11–18)	15.42 (9.2–22)	xx
	Effluent	12.10 (5.4–18.8)	6.36 (4.7–8.0)	4.23 (0.62–7.8)	10.66 (7.7–14)	10.25 (8.2–12)	14.17 (8.3–20)	2.78 (0.88–8.8)
Dissolved Copper (µg/L)	Influent	6.66 (0.73–13)	7.33 (5.4–9.3)	xx	14.15 (10–18)	7.75 (4.5–11)	13.59 (9.8–17)	xx
	Effluent	7.37 (3.3–11.4)	4.37 (3.7–5.7)	xx	8.40 (5.6–11.4)	9.00 (7.3–10.7)	13.92 (4.4–23)	xx
Total Lead (µg/L)	Influent	25.01 (12–38)	14.36 (8.3–20)	4.62 (1.4–12)	19.53 (10–29)	11.32 (6.1–16.5)	18.12 (5.7–30)	xx
	Effluent	15.77 (4.7–27)	5.32 (1.3–9.0)	3.26 (2.3–4.2)	6.70 (2.8–10.6)	3.76 (1.1–6.4)	10.56 (4.3–17)	7.88 (1.6–38)
Dissolved Lead (µg/L)	Influent	1.25 (0.33–2.2)	3.40 (1.12–5.7)	0.50 (0.33–0.67)	2.25 (0.77–3.7)	1.44 (1.05–1.8)	1.89 (0.83–3.0)	xx
	Effluent	2.06 (0.93–3.2)	2.48 (0.98–5.4)	0.87 (0.85–0.89)	1.96 (1.3–2.7)	1.18 (0.77–1.6)	3.34 (2.2–4.5)	xx
Total Zinc (µg/L)	Influent	111.56 (52–172)	60.75 (45–76)	47.07 (25–91)	176.71 (128–225)	92.34 (52–132)	119.08 (74–165)	xx
	Effluent	60.20 (21–100)	29.35 (21–38)	30.71 (13–67)	39.83 (28–52)	37.63 (17–58)	80.17 (53–108)	16.60 (5.9–47)
Dissolved Zinc (µg/L)	Influent	26.11 (5.2–75)	47.46 (38–57)	xx	58.31 (32–79)	69.27 (40–100)	35.93 (5.0–67)	xx
	Effluent	25.84 (11–41)	32.86 (18–48)	xx	25.40 (19–32)	51.25 (29–73)	42.46 (10.4–75)	xx
Total Phosphorus (mg/L)	Influent	0.19 (0.17–0.22)	0.21 (0.13–0.29)	0.27 (0.11–0.43)	0.25 (0.22–0.28)	0.20 (0.15–0.26)	0.24 (0.01–0.46)	xx
	Effluent	0.19 (0.12–0.27)	0.12 (0.09–0.16)	0.14 (0.04–0.24)	0.34 (0.26–0.41)	0.14 (0.11–0.16)	0.26 (0.12–0.48)	0.09 (0.05–0.15)
Dissolved Phosphorus (mg/L)	Influent	0.09 (0.06–0.13)	0.09 (0.06–0.13)	0.10 (0.04–0.22)	0.09 (0.07–0.11)	0.09 (0.03–0.14)	0.06 (0.01–0.11)	xx
	Effluent	0.12 (0.07–0.18)	0.08 (0.04–0.11)	0.17 (0.03–0.31)	0.44 (0.21–0.67)	0.09 (0.07–0.11)	0.09 (0.04–0.13)	xx
Total Nitrogen (mg/L)	Influent	1.25 (0.83–1.7)	1.64 (1.4–1.9)	2.12 (1.6–2.7)	0.94 (0.94–1.7)	1.31 (1.2–1.4)	1.25 (0.33–2.2)	xx
	Effluent	2.72 (1.8–3.6)	1.43 (1.2–1.7)	1.15 (0.82–1.62)	0.78 (0.53–1.0)	0.76 (0.62–0.89)	2.01 (1.4–2.6)	xx
TKN (mg/L)	Influent	1.45 (0.97–1.9)	1.26 (1.0–1.5)	1.15 (0.81–1.5)	1.80 (1.6–2.0)	1.52 (1.1–2.0)	1.09 (0.52–1.7)	xx
	Effluent	1.89 (1.6–2.2)	1.09 (0.87–1.3)	1.05 (0.82–1.3)	1.51 (1.2–1.8)	1.55 (1.2–1.8)	1.48 (0.87–2.5)	1.23 (0.44–3.4)
Nitrate-Nitrogen (mg/L)	Influent	0.70 (0.35–1.05)	0.36 (0.21–0.51)	0.22 (0.01–0.47)	0.59 (0.44–0.73)	0.41 (0.30–0.51)	0.40 (0.06–0.73)	xx
	Effluent	0.58 (0.25–0.91)	0.23 (0.13–0.37)	0.13 (0.07–0.26)	0.60 (0.41–0.79)	0.82 (0.60–1.05)	0.51 (0.08–1.3)	xx

[1] Actual number of BMPs reporting a particular constituent may be greater or less than the number reported in this table, which was based on number of studies reported in the database based on BMP category.
[2] The biofilter BMP category includes vegetated swales, filter strips, and vegetated buffers.
[3] The media filter BMP category includes sand filters, organic filters, gravel filters, bioretention filters, and proprietary filters.
[4] The hydrodynamic device BMP category includes a wide range of proprietary and non-proprietary hydrodynamic device types, catch basins, and oil-water separators.
Notes: xx–Lack of sufficient data to report median and confidence interval. Values in parenthesis are the 95% confidence intervals about the median. More information about the confidence interval can be found in Helsel and Hirsch (2002). Differences between median influent and effluent concentrations does not necessarily indicate there is a statistically significant difference between influent and effluent.

Table 5.5. Qualitative BMP effectiveness ratings (low, medium, and high).

Retrofit Category	BMP Type	Report Section with additional performance information	References	TSS	Particulate Nutrients	Dissolved Nutrients	Trash and Litter	Total Metals	Dissolved Metals	Bacteria	Organic Contaminants	Dissolved Salts	Flow Attenuation	Volume Reduction
Catch Basin	Inserts[4]	4.2.2	Caltrans (2004); Various reports on MASTEP; EC&T (2005); CSU (2005)	L-M	L	0	M-H	L	0-L	0-L	L-M	0	0	0
	Sumped catch basins	4.2.3	Smith (2002); Caltrans (2003c)	L-M	L	L	L	L-M	L	NA	L-M	L	L	L
	Proprietary treatment systems[4]	4.2.4	EC&T (2005); Pitt and Khambhammettu (2006); Yu and Stanford (2007)	L-H	L-M	L	M-H	L-M	L	L	L-M	L	L	L
GSRD	Proprietary trash capture systems, non-proprietary GSRDs	4.3	Caltrans (2005)	NA	NA	NA	H	NA	NA	NA	NA	NA	NA	NA
Hydrodynamic	Various proprietary devices[4]	4.4	BMP Database; Caltrans (2004); Various reports on MASTEP	M	L-M	L	H	L-M	L	NA	NA	L	L	L
Oil-Water Separator	Baffled tanks, coalescing plate separators[4]	4.5	Smith (2002); Caltrans (2004); ETV (2005b)	L-M	L-M	L	H	L-M	NA	NA	L	L	L	L
Detention	Surface detention basins (unlined)	4.6.1	BMP Database	M-H	L-M	L	H	M-H	L	M	M	L	H	L-H[3]
	Wet basins	4.6.1	BMP Database	H	M-H	L-M	H	H	M	M	H	L	L-H[1]	L
	Surface wetland	4.6.1	BMP Database	H	M-H	M-H	H	H	NA	M	H	L	M-H[1]	L
	Underground detention pipes/tanks for flow attenuation	4.6.2		NA	NA	NA	NA	NA	NA	NA	NA	NA	H	L
	Underground detention tanks/wet vaults for water quality[4]	4.6.2	Wright Water (2001, 2002); Li et al. (2008a)	M-H	L-M	NA	NA	M-H	NA	NA	M-H	NA	M	L
Vegetative Filtration	Filter strips	4.8.1	BMP Database	H	L-M	0-L	H	M	M	M	M	L	L-H[3]	L-H[3]
	Swales (unlined)	4.8.1	BMP Database	H	M	0-L	H	H	M	M	H	L	L-H[3]	L-H[3]
	Bioretention with	4.8.1	BMP Database	H	H	0-L	H	H	M	H	H	L	L-M	L-M

(continued on next page)

Table 5.5. (Continued).

Retrofit Category	BMP Type	Report Section with additional performance information	References	TSS	Particulate Nutrients	Dissolved Nutrients	Trash and Litter	Total Metals	Dissolved Metals	Bacteria	Organic Contaminants	Dissolved Salts	Flow Attenuation	Volume Reduction
	underdrains													
Media Filtration	Sand filters (surface or underground)	4.7.2	BMP Database; Caltrans (2004); Shoemaker et al. (2002)	H	M	L-M	H	H	L-M	M	H	L	L	L
	Sand and organics, and engineered media filter drains	4.7.3	Herrera Environmental Consultants (2006); Shoemaker et al. (2002); Claytor and Schueler (1996)	H	H	L	H	H	M-H	M	H	L	L	L-M
	Underground proprietary media filters[4]	4.7.4	Caltrans (2004); ETV (2005a); Various reports on MASTEP	M-H	L-M	L	M-H	M-H	L	M	M	L	L	L
Infiltration Pavement	Infiltration basins, trenches, dry wells, infiltration vaults, and bioretention without underdrains	4.9	BMP Database	H	H	H[2]	H	H	H	H	H	H[2]	H	H
	Porous pavement (assuming runoff is infiltrated)	4.10	BMP Database	H	H	H[2]	L	H	H	H	H	L-H[2]	H	H
	Permeable overlays	4.10	Barrett (2006); Stanard et al. (2008)	H	L-M	0-L	NA	M-H	L	NA	NA	NA	0	0

NA = not applicable or not available;
0, L, M, H = zero, low, medium, and high levels of BMP effectiveness. This is a qualitative scale based on the types of unit processes included in the BMP, available literature information, and available performance monitoring data. Zero indicates the BMP does not include applicable unit processes. A low rating indicates the BMP generally provides little to no treatment and in some cases may export constituents. A medium rating indicates the BMP generally provides some removals but other BMP options can provide more effective treatment. A high rating indicates the BMP provides effective treatment when properly designed and maintained.

[1] Can be high when combined with extended-detention basin.

[2] Removal of dissolved salts and nitrate may be limited if groundwater below the infiltration basin discharges to the receiving water body.

[3] Depends on soil conditions.

[4] Based on a limited survey of devices. Performance may vary for manufactured systems. Device-specific information should be pursued.

SECTION 6

BMP Sizing and Design

This section presents guidance for planning-level sizing and design of volume-based and flow-based BMPs.

A volume-based BMP is one whose performance is limited by size and nature of its storage volume together with the drain time. Volume-based BMPs include most detention/retention basins, underground vaults, and some bioretention installations. In this section, sizing guidance for volume-based BMPs is provided in the form of performance curves that relate the design variables (BMP storage volume and drain time) to performance metrics (runoff capture and sedimentation efficiency). The sizing guidance is applicable to a variety of surface detention basins or underground detention vaults.

A flow-based BMP is one whose performance is limited by the flow rate passing through the BMP. Flow-based BMPs include media filters; filter strips; water quality inlets; and most small, proprietary systems that rely on hydrodynamic separation of particles. This section presents sizing guidance for generic non-proprietary media filtration systems in the form of performance curves that relate the surface area and detention volume to the runoff capture and media contact time.

The BMP performance curves are based on continuous hydrologic simulation analyses for each of the 15 climate divisions specified by Driscoll et al. (1989). An accompanying spreadsheet tool provides users with planning-level sizing estimates for detention and media filtration BMPs in each of the 15 rain zones and allows users to explore tradeoffs between BMP design criteria and performance metrics.

6.1 BMP Sizing and Design Analysis Approach

6.1.1 Overview

Design Storm Analysis: Event-based analyses are the most common approach for BMP sizing and design. Municipalities and DOTs typically specify a design rainfall event or a design storm, which is then converted to a synthetic design hydrograph by standard hydrologic techniques or by application of a rainfall-runoff model. The resulting event-based hydrograph is used to determine the BMP design parameters that will achieve the required percent capture, detention time, and peak flow attenuation. Hence, the BMP is designed to a single condition that may not have been observed and does not take into account BMP performance under a full range of hydrologic conditions.

Continuous Simulation Analysis: Continuous hydrologic simulation has emerged over the last 30 years as a more robust alternative to event-based simulations for assessing the performance of BMPs (WEF, 1998; Strecker et al., 2005; Oregon State University et al., 2006). Results from continuous hydrologic simulations are based on the observed long-term precipitation patterns that are more representative of the variety of hydrologic conditions that affect runoff response and BMP performance. The continuous model generates a physically based long-term runoff hydrograph by accounting for changes in soil moisture, infiltration, depression storage, and the long-term precipitation pattern. In some areas they also can include snow and snowmelt effects as well. Modeling BMP performance in response to the long-term hydrograph produces a more robust and comprehensive analysis of expected operational conditions than is possible from discrete, single-event models.

Continuous simulation using the USEPA Storm Water Management Model (SWMM) was conducted to develop planning-level BMP sizing and design guidance for BMPs in an ultra-urban highway setting. The legacy SWMM4 was used for this effort instead of the current SWMM5 in order to utilize the plug-flow particle settling routine found in the legacy model that has yet to be incorporated into SWMM5. All other functionality is found in SWMM5 as well. SWMM was selected because of its ability to simulate (1) the long-term rainfall-runoff response of highway catchments, (2) the hydraulic performance of volume-based and flow-based BMPs, and (3) TSS settling in storage/detention units.

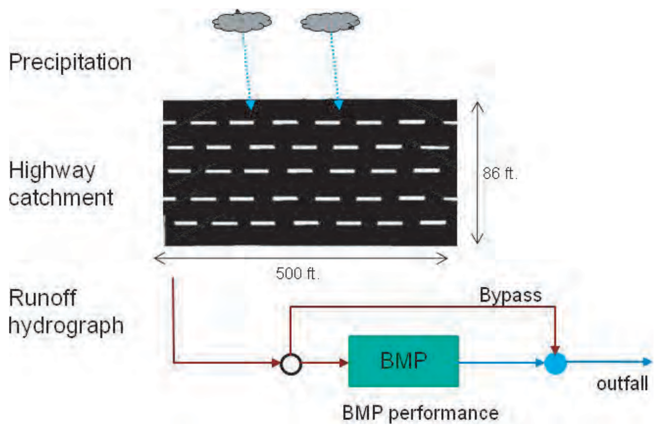


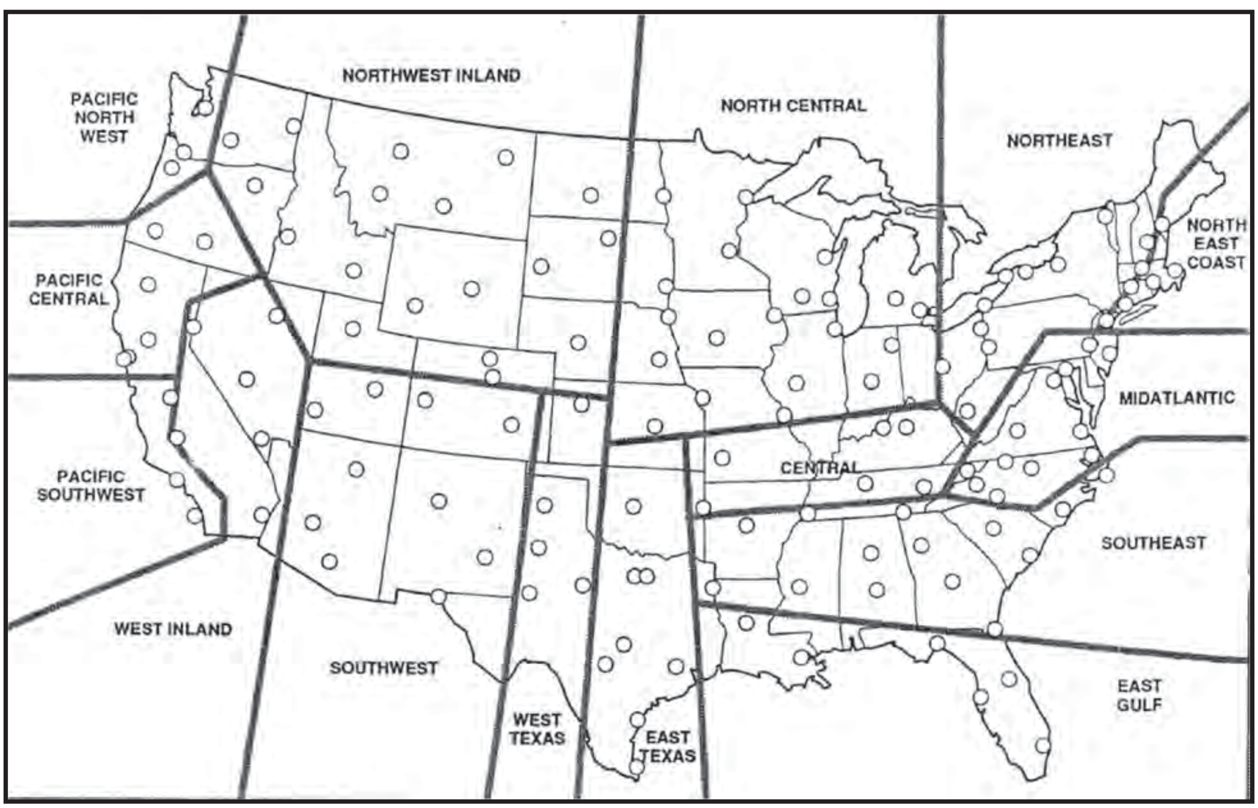
Figure 6.1. Continuous hydrologic simulation conceptualization.

Figure 6.1 shows a conceptualization of the modeled ultra-urban highway catchment. The general modeling and evaluation approach is as follows:

1. ***Define the catchment parameters.*** Catchment properties presented in Section 6.1.2 represent typical ultra-urban highway environments.
2. ***Compile appropriate precipitation data.*** Because precipitation characteristics vary across the country and can affect BMP performance, sizing evaluation was conducted for 15 separate precipitation zones defined by Driscoll et al. (1989). Figure 6.2 shows the 15 rain zones and Section 6.1.3 describes the representative precipitation data.
3. ***Define representative BMPs for analysis.*** For this study the research team selected a generic non-proprietary detention vault to represent volume-based BMPs and a non-proprietary media filter system as the representative flow-based BMP. Sections 6.1.4 and 6.1.5 describe the BMP modeling approach used in the SWMM model, the primary design parameters evaluated, and the performance criteria quantified.
4. ***Develop performance curves.*** The results from hydrologic simulations have been integrated into a spreadsheet sizing tool intended to provide planning-level sizing guidance that is included with this report. The tool enables users to explore tradeoffs between the primary sizing and design criteria and BMP performance. Section 6.1.6 describes the spreadsheet tool.

6.1.2 Highway Catchment Characteristics

To capture the general characteristics of ultra-urban highway, a 1-acre paved highway catchment (100% impervious) as shown in Figure 6.1 was modeled. The catchment



Source: After Driscoll et al. (1989)

Figure 6.2. Hydrologic representation scheme for the United States.

Table 6.1. Highway catchment parameters used in SWMM.

Parameter	Value
Area	1 acre
Imperviousness fraction	100%
Width (highway length)	500 ft
Flow length (highway width)	87 ft (6 lanes)
Slope (width direction)	2%
Impervious Manning's n	0.013
Impervious depression storage	0.02 in.

width is 500 ft and the drainage length is 86 ft. This roughly corresponds to a six-lane highway section with 12 ft lanes, plus two 7 ft shoulders. Table 6.1 lists the catchment parameters used in SWMM.

6.1.3 Precipitation Data

To capture the effects of rapid precipitation responses that are typical of small highly impervious areas, a precipitation record with fine temporal resolution was required. Short-duration, high-intensity rainfall events typically control hydrologic engineering design for small, highly impervious urban catchments with short times of concentration (T_c). Therefore, precipitation recorded at a maximum of 5-minute intervals was desired.

Continuous data sets for 1 and 5 min intervals are available online via the National Climatic Data Center (NCDC) for the period of 2000 through the present. The data are from the Automated Surface Observation System (ASOS) at locations within the United States. ASOS is a joint effort by the National Weather Service, Federal Aviation Administration, and the Department of Defense. The system has been collecting a full spectrum of surface climatic data at 1 and 5 min frequencies since the 1990s for a growing number of locations across the country.

Hourly precipitation data tend to mask the sub-hour peak intensities. To demonstrate this, Figure 6.3 compares 5 min ASOS and hourly NCDC rainfall data for a single storm event in Boston, Massachusetts. In this example, if a flow-through BMP had been sized to be able to treat up to 0.2 in./h of runoff, it would have had a significant amount of bypass that would not have been accounted for by the use of hourly data. For ultra-urban highway drainage areas with characteristically short times of concentrations, finer resolution ASOS data are recommended for use in this BMP sizing modeling. Hence, the 5-min ASOS records were selected for this study, recognizing that a maximum duration of 10 years is placed on the continuous simulations, unless there are local data available from sources other than NCDC.

Precipitation characteristics for each of the 15 rain zones are represented by available 5 min precipitation data from

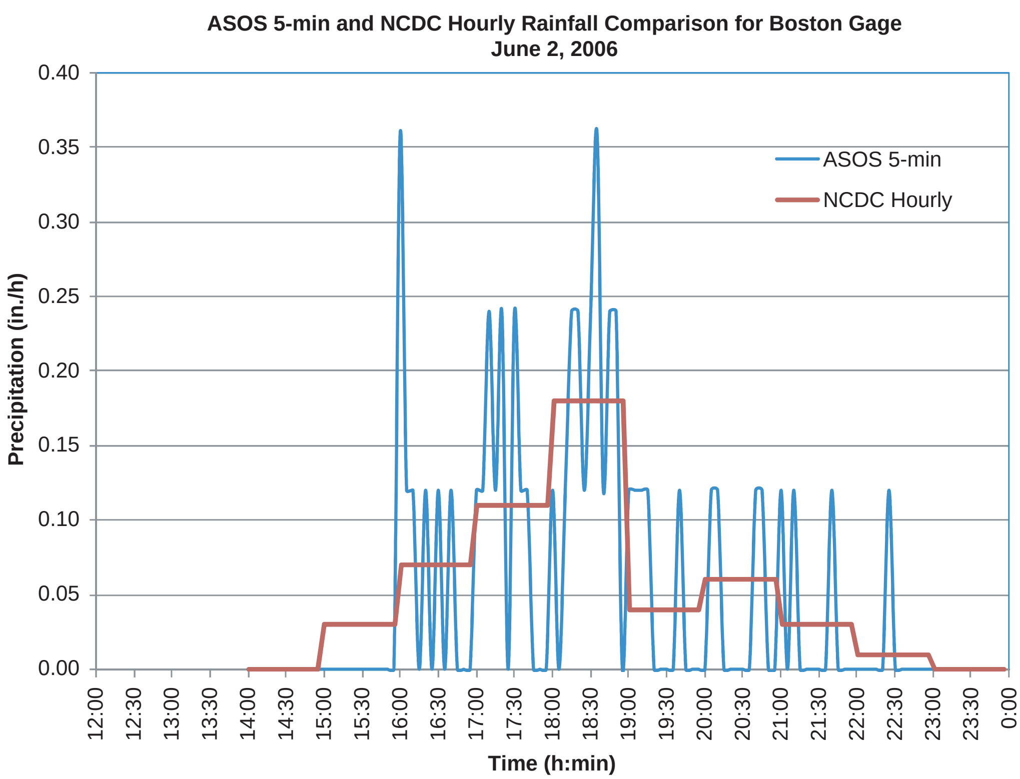


Figure 6.3. Precipitation intensities from NCDC hourly data and ASOS 5-min data.

Table 6.2. Storm event statistics of ASOS stations selected from 15 precipitation zones.

Precipitation Zone	Representative City (ASOS Gage ID)*	Annual No. of Storms	Average Storm Duration (h)	Average Storm Volume (in.)	Average Storm Intensity (in./h)	Average Annual Precipitation (in.)
Northeast	Buffalo, NY (KBUF)	73	10.6	0.41	0.055	29.6
Northeast Coastal	Boston, MA (KBOS)	64	11.1	0.56	0.067	35.8
Mid-Atlantic	Washington, DC (KDCA)	58	10.1	0.62	0.094	36.0
Central	Nashville, TN (KBNA)	66	8.8	0.63	0.107	41.3
North Central	Chicago, IL (KORD)	56	9.4	0.60	0.094	33.5
Southeast	Atlanta, GA (KATL)	61	9.0	0.68	0.109	41.7
East Gulf	Miami, FL (KMIA)	74	6.3	0.70	0.166	52.3
East Texas	Dallas, TX (KDAL)	41	8.8	0.73	0.125	29.9
West Texas	Lubbock, TX (KLBB)	29	7.2	0.54	0.118	15.6
Southwest	Phoenix, AZ (KPHX)	15	7.3	0.52	0.104	7.8
West Inland	Las Vegas, NV (KLAS)	11	7.8	0.55	0.109	6.2
Pacific Southwest	Los Angeles, CA (KLAX)	15	11.3	0.62	0.075	9.5
Northwest Inland	Salt Lake City, UT (KSLC)	43	8.4	0.42	0.062	18.1
Pacific Central	San Francisco, CA (KSFO)	31	13.2	0.56	0.046	17.2
Pacific Northwest	Seattle, WA (KSEA)	78	12.9	0.62	0.051	48.3

* Duration of precipitation data analyzed: 2000–2009

a major metropolitan center selected within each zone. The ASOS data have a resolution of 0.01 in. Data spanning 2000 through 2009 (10 years) were used in the simulations. For this effort, snow accumulation and snowmelt processes were not modeled. Where snow accumulation and melt are important, it is recommended that they be incorporated. Table 6.2 presents the storm event statistics of selected stations representing each of the 15 rainfall zones. The storm statistics are based on a 6 h interevent dry period that was used to separate precipitation data into storm events and exclude events less than or equal to 0.1 in.

6.1.4 Representation of Volume-Based BMPs

BMP Scenario: Volume-based BMPs are represented by a generic non-proprietary rectangular extended-detention vault shown in Figure 6.4. This simple configuration can represent a variety of BMPs with roughly similar storage and outlet configurations to the modeled facility, including for example surface extended-detention basins, underground vaults, and settling basins that are designed to promote sedimentation. Table 6.3 lists the geometry and conditions used to model the extended-detention basin with SWMM.

When considering extended-detention facilities in ultra-urban applications, evaluation criteria include the volume and footprint of the facility and the sedimentation efficiency that can be achieved. These criteria are interdependent. The settling of solids depends on the amount of time a given slug of water resides in the storage facility, as well as the size, shape, and specific gravity of the particle and the viscosity of runoff (temperature dependent). Basins with large storage capacity and longer detention times favor settling of particulates. However, a longer residence time increases the amount of bypassed or overflowed runoff due to exceedance of the basin capacity. Thus, the residence time needed to settle out particles represents a tradeoff between water

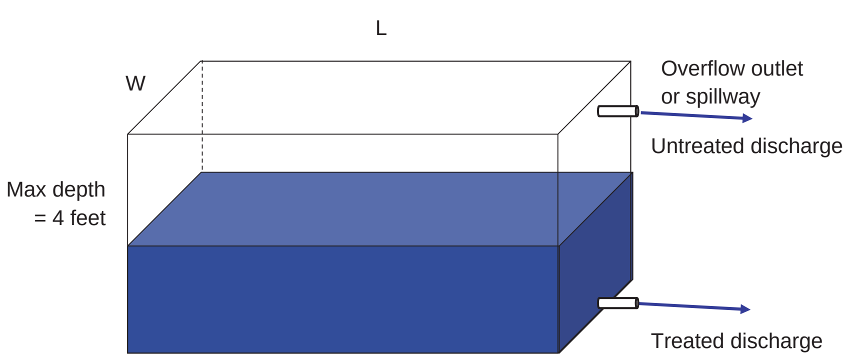


Figure 6.4. Conceptual representation of volume-based BMPs.

Table 6.3. Extended-detention basin parameters used in SWMM.

Parameter	Value
Volume	0.1 to 2.0 watershed in. or 363 to 7260 ft^3 (~2,500 to 47,000 gallons)
Length-to-width ratio	4:1
Active storage depth*	4 ft
Surface area	Design volume divided by 4 ft (~90 to 1800 ft^2)
Drain time	3, 6, and 12 h
Outlet rating curve	Top half in 1/3 of the drain time Bottom half in 2/3 of drain time

* Depth based on common design depth for urban BMPs. Additional dead storage can be included to help reduce sediment resuspension.

quality and runoff capture. Continuous hydrologic simulations can specifically be used to evaluate this tradeoff.

Design Parameters Evaluated: Storage volume and basin drain time are the design parameters evaluated in this study.

- ***Storage volume:*** The modeled storage volume of the facility varied over a wide range between 0.1 to 2.0 watershed in. For a fixed 4 ft depth, the corresponding footprints range from about 90 ft^2 to 1800 ft^2. The types of facilities that are represented range from small vault structures up to relatively large surface or underground detention systems.
- ***Drain time:*** The full-depth drain time varied between 3 to 12 h, which is typical for space-constrained detention facilities. The outlet rating curve was specified to release the top half of storage in one-third of the drain time and the bottom half in two-thirds of the drain time (to maximize small storm retention/treatment).

Performance Criteria Quantified: BMP performance was quantified by the runoff capture and sediment capture as follows:

- ***Average volume capture:*** The average capture volume is the fraction of total runoff that is detained and treated in the basin vs. the amount that overflows (i.e., the ratio of treated runoff to total runoff). Design specifications often require an 80% to 90% annual volume capture. Volume capture may be increased by enlarging the basin volume and/or by reducing the drawdown time. However, these strategies may correspondingly increase the required footprint and/or reduce the ideal sedimentation efficiency. Note that for retrofit applications, it may be appropriate to design a system that captures less than typical requirements for new or redevelopment projects if space or other constraints exist or TMDLs or other goals can be met with a smaller facility.
- ***Average sediment capture:*** Percent runoff capture is not a complete indicator of water quality performance in and of itself. High runoff capture is achieved with a larger outlet and rapid drawdown times at the expense of detention time that promotes sedimentation. Therefore, the research team quantified the sediment capture efficiency with the basic model of particle settling in SWMM4. Using Stokes Law, SWMM directly calculates the settling that takes place for each slug of water (plug flow) that is routed through the system. This analysis assumes that sedimentation processes in the BMP are represented by ideal settling theory and that sediment resuspension and washout are controlled through design features such as baffles and sediment traps. Thus, the estimated sediment capture represents the maximum sediment capture efficiency. Actual sediment removals will depend on site conditions and BMP design and would likely be lower than estimated efficiencies due to non-ideal settling and the potential effects of resuspension and washout. Note that sediment removal estimates may also be used to assess the removals of other pollutants that are associated with sediment. The following describes the procedures used to establish the modeled particle sizes and particle density.

Total Suspended Solids Characteristics: Particle size distribution is an important design consideration for water quality treatment due to its influence on settling and because pollutant speciation is dependent on particle size (Wong et al., 2000). Literature information indicates there are large variations in PSDs in stormwater due to variations in site conditions, vehicular activity, wind patterns, rainfall/runoff characteristics, and the application of winter de-icing materials (Sansalone et al., 1998; Bent et al., 2003; Kim and Sansalone, 2008a). Thus, an assumed PSD used for the design of ultra-urban BMPs may often be significantly different from the actual PSD of suspended solids emanating from the site under investigation. Therefore, the distribution of particle size ranges (percentage by mass) is kept independent of the simulation runs. Particle settling analyses are conducted separately for a range of sediment types and particle sizes, and the results for an arbitrary PSD are determined by integrating the individual results in a post-processing procedure.

Five individual particle size ranges were modeled as shown in Table 6.4. The selected particle sizes are based on the AASHTO soil classification; however, the focus was on fine-grained sediments that are difficult to remove in BMPs and are associated with higher concentrations of particulate pollutants. Therefore, silty-clayey grain sizes less that 75 μm were subdivided into four classifications, and a maximum grain size of 200 μm was assumed as larger sizes are easily settled and removed in BMPs. The particle specific gravity was based on average measurements of stormwater particulates (Li et al., 2008b; Krein and Schorer, 2000). Stormwater sediments exhibit a range of settling velocities and are usually significantly less dense than pure silica sands (specific gravity ~2.65). Table 6.4 also shows

Table 6.4. Particle size distributions and their properties used in simulations.

Sediment Type	Size (μm)	Representative % by Mass[1]	Specific Gravity[2]
Clay	1-2	5	1.2 to 1.3
Fine silt	2-8	15	1.3 to 1.35
Medium silt	8-32	20	1.35 to 1.4
Coarse silt	32-75	20	1.4 to 1.45
Fine sand	75-200	40	1.45

[1]Representative size distribution approximately based on NJDEP Laboratory Test Protocol (NJDEP, 2009a)
[2]Specific gravity based on wet particle specific gravity measured by Li et al. (2008b)

a representative PSD based roughly on the NJDEP BMP testing protocol. The effects of alternative PSDs may be estimated by users of the spreadsheet in a post-processing analysis that is included in the accompanying spreadsheet sizing tool.

6.1.5 Representation of Flow-Based BMPs

BMP Scenario: A generic non-proprietary media filter system was chosen for the representative flow-based BMP because of the broad applicability of media filters to highway facilities. Media filters provide effective treatment for a range of highway pollutants, and they have flexible designs that are advantageous for surface and underground retrofit applications. Other types of flow-based BMPs, such proprietary cartridge filters and hydrodynamic separators, generally have well-defined sizing and design criteria specified by the manufacturer.

Figure 6.5 shows the media filter system evaluated in this study. A 24-inch media bed with variable area was assumed, based on standard media bed designs. The long-term infiltration capacity of the media bed controls the hydraulics of the flow-based BMP. The system includes active detention storage above the media, and untreated bypass occurs when the detention storage is exceeded. Discharge from the media bed collects in a freely draining underdrain system; however, the pore space in the media and underdrain were not included in the active storage. This simple system may represent sand filters, organic filters, bioretention, and other media filters with similar media depth, area, detention storage, and conductivity. Table 6.5 lists the geometry and conditions used to model the flow-based media filters.

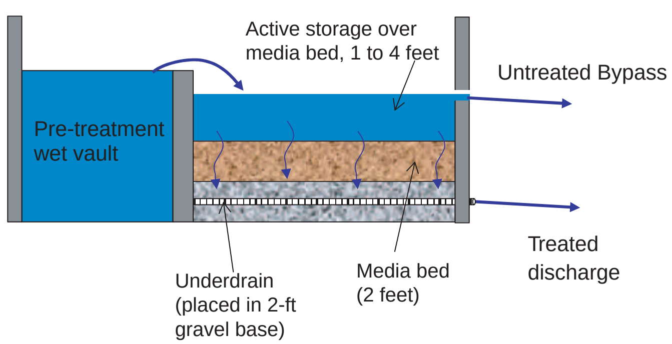


Figure 6.5. Conceptual representation of flow-based BMPs.

Design Parameters Evaluated: Evaluation criteria for media filtration in ultra-urban applications include the footprint of the facility and the runoff capture. The runoff capture depends on the hydraulic capacity of the facility, as well as the available detention storage. The hydraulic capacity depends largely on the media bed area and hydraulic conductivity, which are the fundamental design parameters evaluated in this study. The media composition was not considered in this study, as media selection is typically evaluated through column and treatability tests. Specific parameter values used in SWMM are as follows:

- ***Media bed area:*** The media bed area was varied between 100 to 1000 ft^2/acre, which corresponds to 0.23% to 2.3% of the tributary drainage area.
- ***Detention storage:*** Detention storage is modeled with a fixed depth of 1 to 4 ft above the media bed (Urbonas, 2002). A pretreatment sedimentation wet vault, and the pore volume within the media and underdrain are not included in the active storage. On a unit acre basis, the corresponding detention volume ranges from 100 to 4000 ft^3. The effects of alternative ponding depths between 1 and 4 ft are estimated by interpolation in the spreadsheet sizing tool.
- ***Flow-through rate:*** The flow-through rate is calculated from Darcy's law as shown in Table 6.5. The maximum flow-through rate or infiltration capacity is constant when surface ponding is at the maximum height. For a fixed ponding depth and media thickness, the infiltration capacity is controlled by the selection of the media hydraulic conductivity.
- ***Media conductivity:*** The media conductivity was held constant in the simulations and was assumed to control the flow-through capacity of the media filter. Thus, the modeled design media conductivity represents a long-term infiltration capacity of the facility. The initial media conductivity is higher, but is expected to diminish over time due to clogging and surface crusting from fine particulates. Regular maintenance and periodic change-out of the media are required to retain the design infiltration capacity. The

Table 6.5. Media filtration characteristics and parameters used in SWMM.

Parameter	Value
Media depth	2 ft
Media area	100 to 1000 ft^2 (0.23% to 2.3% of the tributary watershed)
Detention storage volume	1 to 4 ft times the media area
Long-term media infiltration capacity	1, 5, and 50 in./h
Flow-through capacity	0.002 to 1.73 ft^3/s Determined by Darcy's law: Q = KAJ where Q = discharge K = hydraulic conductivity A = media bed area J = hydraulic gradient = (2+hp) ÷2 hp = ponding height above the media bed
Average media contact time	Determined by 2 ft ÷ v_{ave} where v_{ave} = average interstitial velocity = Q_{ave} ÷ (A ϕ) Q_{ave} = average filter bed discharge from SWMM A = filter bed area ϕ = media porosity assumed to be 0.35

maintenance frequency and time until clogging depends on the media area and sediment-loading rate. Note, an alternative to using the media conductivity as the hydraulic control is to use a medium with high conductivity and design an outlet control orifice. This would help to reduce the onset of clogging. An outlet-controlled system with a known area can be approximately modeled within the spreadsheet tool by assuming a unit gradient (head-independent flow) and setting the hydraulic conductivity to the specific discharge Q_{outlet}/A, where Q_{outlet} is outlet-controlled discharge and A is the media bed area.

Performance Criteria Quantified: BMP performance was quantified by the runoff capture and average media contact time as follows:

- ***Average volume capture:*** The average capture volume was calculated from model results as the fraction of total runoff that percolates through the media bed. Darcy's law establishes the stage-discharge relationship used to calculate the discharge through the media bed in SWMM, taking into account the ponding head on the media bed as shown in Table 6.5.
- ***Average media contact time:*** For filterable pollutants, longer contact times generally correspond to greater pollutant removals. The contact time is controlled by the media area, depth, and porosity as shown in Table 6.5. In this analysis, the media depth and porosity is constant, such that contact time mainly depended on media area. Optimal contact times for the treatment of dissolved pollutants may range from less than 1 h to more than 10 h depending on the target pollutant and media properties (Pitt and Clark, 2010). Longer contact time may not necessarily improve removals, as it could potentially enhance leaching of undesirable constituents from the media.

6.1.6 BMP Spreadsheet Sizing Tool

The results of continuous simulation modeling studies have been synthesized into a Microsoft Excel®-based BMP sizing and design tool, which is included on a CD-ROM bound into this report. The purpose of the tool is to assist stormwater and highway professionals with planning-level sizing and design of detention and media filtration BMPs for ultra-urban highway runoff control. The tool generates BMP performance curves that relate the performance and design criteria described in the previous sections for each of the 15 rain zones. One of the significant features of the tool is that it allows users to explore BMP performance and retrofit sizing and design options based on selected design criteria and user-supplied inputs.

6.2 Sizing and Design of Detention-Based BMPs

6.2.1 Sizing Tool Example for Detention BMPs

The Detention tab in the spreadsheet tool shows the sizing and design results for detention BMPs. There are four user-supplied inputs highlighted in yellow:

- ***Drainage area:*** The drainage area is used to estimate the average annual runoff volume, detention volume, and TSS capture volume by proportional scaling of model results developed on a 1-acre catchment.

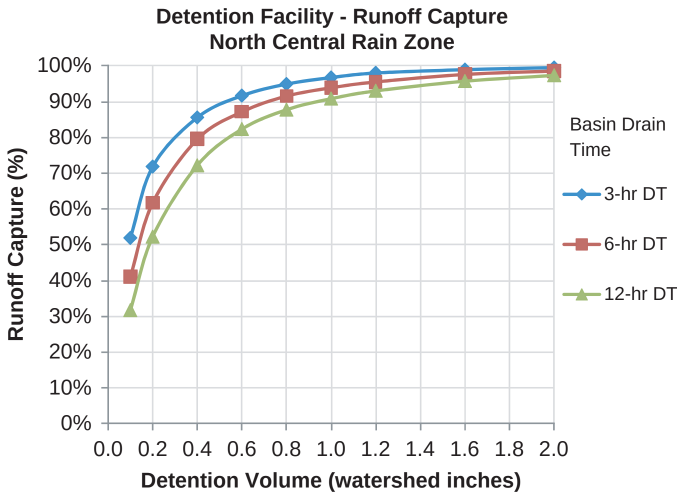


Figure 6.6. Percent runoff captured for detention BMPs in the North Central rain zone.

- ***Average TSS concentration:*** Used to estimate the average annual sediment capture volume for varying detention volumes, drawdown rates, and assumed PSDs.
- ***Particle size distribution:*** Defines the average mass fraction of clay, silt, and sand particles in runoff. The mass fraction must sum to 100%. The PSD is used to estimate the TSS capture as a function of basin size and drawdown time.
- ***Rain zone:*** A dropdown menu listing the 15 rain zones. Representative storm statistics are listed for the selected rain zone.

As an example, consider model results for a 1-acre catchment in the North Central rain zone, with an average TSS concentration of 100 mg/L. The North Central rain zone was modeled with precipitation data collected at the Chicago O'Hare Airport. Figure 6.6 shows the estimated runoff volume captured as a function of detention volume and basin drain time. Results show that a basin volume in the range of 0.4 to 0.8 watershed inches (~1500 to 3000 ft^3) will capture and treat about 85% of the annual runoff. An 85% capture approximately represents the knee of the curve (point of diminishing return) beyond which increasing the size of the basin achieves increasingly lower returns in additional runoff treated. Figure 6.6 also indicates that better volume capture occurs with faster drain times (DT) as expected in identically sized basins.

Although volume capture improves with shorter detention time, this is not necessarily the case for sediment capture. Figure 6.7 illustrates the change in TSS treatment performance based on the user input PSD. The left-hand plot shows the estimated sediment capture for a PSD dominated by sand and coarse silts. In this case, results suggest that 80% TSS capture can be achieved with a moderately sized basin and short drain times. In contrast, the right-hand plot shows estimated sediment capture for a PSD dominated by finer silts and clays. For fine-grained sediment, better overall removals are obtained with longer detention times. However, an 80% capture is not achievable even at very large basin sizes. To achieve the 80% TSS performance standard with this PSD, a detention time much greater than 12 hours is required. Thus, alternative BMPs, such as wet vaults or media filtration, are likely more appropriate.

6.2.2 Evaluation of Batch Mode Operation

The first flush phenomenon observed in highway runoff presents opportunities for stormwater treatment strategies (Stenstrom and Kayhanian, 2005). Fill-and-hold batch mode operation is a strategy that has been proposed and tested for improving the effectiveness of detention facilities. The higher residence time achieved by holding the runoff provides a greater opportunity for small particles to settle and reduces the potential for sediment resuspension and washout. Batch mode operation may be well suited for small underground vault systems, as it has been shown to effectively reduce sedi-

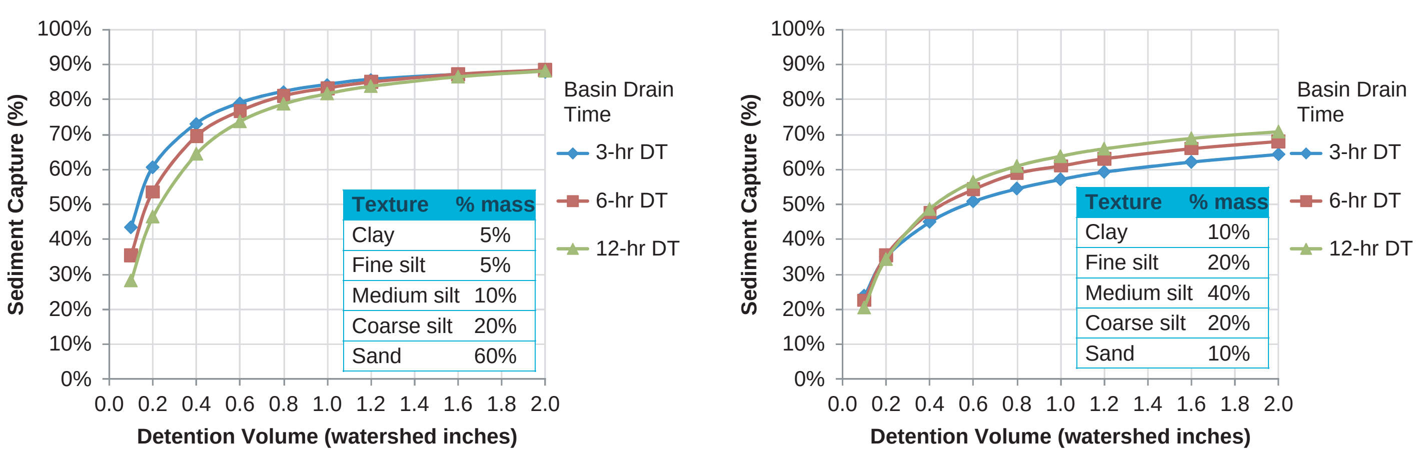
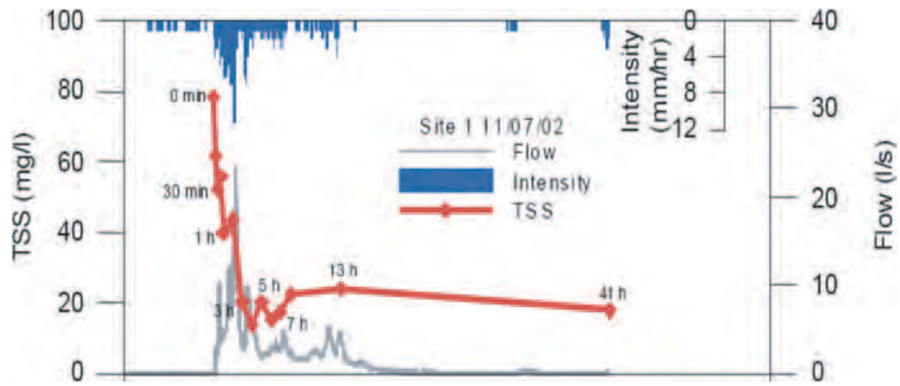


Figure 6.7. Effect of PSD on percent sediment capture for detention BMPs in the North Central rain zone.



Source: Stenstrom and Kayhanian (2005)

Figure 6.8. Flow and pollutant concentration from a first flush characterization study used in an event-based hydrologic simulation.

ment resuspension and washout and improve sediment capture (Landphair et al., 2007; Li et al., 2008a).

Hydrologic simulation with SWMM was used to investigate and illustrate the potential improvement in overall sediment capture with small vaults. SWMM was customized to simulate a dynamic controller that opens and closes an orifice outlet based on the following simple operating rules:

- The basin outlet is closed when a lower-level depth sensor (e.g., 0.25 ft) is triggered.
- The hold time is initiated when the upper-level depth sensor (full depth) is triggered. The outlet is automatically opened when the hold time is reached (1 to 3 h).

To investigate the effectiveness of batch mode operation, event-based hydrograph and pollutograph data from the Caltrans first flush characterization study were used in the simulation study (Stenstrom and Kayhanian, 2005). The flow and pollutant monitoring data are shown in Figure 6.8 and clearly exhibit a first flush occurrence. These data were collected from a 3.2-acre ultra-urban highway catchment with nearly 100% impervious cover. Five different particle size ranges that represent the total TSS load in the runoff were simulated including 4–8 μm, 8–16 μm, 16–32 μm, 32–64 μm, and 64–128 μm. Based on this monitoring study, nearly 80% of the particles were observed to be less than 64 μm in size.

Results of the batch mode modeling comparison are shown in Figure 6.9. Batch mode operation was evaluated for three small vault sizes—2000, 3000, and 4000 ft^3—which correspond to about 0.17, 0.26, and 0.34 watershed inches. In each case, the outlet was sized for a 3 h drain time. Sediment removal was modeled with the ideal particle settling algorithms in SWMM, which does not account for sediment resuspension and washout. The TSS removal efficiencies shown in Figure 6.9 represent the percentage of sediment captured from the total sediment mass in the entire storm event.

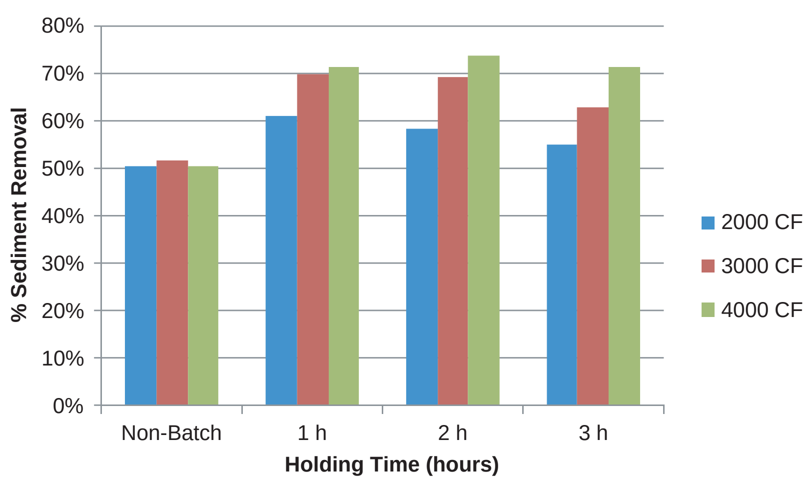


Figure 6.9. Comparison of sediment removal performance between conventional and batch mode-operated detention vaults.

Simulation results shown in Figure 6.9 suggest that batch mode operation of small detention vaults can potentially improve sedimentation efficiency in comparison to conventional orifice outlets. Moreover, greater removal efficiency can be achieved with a smaller footprint facility operated in batch mode compared to a larger facility operated in conventional mode. For example, Figure 6.9 indicates that a batch mode-operated detention facility with a footprint of 2000 ft^3 (~0.17 watershed inches) achieves 11% more sediment removal efficiency than a conventionally operated facility with a volume of 4000 ft^3 (~0.34 watershed inches). Model results also suggest there is an optimum holding time that depends on the size of the detention facility. For the smallest basin size (2000 ft^3), the best removal efficiency is with the shortest holding time of 1 h because longer shut-in periods cause greater bypass losses. For the largest basin size (4000 ft^3), a 2 h hold time provides the most efficient removal. For comparison, researchers at the Texas Transportation Institute found that a hold time of 3 h diminished the problems of resuspension and improved sediment capture above 80% capture in controlled pilot tests (Landphair et al., 2007; Li et al., 2008a).

Although batch mode operation is an emerging technology, it is potentially an effective strategy for improving sedimentation efficiency in small underground vaults that are applicable in space-constrained settings. The spreadsheet sizing tool does not provide for a batch mode analysis. The user would need to examine this option through his/her own modeling effort.

6.3 Sizing and Design of Media Filtration-Based BMPs

The Media Filter tab in the spreadsheet tool shows the sizing and design results for media filtration BMPs. There are five user-supplied inputs highlighted in yellow:

- ***Drainage area:*** Determines the average annual runoff volume, filter area, and detention volume.
- ***Average TSS concentration:*** Used in estimating the average annual sediment-loading rate for varying filter areas. This is useful for estimating clogging rate and associated maintenance requirements.
- ***Design media hydraulic conductivity:*** The long-term media conductivity will be achieved through ongoing maintenance and periodic media change-out. Results for the specified infiltration capacity are estimated by interpolation of the modeled results using infiltration rates of 1, 5, and 50 in./h. Thus, the specified infiltration must be in the range of 1 to 50 in./h.
- ***Active detention storage depth:*** Active storage is assumed over the entire media filter area at depths between 1 and 4 ft. Results for intermediate depths are estimated by interpolation of the modeled results at depths of 1 and 4 ft.
- ***Rain zone:*** A dropdown menu listing the 15 rain zones. Representative storm statistics are listed for the selected rain zone.

As an example, consider the results for a 1-acre catchment in the North Central rain zone, with an average TSS concentration of 100 mg/L, and a design infiltration capacity of 10 in./h. Results from the spreadsheet tool (shown in Figure 6.10) illustrate the tradeoffs between runoff volume capture and filter area, media conductivity (K), and detention depth. To achieve capture and treatment for 80% of the annual runoff, a filter area of about 2.0% of the tributary watershed (~870 ft^2/acre) is needed when the active storage depth is 1 ft. If sufficient head and storage are available, increasing the active storage to 4 ft will reduce the required filter area to about 0.75% of the tributary watershed (~325 ft^2/acre). However, the TSS loading rate (mass per unit area) will more than double, increasing the clogging rate and maintenance requirements.

Media filters can generally be expected to provide good effluent quality for particulate pollutants as supported by

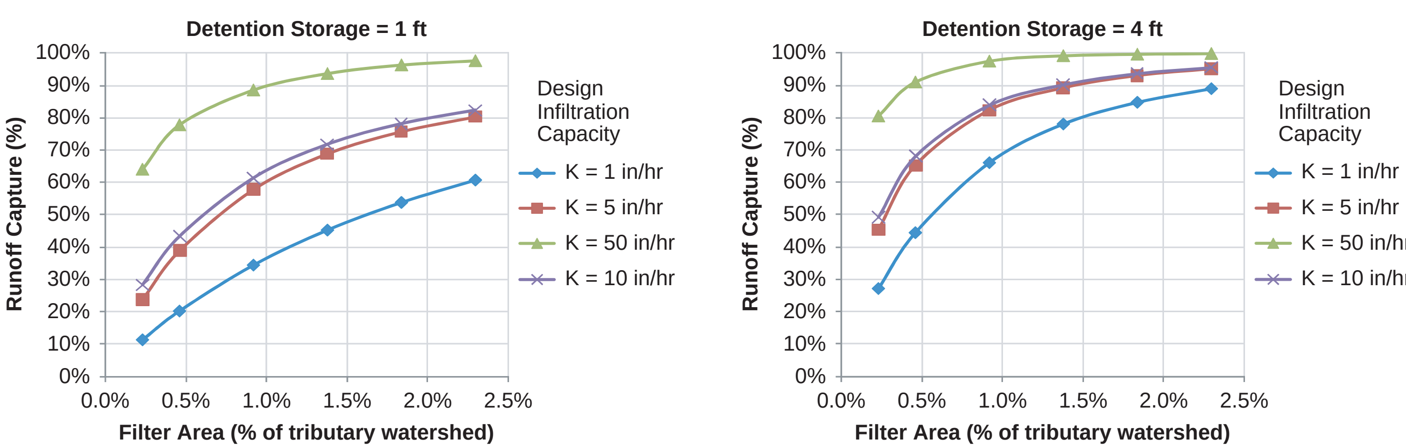


Figure 6.10. Percentage of runoff capture for media filtration in the North Central rain zone.

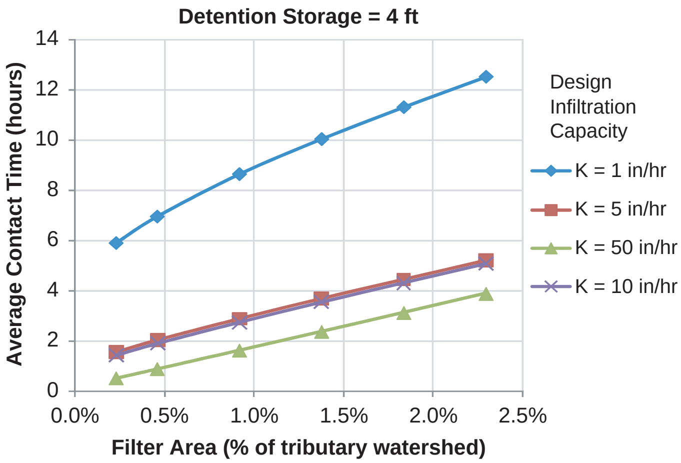


Figure 6.11. Average media contact time for media filtration in the North Central rain zone.

monitoring data from the BMP Database (Table 5.4). When media are tailored for removal of dissolved pollutants, the media contact time is an important design variable that is established through batch or column testing. Figure 6.11 shows the tradeoffs between average contact time and infiltration capacity for a 2 ft thick media bed. Contact time is largely controlled by the infiltration rate, media thickness, and porosity. For this example, the average contact time ranges from less than 2 h to about 5 h at the design infiltration capacity of 10 in./h. If shorter contact time is sufficient or is required to reduce leaching concerns, then the design media thickness can be reduced, which will also help to lower construction costs. The information in Figure 6.11 would need to be considered with that in Figure 6.10 (detention storage = 4 ft) to evaluate the appropriate sizing of the facility. For example, a filter area at 1.5% of tributary area would treat 90% of the runoff with a K of 5 to 10 in./h, with an average contact time of about 4 hours. This may be an adequate result, depending on the contact time needed.

6.4 Summary of Spreadsheet Sizing Tool

The spreadsheet sizing tool is available on a CD-ROM bound into this report. Specific assumptions and user design variables are described in Sections 6.2.1 and 6.3 as well as in the tool itself. Modeling assumptions and caveats are given in those sections as well. While the spreadsheet comes to the user with protected cells, the user is free to unprotect all cells and view formulas. Similarly, the user is free to "unhide" the worksheets with SWMM results for each rainfall zone, from which the summary screening guidelines are derived by interpolation.

The sizing tool is provided as a first-cut screening methodology for sizing guidance for BMPs in the ultra-urban highway setting. Users will naturally refine such guidance by using the spreadsheet output as good candidates for initial BMP design using simulation models, which include the option of focusing on the user's immediate location. Example SWMM4 input files are included for a representative detention basin simulation and media filter simulation within the spreadsheet tool. The example SWMM files are included in a hidden worksheet, which can be viewed with the "Hide and Unhide" command in Excel. While not necessarily a simple task, it is at least a straightforward process to change SWMM input to desired local rainfall and evapotranspiration data so that the user may focus the sizing tool to his/her specific location.

SECTION 7

Maintenance and Monitoring

Post-construction activities include BMP operation and maintenance, and BMP testing and monitoring. Maintenance is essential for design-level performance. BMP testing and monitoring is a means for evaluating and gaining operational information of BMPs. Developing and successfully conducting post-construction activities requires upfront planning and coordination. This section describes recommended BMP maintenance and monitoring practices.

7.1 Types of Maintenance

DOT maintenance crews and departments routinely address three types of BMP maintenance categories:

- **Routine inspection and maintenance:** Regular and scheduled BMP inspections and maintenance practices to ensure design-level performance, for example, mowing and vegetation clearing, sediment clearing, and trash and litter pickup.
- **Major maintenance activities:** Longer-term, periodic maintenance practices to remediate worn-out components (for example, media bed replacement and major sediment clearing) or to correct BMP deficiencies.
- **Emergency maintenance practices:** Unscheduled and unanticipated maintenance in emergencies, for example, the repair of malfunctioning stormwater pumps or emergency actions to address spills of toxic materials.

7.2 Maintenance Factors That Affect Performance

BMP maintenance issues and problems that commonly affect BMP performance include the following:

- **Sediment and debris buildup:** Insufficient maintenance can allow sediments, trash, and debris to accumulate in settling basins, underground sumps and vaults, pipes and outlet, and detention and sedimentation facilities (Figure 7.1A). Buildup of solids can cause reduced treatment performance and poor effluent quality due to resuspension and washout and reduction of capacity. Sediment and debris clearing is among the most common BMP maintenance practices. Underground BMPs that have limited storage capacity require more frequent inspection and cleaning to maintain design capacity.
- **Clogging:** Clogging occurs when trash, debris, sediment, or ice accumulates at inlets, weirs, pipes, outlets, or screens or on surface media beds, blocking or restricting the flow of water (Figure 7.1B). Clogging may occur gradually due to general BMP operation (e.g., media beds and infiltration facilities) or due to inadequate maintenance. Clogging may also occur rapidly from large storm events that transport large amounts of debris and/or sediment. Problems due to clogging include increased bypassing, diminished or ineffective treatment, ponding and safety concerns, and erosion. The assessment of sediment and debris accumulation and potential blockages is a primary task during BMP inspections. Inspection of underground BMPs, however, are more difficult and rigorous, and the effects of clogging may not be apparent and can go undetected.
- **Mechanical and structural failures:** Mechanical equipment and structural facilities such as pumps, gates, valves, and conveyances can fail due to wear, corrosion, vandalism, clogging, and lack of maintenance. Underground BMPs that require pumping due to high head requirements, grade separation, and/or flat terrains may be subject to significant pump maintenance requirements.
- **Vegetation:** Poor vegetation maintenance can result in improper type and/or inadequate or excessive growth of vegetation (Figure 7.1D). Potential problems due to vegetation management include poor treatment performance, clogging of conveyances, lack of visual access for inspections, habitat for rodents and vectors, and aesthetic concerns. In space-limited settings, equipment access will be a key issue for vegetation management.

Figure 7.1. Four examples of BMP conditions requiring maintenance: (A) excessive accumulation of sediments in underground detention; (B) clogged pipe; (C) accumulation of trash and debris in a GSRD; and (D) excessive vegetation near an outlet.

- **Groundwater:** Shallow groundwater can affect the siting and capacity of infiltration BMPs, and groundwater flows into surface and underground BMPs may diminish the treatment effectiveness, cause excessive bypass, or require additional flow control and pumping. Maintenance activities due to high groundwater may include temporary or permanent pumping, more frequent routine and vegetation maintenance, and structural repairs or modifications.
- **Vectors:** Burrowing rodents and animals can damage vegetation and embankments, diminishing treatment performance and potentially affecting structural integrity. Standing water in BMPs that do not fully drain is a potential breeding habitat for mosquitoes, which can prompt concerns by public health officials and require the use of vector control methods.

7.3 Maintenance Considerations for Ultra-Urban Highways

Without proper and consistent maintenance, BMPs will not perform at their capacity. This is particularly valid for many ultra-urban BMPs that have limited storage capacity for accumulated solids, and proprietary filtration systems that are susceptible to clogging. Neglected maintenance can ultimately lead to significant costs for major cleaning, repairs, or emergency actions. On the other hand, DOT maintenance departments are very concerned about potentially burdensome requirements and high costs of maintaining ultra-urban BMPs due to the following conditions:

- **Space and access limitations:** Space limitations in ultra-urban settings potentially constrain maintenance access, necessitate expensive lane closures and traffic-control procedures, and prompt safety concerns.

- **Uncommon requirements:** Underground proprietary BMPs are more difficult to inspect and maintain than surface BMPs. Routine maintenance of proprietary underground BMPs potentially requires costly proprietary components (e.g., filter cartridges), specialized or expensive equipment, uncommon procedures, and/or specific training such as confined-entry practices.
- **Higher frequency:** Ultra-urban highways can have higher loadings of sediment, trash, and debris. Small-footprint or undersized BMPs are more likely to require frequent inspection and maintenance to remove accumulated solids to maintain capacity and/or filtering/infiltration performance.

To address these maintenance department concerns, planning and coordination is necessary to select BMPs that will have acceptable and achievable maintenance requirements, as well as to design BMPs that will facilitate maintenance activities. Specific guidance and recommendations include the following:

- **Understand and evaluate maintenance requirements:** BMP maintenance requirements must be an essential part of the BMP evaluation and selection process. This requires an understanding and evaluation of the specific maintenance practices, materials, equipment, and training for the candidate BMPs. Consider implementing pilot testing programs to evaluate maintenance requirements and to address maintenance department concerns for promising but untested BMPs. For example, Section 10.6 describes a pilot test of construction and design practices for bioretention systems conducted by the District of Columbia DOT. As part of this pilot study, monitoring is conducted to evaluate construction impacts on maintenance, in particular, the need for soil stabilization as part of finalizing the project construction.
- **Coordinate with maintenance personnel.** The maintenance evaluation must be fully coordinated with appropriate maintenance personnel throughout the retrofit planning process. Maintenance departments should have approval authority on BMP selection and design elements.
- **Design for maintenance:** Planning for maintenance during the design stage of retrofit projects can simplify long-term inspection and maintenance requirements.
  - *Lane closures:* Locate BMPs and BMP access points to avoid lane closures for BMP inspection and maintenance. Site underground BMPs to limit lane closure requirements, if unavoidable.
  - *Access roads:* Provide maintenance access for required equipment and practices. Access roads must have adequate width and slope to ensure that heavy equipment can safely reach and exit the BMP site under its own power (Hunt et al., 2008).
  - *Internal access of underground BMPs:* It is essential that there is safe access to all internal components and spaces of underground BMPs to facilitate inspections, long-term cleaning, and repairs (Scott, 2008). Hunt et al. (2008) note that many chambers within the underground manufactured BMPs are not accessible or are very difficult to access. Ability to visually inspect and clean components of the BMP must be factored into the design. Most manufacturers are aware of BMP maintenance issues and typically provide detailed maintenance specifications that can be reviewed, evaluated, and tailored for the actual design. Some manufacturers are including design components to address maintenance issues, such as providing more access options for easier inspection and clean-out, and the use of baskets for sediment storage and easy cleaning.
  - *Structural design:* Underground BMPs must be structurally designed for vertical and horizontal AASHTO H-20 loadings to ensure that heavy maintenance equipment can access the site.
  - *Manhole design:* Locate access manholes to underground BMPs no more than 5 m (15 ft) from access roads, as the boom of typical vacuum trucks can only reach 5 m (15 ft). Access manholes should have a minimum diameter of 75 cm (30 in.) to facilitate cleaning and confined-space entry, as well as all required appurtenances such as hoses and booms. Filter boxes and certain hydrodynamic devices may require larger openings, as some components may not be able to fit through a 75 cm (30 in.) opening. There must also be sufficient manhole access to ensure that high-pressure spray washers operated by persons or remotely operated can reach all areas and surfaces in the underground facilities to remove all collected sediment and debris (Hunt et al., 2008). Ideally, underground BMPs should have at least two access manholes.
  - *Conveyance design:* To minimize scouring and erosion in surface conveyances, make sure there is sufficient energy dissipation at inlets and outlets. Consider hard armoring or stabilization fabric as needed. To minimize maintenance problems of pipes, coordinate with geotechnical engineers, structural engineers, and/or manufacturers in pipe material selection and design. Consider clogging potential and maintenance access in the design of outlets, orifices, and trash racks. Design considerations may include reverse slope pipes, gravel or filter blankets around perforated pipes, and properly designed trash racks.
  - *Cold weather design:* Retrofit designs in cold weather regions require adaptations to mitigate cold weather problems and associated maintenance requirements. This may include over-sizing BMPs and conveyances,

burying pipes, increasing pipe slopes, and selection of salt-tolerant vegetation. Caraco and Claytor (1997) provide specific design recommendations for cold weather BMP applications.

 – *Groundwater elevation:* Consider the elevation of seasonal high groundwater levels and the potential impacts on the operation, performance, and maintenance of BMPs. Design underground BMPs to limit groundwater intrusion and select materials to mitigate potential groundwater impacts.
 – *Vegetation design:* Coordinate with biologists, landscape personnel, and maintenance crews to select native and natural vegetation that will be easy to establish, will not contribute to invasive-species issues, and will not hinder BMP inspection and maintenance. Coordinate the design of vegetated BMPs with maintenance crews to evaluate maintenance requirements and capabilities.
 – *Vandalism design:* Consider design components to discourage vandalism, such as fencing and gates to limit site access, locking manholes, and locking hand wheels and gates.
 – *Vector control design:* Coordinate BMP designs with health official and maintenance crews as needed to evaluate potential vector issues. Mitigation measures may include active vector control or design modifications to reduce vector attraction such as vegetation selection and location, selection of BMPs that fully drain, and inclusion of screens on manhole covers.

- **Ensure construction management and quality control:** Detailed BMP design specifications and good quality control during construction can reduce or eliminate BMP problems and maintenance requirements. Inspectors should have sufficient background and training to ensure that BMP materials meet specifications (e.g., plant palettes and media properties); that specified inverts and slopes are constructed; and that specified construction practices such as proper compaction of backfill, proper installation of conveyances, and manufacturers' specifications for installation of proprietary BMPs are followed.
- **Confirm construction erosion control:** Sediment loadings from inadequate sediment control during and immediately following construction can damage or overload BMPs during initial operations and may cause early maintenance issues. Planners should coordinate with construction personnel to evaluate potential sediment sources and to ensure adequate sediment control during and immediately following construction. Construction specifications should require that newly constructed BMPs are transferred to DOTs in a clean and operating condition.
- **Increase early inspection schedules:** Newly constructed BMPs should be inspected frequently (quarterly, monthly, or more often as needed) to assess one or more of the following:
  – *Proper function:* Ideally, newly constructed BMPs will be inspected during and immediately following storm conditions to determine that they are functioning as designed (e.g., flow patterns and drawdown rates) and that there is no excessive sediment accumulation or erosion issues due to improper site stabilization.
  – *Vegetation establishment:* Vegetated BMPs should be inspected frequently during the establishment period to ensure the vegetation is establishing as expected, that there are no or minimal invasive plants, and that there is no erosion or washout issues from storm flows.
  – *Sediment loading:* Pollutant loadings vary both seasonally and spatially and are likely to deviate from anticipated design loadings (Brzozowski, 2004). Newly constructed BMPs should be inspected frequently (quarterly, monthly, or more often as needed) to establish loading rates and seasonal factors and to assess if planned maintenance frequencies are appropriate. Increased frequencies should be considered for areas with heavy sanding or other sediment/debris loadings.
- **Develop maintenance triggers/indicators:** To ensure adequate BMP maintenance, BMPs should have clearly defined maintenance indicators and triggers; for examples, see the indicators developed for the Caltrans retrofit program (Caltrans, 2002a). Section 7.4 presents general maintenance triggers of selected retrofit BMPs.
- **Determine responsible parties for maintenance and training:** DOTs typically assume maintenance responsibilities for BMPs in the ROW and have well-established and -equipped maintenance departments. However, underground proprietary BMPs can have specialized practices, equipment requirements, and components that are not agreeable with maintenance departments. The use of properly trained maintenance contractors should be considered during BMP evaluation and selection when DOTs lack adequate maintenance capability. Hunt et al. (2008) recommend that specific training should be provided by the BMP manufacturer and, in the absence of training films, detailed maintenance manuals specific to the BMP must be provided by the BMP manufacturer.
- **Maintain documentation:** Comprehensive documentation of ongoing BMP maintenance practices supports periodic review and assessment of BMP maintenance requirements and costs, as well as BMP evaluations and potential refinements. Maintenance documentation includes maintenance logs, checklists, and digital photographic records.

7.4 Maintenance Practices

To support initial development and evaluation of retrofit options, Table 7.1 shows general maintenance practices and maintenance indicators by retrofit categories. Example maintenance practices are illustrated in Figure 7.2.

Detailed and site-specific maintenance indicators and maintenance practices should be developed during retrofit design and may be refined based upon the experience gained from ongoing post-construction maintenance and monitoring efforts. Sources of maintenance information include:

- DOT manuals and guidance documents,
- Manufacturer specifications and manuals,
- DOT maintenance crews and personnel, and
- BMP handbooks and maintenance guidance documents.

7.5 BMP Monitoring and Performance Assessment

DOTs commonly conduct BMP pilot testing and BMP performance monitoring to evaluate and gain operational experience of promising and/or innovative BMPs. Such efforts are especially suitable for ultra-urban retrofit situations where BMP options likely include proprietary BMPs and BMPs that are unfamiliar to DOTs, BMPs or BMP treatment trains with limited performance information, and underground BMPs that have high installation costs and unique and/or costly maintenance practices. The objectives of BMP monitoring programs may include:

- Evaluating BMP construction specifications and construction practices;
- Determining BMP hydraulic performance (flow patterns, effective sizing, volume reduction);
- Establishing BMP treatment performance and effluent quality for various highway POCs and comparing performance to other BMPs;
- Assessing factors that affect performance (climate, operating conditions, maintenance);
- Evaluating maintenance practices;
- Determining construction and maintenance costs; and
- Complying with regulatory or legal requirements.

7.5.1 Information Sources

BMP monitoring practices are specific to particular site conditions and objectives, and thus only general information is included herein. The following documents provide detailed guidance and information to support the development of site-specific BMP monitoring and performance assessments:

- FHWA Guidance Manual for Monitoring Highway Runoff Water Quality (FHWA, 2001). This manual describes procedures for developing highway monitoring programs, for selecting specific equipment and monitoring methods, and for installing and operating monitoring equipment.
- FHWA Guidance Manual of Stormwater Best Management Practices in an Ultra-Urban Setting (Shoemaker et al., 2002). Details a process for implementing BMP performance monitoring programs in ultra-urban settings, and presents a number of case study examples for a variety of BMPs.
- Caltrans BMP Pilot Study Guidance Manual (Caltrans, 2009). This planning document presents detailed guidance for developing and implementing BMP pilot tests in highway settings and additionally for managing and interpreting monitoring data results.
- WERF and USEPA Urban Stormwater BMP Performance Monitoring (Geosyntec and Wright Water, 2009). This guidance document was developed in support of the International BMP Monitoring Database Program. It presents detailed procedures for developing monitoring plans for BMP performance monitoring, for selecting and installing monitoring equipment, and for analyzing and interpreting monitoring results. It is also one of the few manuals that address monitoring the performance of distributed/LID BMPs.

7.5.2 Monitoring Plan Design

Designing an effective pilot testing and BMP monitoring plan requires detailed planning and quality control. The WERF and USEPA manual presents a detailed systematic approach for developing and implementing urban BMP monitoring plans and for interpreting the monitoring results. The following steps summarize the main principles of this approach:

1. *Define study objectives/state the problem:* The first step is explicitly defining the objectives and scope of the monitoring study. This entails:
   - A concise description of the problem being investigated and the monitoring objectives;
   - A clear understanding of the BMP operation and site conditions, including key parameters for evaluation; and
   - A summary of resources including budget, staff, equipment, schedule.
2. *Define the study goals:* Step 2 further defines the study objectives by developing detailed study questions and determining key measurement parameters. The products of this step are (1) well-defined study principles, (2) a list of alternative outcomes, and (3) a decision statement indicating how the study findings will be used.

Table 7.1. Common maintenance practices and indicators for retrofit categories.

Maintenance Objective	Frequency and Maintenance Indications	Typical Maintenance Activities	Comments	Catch Basin Retrofit	GSRD Retrofits	Hydrodynamic Systems	Oil-Water Separators	Aboveground Detention	Underground Detention	Media Filtration	Vegetated Filtration	Infiltration Facilities	Porous Pavements
Site inspection	• As scheduled per DOT or manufacturer guidance • Following major storms • As needed to address emergency, safety, and maintenance issues	• Measure accumulated sediment, debris, and floatables and oil accumulation in sumps, forebays, basins, and vaults by visual inspection, with calibrated dipsticks, or by video inspection. • Check for visible signs of clogging at inlets, racks, outlets, and pipes. Look for bypassing, erosion, channeling, and standing water. • For media filtration and infiltration BMPs, look for signs of clogging, bypassing, poor drainage through media, standing water, accumulation of fine sediments, and cake on the surface. • For vegetated BMPs, check vegetation health, type, and distribution. Look for poor or excessive growth, blockages, unwanted vegetation. • Check water levels of BMPs with permanent pools. • Check for oil accumulation and gummy deposits in oil-water separators, coalescing plates, and devices with oil-adsorbent pads. • Look for signs of windblown transport of trash. • Inspect for structural problems, corrosion, undercutting, cracks, and vandalism. • Inspect for vector issues (mosquitoes, burrowing rodents).	• Essential activity for all BMPs. • Catch basin retrofits and small vault BMPs (hydrodynamic systems, oil-water separators) require more frequent inspections to identify and address maintenance and clogging issues in a timely manner. • Inspections of underground BMPs are more likely to be neglected because they are out of sight and more difficult to inspect. Neglected or incomplete inspections can delay the identification of maintenance needs.	R	R	R	R	R	R	R	R	R	R
Minor removal of sediment, trash, and debris	• Per DOT or manufacturer guidance • Visible accumulation or potential clogging at key locations • Aesthetic concerns	• Remove minor accumulations of sediment, trash, and debris from inlets, outlets, and other locations as needed to ensure operation. • Routine sweeping and trash pickup to reduce sources, reduce potential clogging of porous asphalts, and address aesthetics.	• Routine activity applicable to all BMPs. • Routine minor clearing activities are more challenging in underground BMPs with poor access. Maintenance activities may be delayed until major cleaning is warranted.	R	R	P	P	R	P	R	R	R	R

R = routine or common maintenance activity; P = periodic maintenance activity as needed

(continued on next page)

Table 7.1. (Continued).

Maintenance Objective	Frequency and Maintenance Indications	Typical Maintenance Activities	Comments	Catch Basin Retrofit	GSRD Retrofits	Hydrodynamic Systems	Oil-Water Separators	Aboveground Detention	Underground Detention	Media Filtration	Vegetated Filtration	Infiltration Facilities	Porous Pavements
Major clearing of sediment, trash, and debris	• Prescribed clean-out schedule • Accumulated levels exceed threshold • Visual clogging • Accumulated levels affect BMP performance	• Remove sediments for forebays, basins, and vaults of surface BMPs with backhoes or vactor equipment. • For underground BMPs, vactor sediments, debris, and water from sumps and chambers per DOT or manufacturer guidance. Use high-pressure jets to flush sediments to sumps and access locations as needed or per manufacturer guidance. • Remove trash and debris from sumps, screens, and vaults. Remove and replace trash nets in accordance with O&M and/or manufacturer procedures. • Pressure wash (capturing and managing wash waters) screens to remove accumulation (e.g., CDS units). • Properly transport and dispose of all sediments, trash, debris, and water.	• One of most common maintenance activities. • Major cleaning of underground BMPs can be difficult, may require specialized procedures or confined-space entry practices, and can be costly. Underground BMPs with small storage volumes may require frequent cleaning (more than once per year) to maintain design treatment capacity. • If jetting is required to wash solids to collection areas, use care to not cause and/or minimize flushing to outlets. • Accurate estimation of accumulation is important for establishing maintenance schedule and costs (Gulliver et al., 2008).	R	R	R	R	R	R	R	R	R	
Vegetation maintenance	• Prescribed schedule • Poor growth, type, or distribution of vegetation • Excessive growth or blockages	• Routine grass and turf maintenance • Vegetation pruning, clearing, thinning, and harvesting • Planting and reestablishment of bare areas • Fertilizer, pesticide, herbicide application	• DOTs have reported that vegetation maintenance for wet basins, wetlands, and bioretention can require significant staff time (Gulliver et al., 2008; Caltrans, 2004).					R			R	P	
Media replacement and infiltration system maintenance	• Per DOT schedule or manufacturer guidance • As needed to address observed clogging or reduced infiltration capacity	• For non-proprietary systems, scrape, remove, and replace top inches or entire media bed as needed • For proprietary systems, remove cartridges and/or replace media in accordance with manufacturer instructions • Rototill upper layers of filter media	• Proprietary cartridges are potentially costly and may require regular and frequent replacement (Caltrans, 2004). • Maintenance of underground systems may require confined-space entry procedures.	P						R			

R = routine or common maintenance activity; P = periodic maintenance activity as needed

Table 7.1. (Continued).

Maintenance Objective	Frequency and Maintenance Indications	Typical Maintenance Activities	Comments	Catch Basin Retrofit	GSRD Retrofits	Hydrodynamic Systems	Oil-Water Separators	Aboveground Detention	Underground Detention	Media Filtration	Vegetated Filtration	Infiltration Facilities	Porous Pavements
Remove oil	• Per DOT schedule or manufacturer guidance • Oil-adsorbent pads are discolored or saturated • Oil accumulation in oil-water separators exceeds threshold (e.g. 1 to 2 in.) • Coalescing plates have oil deposits	• Vactor oil and water from chamber and dispose in accordance with regulations • Remove and pressure wash plates. Properly dispose of rise water • Replace oil-adsorbent pads in accordance with manufacturer instructions	• Design and system dependent. • Pads are generally low cost and easy to replace.	R		R	R						
Structural repairs	• Observed structural problems • To correct/improve design	• Fix/replace pipes, inlets/outlets, pumps, and other control devices as needed • Repair/stabilize eroded embankments and other erosion problems • Work with manufacturers and contractors to repair facilities	• Infrequent.	P	P	P	P	P	P	P	P	P	P
Vector control	• Scheduled • As needed to address problems	• Routine mosquito abatement practices • Pest control for burrowing rodents	• Mosquito control is a potential issue for all BMPs with permanent wet pools or BMPs with a potential to create standing water. • Burrowing rodents can potentially damage embankments and vegetation.	P	P	P	P	P	P	P	P	P	

R = routine or common maintenance activity; P = periodic maintenance activity as needed

Figure 7.2. Four examples of BMP maintenance activities: (A) vactoring solids from underground sumps; (B) removing sediments from surface BMPs; (C) replacing media in filtration BMPs; (D) replacing proprietary media cartridges.

3. *Identify information inputs:* The purpose of this step is to identify the specific types of information and data needed to meet the study objectives. The key activities are:
   - Determining the types and potential sources of information needed, for example, the types of precipitation measurements, water quality monitoring samples and parameters, and cost and labor-hour data.
   - Determining the basis for specifying performance criteria for the collected data. This includes an assessment of the number of samples required to achieve statistical confidence, and the laboratory protocols, detection limits, and acceptance criteria.
   - Verifying the availability of appropriate sampling equipment. In this key task, the team evaluates and selects the monitoring approaches and equipment. This requires an understanding and familiarity with the many types of monitoring approaches and equipment that are available, including assessment of the benefits and limitations of equipment options.
4. *Define the study area and parameters:* In this step, the monitoring team conducts site investigations and field reconnaissance to fully characterize the site conditions including the precipitation characteristics, tributary and drainage characteristics, and physical constraints. The team decides the location of monitoring stations and defines the specific parameters to be measured, the monitoring protocols, and the timeframes and frequency of measurements.
5. *Develop the analytical approach:* In this step, the team establishes how the collected data will be analyzed. For example, BMP treatment performance monitoring may utilize mean or median EMCs, or may require the estimation of annual loads from EMC and flow data. Other types

of monitoring objectives may require the use of decision rules, for example, maintenance triggers based on annual loadings or levels of accumulated sediments.

6. *Specify performance or acceptance criteria:* For BMP effectiveness studies, there must be a procedure for determining the level of confidence in the analysis. In this step, the team establishes the statistical hypothesis testing protocols for assessing BMP effectiveness.
7. *Develop the plan for obtaining data:* The next step is to develop a Quality Assurance Project Plan (QAPP) that describes the details of the sampling and analysis techniques. The elements of the QAPP include (1) project management procedures and a description of roles and responsibilities of team personnel, (2) description of data collection and analysis procedures, (3) quality assurance and quality control procedures to ensure the QAPP is properly implemented, and (4) data validation procedures.
8. *Assess reasonableness of plan and refine:* Developing a monitoring plan is an iterative process. In this key step, the team evaluates the monitoring plan to assess whether it can reasonably achieve the objectives within the physical and administrative constraints. Revision and refinements to the plan in order to improve outcomes and/or conform to constraints are likely.

The WERF and EPA guidance report (Geosyntec and Wright Water, 2009) provides details for applying these principles to specific sites.

7.5.3 Monitoring Plan Implementation

Successfully implementing the monitoring plan requires careful attention to details by the team personnel and a systematic approach such as the following:

- **Prepare health and safety plan:** The first step is to develop a monitoring health and safety plan. The goal of the plan is to fully define the potential hazards, safe working practices and protocols of work activities, the site-specific health and safety requirements, and emergency response procedures.
- **Train personnel:** All personnel should be completely familiar with the monitoring and health and safety plans. All personnel should receive training and periodic refreshers on applicable monitoring activities, on quality control activities, and on the health and safety procedures. Training may include practice events and monitoring run-throughs.
- **Install equipment:** All equipment must be properly installed and functioning in accordance with site-specific requirements. Upfront planning is needed. The team should prepare equipment preparation checklists and well-stocked and -organized field boxes that include tools, health and safety supplies, and equipment operation manuals.
- **Test and calibrate equipment:** Once installed, all equipment should be thoroughly tested and calibrated. A dry run may be conducted to test equipment and train personnel.
- **Conduct monitoring:** The monitoring is conducted in accordance with the established protocols for weather tracking, team mobilization, and monitoring activities.
- **Coordinate with laboratory:** Mobilization protocols should include laboratory notification and coordination. Frequent and close coordination with the laboratory will help to minimize problems and improve quality assurance. All samples should be collected, packed, and shipped to the laboratory in accordance with laboratory and quality assurance protocols.

7.5.4 Data Management and Evaluation Monitoring

Effective data management, validation, and reporting are fundamental components of an effective stormwater BMP monitoring study. Well-established protocols are described in the ASCE and USEPA guidance manual (Geosyntec and Wright Water, 2009). On the other hand, data evaluation can be challenging and complex. Procedures must suit the objectives and support interpretation and conclusions about the BMP's effectiveness. Detailed descriptions of data analysis procedures are found in guidance documents listed in Section 7.5.1.

SECTION 8

Retrofit Costs

Cost evaluation is a vital component in the practicality assessment of retrofit alternatives. This section describes the factors that affect retrofit costs and presents general retrofit cost information and cost reduction strategies.

8.1 Cost Elements

Planning, Design, and Permitting Costs: BMP retrofitting requires significant upfront time and cost for scoping, siting, site characterization, permitting, and BMP design. Effective planning and design, however, are crucial for successful retrofitting. Early and comprehensive coordination and site characterization can help to identify efficient retrofit options, as well as site constraints that will avoid added costs and construction delays down the road. Significant planning and design costs should be expected for retrofit projects. For resource planning, Caltrans estimates average design costs as 10% to 12% of the construction cost (Caltrans, 2001). Higher planning and design costs should be anticipated for small projects and for projects in highly constrained settings. Permitting costs can vary substantially based upon the environmental and infrastructure setting. In some cases, very minor permitting costs can be anticipated (i.e., a project completely within ROW and no environmental impacts); in other cases, where projects are outside the ROW and/or would impact environmentally sensitive species, for example, fairly high costs can be anticipated.

Land Costs: Land acquisition costs are site specific but are characteristically high in dense urban areas. Approximate land costs can range from $500,000 to $2,000,000 per acre (Strecker et al., 2005). ROW acquisition in ultra-urban settings is generally not practical due to high land costs and existing development/infrastructure.

Capital Costs: Capital costs are the expenditures associated with the construction of the BMP retrofit. BMP construction costs are highly variable and critically dependent on site-specific conditions. Cost information from past projects can only serve as a guide to inform estimates of future projects and not as a definitive reference since every retrofit is different. Factors that make it difficult to apply unit costs from one project directly to another project include:

- Regional variations in design, price of materials, and labor rates;
- Physical site-specific constraints;
- Differences in quality and efficiency of planners, designers, and contractors;
- Differences in regulatory framework;
- Differences in inflation and macroeconomic conditions at the time of construction; and
- Regional variations in weather conditions.

Accurately estimating costs for new construction is challenging for the reasons just listed. It is even more challenging to develop accurate cost estimates for retrofit situations due to the uncertainty of site-specific complications. Retrofit costs, therefore, are typically much higher than new construction costs for most BMPs other than BMPs such as inserts. According to Schueler et al. (2007), the base construction cost of retrofits generally exceeded equivalent new construction costs by a factor of 1.5 to 6 based on evaluation of nearly 100 projects around the country. Still higher construction costs should be expected for ultra-urban retrofits due to physical site constraints. The costing tools that are available typically do not factor in retrofit conditions that can significantly increase costs, e.g., the whole-life cost model and spreadsheet framework developed by WERF (2005).

Contingency and Escalation Costs: Contingency costs address unforeseen costs encountered during construction. Contingency costs for retrofit projects should be higher as compared to new construction, reflecting greater uncertainty about site-specific conditions and constraints and less flexibility for corrective measures. Design and contingency factors for BMP retrofits range between 32% to 40% (Brown and

Schueler, 2007; Schueler et al., 2007). Contingency factors can also depend on the BMP type. Vegetated BMPs are more likely to stay on budget for capital and installation in comparison to infiltration basins, porous pavement, and media filters (Phillips et al., 2008). Projects that have significant construction periods should incorporate appropriate cost escalation factors in the project cost (Caltrans, 2009).

Operation and Maintenance Costs: All retrofits have to be maintained after construction. While maintenance might not factor into retrofit installation costs, maintenance is a major component of the life-cycle cost of any retrofit and should be taken into consideration at the planning stages of any retrofit process. The most common and costly O&M practices are sediment management at inlets and outlets, trash and debris removal, and vegetation management (Kang et al., 2008a).

O&M costs can compose a substantial fraction of the total BMP cost. Annual O&M costs for surface detention facilities are on the order of 5% or less of the construction cost. Dry detention facilities and infiltration basins have the lowest and least variable O&M costs (Weiss et al., 2005). More variable O&M costs as a percentage of construction cost are reported for infiltration trenches (5% to > 20%), sand filters (1% to 13%), swales (4% to > 7%), and bioretention (1% to > 11%). As a rule-of-thumb, annual O&M costs are on the order of 10% of total construction costs for stormwater BMPs that cost about $10,000 (circa 2005), and on the order of 5% for stormwater BMPs that cost $100,000 (circa 2005) (Kang et al., 2008a). Greater O&M costs can be anticipated for proprietary underground BMPs, particularly, if they require frequent inspection and maintenance; there are access or safety issues; or they require proprietary components such media cartridges. However, long-term maintenance cost data for proprietary BMPs are not well established.

Life-Cycle Costs: These costs are the total project cost over the life span of the retrofit BMP, including planning and design, construction, and O&M. Examples of life-cycle cost estimation for BMPs are given by Oregon State University et al. (2006).

8.2 Cost Factors in Ultra-Urban Settings

In ultra-urban retrofit situations, the site conditions can strongly affect retrofit costs. Even when capital costs are known, such as the cost of proprietary BMPs, site conditions can greatly affect the installation costs. Understanding site constraints at the design stage can translate into more accurate cost estimates. The site constraints most likely to impact cost estimates are factors that limit constructability such as space constraints, site accessibility, and obstructions.

Space Constraints: Limited space can prevent the use of the most efficient tools and machinery and/or can increase the amount of manual labor that has to be done to complete a project. Space limitations can force contractors to reduce the size of the staging areas or relocate the staging area to inconvenient locations, lowering construction efficiency. Cost estimates must account for alternative methods of construction in space-constrained situations.

Site Accessibility: The distance from construction materials and excess material haul sites can significantly increase retrofit costs. Similarly, limited access to retrofit sites can also significantly increase project costs. Cost estimates must account for site accessibility.

Obstructions: The presence of obstructions both known and unknown can significantly impact construction costs and schedules. Large rocks and boulders, unsuitable and contaminated soils, high groundwater tables, utility conflicts, existing structure foundations, historic buildings, wetlands, water bodies, and other protected areas can cause costly construction delays and construction change orders.

Ultra-urban highways are prone to unforeseen obstructions because of the density of development. In many cases, as-built drawings are not available, particularly in older highway settings, and even when available, they may not be accurate. During the Caltrans retrofit study, the discovery of unsuitable subsurface materials and buried utilities was a reoccurring issue, even when as-builts were available (Caltrans, 2004). Buried objects and utility conflicts accounted for 4.3% of the total adjusted retrofit construction costs in the Caltrans study (Caltrans, 2001).

Ultra-urban retrofits warrant greater efforts in early planning, coordination, and site characterization to help identify potential obstructions. Even with such efforts, unknown obstructions are potential constraints that cannot be completely forecast. Contingency costs should be increased as necessary to reflect uncertainties about the site conditions.

Environmental Mitigation and Permitting Challenges: Additional costs relating to mitigation of environmentally sensitive areas, protection of wetlands and endangered species habitat, and related permitting can significantly increase the total cost of a retrofit. Retrofit selection, design, cost estimates, and construction should anticipate the need for mitigation, protection, and special permits.

Safety and Security: Safety and security considerations require additional components such as fences, gates, locks, screens, and security lights to be included in retrofit designs. During construction, additional signage and traffic control may be needed for the safety of the construction workers and the general public. For example, traffic-control and safety/security costs accounted for about 7.5% of the total adjusted retrofit construction costs in the Caltrans study (Caltrans, 2001). Failure to include safety components in the design or failure to anticipate the cost of construction and inspection/maintenance safety procedures can lead to inaccurate cost estimates.

Longevity: The longevity of a BMP is affected by factors such as maintenance (most importantly); deterioration of materials (as in a filter); damage due to accidents, cold weather, vandalism, etc.; changing drivers such as traffic conditions, urban density, etc.; preference for alternative use for site; changes in treatment preference; changes in transportation mode; and so forth. Longevity directly affects estimates of life-cycle costs. At the end of a BMP's life, engineering options are similar to those for any facility: rebuilding or renovation, abandonment in favor of a new facility or alternative treatment, or rejuvenation of components such as filter material.

8.3 BMP Cost Estimates

8.3.1 Sources of Cost Data

BMP cost data are limited, particularly for highway retrofit projects in space-constrained settings. Potential sources of cost data follow:

- **Reference manuals:** RS Means (http://rsmeans.reedconstructiondata.com/) and similar reference manuals provide current cost-estimating data for a variety of construction categories. Use of cost data from new construction or significant redevelopment without adjustment, however, is not appropriate for retrofit projects as site-specific conditions and constraints are likely to increase costs.
- **Proprietary device manufacturers:** Manufacturers are good sources of capital cost information for proprietary BMPs and expected O&M costs. They may also have information on construction requirements that can help to refine cost estimates.
- **Industry literature:** BMP cost information is compiled in various reports including Heaney et al. (2002); Sample et al. (2003); Young et al. (1996); and Weiss et al. (2005). Several of these sources are summarized by Oregon State University et al. (2006). The data represent many types of BMPs and applications, but most are for new construction. Available cost data are frequently normalized by area or volume treated, and summarized as power function equations. General cost information is useful for preliminary retrofit planning.
- **Contractors and DOT in-house databases:** The most useful cost information is gained through experience of engineers and construction personnel as DOTs implement retrofit programs. DOTs should actively coordinate and develop working relationships between designers, engineers, field personnel, and contractors to gain experience and insights into retrofit cost drivers and to develop cost reduction approaches. Some state DOTs, such as WSDOT, are beginning to perform value-engineering studies on stormwater facilities in urban areas, to discern the most cost-effective solutions.

8.3.2 Retrofit Cost Data

Published BMP retrofit cost data are limited. Primary sources of retrofit cost data are the Center for Watershed Protection (CWP) guidance document (Schueler et al., 2007) and the Caltrans retrofit study report (Caltrans, 2004). Table 8.1 summarizes retrofit cost information from these sources.

The Center for Watershed Protection (Schueler et al., 2007) compiled cost data from 100 BMP retrofit projects that reflect a variety of retrofit project types. The cost information is for retrofit projects generally aimed at watershed restoration goals where space constraints do not significantly impede design and construction. Therefore, the cost guidance does not entirely reflect costs associated with ultra-urban environments where higher costs are expected.

The Caltrans retrofit study (2004) included detailed accounting of capital and maintenance costs with independent third-party review. The costs reflect stand-alone retrofit projects of transportation drainage facilities in urban settings. Caltrans noted that there is uncertainty about how well the cost data may reflect actual costs in a large-scale retrofit program due to the pilot-specific nature of some of the costs and the lack of standard competitive bidding. Nevertheless, the Caltrans cost data are likely the most representative cost data available for ultra-urban highway retrofits, but should be used only as a general guide.

8.3.3 General Findings and Cost Guidance

Site-specific and national cost information compiled in the Caltrans (2004) and CWP (Schueler et al., 2007) reports support the following findings and general cost guidance regarding BMP retrofits:

- **Retrofit costs vary greatly:** Available retrofit costs are highly variable, even within similar BMP categories and for similar treatment volumes. Variable costs reflect the site-specific characteristics and general uncertainties associated with retrofit situations. Consequently, it is difficult to develop non-specific forecasts of retrofit costs.
- **Retrofit costs are significantly greater than new construction:** Schueler et al. (2007) report that retrofit base construction costs generally exceeded the cost of new stormwater practices by a factor of 1.5 to 6. Caltrans (2004) finds that retrofit construction costs were as much as an order of magnitude or more than costs gathered in a nationwide survey, reflecting the stand-alone and site-specific characteristics of the Caltrans retrofit projects as well as the general nature of more difficult conditions encountered in highway/freeway environments.
- **The most cost-effective BMPs are surface storage and vegetated BMPs:** The most cost-effective BMP categories

Table 8.1. Retrofit cost information from Caltrans (2004) and Schueler et al. (2007).

Retrofit Category	Caltrans: BMP Type (number of installations)	Caltrans: Adjusted Construction Cost* ($/m³): Range	Caltrans: Adjusted Construction Cost* ($/m³): Average	Caltrans: O&M ($/m³)	Caltrans: Life-Cycle Cost** ($/m³)	Center for Watershed Protection: BMP Type	Center for Watershed Protection: Construction Cost* ($/m³): Range	Center for Watershed Protection: Construction Cost* ($/m³): Median
Catch basin	Various types (6)	$3–$27	$13	$37	$50			
Hydrodynamic	CDS units (2)	$224–$353	$340	$127	$467			
Oil-Water Separator	Areo-Power (1)		$2537	$27	$2,564			
Detention	Extended detention (5)	$390–$1683	$760	$107	$867	Ponds	$38–$367	$113
	Wet Basin (1)		$2229	$582	$2,811			
Vegetative filtration	Biofiltration Swale (6)	$182–$2005	$968	$95	$1,064	Swale	$267–$827	$470
	Biofiltration Strip (3)	$384–$1237	$963	$95	$1,058	Large bioretention	$282–$648	$395
Media filtration	Storm filter (1)		$2024	$263	$2,287			
	Delaware Sand Filter (1)		$2462	$100	$2,563	Structural sand filters	$601–$827	$752
	Austin Sand Filter (5)	$746–$2118	$1863	$100	$1,964	Underground sand filter	$1052–$2818	$2442
Infiltration	Infiltration Basin (2)	$340–$397	$475	$104	$579	Infiltration retrofit	$376–$864	$564
	Infiltration trench (2)	$691–$775	$944	$91	$1,035	French drain/ dry well	$395–$507	$451
Advanced treatment	MCTT (2)	$1856–$1895	$2414	$220	$2,635			

* Cost per cubic meter of design storm treated, inflation adjusted to 2009 dollars. Design storms and design treatment volumes vary reflecting differences in regulatory and precipitation characteristics.
** 20 years @ 4%
Note: To convert from $/m³ to $/ft³ divide by 35.3; to convert from $/m³ to $/acre-ft multiply by 1233.6.

in terms of cost per volume treated are surface storage and vegetated facilities, including detention and infiltration basins and vegetative filtration BMPs. A few types of catch basin retrofits, GSRDs, and proprietary hydrodynamic systems also have good to moderate cost effectiveness.

- **The least cost-effective BMPs are underground BMPs:** The most costly BMPs are those that require underground installation including underground detention vaults, oil-water separators, and underground media filtration systems.
- **Unit costs decline as the size of the impervious acreage increases:** Caltrans and the CWP both found the size of treated area to be one of the most influential cost factors. There is an economy of scale in terms of construction per unit volume treated as the size of the treated area increases. Schueler et al. (2007) state that smaller on-site retrofits that treat less than a 1/2 acre of impervious cover tend to be two orders of magnitude more expensive per treated area than larger storage retrofit practices.
- **BMPs with simple and standard designs tend to be more cost effective than specialized and proprietary BMP devices:** In general, cost efficiencies are gained when BMPs have simple designs (e.g., surface detention, infiltration and vegetated filtration BMPs) and/or make use of standardized designs and components (i.e., inlet structures and precast units). BMPs with complex and unique designs (e.g., underground cast in-place designs) and proprietary components (e.g., specialized media cartridges) tend to be more costly on a cost per volume treated basis.

8.4 Cost Reduction Strategies

Cost reduction approaches and strategies are developed through experience as DOTs develop and implement retrofit programs. The retrofit pilot study conducted by Caltrans (2004) identified a number of cost reduction strategies as outlined in the following paragraphs.

Integrate BMP Retrofits with Larger Projects: For major projects, stand-alone retrofits are the most expensive approach. Integrating retrofits with other highway improvement projects reduces costs by:

- Providing more flexibility and opportunity for BMP selection, BMP siting, and connection with existing drainage systems;

- Reducing mobilization, traffic-control, and equipment costs, and generally increasing the economies of scale during construction; and
- Reducing regulatory compliance cost by using a single permit for the entire project.

DOT retrofit programs should emphasize long-range planning to coordinate retrofits with other highway improvement projects.

Consider Cost Implications of BMP Selection: BMP options have varying cost attributes:

- ***Larger treatment capacity is more cost effective.*** Because of economies of scale, BMPs that treat larger areas/volumes are generally more cost effective than smaller facilities; for example, regional facilities are more cost effective than distributed facilities, unless there would be significant conveyance costs to address or larger land areas would need to be purchased to site the larger facility. When options are available, BMPs should be selected and designed to treat larger drainage areas. This guidance may be constrained by maintenance issues. For example, O&M personnel may prefer taking care of a single, large facility rather than several smaller ones, or depending on the difficulty/frequency, there may be occasions when several small installations of one type might be preferable to a single large site with another type.
- ***Non-structural vegetated controls are less costly than structural controls.*** Vegetated BMPs have minimal structural features, have flexible designs allowing for easy integration into landscaping, and can provide conveyance functions. This provides savings in the design and construction of structural stormwater facilities such as pipes, conveyances, and storage facilities. Land costs if required can make them more expensive.
- ***Specialized proprietary BMPs are generally less cost effective.*** Specialized proprietary BMPs can have higher capital and maintenance costs than standard alternatives and should be a second-tier alternative. Proprietary specialized BMPs are most suitable where standard alternatives are not practical (highly space-constrained settings) or when they are required to meet higher levels of treatment performance (for example, as part of a treatment train or if specialized media is required to address a particular POC).

Partner with Other Entities: Cross-jurisdictional partnerships within the watersheds where the highways are located can provide significant cost savings.

Consider Engineering Design and Construction Factors: BMP design and construction are major cost drivers. Significant cost savings are realized as personnel gain experience with BMP technologies, BMP siting, and BMP design and modifications:

- ***Consider undersized BMPs for cost savings.*** BMPs are sized to conform with DOT design storm sizing requirements. However, in space-constrained situations, BMP sizing requirements can be cost prohibitive. Undersized BMPs that are cost effective should be pursued consistent with the overall goal of maximizing pollutant reduction. In some situations, it may make sense to oversize BMPs in areas where one can offset reductions in performance for undersized BMPs. Note that undersized BMPs if designed properly can still achieve significant water quality benefits.
- ***Use landscape features.*** Integrate BMPs into natural topography and landscaping to reduce construction and material costs. If this is feasible, distributed BMPs may be more cost effective than a larger facility.
- ***Limit structural requirements.*** Select BMPs that do not require pumping and extensive shoring as feasible.
- ***Use of standard components.*** Flexible designs that utilize standard components and construction practices tend to be easier to construct and are more likely to be completed on schedule with a reduced risk of budget overruns.
- ***Limit sod and irrigation for vegetation installation.*** Minimize the use of sod as a primary means of establishing or restoring vegetation, and install vegetation when there is a reasonable chance of successful establishment without irrigation (Caltrans, 2009) or with minimal irrigation (during establishment period in particular).

SECTION 9

Retrofitting Strategies and Process

This section describes general retrofitting approaches and strategies. A general process for planning and implementing ultra-urban highway stormwater control retrofits is presented.

9.1 Types of BMP Retrofits

Redevelopment BMP Retrofits: Redevelopment retrofits are retrofits of existing untreated highway facilities in association with highway improvement projects. For example, highway-widening projects may require BMPs to treat all highway runoff associated with the project, including the untreated pre-project highway surfaces. In redevelopment retrofits, the retrofit project location is established by the location of the improvement project. There is no need for prioritizing and selecting retrofit project locations. Because of the high cost of retrofitting ultra-urban highways, most projects will likely be redevelopment retrofits associated with planned highway improvement projects.

Stand-alone BMP Retrofits: Stand-alone retrofits are retrofits of existing highway infrastructure or existing BMPs for the sole purpose of improving water quality. They are independent of other highway projects. TMDL wasteload allocations are likely the most common regulatory driver for stand-alone retrofits, but NPDES permits can also explicitly mandate stand-alone retrofits (e.g., the North Carolina DOT permit requires 14 statewide retrofits per year) as well as requirements of CERCLA or the Resource Conservation and Recovery Act (RCRA) in contaminated sediment circumstances or ESA requirements, particularly for aquatic species. Stand-alone retrofits are usually more costly than redevelopment retrofits. Therefore, it may be more cost effective to delay and integrate stand-alone retrofits into planned highway projects when feasible and allowed.

9.2 Retrofit Prioritization Approaches

Regulatory drivers will determine the type of retrofit project and the need for prioritizing and selecting the retrofit project location. Stand-alone water quality retrofits may require a retrofit scoping, evaluation, and prioritization process to establish the project location within specific jurisdictions, regions, or watersheds. Retrofit prioritization approaches are discussed in the following paragraphs.

Benefit-Cost Approach: A benefit-cost approach for outfall prioritization requires the quantitative assessment of retrofit costs and benefits. As an example, Kalman et al. (2000) conducted a benefit-cost evaluation of stormwater treatment for impaired reaches of the Ballona Creek watershed in Los Angeles, California. In this evaluation, the BMP costs were estimated on the basis of treatment levels: Level 1 control was for floatables and TSS; Level 2 control provided filtration and disinfection; and Level 3 control included advanced treatment to meet all beneficial use standards. The benefits were estimated on the basis of economic value of the restored beneficial uses in the receiving waters.

Weighted Scoring Approach: WSDOT developed an outfall prioritization scheme in 1996 using numeric scoring prioritization (WSDOT, 1996; Barber et al., 1997). This outfall prioritization study found the highest priority outfalls were concentrated in urban areas that discharge to small streams. Landphair et al. (2001) adapted the WSDOT weighted scoring approach for the Texas Department of Transportation (TxDOT). The scoring categories used by WSDOT and TxDOT included:

- Type and size of receiving water body,
- Beneficial uses of receiving water body,
- Pollutant loading,
- Percentage contribution of highway runoff to watershed,
- Cost/pollution benefit, and
- Values tradeoff.

Multiple Screening Approach: A multiple screening approach is a general prioritization process that may include quantitative and qualitative retrofit evaluation criteria. A multiple screening approach is employed by WSDOT and

NCDOT for retrofit prioritization and is used in the CWP retrofit guidance manual (Schueler et al., 2007) for watershed restoration. The general steps include the following:

1. *GIS screen/scoping.* The first screen is to conduct GIS-based assessments using existing information to initially identify potential retrofit sites. Criteria may include watershed size, highway area to watershed ratio, impervious area, receiving water impairments, ADT, maintenance capability, etc. GIS-based decision support tools are available that can aid such efforts. For example, the Structural BMP Prioritization and Analysis Tool (SBPAT) was developed to identify and prioritize potential structural BMP retrofit projects throughout Los Angeles County, as well as estimate planning-level costs and potential pollutant concentrations and load reductions resulting from the implementation of the prioritized projects (Geosyntec, 2008).
2. *Reconnaissance:* The second screen is more rigorous. In this stage, field-based reconnaissance and site-specific characterization studies are used to further prioritize candidate sites. Field reconnaissance could include mapping of the ROW, topography, soils, drainage system, verification of infrastructure, evaluation of receiving water conditions, and coordination with field personnel and biologists.
3. *Retrofit evaluation and prioritization:* The final screen involves quantitative and qualitative evaluations to select and prioritize feasible retrofit sites. The evaluation criteria may include numeric scoring of site conditions, and/or other more qualitative stakeholder and regulatory input. The goal of this level of screening is to complete a retrofit project priority list.

Caltrans used a similar multiple screening process to select sites for the retrofit pilot study (Caltrans, 1998). In their approach, a general scoping process based on review of as-built drawings was used to determine initial candidate sites in target watersheds. Field reconnaissance studies were next conducted to gather site information and refine the list of candidate sites. Final retrofit site selection was determined using a weighted scoring evaluation approach, where scoring criteria were based on the BMP type.

Multiple screening approaches are recommended for retrofit site prioritization for the following benefits:

- They are designed to screen out poor candidate sites with reduced/minimal evaluation.
- They take into account both receiving water conditions/benefits, cost/benefits, and the site constraints that can limit retrofit feasibility.
- They allow for direct input from stakeholders, field personnel, contractors, and other design and O&M personnel.
- They include opportunities for collaboration with other jurisdictions and groups. This is especially important when combining efforts may result in more cost-effective solutions, if only through economies of scale.

9.3 Attributes of Successful Retrofitting

The retrofitting process requires a comprehensive and flexible approach to address the challenges of complex site-specific conditions and the high costs of modifying ultra-urban highway infrastructure. The CWP has identified the following attributes of successful retrofitting (Schueler et al., 2007).

- **Investigation:** "Retrofitting requires a different way of thinking; it requires sleuthing skills to determine what can work at highly constrained sites." Information gathering is more comprehensive. Retrofitting requires significant data gathering and site characterization, as well as greater coordination with highway maintenance crews, roadway engineers, BMP designers, neighboring municipalities, utility agencies, watershed stakeholders, regulators, and construction managers and contractors.
- **Foresight:** Retrofit designers need to simultaneously envision BMP possibilities and anticipate problems. Retrofitting requires significant effort to understand site conditions and greater experience with the constructability and performance of BMPs. Foresight is gained through data gathering, coordination, research, and pilot testing.
- **Creativity:** Retrofit designers must be creative to find and design effective and affordable BMP retrofits that will produce the desired treatment objectives. Retrofitting requires a willingness to develop and consider a range of approaches. This may include consideration of new, irregular, and non-standard BMP approaches, or a willingness to coordinate and partner with regulators and other watershed stakeholders.

The key factor is the experience level of the DOTs, designers, and team members with retrofitting and with designing and constructing non-traditional and site-specific BMPs. DOTs can gain retrofit experience and BMP development through pilot testing programs, research and development initiatives, and ongoing coordination and cooperative relationships with construction contractors, universities, and research institutions.

9.4 Project Planning and Coordination

The planning stages for BMP siting and design are usually the most critical phases of the retrofit process. Project planning can be a major cost element of retrofit projects, but broad and early coordination with regulators, local officials, and personnel familiar with the site can benefit and reduce likelihood of encountering problems and increasing costs in the later project stages. Recommended project planning and coordination practices include the following:

- **Proactively engage regulators and local officials.** Proactively involve regulators and local officials in a collaborative role throughout the retrofit planning and implementation. Regulators can help to identify local and regional permit requirements for the project. In addition, involving regulators and local officials can: (1) cultivate a common appreciation of the challenges of working in ultra-urban settings and (2) potentially help to develop and gain acceptance and approval of workable alternatives that provide the most practical benefit to receiving waters.
- **Involve field and maintenance personnel, pavement designers, biologists and environmental personnel, and construction managers early in the planning process.** Lots of upfront coordination during the early planning stages will support the identification of sensible and acceptable retrofit alternatives and will reduce the likelihood of costly project changes and redirects down the road. Early coordination will also help to identify constraints and establish construction and maintenance schedules.
- **Coordinate with personnel that have knowledge of site conditions.** Planners should search for and coordinate with personnel that can potentially supply information about the site conditions and site constraints. These may include the following:
  – *DOT personnel:* Seek out and coordinate with DOT planners, engineers, and construction personnel with previous project experience at the site.
  – *Field personnel:* Coordinate and conduct site visits with DOT field and maintenance crews that can provide working knowledge about site conditions, including known problems/issues, and drainage patterns, and can confirm the location and characteristic of stormwater infrastructure.
  – *Municipalities and utility agencies:* Planners should actively coordinate with adjacent municipalities, public works departments, utility agencies, and as appropriate private landowners that have knowledge of the site and adjacent infrastructure and can help to identify unmapped utilities and constraints as well as help to assess potential BMP alternatives and in some cases partnerships.
- **Conduct thorough site investigations.** Unidentified buried utilities or other underground constraints are major causes of construction delays, construction change orders, and budget overruns. A thorough site investigation upfront can reduce uncertainties, lead to more applicable BMP designs, and potentially mitigate delays and overruns during construction stages. When a thorough site investigation is not possible, a preliminary excavation (pot holing) should be conducted prior to excavation to confirm accuracy of as-builts and to discover project infrastructure that may need relocation. A variety of surface and borehole geophysical methods summarized in Table 9.1 can be useful in detecting underground utilities and objects and/or guiding test pit excavations. Subsurface utility engineering (SUE) is an engineering practice promoted by the FHWA and used by DOTs (FHWA, 2011). It combines the use of vacuum extraction and geophysical techniques to detect buried objects. If belowground issues are discovered, more detailed site investigations are likely warranted. Otherwise,

Table 9.1. Summary of surface geophysical method applicability.

	Ground-Penetrating Radar	Metal Detection	Magnetometry	Electromagnetic Methods
Purpose	Focused investigation	Reconnaissance survey	Reconnaissance survey	Reconnaissance survey
Typical Depth of Penetration	3 to 15 ft	10 to 12 ft (55 gal. drum)	10 to 15 ft (55 gal. drum)	8 to 10 ft
Materials Detected	Metal and non-metal	Metal	Ferrous materials	Metal and non-metal
Cultural Interferences	Densely packed rebar, wire mesh	Metal surface structures, power lines	Metal surface structures, power lines	Metal surface structures, power lines
Natural Interferences	Conductive soils (e.g., silts, clays)	Mineralized soils	Mineralized soils, iron deposits	Highly conductive saline soils
Resolution	0.1 to 4 ft	20% vertically and horizontally	10% to 15% vertically and horizontally	Vertical resolution is between 4 and 12 ft; 4 ft horizontally
Produces Usable Field Data	Yes	Yes	Yes	Yes
Time	Slow to Moderate	Moderate to Fast	Fast	Moderate to Fast
Cost	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate

Source: USEPA (1997)

costs can potentially increase significantly due to redesign and/or removal of the contamination or infrastructure during construction.

- **Strive for vision and creativity in developing BMP alternatives.** Do not rely solely on traditional BMP practices and as appropriate do not limit options to DOT-specific BMP guidelines. To meet the challenges of retrofitting ultra-urban highways, consider a wide range of BMP options described in Section 4 and investigate and become knowledgeable of new and innovative practices. Designers should understand the processes needed to treat target pollutants and develop a vision of BMP elements and treatment trains needed to achieve those processes. If candidate BMPs are not approved by DOTs, planners should be amenable to pursuing these approaches, possibly through BMP pilot testing, other internal approval processes, and/or through coordination with regulators.
- **Use sound engineering.** Attention to details and quality control can help to avoid change orders and cost overruns as well as to ensure effective performance. Some specific lessons learned from the Caltrans retrofit study follow (Currier and Moeller, 2000; Currier et al., 2001):
  - Quality control during surveying is critical and can help to avoid subsequent adjustments.
  - Material quality specifications should be included with BMP product orders (e.g., vegetation conditions), and specifications checked and confirmed before acceptance of product delivery.
  - Manufacturer installation instructions should be followed for proprietary BMPs; otherwise poor performance can result.
- **Plan for contingencies.** Even with the most comprehensive planning, unforeseen circumstances can arise during construction, particularly in older and dense urban environments. For example, designers may want to avoid precast units at sites where there are tight tolerances because as-built maps can be inaccurate. Cast in-place features would allow for adjustments that may be needed to adjust to actual field conditions or changes due to construction (Currier and Moeller, 2000). In addition, planners should allow for budget and time contingencies that are commensurate with the degree of uncertainty about site conditions and the experience level with the construction and operation of the retrofit BMPs.

9.5 Retrofitting Process Framework for Specific Retrofit Sites

Table 9.2 outlines the recommended retrofitting process for specific sites that are associated with the redevelopment project or are first identified through a retrofit prioritization analysis, as discussed in Section 9.2. The retrofit process follows a general top-down planning framework based on fundamental steps commonly used in water resources planning. For many retrofit projects, the process may not proceed sequentially. As appropriate, steps will be conducted concurrently, out of sequence, and will be repeated as new information is gained. The following subsections discuss the steps of the retrofitting process.

9.5.1 Step 1: Project Scoping

The first step is to define the scope of the retrofit project. Retrofit scoping includes the following tasks:

- **Establish the regulatory/DOT retrofit requirements.** The project retrofit requirements will likely be prescribed in DOT policy manuals, TMDL implementation plans, NPDES permits, or other regulatory requirements. Complex projects in sensitive areas may require negotiation with regulators and stakeholders to establish regulatory requirements. A clear understanding and agreement of the regulatory requirements at the outset of the project is essential.
- **Define the scope of treatment requirement for new and existing impervious areas.** Know the new and/or existing impervious areas that will require treatment or enhanced treatment. Different levels of retrofit treatment could be required depending on regulatory policy. For example, redevelopment projects may require retrofit treatment of all existing highway impervious areas associated with the highway improvement project. Alternatively, requirements may allow exclusion of some sub-basins that are not feasible or practical to treat (e.g., pollutant reduction trading may be allowed), or planners may consider allowable alternative mitigation measures. Stand-alone retrofits may have specific performance objectives (e.g., wasteload reductions) or may be opportunistic retrofit projects with no minimum performance requirement.
- **Identify the receiving waters and environmental areas.** Knowledge of the project's receiving waters (surface and potentially groundwaters) and potential environmental impact areas (sensitive areas, conservation areas) supports scoping of environmental permit requirements and BMP planning.
- **Understand the issues of concern.** Gather and review water quality information and consult with stakeholders and biologists as necessary to understand the receiving water issues of concern. An assessment of surrounding land use within the drainage area and a pollutant loadings analysis can help characterize the DOT contributions to receiving water issues. Collectively, this information supports the identification of project POCs, assessment of flow control requirements, and BMP planning. Section 2 provides background information on highway runoff issues

Table 9.2. Retrofitting process framework for specific sites.

Step	Key Tasks
Step 1. **Project Scoping**	• Establish regulatory/DOT requirements • Define highway facilities that require retrofit treatment • Define receiving waters and environmental areas • Gather water quality information • Understand receiving water issues of concern and highway contributions • Gather available site data as needed to support project scoping • Determine the planning team, budget, and schedule
Step 2. **Definition of Retrofit Project Objectives**	• State the regulatory/DOT compliance objectives • State the water quality treatment objectives • Establish performance criteria: treatment standards, sizing requirements, flow objectives
Step 3. **Characterization of Site Conditions and Constraints**	• Gather available information about the site • Coordinate control with knowledgeable personnel and stakeholders • Conduct site characterization investigations and field studies (e.g., surveys, utility searches, soils and infiltration tests, etc.) • Characterize site conditions and constraints
Step 4. **Identification of BMP Retrofit Alternatives**	• Task 1: Determine applicable unit operations and treatment trains • Task 2: Identify feasible candidate BMPs that provide UOPs. Give primary consideration to aboveground alternatives ▪ 2a) ROW options ▪ 2b) Jurisdictional partnerships ▪ 2c) Pollutant trading • Task 3: Consider underground options as necessary • Task 4: Evaluate, refine, and screen concepts; select alternatives for assessment
Step 5. **Practicality Assessment**	• Hydrologic and hydraulic analyses • BMP sizing • Treatment performance assessment • Maintenance assessment • Preliminary design preparation • Cost evaluation • BMP retrofit selection
Step 6. **Design and Construction**	• Prepare final designs, specifications, O&M plan, and cost estimates • Obtain permits • Bid and contract • Manage construction
Step 7. **Post-Construction Operation and Evaluation**	• Ongoing BMP inspection and maintenance • Retrofit project evaluation • BMP performance monitoring as needed

and lists potential data sources. The data sources may include DOT policy documents, DOT monitoring data, and regulatory and stakeholder reports.

- **Determine the project team.** The project team must include appropriate personnel to meet DOT requirements and to support the identification of retrofit constraints and opportunities. Personnel may include, but are not limited to, design engineers, construction personnel, maintenance departments, real estate and surveying personnel, environmental specialists, regulatory contacts, geotechnical engineers, and traffic and safety personnel.

9.5.2 Step 2: Define Retrofit Objectives

The regulatory and treatment objectives will develop from the scoping process. A narrative statement of the main retrofit objectives can help to establish a common understanding of the water quality goals. The retrofit objectives include one or more of the following:

- Regulatory and/or DOT compliance requirements
- Identification of the specific project pollutants and conditions of concern and the corresponding treatment objectives
- Specification of performance criteria, such as:
  – BMP treatment performance requirements
  – Maximum discharge loads to meet TMDL wasteload allocations
  – BMP sizing specifications
  – Flow control and attenuation requirements
- Other objectives such as pilot testing objectives and performance monitoring objectives

In setting the objectives, it is important to keep in mind the potential limitations of retrofitting in ultra-urban settings. The objectives may include alternatives to retrofitting and/or reduced performance metrics as allowable or pollutant trading amongst project areas (i.e., over-treating some areas and under-treating others) consistent with the ultimate goals of improving receiving water quality by cost effectively treating runoff from existing highway facilities.

9.5.3 Step 3: Characterize Site Conditions and Constraints

Detailed site investigations improve the likelihood of siting and selecting appropriate and workable BMPs and will help to avoid or reduce redesigns and change orders to address unforeseen conditions. The objective of Step 3 is to characterize the site conditions and constraints for BMP siting and design.

During site characterization studies, a constraints map will help visualize BMP siting options and limitations. DOTs have well-established GIS and environmental management tools that support development constraints maps. The site investigation studies should include as appropriate:

- **Data gathering and coordination:** Compile and review as-built drawings, design reports, and historical information as available. Identify and coordinate with personnel that are potentially knowledgeable of the site conditions, including field crews and adjacent municipalities.
- **Highway development/redevelopment plans:** Review current (if applicable) and planned future uses for the site. Assess implications for BMP siting opportunities and constraints.
- **Land surveys:** Coordinate with real estate departments and conduct surveys to confirm and identify vacant and potentially available ROW area for siting BMPs, taking in account existing and future highway construction plans. Use aerials and field surveys to investigate construction staging areas and to explore potential off-site treatment locations areas such as parks.
- **Topographic surveys:** Use detailed topographic mapping to establish and verify elevations of existing drainage infrastructure, to delineate drainage boundaries, and to establish the available head for stormwater conveyance and treatment. Quality control during surveying is critical and can help to avoid subsequent adjustments (Currier and Moeller, 2000).
- **Archeological survey:** A professional archeological survey is potentially needed if working in known archeological areas or artifacts are discovered during field work. Archeological involvement may include literature searches, field inspections, and site excavations.
- **Storm drain infrastructure:** Fully characterize existing drainage facilities to support hydrologic analyses and assessment of connectivity options. Review as-builts and conduct field verification of the type, elevations, and condition of existing facilities, including ditches and open channels, catch basins, piping, and outfalls.
- **Existing treatment BMPs:** Determine the presence of existing treatment BMPs that can potentially be modified or enhanced to meet retrofit objectives. Characterize and evaluate any existing treatment BMPs in terms of the size, location, elevation, target pollutants, general effectiveness, maintenance requirements, and other benefits and limitations.
- **Drainage patterns and hydrology:** Determine existing drainage patterns to support hydrologic analyses, BMP sizing, and for identifying the options for connecting BMPs to existing facilities. Analyses include the delineation of catchment areas; the identification of off-site sources, springs and seeps, outfalls, and receiving waters; and the identification of flood plains and wetlands.
- **Hydrologic conditions:** Compile precipitation data and determine storm characteristics or design storms for sizing BMPs.
- **Soil conditions and properties:** Review and conduct geotechnical investigations as necessary to evaluate soil conditions, soil infiltration rates, depth to groundwater, and the presence of hazardous materials.
- **Utilities and buried obstructions:** Conduct utility searches and review and confirm as-built drawings for abandoned structures such as building foundations, historic structures, and abandoned utilities.
- **Maintenance access:** Coordinate with designers, and maintenance and safety departments as necessary to assess potential maintenance access routes for safe access and maintenance functions without requiring lane closures or significantly impacting traffic flow.
- **Environmental resources:** Coordinate with environmental department to identify environmental resources, wetlands, or sensitive areas that may impact BMP siting or design.
- **Societal issues:** Investigate possible historic, archeological, or socio-economic concerns.
- **Traffic and safety:** Work with traffic and safety departments to collect traffic data and to assess potential safety issues/requirements for BMP siting and construction, for example, clear zone and slope requirements. Also, include possible safety issues for maintenance operations.
- **BMP design constraints:** Work with project team members to establish BMP design constraints, for example, limits on infiltration above the subbase.

9.5.4 Step 4: Identify BMP Retrofit Alternatives

Step 4 is the retrofit scoping stage. In this step, the project team identifies BMP opportunities that are potentially feasible within the site constraints and develops preliminary retrofit concepts and evaluations. The authors recommend a

BMP-driven approach where the project team first identifies appropriate BMPs, followed by site scoping, conceptualization, and evaluation. The process is iterative and includes the following tasks:

1. Determine candidate BMPs that provide applicable treatment processes in the appropriate sequence.
2. Evaluate aboveground retrofit opportunities first:
   a. Look for opportunities within the ROW,
   b. Consider jurisdictional partnerships, and
   c. Evaluate water quality trading.
3. Pursue underground BMPs when aboveground approaches are not practical.
4. Select BMPs for detailed evaluation.

Task 1: Determine Candidate BMPs

The first task is to identify candidate BMPs and BMP combinations that provide the unit operations needed to achieve the retrofit objectives for the identified POCs. Section 5 describes the BMP unit processes, and Table 5.1 shows the unit processes inherent in retrofit categories. The intent of Task 1 is to identify appropriate and potentially effective BMP approaches and not to limit BMP options. The product of this task is a listing of applicable BMPs and BMP treatment trains for scoping and evaluation.

When identifying the candidate BMPs and BMP components, the project team should consider a hierarchy or treatment train of BMP components that targets the more easily treated pollutants first, in most cases also reducing potential clogging or other issues for later processes, and progressively targets the more difficult to treat finer particles and dissolved pollutants as shown in Table 9.3.

Tables 5.1 and 5.5 can be used to help select and configure BMP components based on the BMP unit processes, the typical sequence of the BMP components in a treatment train, and expected performance for specific POCs. For example, many retrofit projects will target basic treatment of sediments and associated pollutants such as total metals and oil and grease. This objective requires primary and secondary treatment processes, depending on expected sediment loads and particle sizes in highway runoff. Table 9.3 shows there are a number of candidate BMPs and BMP combinations that are potentially effective options including the following:

- Conventional approaches:
  – Vegetated filtration swales with trash racks at outlets. Optionally include check dams to promote settling
  – Extended detention with various pretreatment approaches (pre-settling basins, sumped catch basins, hydrodynamic systems)
  – Sand filters with pre-settling basins

Table 9.3. Treatment train processes, goals, and example components.

Treatment Train Processes	Retrofit Goal	Candidate BMP Components
1) Hydrologic control	Reduce runoff volume and/or flow control	• Capture and use system • Infiltration BMPs • Detention facilities • Vegetative filtration BMPs
2) Pretreatment	Remove bulk pollutants > 5 mm (trash, debris, large solids)	• Screens, racks, gross solids removal device • Pretreatment settling basins, catch basins • Hydrodynamic systems • Oil-water separators • Filter strip/swales • Permeable asphalt overlays
3) Primary/ secondary treatment	Remove easily settleable solids (> 50 µm) and pollutants associated with particles (metals, organics, particulate nutrients)	• Extended-detention, wet basins • Filter strip/swales • Infiltration BMPs (trenches, basins, vaults) • Underground detention facilities • Hydrodynamic systems
4) Secondary treatment	Remove finer solids (< 50 µm) and provide more effective treatment of pollutants associated with particles (metals, organics, particulate nutrients)	• Sand filters • Bioretention, swales with underdrains • Proprietary storm filters • Media filter drains • Infiltration BMPs (trenches, basins, vaults)
5) Enhanced treatment	Remove dissolved pollutants such as metals and nitrate	• WSDOT media filter drain • Multi-chambered treatment train • Constructed wetlands • Media filters with amended and engineered media (proprietary and non-proprietary)

  - Bioretention
  - Infiltration BMPs (basins, trenches)
- Underground and non-traditional approaches for space-limited sections:
  - Various proprietary underground detention vaults for water quality treatment. Many integrate pretreatment settling areas. Underground detention could also be integrated with other pretreatment approaches including sumped catch basins, hydrodynamics systems, and permeable asphalt overlays.
  - Non-proprietary underground vaults with batch-mode operation.
  - Permeable asphalt overlays used for pretreatment to proprietary small-footprint storm filters (catch basin systems or underground inline systems)
  - Hydrodynamic systems used for pretreatment to proprietary underground storm filters
  - Underground infiltration systems

Task 2: Give Primary Consideration to Aboveground Retrofit Opportunities

Next, the project team must conceptualize and evaluate potential BMP configurations within the site using the components identified in Task 1.

A core retrofitting principle is that primary consideration is given to finding aboveground retrofit opportunities. Aboveground BMPs are preferable to underground BMPs for the following reasons:

- Typically less expensive to construct and operate
- Can be easier to connect with existing conveyances and are less likely to require pumping facilities in flat terrains
- Simpler to inspect, increasing the likelihood that maintenance needs will be identified and carried out
- Easier maintenance access and require less specialized equipment and training for maintenance
- Allow the use of vegetated treatment components, which typically provide better treatment performance, and can also provide volume reduction and conveyance functions.

The team should fully explore all the following options for identifying aboveground BMPs before selecting underground BMP alternatives.

Task 2a: Evaluate Opportunities for Locating Aboveground BMPs. Ultra-urban highways by definition are space constrained, but even in ultra-urban settings there are highway features that can provide opportunities for siting aboveground BMPs.

Interchanges and Cloverleafs. Interchanges and cloverleafs often have landscape or vacant areas within the ROW that provide opportunities for locating aboveground BMPs (Figure 9.1). These areas can be comparatively large and well isolated from traffic flow and can have safe maintenance access. Consequently, such areas can be ideal for locating detention, infiltration, or media filtration facilities that provide treatment for adjacent highway sections and elevated overpasses.

ROW Strips Adjacent to Highway Sections and Ramps. Many highway sections include vacant strips adjacent to highways and ramps (Figure 9.2). ROW strips are potential opportunity areas for vegetated BMPs that are integrated into the landscaping, such as swales, filter strips, bioretention, and WSDOT media filter drains. ROW strips and landscaped areas should be exploited to the maximum extent feasible. Guardrails and concrete barriers can be used if clear zone setbacks are not adequate within the available ROW strip. Other potential opportunities for intercepting storm conveyances

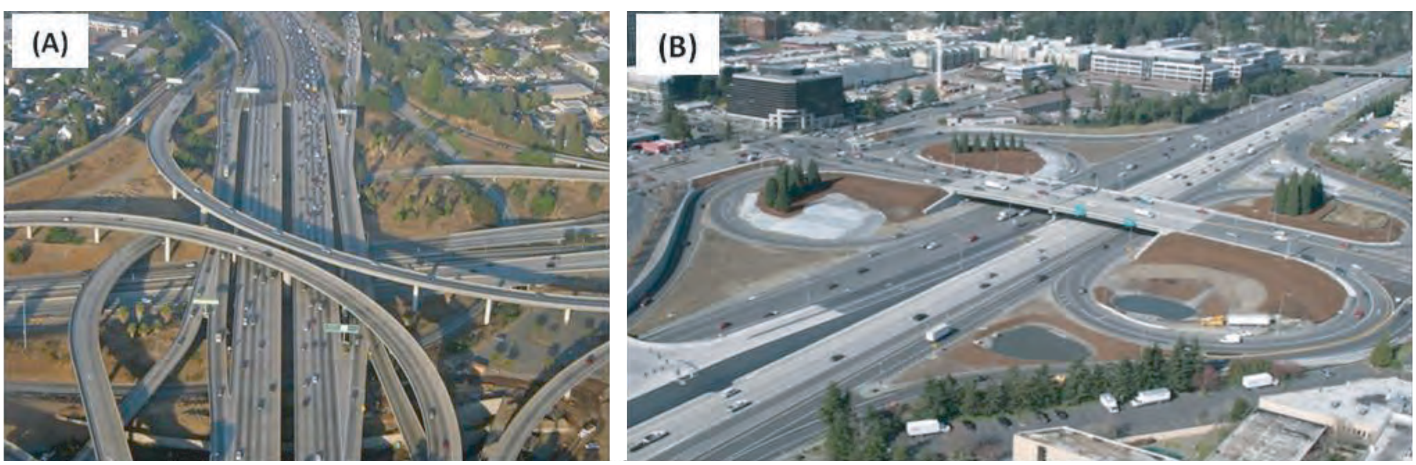


Figure 9.1. Interchanges and cloverleafs are opportunity areas for locating aboveground BMPs: (A) vacant areas within I-280/I-87 interchange, San Jose, California, and (B) detention facilities constructed in cloverleafs, I-405 near Bellevue, Washington.

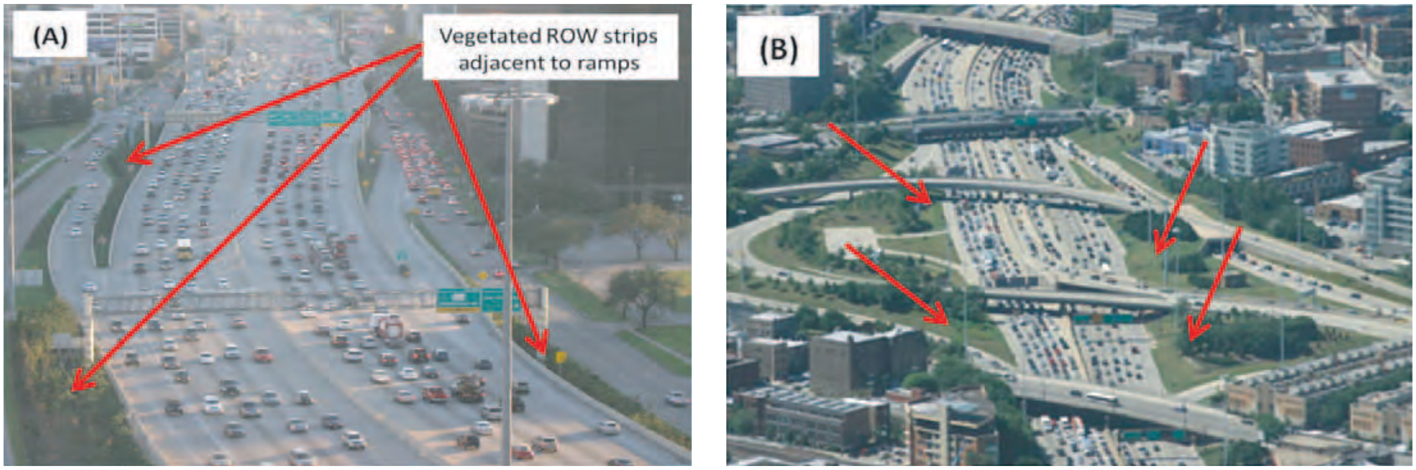


Figure 9.2. Two examples of ROW strips adjacent to ramps: (A) Houston, Texas, and (B) Kennedy Expressway, Chicago.

in ROW strips are embankment cuts along downslope sections and at down-gradient outfalls. Such areas are potentially suitable for aboveground filtration systems, sand filters, and GSRDs.

Underneath Elevated Sections. Vacant areas beneath elevated highway sections, ramps, and stacked highway sections are potential opportunity areas for locating aboveground BMPs such as detention basins, media filtration facilities, and GSRDs (Figure 9.3). Vegetated BMPs are potentially suitable if there is adequate light.

Conveyances. Existing stormwater conveyances can be modified with aboveground treatment using vegetated biofiltration swales or biofiltration/infiltration facilities for example, which provide both effective treatment and conveyances function (Figure 9.4). Concrete ditches and roadside strips can be converted to biofiltration swales, or treatment functions of existing roadside ditches can be improved with check dams. Ideal locations are low-lying linear pervious areas or cut sections adjacent to roadways that intercept highway drainage. The topography or graded sections should meet design criteria, typically 1% to 5%, but check dams can be used to allow for higher slopes. Lateral slopes should conform to highway safety requirements, typically 6:1, but can be steeper if potential access is prevented (i.e., guard rails, etc.).

The following list identifies items to look for when evaluating vacant ROW areas in interchanges and ROW strips and underneath elevated sections:

- *Space:* Look for usable ROW with adequate space/width, taking into consideration clear zone setbacks, future planned uses of the ROW, and other constraints/obstacles identified in Step 3. Consider ways to adapt available ROW spaces by:
  – Using embankment cuts and retaining walls to increase BMP surface space,

Figure 9.3. Two examples of vacant areas below elevated highway sections: (A) I-405/I-105 interchange, Los Angeles, and (B) dry extended-detention basin beneath SR-125/SR-94 interchange, San Diego County.

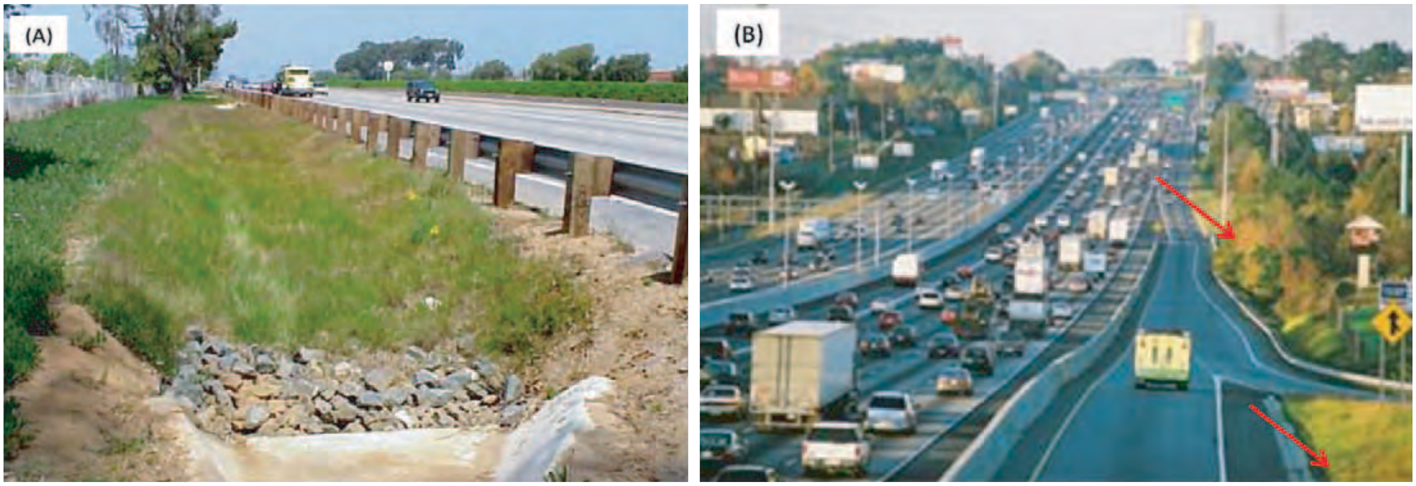


Figure 9.4. Highway surface conveyances: (A) Caltrans retrofit of a ROW strip adjacent to I-5 with a vegetated biofiltration swale and (B) roadside ditches adjacent to ramps, Atlanta, Georgia.

- Using guard rails and concrete barriers if clear zone setbacks or slopes are not adequate, and
- Modifying BMP sizing and design to fit within space and contours, or to meet design constraints.

- *Drainage and connectivity:* Look for sufficient hydraulic gradient to potential connection points with existing conveyances, taking into account the BMP head requirements. Whenever possible, look for opportunities to utilize existing collection and conveyance facilities in the retrofit concept to reduce costs. Potential opportunities for intercepting storm conveyances are embankment cuts along downslope sections and at down-gradient outfalls. New conveyances and outfalls must be considered when existing facilities cannot be used due to unsuitable location, insufficient capacity, or poor condition. Consider surface conveyances when there is adequate space, as they can combine treatment and conveyance functions, reduce costs of stormwater conveyance infrastructure, and have low head requirements.
- *Opportunities to modify and integrate existing BMPs:* Existing BMPs should be evaluated for potential modifications and/or integration into a treatment train. For example, existing detention basins can be modified to improve treatment of target conditions, such as adding GSRDs to reduce trash loads, adding/improving vegetation to enhance treatment, and modifying outlet structures with batch operation to improve sedimentation of fine particulates. Similarly, swales and filters can potentially be modified with check dams or amended soils to improve treatment functions.
- *BMP head requirement:* The available head is a significant constraint in flat terrains. Tight tolerances may require additional design and construction requirements. In flat terrains, BMPs with low head requirements should be the primary siting consideration. Ideal BMPs would include surface conveyances, biofiltration swales, surface BMPs such as filter strips and bioretention within landscape areas, surface detention facilities, and porous pavements (see Section 5 for details). Avoid new pumping facilities when possible because they can significantly increase capital and operation costs and are subject to possible power failure and equipment failure. Maintenance and operation of pumps were recurring problems at sites with insufficient hydraulic head in the Caltrans retrofit pilot study (Caltrans, 2004). When pumping is unavoidable, designers should explore opportunities for using pumping facilities to increase BMP siting options. Where possible, utilize pumping to slowly draw down the storage within a BMP and allow gravity overflow. This will minimize pumping sizes and operating costs as well as reduce impacts of pump failure.
- *Soils and infiltration rates:* For infiltration BMPs, look for sites with soil infiltration rates that more than adequately meet minimum requirements, and where there is adequate separation above the seasonal high groundwater table. As noted earlier, siting infiltration devices under marginal soil and subsurface conditions entails a substantial risk of early failure due to clogging (Caltrans, 2004). Consider the potential impacts of infiltration on the pavement base or other structures, and use liners only where there is risk to infrastructure. Also, consider the possibility that soils and sediments removed from infiltration facilities during maintenance could potentially be classified as hazardous materials, which would necessitate additional disposal requirements and costs.
- *Maintenance access:* Look for acceptable and safe maintenance access routes and sufficient space for maintenance equipment without the need for lane closures or traffic controls.

Task 2b: Consider Jurisdictional Partnerships. If aboveground BMPs within the ROW are not feasible or excessively costly or where a partnership would be more cost effective overall, planners should consider and investigate potential cross-jurisdictional partnerships with local municipalities to develop off-site aboveground retrofit solutions. This can provide more cost-effective treatment and can be mutually beneficial if there are common objectives such as meeting TMDL allocations. Although collaborating with local municipalities will require a greater level of planning and coordination, there are a number of potential benefits (Yu et al., 2003; Caltrans, 2004):

- **More flexibility in locating and designing aboveground BMPs:** Local municipalities are likely to have greater options for siting aboveground BMPs on public ROWs such as parks, schools, other public properties, and public easements adjacent to roads, drainages, and utility corridors. Greater siting options lead to more flexibility in BMP design and more effective treatment.
- **Greater benefit to receiving waters:** Off-site BMPs can potentially be designed as regional facilities that treat combined highway and municipal drainage areas. Regional facilities using effective aboveground BMPs would provide more overall load reduction and greater benefits to receiving waters in comparison to underground retrofit options targeting only highway catchments. In some cases, the larger regional system that is treating untreated runoff from existing development may be utilized to provide pollutant "credits" for areas of the highway that are difficult to treat (i.e., pollutant trading).
- **Reduced costs:** Off-site retrofits potentially generate cost savings from:
  - Economies of scale for the construction of facilities that treat larger areas;
  - Lower construction and maintenance costs with the use of aboveground BMPs in comparison to underground alternatives;
  - Lower probability that groundwater table issues could impact the effectiveness of the BMP and result in potential project redesigns;
  - Avoidance or reduction of traffic-control costs and more efficient construction due to reduction of space constraints; and
  - Sharing of design, construction, and O&M costs between the DOT and municipalities.

Task 2c: Consider Water Quality Trading. Water quality trading is a voluntary exchange of pollutant reduction credits. A facility with a higher pollutant control cost can buy a pollutant reduction credit from a facility with a lower control cost thus reducing their cost of compliance. Thus, water quality goals can be achieved more efficiently and more economically. Water quality trading programs can potentially be used to offset costly ultra-urban retrofit mandates with less costly off-site retrofits that are more beneficial to receiving waters.

The USEPA's 2003 policy statement on water quality trading supports trading of nutrients and sediment loads as well as cross-pollutant trading of oxygen-demanding pollutants. The USEPA may consider supporting trades of other pollutants but believes that these trades require a higher level of scrutiny. The USEPA does not support trading of persistent bioaccumulative toxics (USEPA, 2003).

DOTs recognize that water quality trading credit approaches are imperative for economically complying with TMDLs in areas where BMP implementation costs are excessive (Hon et al., 2003; McGowen et al., 2010). However, water quality trading programs are not yet widely developed and trading approaches are likely to be inconsistent among states. Only a few DOTs have experience with trading programs. One example is the Maryland SHA, which is allowed to trade treatment credits (treated impervious surface) between watersheds, with a 20% "charge" each time credit is withdrawn from the "bank" (stored treatment credit) and used to offset treatment requirements for a project (McGowen et al., 2010).

Although pollutant trading programs are not yet widely used, it is likely that future programs similar to the Maryland SHA example will be available as retrofit and TMDL requirements increasingly impact DOTs. In ultra-urban areas where BMP costs are excessive, pollutant trading may be a viable cost-effective alternative for meeting highway retrofit requirements. As mentioned in previous tasks, "pollutant credits" that are less formal than a trading program may be possible by working with local regulators. This is particularly true for TMDL situations where an overall loading reduction is specified and it is left to the DOT to determine how to achieve the reduction.

Task 3: Pursue Underground BMPs Options

It is necessary to consider underground BMPs for many ultra-urban retrofit projects or highway sections (Figure 9.5). The objective of this task is to identify and develop conceptual plans for potentially feasible underground BMP options when:

- There is insufficient surface area in the ROW;
- It is not possible or cost effective to use available ROW area;
- Off-site alternatives are not feasible; and
- It is appropriate and cost effective to use underground BMPs for pretreatment to other BMPs.

Retrofit planners and designers have a wide variety of proprietary and non-proprietary underground BMPs from

Figure 9.5. Examples of ultra-urban highways with limited space for aboveground BMPs.

which to choose. Considerations when evaluating underground BMPs include the following:

- **Existing infrastructure.** To simplify construction and reduce costs, look for opportunities to integrate underground BMPs within existing infrastructure:
  - **Existing conveyances:** Locate underground BMPs to take advantage of existing catch basins and storm lines when practical.
  - **Catch basins:** Catch basins that are safely and conveniently accessed for maintenance (e.g., behind barriers) can be modified for pretreatment, for example, retrofits using sumped basins or proprietary catch basin devices (Section 4.2), including adding new water quality catch basins just upslope and retaining the existing basins for drainage.
  - **Existing treatment BMPs:** Cost savings can be realized when existing treatment BMPs are modified and/or integrated into a BMP treatment train. For example, existing hydrodynamic separators or detention facilities could be used as pretreatment devices for underground media filtration systems that target dissolved constituents.
  - **Existing pumping facilities:** Existing pump stations at below-grade sections may provide opportunities for conveying runoff to more feasible sites or for meeting BMP head requirements.
  - **Pavement retrofits:** Permeable asphalt overlays on existing roadbeds increase highway safety in wet weather and have shown promising water quality treatment benefits. Permeable asphalt overlays can be cost effectively integrated into retrofit designs as pretreatment components. Because performance life and maintenance requirements are not well established, it may be appropriate to consider pilot projects to gain operational experience and additional performance information or to include redundant pretreatment components.
- **BMP size.** The project team should weigh the tradeoffs of using small-footprint proprietary BMPs. Many underground BMP options will be feasible because of the benefits they provide in terms of space requirements, simple installation, and cost. However, small-footprint proprietary BMPs can also have significant inspection and maintenance requirements, high maintenance costs, and poor effectiveness. Larger BMPs, such as underground detention and underground media filtration, have greater capital costs in comparison to small-footprint BMPs but can potentially deliver more effective treatment with less frequent or similar maintenance requirements.
- **Acceptability.** Some state DOTs are limited in the types of allowable proprietary BMPs, and some states have established certification procedures. Consider and explore pilot testing for BMP options that are unapproved but thought to be effective.
- **Maintenance practices.** Underground BMPs must have acceptable inspection and maintenance practices. Some DOTs do not allow routine use of various underground BMPs (storm filters, hydrodynamic systems) primarily because of excessive maintenance requirements. It is imperative to coordinate with maintenance personnel to screen BMPs with unacceptable maintenance requirements. However, as water quality requirements become more stringent, DOTs may have to consider undertaking projects that require more maintenance.
- **Treatment performance.** There must be reasonable confidence that the candidate BMPs can meet treatment objectives. Suitable performance information, however, may be limited or lacking for many proprietary BMPs. An assessment of the expected treatment performance of underground BMPs may be supported by:
  - DOT familiarity and experience with the BMPs,
  - Regulatory certification,

  – Review of independent performance evaluations, and/or
  – Modeling of expected performance by the DOT.

  Consider retrofit pilot tests for promising BMP approaches with incomplete performance information.
- **Design and performance specifications.** Some DOTs may choose to use detailed bid specifications as the means for selecting proprietary BMPs (see Case Study 5 in Section 10) that are expected to meet the desired performance. At a minimum, comprehensive specifications should include criteria for the size and/or volume, bypass capacity, treatment capacity and performance, maintenance access and frequency, resuspension performance, and supporting performance evaluations.

Task 4: Evaluate and Select Primary Retrofit Alternatives

The product of this task is the selection and ranking of a limited number of primary alternatives. A systematic evaluation of alternatives is beneficial for projects or project sections where there are no clear superior alternatives. Developing an alternatives analysis matrix will help to relate and visualize the constraints and opportunities and evaluate the tradeoffs. The following are the basic steps:

- Compile and list the retrofit options identified during, and in conjunction with, the scoping and conceptual Task 3.
- Define the criteria for evaluating alternatives. The most useful criteria will distinguish differences between the alternatives, such as cost, maintenance, etc. Table 9.4 provides example criteria for consideration. To help narrow alternatives, identify mandatory criteria such as safety.
- Construct the analysis matrix with alternatives versus criteria. Assess applicable criteria for each alternative with qualitative descriptions and/or numeric scoring. Weighting factors are often applied to the criteria based on predetermined importance.
- Evaluate the alternatives and choose the primary alternatives.

9.5.5 Step 5: Conduct Practicality Assessment

In Step 5 the project team prepares preliminary designs, costing, and performance assessments of the primary alternatives and chooses the final retrofit approach. The tasks include the following:

- **Hydrologic and hydraulics analysis:** Detailed hydrologic and hydraulics analyses are conducted to finalize contributing drainage areas and to support design and sizing of conveyances.
- **BMP sizing:** Detailed sizing of BMPs, typically using DOT procedures and specifications based on design storm analyses, are conducted. Such DOT approaches are suitable for conventional and approved BMPs where there is adequate space and no design constraints.

  Section 6 describes BMP sizing and design using continuous hydrologic simulation analyses. Alternative sizing approaches are appropriate for severely space-constrained and cost-prohibitive settings where undersized facilities may be considered. For example, undersized vaults that target first flush can provide meaningful treatment, consistent with the goal of cost effectively maximizing pollutant reduction and receiving water benefit. Continuous hydrologic simulation allows for analysis of BMP sizing based on conventional volume capture criteria, as well as other performance metrics including ideal sedimentation efficiency in volume-based BMPs (detention facilities) and average contact time in flow-based BMPs (media filtration BMPs). Furthermore, the approaches described in

Table 9.4. Example criteria for alternatives evaluation.

BMP Selection/Performance ▪ Regulatory/DOT compliance ▪ Expected treatment performance ▪ Cold weather performance ▪ Longevity ▪ DOT experience with BMPs **Location/Siting** ▪ Space availability, compatibility ▪ Aboveground vs. underground ▪ Areas treated ▪ Hydraulics (head, connectivity, use of existing facilities) ▪ Major construction, grading/shoring, obstructions ▪ Safety concerns ▪ Environmental issues/permitting ▪ Aesthetic issues ▪ Site uncertainties	**Design/Construction** ▪ BMP sizing ▪ Cold weather design modifications ▪ Special material/design requirements ▪ Construction/installation requirements ▪ Construction schedule/phasing ▪ Staging, traffic control **Operation & Maintenance** ▪ Inspection and maintenance requirements ▪ Available equipment/personnel ▪ Access and safety concerns ▪ Proprietary materials ▪ Major maintenance requirements **Cost** ▪ Capital ▪ O&M ▪ Uncertainties

Section 6 provide a means of assessing sizing tradeoffs with alternative operation strategies, such as batch mode operation of detention facilities versus extended detention.

For proprietary systems, manufacturer sizing criteria should be used as minimum sizing guidance. The effectiveness of small-footprint BMPs such as hydrodynamic separators and small underground vaults (oil-water separators) is directly associated with the size/volume of the device; better performance is obtained with increasing size, although controlled testing has shown a plateau at which further increases in size provide no additional benefit. Cold weather also diminishes performance of small-footprint BMPs. Sizing of manufactured systems should be based on thorough evaluation of available performance information, ideally including direct DOT experience. Designers may want to consider over-sizing or including a factor of safety for small-footprint BMPs to improve performance, particularly in cold climate applications.

- **Performance assessment:** An assessment of water quality treatment and/or hydrologic performance may be required to verify compliance or to compare alternatives. In other cases, BMPs selected and designed in accordance with approved policies may have a presumptive level of performance and no formal performance assessment is needed.

  Section 5 describes approaches for assessing the water quality treatment performance of BMPs. Recommended performance criteria include the runoff capture efficiency of the BMPs, the ability of the BMP to reduce runoff volumes, and expected effluent quality of treated runoff. Designers may also need to perform pollutant loadings calculations to assess compliance with TMDL wasteload allocations or BMP efficiency standards.

  Hydrologic performance calculations typically include basin routing calculations for assessment of peak discharge–frequency analysis. A more comprehensive assessment of hydromodification impacts could include flow-duration analysis using continuous simulation approaches.
- **Preparation of preliminary designs:** Preliminary BMP designs are developed to (1) obtain a clear picture of the structural elements, layout, and dimensions; (2) to discover and resolve critical issues and problems; (3) to obtain material quantities for estimating costs; and (4) to use the preliminary design as a check on the final design.

  Considerations for BMP design include the following:
  - Address maintenance equipment and access in the design. Also, consider maintenance impacts on biological or environmental resources.
  - Avoid precast proprietary units in cases when there are tight tolerances because as-built maps can be inaccurate. Cast in-place features allow for adjustments that may be needed to match actual field conditions or changes due to construction (Currier and Moeller, 2000).
  - BMP designs should consider and avoid standing water that may promote mosquito breeding as necessary.
- **Cost estimation:** Section 8 describes retrofit cost factors, available cost information, and potential cost reduction strategies. Cost estimates should include both capital and O&M costs, and appropriate contingency costs. They should also consider major maintenance or replacement cycle as well.
- **Choose retrofit approach:** The project team chooses the retrofit approach based on results of the practicality assessment and input from DOT representatives, team members, and stakeholders.

9.5.6 Step 6: Prepare Final Design and Construction Specifications

In this step, the project team prepares the final designs and specifications, obtains permits, and oversees construction. Guidance and considerations include the following:

- **Permitting:** Obtaining and complying with local and regional permits can be a major effort and can impact construction and O&M. Coordinate with local officials and regulators from the outset of the project to ensure permitting will not delay or impact construction and O&M.
- **Construction phasing:** Coordinate construction with other planned construction activities as feasible. This can produce savings and help to solicit and receive more bids for smaller jobs. It can also expand the scope of the retrofit by including larger drainage areas.
- **BMP specifications:** Order materials with long lead times as soon as possible and check availability. Specifications must be very explicit and the materials must be readily available. Check and confirm specifications of ordered products. For example, the specification of media composition can be critical as substitution of media components can substantially impact cost and/or result in unintended leaching of pollutants.
- **Installation of proprietary systems:** Manufacturer installation instructions should be considered as guidelines and followed; otherwise, poor performance can result.
- **Construction inspection:** Because retrofits are likely to involve unique designs and material, construction inspection is important to ensure that design specifications are met. The construction inspectors must have sufficient training in the identification of construction materials and construction practices, for example, media specifications and vegetation type (see the case study in Section 10.6). Include material quality specifications with orders (Currier and Moeller, 2000).

9.5.7 Step 7: Post-Construction Operation and Evaluation

Post-construction BMP maintenance and monitoring evaluations are key activities to ensure the retrofits perform at the design capacity, and for obtaining feedback about BMP design and ongoing performance.

- **Ongoing BMP inspection and maintenance:** As discussed in various sections previously, an initial BMP O&M plan should be coordinated and developed early in the retrofit planning process. Following construction, the maintenance crews must implement and refine the O&M plan as necessary to ensure proper BMP performance. Ideally, the O&M plan will include more frequent early inspections to ensure proper function and to allow for early adjustments if needed. Designers and planners should proactively seek feedback from maintenance crews regarding BMP O&M practices. For new and/or unfamiliar BMPs, planners and maintenance departments should consider a detailed maintenance monitoring/auditing program to establish and document the required maintenance practices and costs.
- **Water quality and BMP monitoring:** Post-construction activities may include the development and implementation of a formal monitoring program to meet objectives such as:
  - Establish BMP performance: DOTs may want to establish the treatment and/or hydraulic performance of retrofit BMPs, particularly if unfamiliar, proprietary, or non-standard BMP designs with little direct performance data are selected in order to meet site constraints and/or other retrofit objectives.
  - Regulatory compliance: Regulators or permit conditions may require DOTs to conduct water quality monitoring to establish BMP effluent quality, receiving water quality, and/or to establish if wasteload allocations are met.
- **Retrofit project evaluation:** Post-construction coordination to review and evaluate the retrofit project can provide valuable information to support future retrofit projects. A formal review should address all project phases including project planning, design, costing, construction, and post-construction activities.

SECTION 10

Case Studies

This section describes seven case studies of ultra-urban BMP retrofits and retrofit pilot testing as listed in Table 10.1. The case studies illustrate how some DOTs are meeting the challenges of ultra-urban retrofits, as well as the range of regulatory requirements and objectives that can drive the projects. It is interesting to note that almost all of the case studies are associated with highway improvement projects. Only one project was constructed as a stand-alone water quality retrofit of an ultra-urban highway (Case Study 6), and that project was implemented as a pilot test to evaluate construction practices. Those DOTs that have mandates for stand-alone retrofits have generally pursued more cost-effective retrofits in areas without significant space constraints or, alternatively, the DOTs are pursuing approaches using pollutant trading avenues.

10.1 ODOT Highway Retrofit with a Media Filter Drain

Step 1: Project Scope

Project Location and Description

Oregon DOT (ODOT) is widening US Highway 26 from four to six lanes along a 2-mi segment west of Portland, Oregon (Figure 10.1). This highway segment is in a sub-

Table 10.1. List of case studies.

Case Study	Description	Page
1	**Oregon DOT (ODOT) Highway Retrofit with a Media Filter Drain:** ODOT developed an innovative approach to meet low stormwater treatment objectives for dissolved copper in a highway-widening project.	124
2	**Washington State DOT (WSDOT) Bridge Replacement with BMP Retrofit:** WSDOT used underground BMPs to meet treatment and LID objectives in a highly space-constrained setting.	130
3	**Washington State DOT (WSDOT) I-405/I-5 to SR-169 Stage 2 Widening:** WSDOT adapted media filter designs to achieve opportunistic highway retrofits in association with a highway-widening project.	136
4	**Illinois DOT (IDOT) Mississippi Bridge Tri-Level Interchange Drainage:** IDOT developed flow control retrofits to mitigate flooding impacts from a major Mississippi River bridge project.	142
5	**Minnesota DOT (MnDOT) Crosstown/I-35 Highway Retrofit:** MnDOT used surface and underground BMPs to provide full water quality treatment of existing and new highways in a major urban interchange project. MnDOT worked closely with local cities to integrate treatment into off-site BMPs.	145
6	**District of Columbia DOT (DDOT) Interchange Retrofit:** This is a pilot test to evaluate design and construction procedures for bioretention BMPs constructed within an urban cloverleaf interchange.	152
7	**Maryland State Highway Administration (SHA) Concrete V-Ditch Conversion Pilot Study:** This is a retrofit pilot study to evaluate design and performance of water quality swales that are suitable in design for retrofitting concrete V-ditches.	156

Figure 10.1. ODOT Highway 26 widening project location, Portland, Oregon.

urban commuter corridor with an ADT of 122,000. Land use adjacent to the highway is a mixture of residential and commercial uses. The project is planned for construction in 2010–2011.

Pre-Project Stormwater Treatment

Stormwater treatment along the highway segment prior to widening is accomplished by routing runoff through grass-lined ditches and vegetated side slopes of the highway embankment (Figure 10.2). The vegetated ditches and side slopes provide some water quality benefits but are not engineered treatment BMPs.

Figure 10.2. ODOT Highway 26 ROW perimeter for planned lane expansion.

Receiving Waters and Issues of Concern

The project receiving waters include the Tualatin River, which has established TMDLs for phosphate, temperature, and bacteria. Highway runoff is not considered a major contributor of these pollutants, although ODOT is a Designated Management Agency for the Tualatin River TMDLs.

The major water quality issue for the project receiving waters was the presence of salmon populations that have been designated as "threatened" under the ESA. Recent research by the NMFS in Seattle has shown that dissolved copper can cause neurophysiologic and behavioral changes in salmon at concentrations of 2 μg/L or lower during durations as short as 3 h (Hecht et al., 2007). Copper-exposed fish may be more vulnerable to predation, because their response time to predator danger signals decreases and they are less capable to capture food. Highway runoff is a source of dissolved copper, believed to be largely derived from automobile brake pads. Other sources of copper in urban receiving waters include agricultural and urban-use pesticides, wood preservatives, algaecides, architectural and building materials, atmospheric deposition, and marine antifouling coatings.

Regulatory Requirements

The primary regulatory driver for water quality in this project is the CWA Section 401 Water Quality Certification for projects with CWA 404 permits, and ESA compliance. CWA Section 401 certification requires that water quality treatment be provided to the "maximum extent practicable" and that state water quality standards not be violated.

ESA compliance is focused on dissolved metals, particularly dissolved copper. The concentration of concern is based on best available science and is not yet set in regulations. At the time of the project, an increase of 2 μg/L over natural background was considered to have the potential to harm juvenile salmonids, and therefore constituted an ESA "take."

ODOT's current NPDES MS4 permit mandates an agency Stormwater Management Plan (SWMP). The SWMP calls for assessing projects' water quality impacts and providing treatment to prevent violation of water quality standards (ODOT, 2009). The permit does not call for stand-alone stormwater retrofit projects.

ODOT has developed a stormwater performance standard based on the results of the multi-agency Stormwater Action Team (SWAT) effort. The SWAT consisted of ODOT, the

NMFS, Oregon Department of Environmental Quality, the FHWA, USFWS, USEPA, and the Oregon Department of Fish and Wildlife. The products of the SWAT effort included triggers for stormwater treatment, water quality and flow control design storms, definition of the "contributing impervious area" targeted for treatment by a project, and a general ranking of stormwater BMPs. Those BMPs that were determined to be effective against a wide range of pollutants, specifically including dissolved metals, were designated "preferred BMPs." The performance standard with the agreed-upon elements has been adopted by ODOT, presented in ODOT Geo/Environmental Section Technical Bulletin 09-02b, and incorporated as a condition of the NMFS and Corps of Engineers Standard Local Operating Procedure for Endangered Species IV (SLOPES IV) programmatic Biological Opinion.

The accepted stormwater performance standard is: "Treat all of the runoff from the Contributing Impervious Area (CIA) generated by the Water Quality Design Storm by using preferred BMPs." Numerical effluent limits are not included in the performance standard.

Step 2: Define the Retrofit Objectives

Regulatory Objective

The regulatory compliance objective was to address resource agency goals for salmon protection and salmon recovery under the ESA, and to meet state water quality standards as required for 401 Water Quality Certification. To meet this objective, ODOT sized treatment BMPs to treat all runoff from the project's CIA in accordance with ODOT's stormwater performance standard. Consequently, the project will provide stormwater treatment for the entire roadway, which includes treatment for the two new lanes and improved treatment for the existing four lanes and shoulders.

Treatment Objective

The presence of salmon in the receiving watershed made it imperative that the selected BMP effectively treat for dissolved copper. To achieve this treatment objective, the use of "preferred BMPs" was required to satisfy the resource and regulatory agencies. If none of the preferred BMPs were feasible, then the project would have to either assemble a treatment train of comparable capability or develop and negotiate off-project mitigation.

Step 3: Characterize Site Conditions and Constraints

ODOT developed the roadway widening and highway drainage design from site surveys and field investigations. ODOT designers also coordinated extensively with pavement design personnel and the ODOT highway maintenance department. ODOT identified the following site conditions and constraints.

ROW Area

County roads and commercial development adjacent to the highway partially limit the possibility of ROW acquisition on both sides of the highway.

Drainage and Topography

The longitudinal topography is gently sloping towards three drainages that cross the highway segment (Rock Creek, Bronson Creek, and Willow Creek). Drainage ditches convey all pre-project highway runoff to the three receiving streams. The post-project roadbed will have a shed roof design draining toward the ROW perimeters.

Utilities

High-voltage utility poles are located on portions of the north side ROW (Figure 10.2). There is no practical location to relocate the poles in the event that BMPs encroach on the pole foundations.

Soils

Native soils include fine-grained sediments characterized by low infiltration capacity.

Design Constraints

Highway safety design criteria include a 30 ft clear zone with limits on the maximum foreslope and backslope of the ditch components.

Pavement design includes a requirement that water surface levels must be managed to keep standing water levels below the roadway aggregate base. This meant that the chosen BMPs must not restrict drainage of the roadway aggregate base layer or contribute to water logging of the highway base layer.

Step 4: Select Retrofit Alternatives

Unit Operations

BMP selection was primarily targeted at the goal of achieving low dissolved copper concentrations and reduced pollutant loading in highway runoff. Treatment of dissolved metals requires sorption processes that can be achieved with media filtration, particularly with amended and engineered media, or through load reduction achieved in infiltration systems.

Candidate BMPs

The stormwater performance standard developed through the multi-agency SWAT effort required the use of a designated "preferred BMP" to satisfy the regulatory and treatment objectives. The preferred BMPs are:

- 100% infiltration,
- Compost-amended bioswales,
- Media filter drains (also referred to as bioslopes),
- Constructed wetlands, and
- Bioretention.

Initial Concept Evaluation and Selection of Alternatives

ODOT engineers conducted an initial evaluation of candidate BMPs in conformance with the ODOT Hydraulics Manual (2005). Preliminary evaluation and design of candidate BMP designs included the following:

- ***100% infiltration:*** Native soils in the project area have an estimated sustained infiltration rate of 0.8 to 0.2 in./h. This rate will infiltrate only part of the water quality design storm within the project ROW. BMPs based on 100% infiltration of the water quality design storm were therefore rejected for this project.
- ***Compost-amended swales:*** Compost-amended swales were selected as a primary alternative because they could potentially be located within the 30 ft clear zone. They also had benefits of providing conveyance functions similar to pre-project drainage patterns; they had acceptable maintenance requirements; and they have been found to provide good treatment for dissolved metals.
- ***Media filter drains:*** Media filter drains were selected as a primary alternative because they could potentially be located within the 30 ft clear zone and have been found to provide good treatment for dissolved metals.
- ***Constructed wetlands and bioretention:*** These preferred BMPs were not considered for this project because they have excessive space requirements larger than the available ROW and substantial maintenance requirements.

Step 5: Practicality Assessment

ODOT developed preliminary design concepts for each of the candidate BMPs as follows:

- ***Compost-amended bioswale:*** Preliminary design of compost-amended bioswales was based on the ODOT Hydraulics Manual. The design concept is shown in Figure 10.3 and includes the following requirements:
  - Side slopes of 6:1 for shallow bioswales within the highway clear zone
  - A minimum swale bottom width of 4 ft to accommodate mowing maintenance

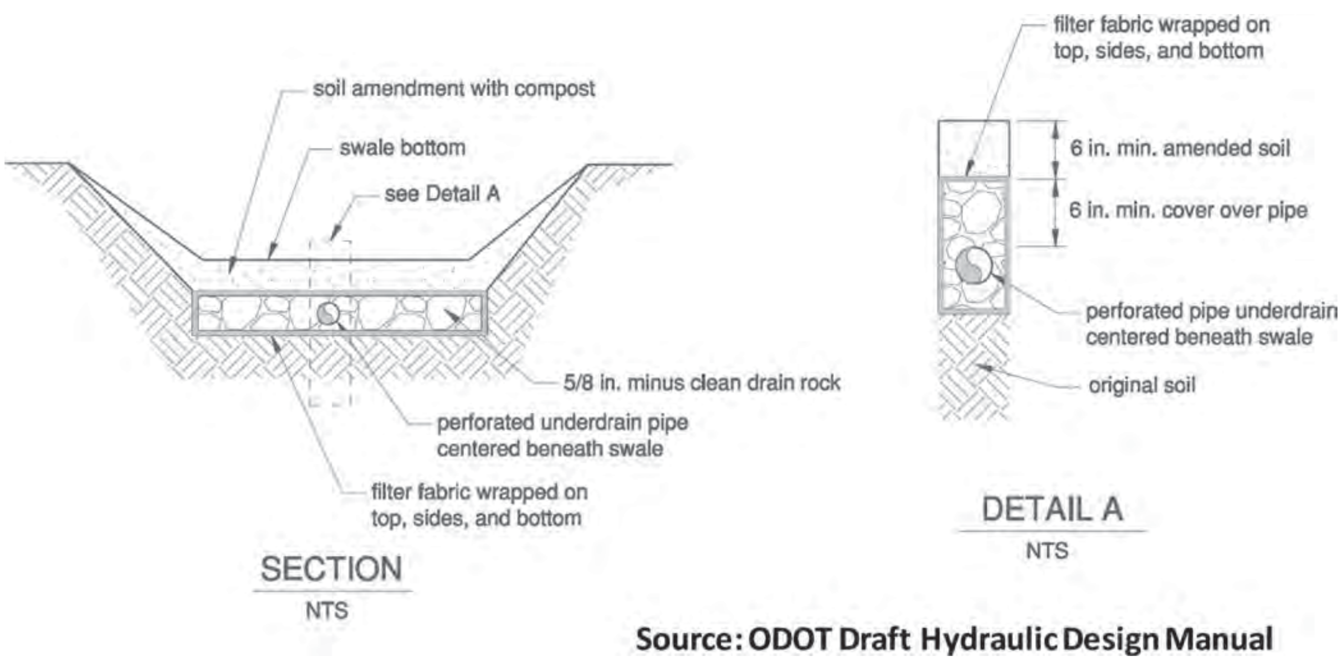


Figure 10.3. ODOT Highway 26, compost-amended bioswale conceptual design.

- Compost-amended soils in the swale bottom to allow as much infiltration as practicable
- A perforated pipe underdrain system constructed below the amended soils to route filtered flow to natural streams
- Retaining walls of approximately 21,000 ft^2 to fit the bioswales to the existing embankment and avoid encroaching on an existing county road
- Substantial grading and the relocation and/or retrofit of existing utility poles to accommodate bioswale widths

- ***Standard media filter drain (bioslope):*** The preliminary design of the standard MFD included the following treatment components and requirements from the WSDOT and ODOT design manuals (See Section 4.7.3 and Figure 4.12):
  - Lateral width requirements of media filter drains are approximately 10 ft. This includes a 1 to 3 ft gravel zone for flow leveling, a 3 to 4 ft grass strip with compost-amended soils, and a 4 ft wide media filter zone.
  - The ODOT media filter mix was the same specification as the WSDOT media filter mix consisting of aggregate, perlite, dolomite, and gypsum.
  - An underdrain system was designed to fit below the media mix.
  - Maintenance crews were concerned about maintaining narrow vegetation strips close to the roadway.
  - Vehicle traversability and safety of the MFD within the clear zone was a concern.

- ***Modified media filter drain:*** To address traversability and maintenance issues, ODOT engineers modified the standard MFD design as shown in Figure 10.4. The modified MFD includes the following design features:
  - The media mix was positioned immediately adjacent to the edge of pavement. A cellular confinement grid was used to increase the compressive strength of the gravels to accommodate occasional wheel loading from errant vehicles. The slope of the media mix is 6:1 at the fore slope of the ditch with a 1:4 back slope of drain rock (see Figure 10.4). This design addresses vehicle traversability and safety concerns.
  - The cellular confinement grid is designed to contain the media mix. This grid is expected to protect against potential channeling, washoff, and redistribution of the media mix caused by storm runoff.
  - The design substituted additional width of MFD mix for the vegetated strip. This substitution accomplished a

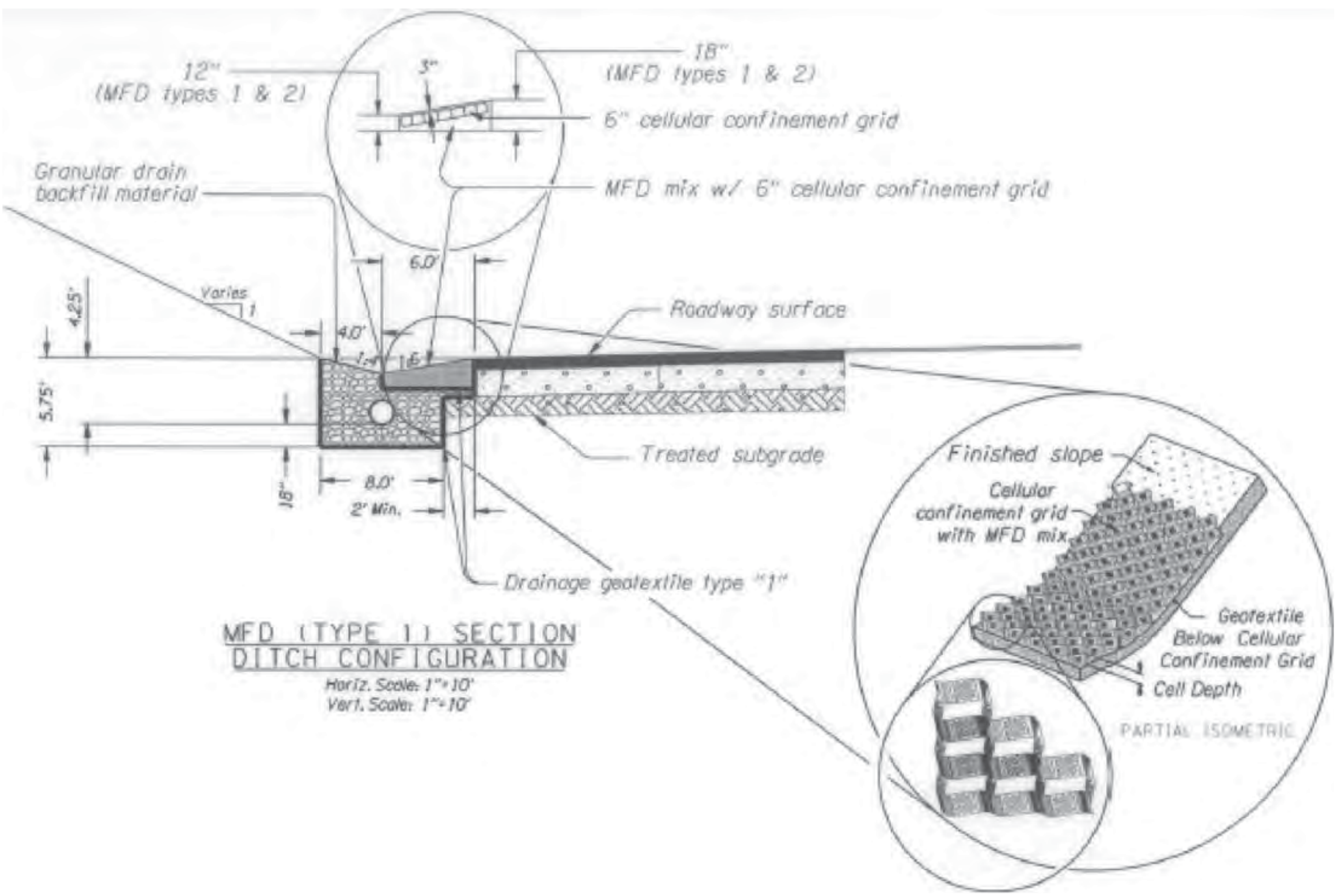


Figure 10.4. ODOT Highway 26, modified media filter drain conceptual design.

major goal of LID, whereby inlets and conveyance pipes are not used in the drainage system, allowing some infiltration. This design also addresses maintenance department concerns about vegetation management.

- An underdrain system was included below the media bed and was enclosed in drainage geotextile. The perforated pipe within the drain and the quantity and aggregate size of the drain rock were designed to ensure that the drain had sufficient capacity to convey the water of the 2-year through 50-year design storm and maintain the water surface below the roadway aggregate base.
- The modified MFD includes compost soil elements below the media mix. Compost filter dams are positioned at 50 ft intervals along the entire drainage trench (not shown in figure) to provide additional treatment processes. The compost filters are constructed with compost-filled filter socks within perforated pipe sections that are positioned across the bottom of the drainage trench below the underdrain pipe, and span the width of the trench. By arranging the treatment train components vertically, the modified MFD can include compost in the treatment train and still reduce the overall width of the BMP.

Cost Assessment

ODOT developed preliminary cost estimates of the candidate BMPs. A main cost driver of the compost-amended bioswale was the lateral space requirement within the crowded urban ROW. Substantial cuts into the existing embankments and approximately 21,000 ft^2 of retaining walls would be needed to retrofit these BMPs within the available ROW. The estimated project cost of these BMPs was approximately $4.4 million.

The modified MFD was specifically designed to address traversability and maintenance concerns, and to fit within a 10 ft zone, eliminating the need for embankment cuts and retaining walls. A majority of the construction cost for this option was associated with the gravel media bed. The treatment systems were stacked vertically to fit them into a narrower zone. Also pumice was determined to be a good substitute for perlite from a cost perspective. Either of these volcanic materials can be used to retain moisture in the mix in order to encourage bacterial growth. Cost of perlite is approximately $85/CY and cost of pumice is approximately $25/CY. The total estimated cost of the modified MFD was $2.5 million.

Maintenance Assessment

ODOT design engineers coordinated extensively with maintenance personnel to develop a BMP design with acceptable maintenance requirements. Routine maintenance practices for the modified MFD design are anticipated to include litter pickup and periodic change-out of the media when it becomes clogged. Herbicide application to control vegetation growth within 7 ft of the edge of pavement is the current practice. The herbicide used is approved for use in natural waterways when applied appropriately. The anticipated media life was approximately 10 years based on WSDOT systems that have been in place for 10 years and continue to have adequate media permeability.

Sizing and Performance Assessment

ODOT engineers based sizing and design of the MFD and bioswale on criteria from the ODOT Hydraulics Manual (2005). Treatment performance of the MFD and compost-amended bioswale has been evaluated in performance assessments (Herrera Environmental Consultants, 2006; WSDOT, 2009). Because the sizing and treatment processes in the modified MFD are similar to those in the WSDOT design, a similar level of treatment performance was also expected.

BMP Selection

The modified MFD was selected for the project because it is less expensive than both bioswales and standard ODOT MFD designs; it was expected to provide better water quality treatment than bioswales; it addresses traversability concerns in the clear zone; and it addresses maintenance concerns.

Discussion and Lessons Learned

ODOT engineers were faced with a difficult retrofit objective of reducing dissolved metal concentrations to the extent practicable along an existing highway section that was being widened and that was severely limited with respect to available ROW. ODOT designed a system that meets regulatory requirements and ODOT design parameters, and is expected to achieve treatment objectives without excessive maintenance requirements. ODOT engineers demonstrated three key actions in developing the BMP plan:

- **Understanding of receiving water issues of concern and BMP processes:** The design engineers of this project exhibited in-depth knowledge of the scientific literature on stormwater and dissolved metal effects on salmonids. Moreover, ODOT engineers were very knowledgeable of the current research on BMPs that target dissolved metals and on the treatment processes in these BMPs. This knowledge combined with the agreements and products of the multi-agency SWAT allowed BMP selection to proceed with assurance of regulatory agency acceptance.
- **Internal and external coordination to understand site and design constraints:** ODOT engineers coordinated

extensively with maintenance staff and roadway designers in an effort to identify crucial design and operational constraints. This coordination allowed design of BMPs that were compatible with highway safety requirements regarding obstacles in the clear zone and that do not overly burden maintenance staff. The coordination efforts increase the likelihood of avoiding unforeseen operation problems and the likelihood of having BMPs that are well maintained and achieve long-term water quality performance goals.

- **Flexibility and insights to adapt solutions to existing constraints:** Project engineers were faced with high BMP costs to accommodate (1) standard designs within the available ROW and (2) the safety and maintenance concerns of standard BMP designs. This challenge motivated engineers to consider design adaptations to fit the BMP components vertically as well as horizontally within the required zone and to address safety/maintenance concerns. To successfully accomplish this goal, the project engineers relied on knowledge of treatment processes and design constraints, as well as experience with the MFD by WSDOT and ODOT. In addition, ODOT policies supported the development of modified BMP designs to achieve treatment and regulatory objectives. The design engineer demonstrated ingenuity in adapting and refining treatment components into a stacked MFD as an innovative BMP design that addresses the site-specific constraints and maintenance concerns and is cost effective. The BMP design is unique, and follow-on studies are planned to assess the performance and maintenance requirements.

Acknowledgments and Project Contacts

Information regarding this project was generously provided by Daniel Gunther (Daniel.C.Gunther@odot.state.or.us) and William Fletcher (William.B.Fletcher@odot.state.or.us) of ODOT.

10.2 WSDOT Bridge Replacement with BMP Retrofit

Step 1: Project Scope

Project Location and Description

WSDOT is replacing the structurally deficient Manette Bridge over the Port Washington Narrows in the City of Bremerton. The bridge is a two-lane undivided highway that connects downtown Bremerton on the west side with East Bremerton. The ADT is 13,300 vehicles. The bridge is located in an urban environment that includes a mixture of residential, commercial, and port-related land uses (Figure 10.5).

The new bridge will parallel the existing bridge to the south and will connect to the existing street system in approximately the same locations. The existing bridge will be demolished once the new bridge is completed. The new bridge is 1,600 ft long and will be slightly taller and wider than the existing bridge. The bridge deck width will increase from 29 to 44 ft. Total impervious surfaces will increase from approximately 1.5 to 2.25 acres (WSDOT, 2010).

Figure 10.5. WSDOT Manette Bridge replacement, project location.

Pre-Project Stormwater Treatment

Stormwater runoff from the existing bridge is not treated. The majority of runoff from the bridge discharges directly into Port Washington Narrows through scuppers in the bridge deck. At the ends of the bridge, runoff flows into catch basins and into the City of Bremerton storm sewer network.

Receiving Waters and Issues of Concern

The project receiving waters are the Port Washington Narrows, which is part of Puget Sound. There are no listed impairments on the 2008 CWA Section 303 list and no established TMDLs for the Port Washington Narrows. Elevated levels of coliform bacteria have been found to impair the beneficial uses of recreation and shellfish harvesting in the Sinclair and Dyes Inlets, which are connected by the Port Washington Narrows (Ecology, 2005). A TMDL for bacteria is under development for these water bodies (Ecology, 2010).

Regulatory Requirements

Outside of the typical highway runoff parameters, there were no specific pollutants of concern for the project. In addition, the receiving waters were exempt from flow control requirements (e.g., hydromodification control) (WSDOT, 2010). Basic treatment was required for the project in accordance with procedures in the WSDOT Highway Runoff Manual (HRM) (WSDOT, 2008a). Basic treatment requires the capture and treatment of all stormwater runoff from pollutant-generating surfaces (excludes sidewalks) on the new bridge deck and bridge approaches. This effectively results in retrofit treatment for the untreated replaced impervious area associated with the existing bridge. BMPs approved for basic treatment focus on the control of sediments and associated constituents.

City of Bremerton policies mandated the use of LID BMPs to the extent feasible. LID practices entail the use of infiltration technologies. This requirement was a key project goal that heavily influenced BMP design.

Step 2: Define the Retrofit Objectives

Regulatory Objectives

The regulatory objectives were (1) to comply with WSDOT stormwater treatment requirements for the replacement bridge as specified in the HRM and (2) to address city policies on the use of LID practices.

Treatment Objectives

The stormwater treatment objective was to achieve basic treatment requirements in accordance to the approved HRM. The performance goal for basic treatment is 80% removal of TSS.

Step 3: Characterize Site Conditions and Constraints

Site surveys and field investigations supported BMP evaluation and design. Figure 10.6 shows the pre- and post-project conditions at the east bridge approach. WSDOT identified the following site conditions and constraints.

ROW Area

Available space for locating BMPs is severely constrained by existing development and city objectives for pedestrian and landscape amenities. The bridge abutments are in proximity to existing development.

Drainage and Topography

The drainage area from pollutant-generating surfaces is about 0.75 and 1.0 acres on the west and east ends of the bridge, respectively. Runoff on the bridge deck will be collected in catch basins and conveyed in 8 in. diameter ductile iron pipe to each end of the bridge. Steep bluffs rise at the shoreline at each end of the bridge.

Utilities

Utilities were present at the intersections at each end of the bridge. Relocation of water and sewer lines is required for implementation of BMPs.

Soils and Groundwater

Soils investigations identified silty sand, poorly graded sand mixed with gravel, and silt. Measured hydraulic conductivity ranged from about 13 to 38 in./h. Site soils are suitable for infiltration BMPs, as measured infiltration rates are well above the design rates of 2 in./h. The groundwater elevations vary with tidal fluctuations, but depths to groundwater range well above 20 ft. Groundwater levels do not restrict use of infiltration BMPs.

Figure 10.6. Manette Bridge replacement, existing (left) and planned (right) eastside bridge approach.

Design Constraints

The primary BMP design constraint was the city's policy to utilize infiltration BMPs to the extent feasible. WSDOT coordinated with the city to locate and design BMPs that could achieve the city's policy for LID practices.

City objectives also included a pedestrian park/viewing area with landscape amenities on the city-owned property adjacent to the east end of the bridge (Figure 10.6). The park site was the only public property available for BMPs on the east end, and the planned park amenities restricted the available surface area for locating surface infiltration facilities.

On the west end of the bridge, existing development and lack of public property severely limited available surface area for infiltration BMPs, or any surface BMPs in general.

Step 4: Select Retrofit Alternatives

Candidate BMPs

WSDOT has a highly structured BMP selection algorithm in its HRM. The HRM was developed in coordination with, and subject to approval of, the Washington State Department of Ecology (WSDOE). Infiltration practices are preferred BMPs when there are suitable site conditions. Approved infiltration practices in the HRM are infiltration ponds, infiltration vaults, infiltration trenches, and drywells. When site conditions are unsuitable for infiltration, approved BMPs for basic treatment are vegetated filter strips, biofiltration swales, bioretention, wet ponds, and any approved enhanced treatment BMP.

WSDOT considered the following approved BMPs in the HRM based on their ability to achieve basic treatment (80% TSS removal) and the city's requirement for LID practices:

- Infiltration systems
- Bioretention
- A wetland pier built at water level

The HRM includes procedures for use of alternative BMPs when site conditions restrict the use of approved BMPs. Alternative BMPs, however, must receive approval from WSDOE. Based on the severe space constraints for locating surface BMPs, WSDOT also considered the following WSDOE-approved underground or small-footprint BMPs for the project:

- Compact underground hydrodynamic sedimentation systems (CDS units or equivalent)
- Compact underground stormwater filtration systems on the bridge (Stormfilter or equivalent)
- Compact stormwater filtration/bioretention systems at the bridge abutments (Stormfilter, Filterra systems, or equivalent)

BMP Evaluation and Selection of Alternatives

A primary consideration for BMP selection was the ability to meet the city's LID requirements using infiltration practices. Compliance with this requirement was necessary to secure local permits in a timely fashion. Preliminary evaluation and design of candidate BMPs for the east and west ends included the following:

- ***East end BMPs:*** The best opportunity for locating infiltration BMPs was adjacent to the east end abutment in the planned park/landscape area. This area is city-owned property that was available for locating BMPs. In addition, the subsurface conditions at this location were suitable for infiltration. Surface-based infiltration basins and infiltration trenches were not practical in the available space because there was insufficient area and because they conflicted with the city's objectives for developing landscaping and pedestrian amenities. The use of subsurface infiltration chambers was the only feasible approach for implementing infiltration BMPs within the available area. Other potentially feasible BMPs for the east end of the bridge were unsuitable because they did not satisfy the city's infiltration requirements. WSDOT hydraulics headquarters in consultation with the city selected subsurface infiltration chambers together with underground hydrodynamic separators for pretreatment as the project BMPs for the east end of the bridge.
- ***West end BMPs:*** On the west end of the bridge there was little to no available ROW or city-owned property for locating surface BMPs. Similarly, there was no available area adjacent to the abutments or roadway where subsurface infiltration chambers could be located. The city agreed with the assessment. Therefore, WSDOT headquarters in consultation with the city selected compact underground stormwater filtration systems together with underground hydrodynamic separators for pretreatment as the BMPs for the west end of the bridge. Maintenance requirements were a main factor in selecting these systems over other candidate BMPs. The city currently operates and maintains similar systems and wanted to have simpler uniform maintenance practices rather than maintaining a variety of systems/brands. In addition, the wetland pier option was viewed as having greater maintenance requirements and there was concern about vector problems.

Step 5: Practicality Assessment

WSDOT developed preliminary design concepts for the candidate BMPs as follows:

- ***East end BMP design:*** The BMP design for the east end of the bridge included a subsurface infiltration system preceded with a pretreatment sedimentation manhole (Figure 10.7). The subsurface infiltration gallery was designed using corrugated infiltration chambers (Stormtech DC780 or equivalent). These chambers are lightweight, traffic-rated subsurface storage systems that are open on the bottom to allow for infiltration (Figure 10.8). They are positioned over and encased by ¾ to 2 in. crushed clean stone (40% porosity). The infiltration chambers are connected to inflow and outflow manifolds that tie into the storm sewer system. The design volume of the infiltration chambers was 6,300 ft^3, which was sized in accordance with WSDOT design procedures. The surface area at the bottom of the chambers is approximately 2,500 ft^2 and the design infiltration rate was 2 in./h. These are conservative design assumptions. Larger storage and infiltration capacity is expected as there is additional storage and surface area in the gravel bed, and measured infiltration capacities of native soils exceeded 2 in./h.

WSDOT engineers considered a treatment train of unit processes in the design of the infiltration system. As required in the HRM, pretreatment sedimentation was included to reduce potential clogging in the infiltration gallery. WSDOT engineers selected a proprietary hydrodynamic sedimentation system (CDS or similar) that can be prefabricated within standard manholes. The specified CDS unit has a treatment capacity of 0.7 ft^3/s (~0.69 watershed inches/hour) and a bypass capacity of 10 ft^3/s to the infiltration gallery. To improve treatment performance for dissolved metals (primarily copper) in the infiltration system, WSDOT engineers specified 2 ft of compost-amended soils below and to the sides of the infiltration gallery. Dissolved metals are a significant pollutant of concern in highway runoff in Washington State due to potential impacts to endangered salmon. WSDOT has actively researched, developed, and successfully used compost-amended soils in a variety of BMP configurations such as swales, filter strips, and media filter drains. The addition of compost-amended soils in the infiltration system is an extension of this experience.

The overall design of the infiltration system included sedimentation, surface runoff volume reduction, filtration, and sorption processes. Collectively, these processes are

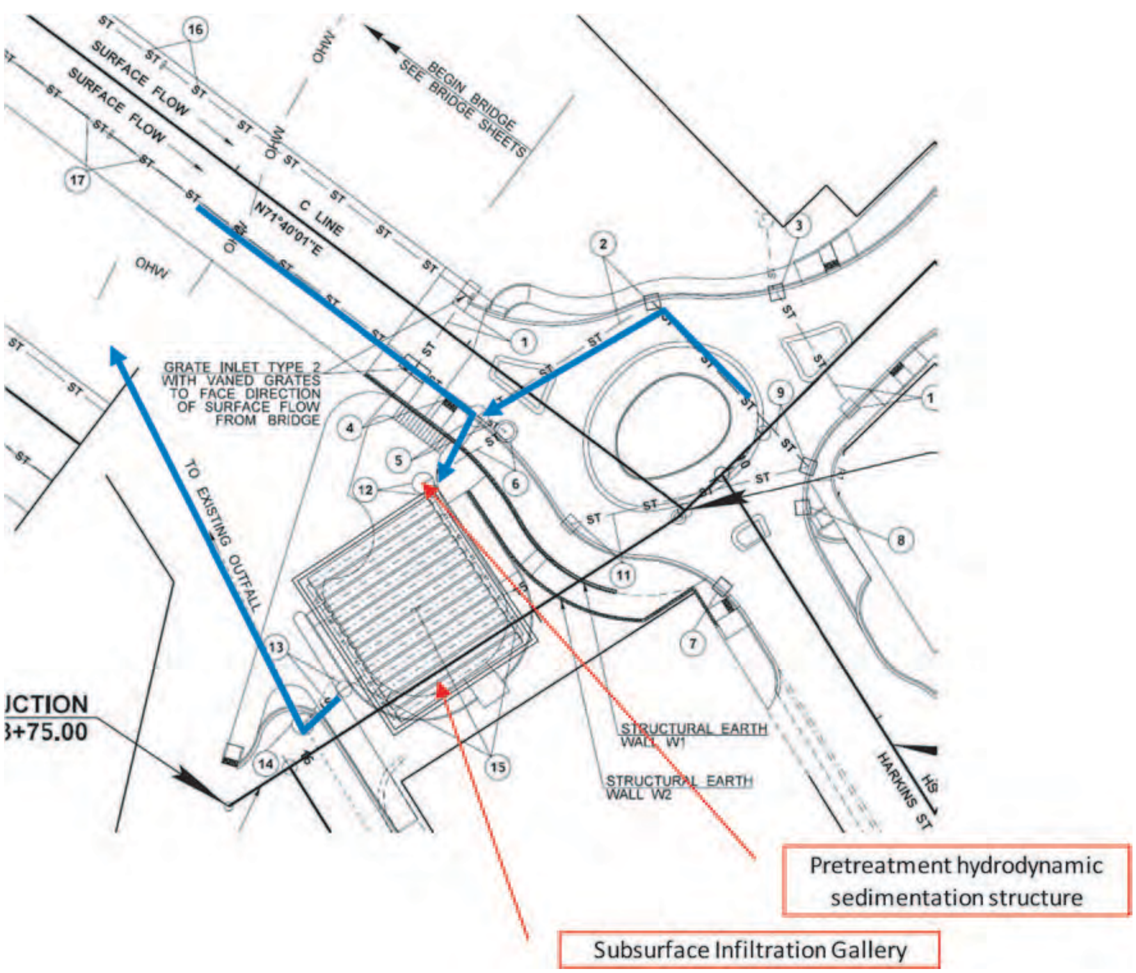


Figure 10.7. WSDOT Manette Bridge replacement, east end BMP layout.

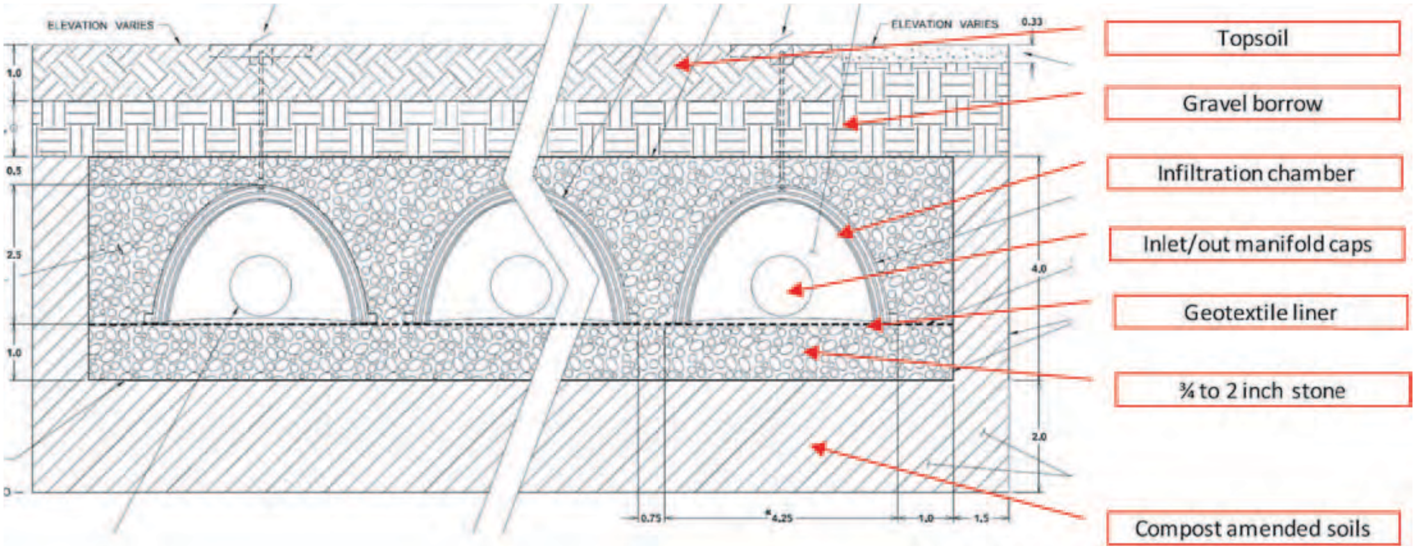


Figure 10.8. WSDOT Manette Bridge replacement, infiltration gallery cross section.

expected to result in overall treatment performance that meets and exceeds the minimum basic treatment requirements in the HRM.

- ***West end BMP design.*** BMP design on the west end of the bridge was severely constrained by space limitations. The lack of available ROW adjacent to the roadway precluded the use of subsurface infiltration systems similar to those used on the east of the bridge. Small-footprint proprietary underground BMPs were needed to fit within the available space (Figure 10.9). WSDOT engineers selected a combination of approved BMPs that provided a treatment train of sedimentation and filtration treatment processes. Specifically, WSDOT engineers selected stormwater filtration systems in a 72 in. vault (Contech Stormwater filter or equivalent), preceded with a pretreatment sedimentation manhole (CDS or similar) (Figure 10.10). The specified Stormfilter system is designed to hold a maximum of seven filter cartridges with a total peak treatment capacity of 0.35 ft^3/s (depending on cartridge and media, assumes 27 in. cartridges with an individual capacity of 2.25 gal/min). The selected medium was a ZPG blend (zeolite, perlite, and GAC), which targets removal of TSS, turbidity and fine sediments, and organics. The maximum hydraulic capacity of the Stormfilter manhole (including filter bypass) is 1.5 ft^3/s.

Cost Assessment

The subsurface infiltration chambers selected to treat the runoff from the east side of the bridge are lightweight, low-cost units that are easy to install. The major cost of the infiltration system is the material and construction cost of the amended soils and gravel blanket. The CDS units and media filter vault are each prefabricated and precast units that are easy to install and have relatively low cost. The estimated installed cost of all stormwater treatment facilities for both sides of the bridge is on the order of $150,000 to $200,000. The total cost of the bridge replacement is approximately $84 million. Stormwater treatment costs were on the order of 0.2% of the project total and include both some conveyance costs as well as treatment.

Maintenance Assessment

The City of Bremerton will maintain all BMPs in accordance with specifications in the HRM. The selected BMPs require only standard maintenance practices and maintenance should be relatively straightforward as the city has ongoing experience with the selected BMPs. Routine maintenance requirements include regular clean-out of the sedimentation manholes and catch basins, and regular change-out of the media filter cartridges. No regular maintenance is anticipated for the infiltration gallery. The expected life of the infiltration system is greater than 25 years, especially given that the runoff is from all paved surfaces and that there is pretreatment included.

Performance Assessment

BMPs on both sides of the bridge provide a treatment train of sedimentation and media filtration processes. The systems are expected to provide a high level of treatment for sediment, as well as some treatment for dissolved metals and organics. The overall treatment performance is anticipated to exceed the

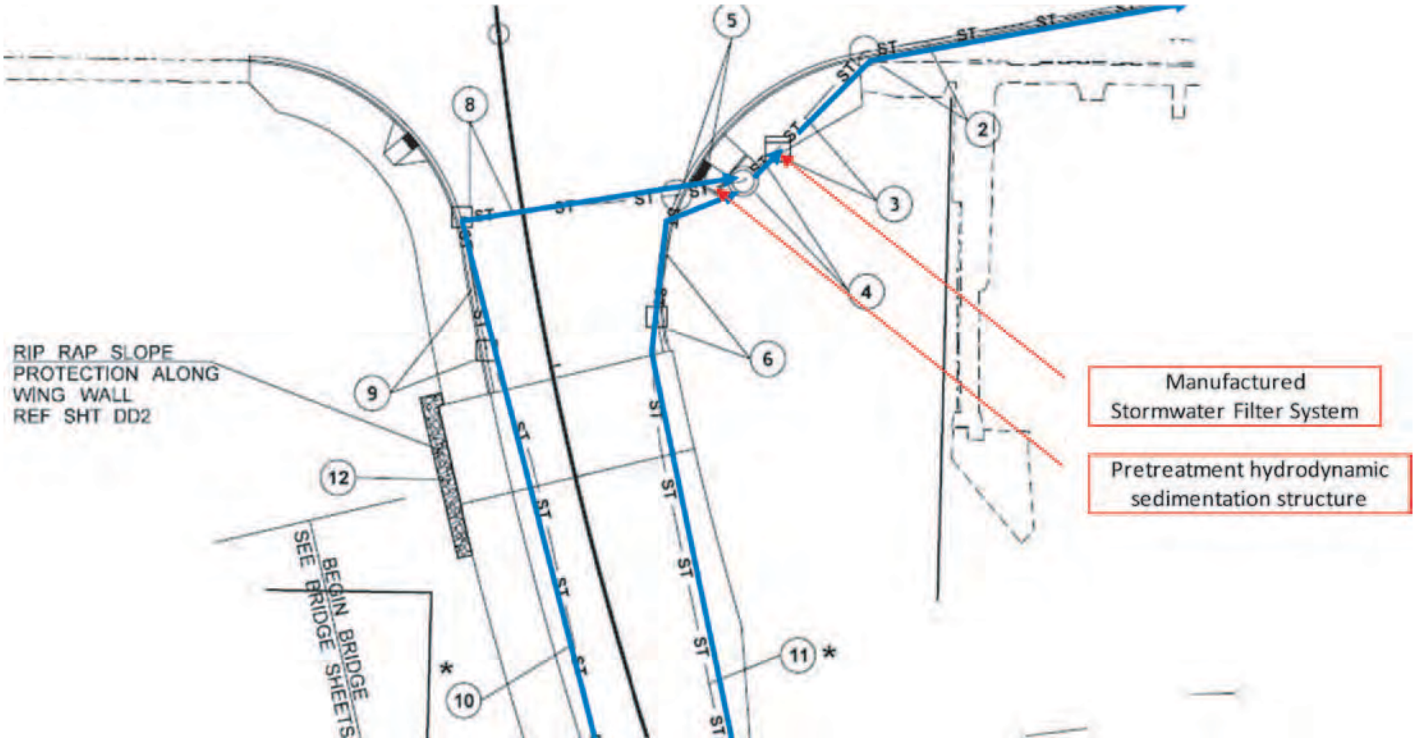
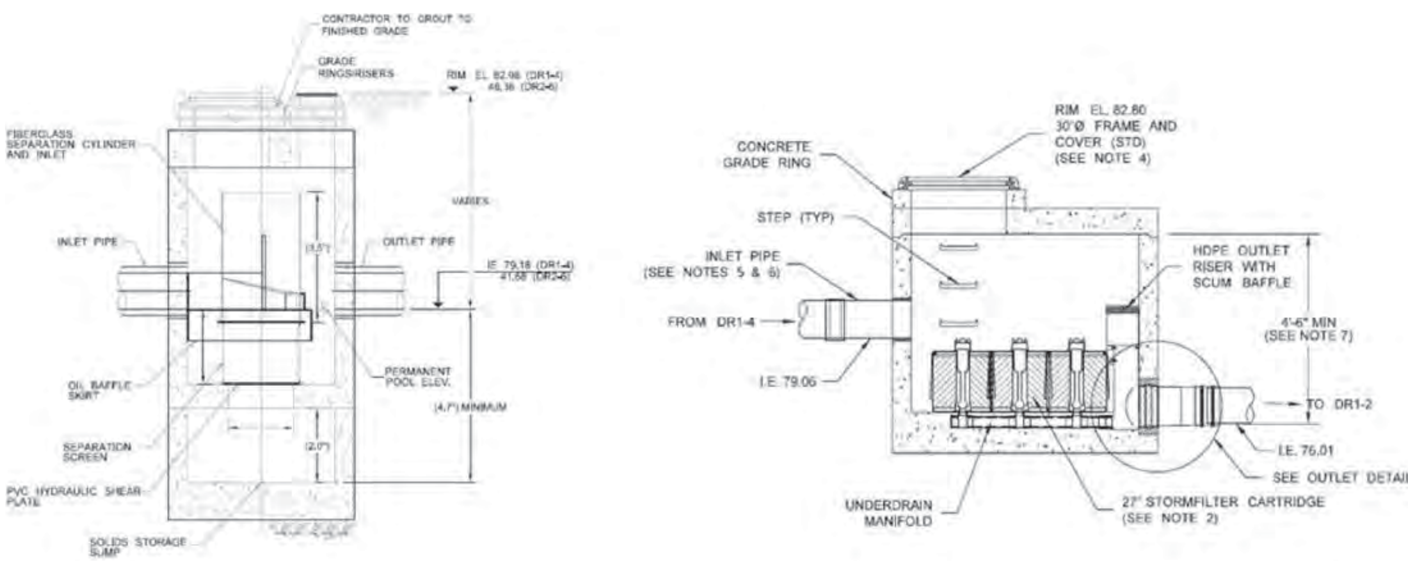


Figure 10.9. WSDOT Manette Bridge replacement, west end BMP layout.



Contech CDS Unit
(48-inch manhole)

Contech Stormwater Filter Vault
(72-inch manhole)

Figure 10.10. WSDOT Manette Bridge replacement, west end BMP components.

minimum basic treatment requirements, which are based on an 80% TSS removal standard. In addition, the infiltration system will substantially reduce stormwater discharges from the east end of the bridge and will achieve project objectives for LID.

Discussion and Lessons Learned

WSDOT engineers were faced with the challenge of designing a BMP plan for retrofit treatment of a bridge replacement project in a highly space-constrained setting. Additionally, BMPs were required to comply with WSDOT and WSDOE-approved design and performance standards, as well as local design requirements. Specifically, LID/infiltration-based BMPs were required to secure local permits in a timely manner to keep the project on schedule. The following strategies helped WSDOT engineers achieve the objectives of the BMP plan:

- **Adaptation of BMP solutions to site constraints.** WSDOT's HRM is a comprehensive BMP design manual with detailed BMP selection procedures. However, approved BMPs in the HRM were not suitable for this project due to space and design constraints. Accordingly, WSDOT engineers used a combination of WSDOE-approved proprietary BMPs to develop solutions that fit within the space constraints and achieved objectives for a high level of treatment performance. The selected BMPs were a unique combination of non-standard BMPs that are not found in the HRM. If the designers were required to strictly follow the HRM, the chosen designs would not have been selected, thereby likely reducing the resulting effectiveness of the design and/or lengthening the project schedule. WSDOT staff stated that education and experience of the designers are key factors for finding and developing practical solutions to unique and challenging conditions.
- **Coordination with local agencies and WSDOT staff to gain acceptance of BMP solutions.** Project engineers coordinated with local officials and WSDOT hydraulics headquarters to develop BMP solutions that met WSDOT standards in the HRM, used WSDOE-approved BMPs, and were acceptable to city officials. This coordination facilitated the selection and design of non-standard BMPs to achieve the city's LID goals on the east end of the bridge. Coordination further assisted in securing city variances on meeting infiltration requirements for the west end of the bridge where infiltration BMPs were not practical. WSDOT staff stated that "open communication with open minds" is central for finding practical solutions to tough challenges.
- **Consideration of the treatment processes in the BMP design.** The minimum treatment requirement for the project was "basic treatment," which is focused on 80% TSS removal. However, WSDOT pursued greater treatment performance to address LID treatment goals promoted by the city and similar goals in WSDOT's NPDES permit. To improve treatment performance, WSDOT engineers incorporated a treatment train of sedimentation, filtration, and sorption processes into the BMP design as follows:
  – On the east end of the bridge, WSDOT engineers incorporated filtration and sorption processes into the BMP design by surrounding the sides and bottom of the infiltration gallery with compost-amended soils. This design is an extension of WSDOT's experience and successful use of amended soils in other BMP configurations. The use of amended soils in a subsurface infiltration system is fairly unusual and is expected to greatly improve removal of dissolved metals prior to discharge to groundwater.
  – On the west end of the bridge, space constraints were severe and there was no practical alternative to the use of small-footprint proprietary underground BMPs. The basic treatment requirement of 80% TSS removal could likely have been achieved with either a CDS or a Stormfilter system used individually. However, WSDOT engineers linked these systems in series to provide a treatment train that is expected to improve overall treatment performance.
- **Consideration of maintenance requirements.** The City of Bremerton will assume maintenance responsibilities for the BMPs. Nevertheless, WSDOT considered maintenance requirements in the selection and design of BMPs. The selected BMPs will be easy to maintain using routine procedures with which city personnel are already familiar. With regular maintenance, the BMPs could potentially last between 25 to 40 years.

Acknowledgments and Project Contacts

Information regarding this project was generously provided and reviewed by Le Nguyen (NguyenL@wsdot.wa.gov) of WSDOT.

10.3 WSDOT I-405/I-5 to SR-169 Stage 2 Widening

Step 1: Project Scope

Project Location and Description

WSDOT is widening portions of the I-405 corridor near Seattle from six to eight lanes. The purpose of the project is to provide congestion relief and safety improvement between I-5 and SR-169, where ADT is 127,000 vehicles. Stage 2 of the project is approximately 1 mi in length. This project will add one lane in each direction, improve interchanges, and reconstruct the Benson Road overpass (Figures 10.11 and 10.12). Construction is currently ongoing.

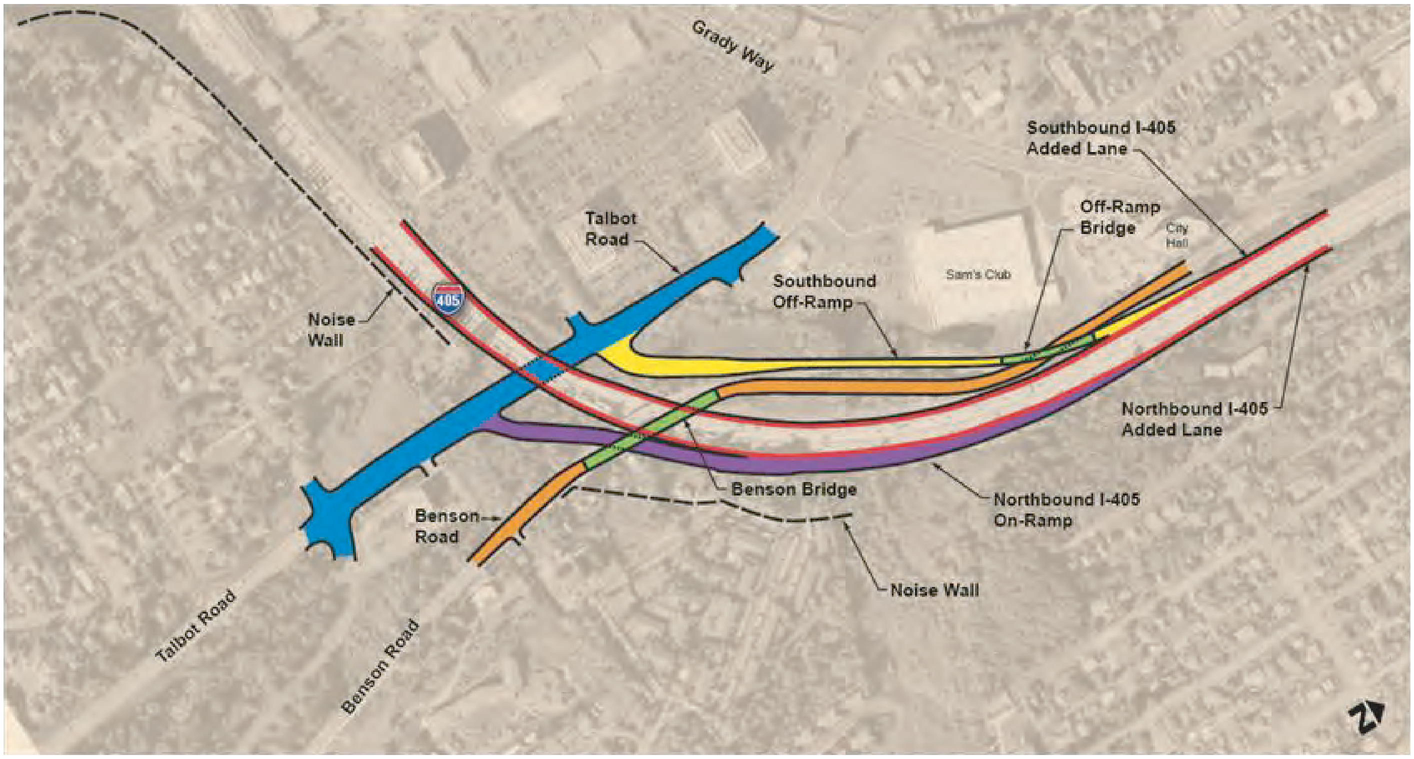


Figure 10.11. WSDOT I-405 Renton Stage 2 widening project, overview map.

Pre-Project Stormwater Treatment

Existing treatment controls (swales, ponds, media filter drains) provide water quality treatment for a small portion of the existing highway area. Large portions of the existing (pre-project) highway were not served by water quality treatment.

Receiving Waters and Issues of Concern

The project receiving waters include the Cedar River, the Green River, and tributaries to the Green River including Springbrook Creek. There are listed impairments in the Green River and Springbrook Creek for low dissolved oxygen, elevated temperature, and elevated coliform bacteria. The

Figure 10.12. View of existing (left) and planned (right) WSDOT I-405 widening project.

receiving waters are considered critical habitat for Chinook salmon and Bull trout, which are federal-listed endangered species.

Regulatory Requirements

Enhanced treatment was required for the project in accordance with procedures in the WSDOT HRM (WSDOT, 2008a). Enhanced treatment targets removal of metals, particularly dissolved copper, which has been associated with impacts on endangered salmon. In addition, flow control for mitigation of hydromodification impacts is also required for the project. Retrofit treatment of untreated pre-project impervious surfaces associated with the project is required to the extent practical to meet environmental commitments made during the pre-planning phase. The project will create about 12.4 acres of new impervious area and will provide treatment for 19.1 acres of impervious surfaces.

In accordance with the HRM, the project must also meet flow control requirements to prevent increases in the stream channel erosion rates beyond those characteristic of natural or reestablished conditions. Flow control BMPs include infiltration and detention facilities. The criteria for detention facilities are to provide sufficient storage volume to match the duration of predevelopment peak flows from 50% of the 2-year storm flow up to the 50-year storm flow, using a flow restrictor (such as an orifice or weir).

Step 2: Identify the Retrofit Objectives

Regulatory Objectives

The regulatory objectives were to comply with WSDOT stormwater treatment requirements as specified in the HRM, and approved by the WSDOE. The HRM includes prescriptive procedures for BMP selection and design.

Treatment Objectives

The stormwater treatment objective was to achieve enhanced treatment requirements in accordance with procedures in the approved HRM. The performance goals for enhanced treatment are:

- To meet the basic treatment objectives for TSS (i.e., 80% removal for influent concentrations that are greater than 100 mg/L, but less than 200 mg/L, and an effluent quality goal of 20 mg/L for influent concentrations less than 100 mg/L) and
- To provide a higher level of treatment for dissolved copper and dissolved zinc.

Step 3: Characterize Site Conditions and Constraints

ROW Area

The most significant constraint was available space for locating both flow control and treatment BMPs. BMPs are required to serve all new impervious areas and to maximize opportunities for retrofit treatment of existing impervious areas.

Drainage and Topography

Significant portions of the ROW are constrained by hillside slopes and embankments (Figures 10.12 and 10.13). There are some open space areas between ramps and the highway, but slopes are steep and not well suited to swales and media filter

Figure 10.13. WSDOT I-405 widening project: aerial views of project area (left) and Benson Road overpass (right).

drains. A design objective was to retain pre-project drainage patterns and conveyances to the extent feasible.

Groundwater Protection

Groundwater in the project area is used for water supply. Groundwater protection through the restrictions on infiltration was a goal for the City of Renton.

Step 4: Select Retrofit Alternatives

Unit Operations

WSDOT has a highly structured BMP selection algorithm in its HRM. The HRM was developed in coordination with, and subject to the approval of, WSDOE. All BMPs that are approved for enhanced treatment include sorption and infiltration processes that provide treatment of dissolved metals.

Candidate BMPs

Infiltration practices are preferred BMPs for flow and treatment control when there are suitable site conditions. The WSDOT HRM has three BMPs that are approved for enhanced treatment:

- Compost-amended vegetated filter strip
- Media filter drains
- Constructed wetlands

WSDOE has also approved Filterra systems for enhanced treatment, but these systems are not applicable for highway settings. There is no underground treatment BMP that qualified as an enhanced treatment BMP (excluding sand filter vault).

BMP Evaluation and Selection of Alternatives

WSDOT evaluated the suitability of the candidate BMPs as follows:

- ***Infiltration:*** Site conditions are not feasible for infiltration BMPs due to limited space, and groundwater protection goals of the City of Renton.
- ***Detention/controlled release:*** As infiltration was not feasible, a detention basin approach with controlled releases was selected for flow control in combination with other BMPs for treatment control.
- ***Constructed wetlands:*** There was not sufficient surface area for constructed wetlands, which have area requirements on the order of 5% or more of the tributary drainage area.
- ***Compost-amended vegetated filter strip:*** Compost-amended vegetated filter strip (CAVFSs) and MFDs are both linear BMPs installed along the roadway shoulders. Typically, the CAVFS has a wider width than the MFD, potentially 15 to 30 ft wide versus 8 to 10 ft wide for the MFDs. The CAVFS width depends on the existing soil infiltration rates, while the MFD is not dependent on the existing soil infiltration rate. Both of them require the embankment slopes to be 4H:1V or flatter, which was not available at this location. Much of the project site is constrained by embankment slopes that are too steep to install the MFD and/or the CAVFS. For these reasons, CAVFSs were not selected for the project.
- ***Standard media filter drain:*** The standard MFD is a roadside BMP that treats sheet flow runoff at the edge of pavement. This design is appropriate for portions of the project area where the roadbed drains toward the outside shoulder, there is adequate space, and embankment slopes do not exceed design criteria. In many sections of the project areas, the standard MFD design is not workable because there is either insufficient space or embankment slopes are too steep.
- ***Modified media filter drain:*** WSDOT engineers have developed a modified MFD design to address situations when the standard MFD is not applicable. The concept is to site media filter beds in opportunity areas such as landscape areas between ramps, and to convey runoff to these areas using piped conveyances. They are essentially "regional" media filters that include the same treatment components as the standard MFD, but with multiple drainage areas conveyed to them. The benefits of the modified MFD include:
  - Location can be in opportunity areas;
  - Existing collection and conveyance systems can be used;
  - There are material cost savings because the system is more compact; and
  - Locations away from highway shoulders can simplify construction and ongoing maintenance.

  The modified MFD was selected for portions of the project where siting and drainage were practical.

BMP Selection

An opportunity-based approach was used to select and site project BMPs taking into consideration existing drainage facilities and site constraints. The project BMPs include a mixture of 12 standard and modified MFDs to treat runoff based on siting constraints and opportunities. Detention facilities were selected for flow control.

An example of the combined opportunity-based approach for BMPs siting is shown in Figure 10.14. The Benson Road overpass (Figure 10.13) will be reconstructed to accommodate highway expansion. Open space between the highway

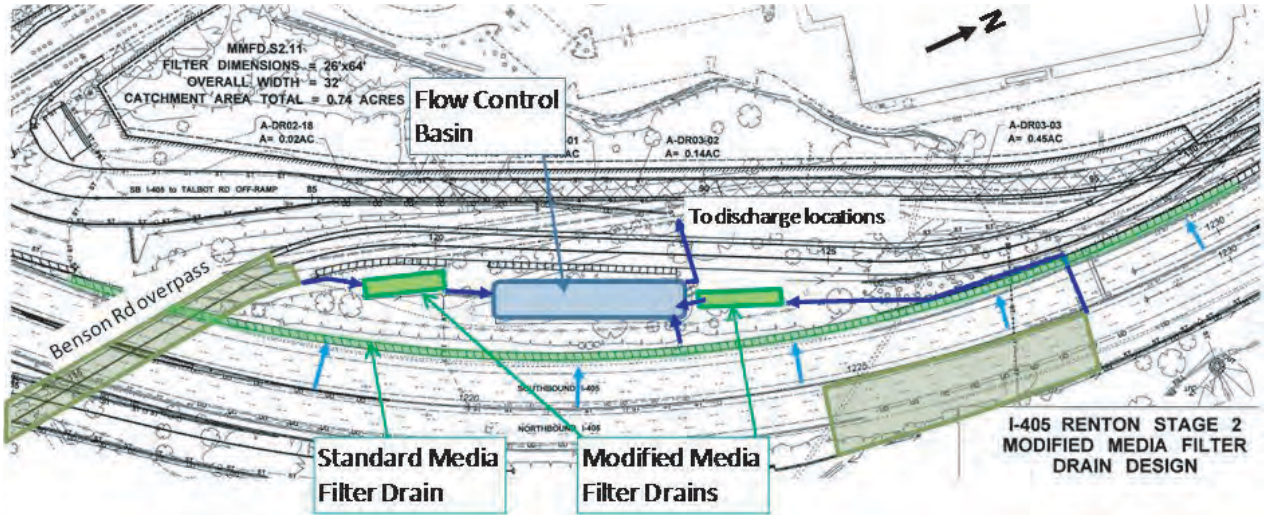


Figure 10.14. Example layout of MFD and modified MFDs north of Benson Road overpass.

and Benson Road is a BMP opportunity area where two modified MFDs and a flow control basin are to be located (Figure 10.14). Runoff from the Benson Road overpass in the southern part of the project will be collected and treated in a modified MFD to the north. A second modified MFD will treat runoff from a section of the northbound lanes where runoff is collected and routed using existing infrastructure. Runoff from the southbound lanes drains to the shoulder where it is feasible to treat with standard MFD designs. All discharges from the MFDs and modified MFDs are routed through a flow control basin to provide hydromodification control prior to discharge to receiving waters.

Step 5: Practicality Assessment

WSDOT developed design concepts for the candidate BMPs as follows:

- ***Media filter drain design.*** Example sections of the MFD design are shown in Figure 10.15. The design includes three functional zones: (1) a 1 to 2.5 ft vegetation-clear gravel strip that provides pretreatment and serves as a level spreader; (2) a 3 ft vegetated strip that provides filtration of particulates and treatment in underlying compost-amended soils; and (3) a media bed composed of aggregate, perlite, dolomite, and gypsum that has been found to provide effective treatment for dissolved metals. Underdrains and retaining walls are used in portions of the project where there are space constraints. In other sections, underdrains are not required and the media bed discharges directly to conveyance channels (Figure 10.15).
- ***Modified media filter drain design:*** The modified MFD includes the same treatment elements as the standard MFD but is constructed as a centralized facility rather than a roadside treatment. As shown in Figure 10.16, a gravel bed, level spreader, and vegetated strips at the head end of the modified MFD provide pretreatment and direct flows to the media bed. The media bed is sized for treatment of the design storm. The facilities in Figure 10.14 have a 150 ft^2 media bed and treat runoff from 0.6 acres, although larger areas could be treated (Black et al., 2010). All discharge from the modified MFDs is collected in underdrains, which is conveyed to flow-duration basins for flow control. The entire facility is underlain with a geotextile liner to meet groundwater goals for the City of Renton, but in general, the liner is not required.

Cost Assessment

This project was built as a design-build project. The MFD and modified MFD were designed to be low-cost BMPs. However, because of the design-build nature of the project, separate cost breakdowns of the BMPs were not developed.

Maintenance Assessment

The MFD and modified MFDs require minimal maintenance. Expected routine practices include regular cleaning of trash and debris and regular vegetation maintenance. The expected life of the media bed is 25 to 30 years.

Performance Assessment

The MFDs and modified MFDs are expected to provide high levels of treatment performance for sediments, metals, phosphorus, and organics including oil and grease.

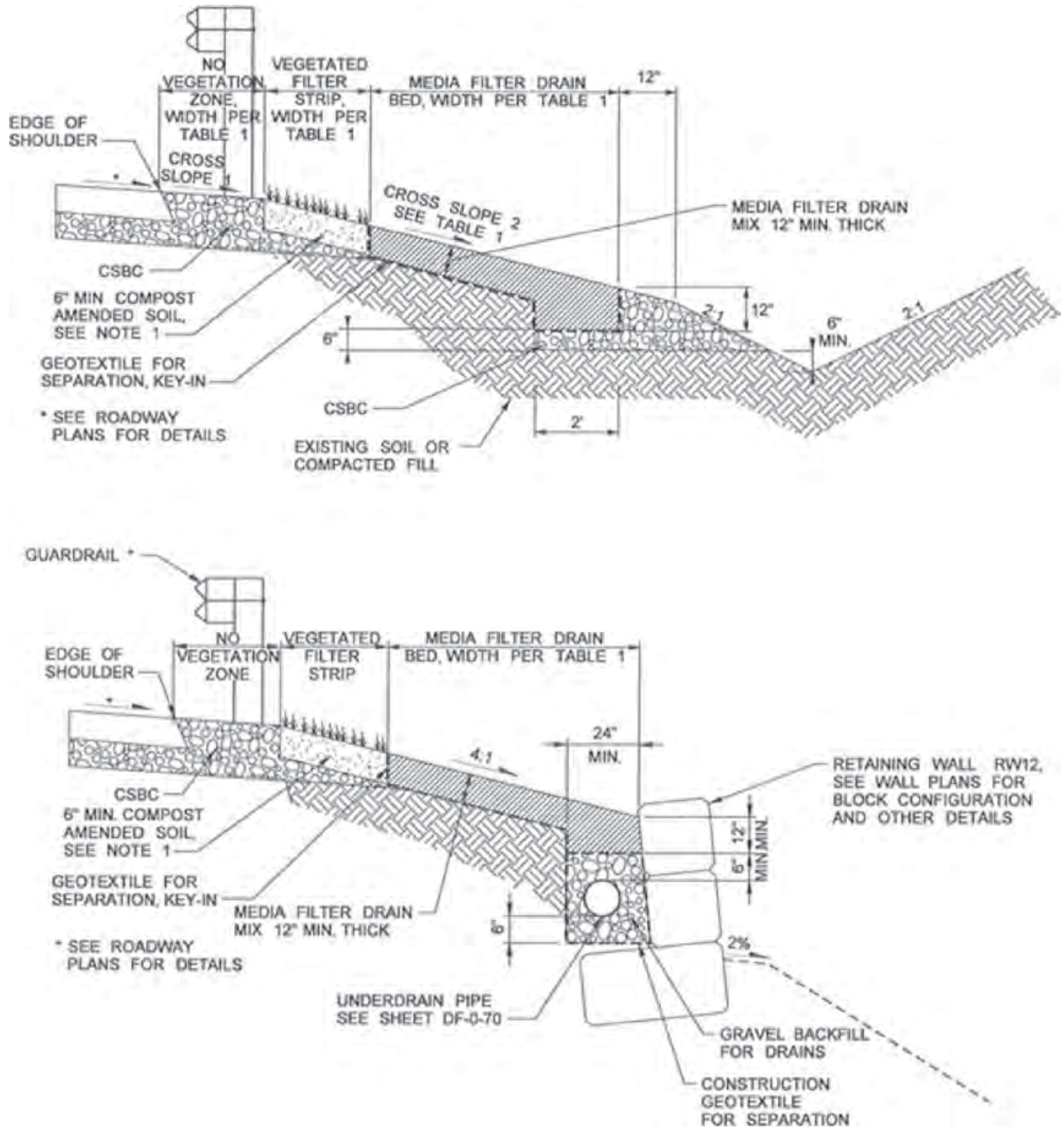


Figure 10.15. WSDOT media filter drain without underdrains (top) and with underdrain and retaining walls in space-limited sections (bottom).

Discussion and Lessons Learned

WSDOT engineers were faced with developing a challenging BMP plan for a highway-widening project in a heavily used suburban commuter corridor. The challenges included (1) achieving difficult treatment objectives for enhanced treatment of dissolved metals and flow control for mitigating hydromodification impacts; (2) finding adequate space for BMPs due to limited ROW, steep slopes, and groundwater protection goals; and (3) providing retrofit treatment for existing impervious surfaces to the extent economically viable. These challenges generally precluded extensive grading and modification of the existing drainage conveyances, and the use of underground BMPs. The following strategies helped WSDOT engineers meet these challenges:

- **Shaping BMP solutions to fit the site constraints.** WSDOT engineers exhibited flexibility in developing BMP solutions that could work effectively within the site constraints.
  - *Identified BMP opportunity areas.* WSDOT engineers identified and exploited opportunity areas between ramps and roads and along highway shoulders for siting detention basins and media filtration facilities.
  - *Used existing conveyance facilities.* WSDOT engineers integrated existing storm sewers into the BMP plan

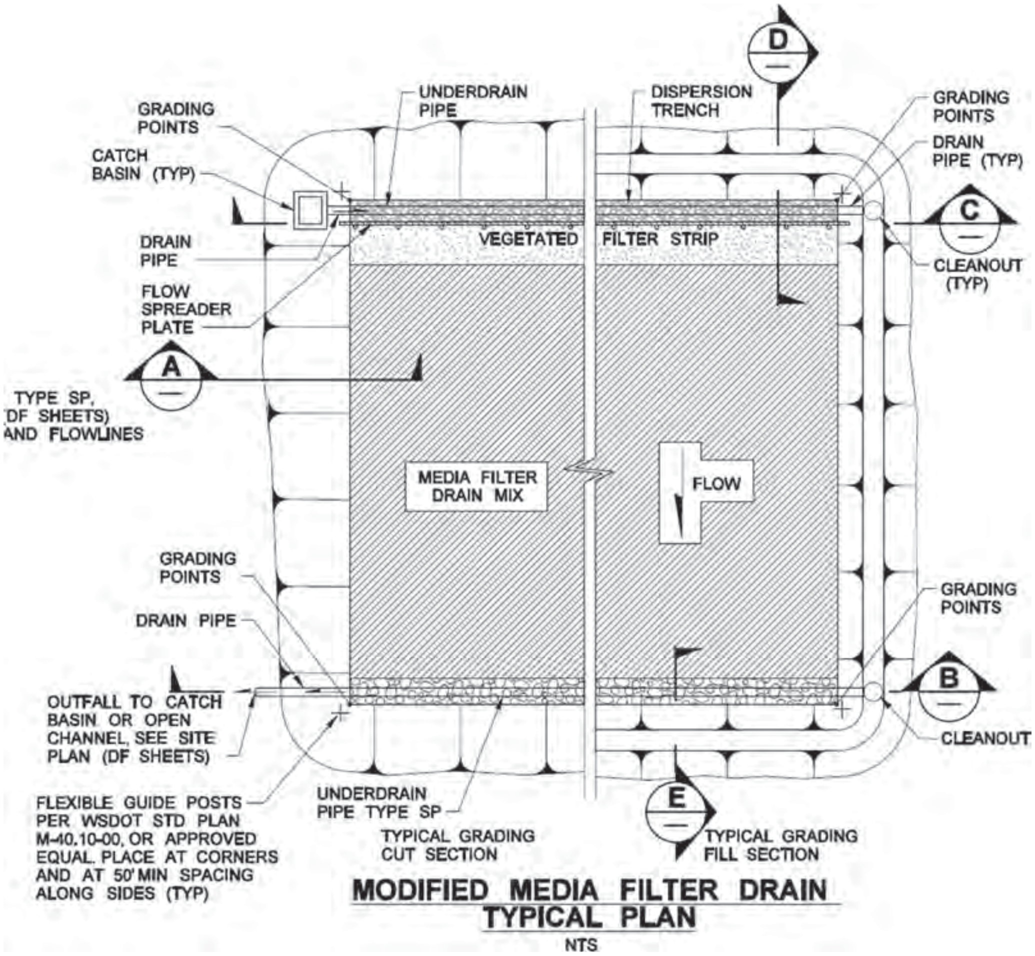


Figure 10.16. WSDOT modified media filter drain design.

where feasible to provide treatment of new and existing highway sections.

– *Used a combination of BMPs to fit site constraints.* WSDOT engineers used the standard linear MFD designs along the roadway shoulder where drainage, space, and slope were suitable. In other areas, WSDOT engineers used the modified MFD to site BMPs within available ROW.
– *Used hydromodification control.* Due to the "prohibition" on infiltration due to local groundwater quality concerns, WSDOT implemented a detention/flow-control approach in centralized detention facilities.

- **Adaptation of BMP designs.** WSDOT routinely uses the standard MFD to effectively meet enhanced treatment requirements. However, the standard MFD is not feasible along sections with limited space or drainage away from the edge of the highway. This motivated WSDOT to develop an end-of-pipe equivalent to the standard MFD. The modified MFD is a centralized media filtration BMP that incorporates the same design elements and treatment processes found in the standard MFD. Because it is centralized, the modified MFD is more compact than the standard MFD and can be adapted to fit within opportunity areas. Additionally it enables engineers to exploit existing infrastructure to convey runoff to the treatment BMP. The modified MFD was an integral component of the BMP plan.

Acknowledgments and Project Contacts

Information regarding this project was generously provided and reviewed by Le Nguyen (NguyenL@wsdot.wa.gov) of WSDOT.

10.4 IDOT Mississippi Bridge Tri-Level Interchange Drainage

Step 1: Project Scope

Background

The Missouri DOT (MoDOT) and Illinois DOT (IDOT) are collaborating on the new Mississippi River bridge. The project elements include constructing an urban interstate bridge between Illinois and Missouri, relocating I-70 from the

Poplar Street bridge to the new Mississippi River bridge, and modifying the existing Tri-Level I-55/I-64/I-70 Interchange to accommodate connections from the existing interstate routes to the I-70 connection (Figure 10.17). However, water quality issues are only now being considered by the design team—not in time for this document. Hence, this write-up only describes an example of designing water *quantity* BMPs for an ultra-urban area. Many publications and related information may be found at the project website: http://www.newriverbridge.org/index.html

Under pre-project conditions, interstate mainline and ramp storm sewers for I-55 and I-64 flow out to the Bowman Avenue pump station (BAPS). The proposed improvements along the I-55 and I-64 mainline and ramps will continue to flow to the BAPS. The BAPS outlet is to a 72 in. storm sewer that flows to an unnamed tributary of Lansdowne Ditch. The roadway section for the proposed I-70 connector will drain to two proposed detention basins located west of 1st Street.

Bowman Avenue Pump Station Constraints

The pre-construction runoff as well as the runoff from additional impervious areas from the construction will be detained as a part of this project to avoid increasing the runoff to the existing pump station system (Figure 10.18).

Section 4(f) Historic Properties Constraints

In the area considered for this project, there are four historic properties that may have constrained the available area in which to build further, but the option chosen includes demolishing these four properties.

Flooding Issues of Concern

Several areas near the interchange have been designated by the Federal Emergency Management Agency (FEMA) as floodplains. Some fill in the floodplain (Figure 10.19) will be required, and mitigation for lost floodplain area must be provided.

Step 2: Define Retrofit Objectives

Regulatory Requirements

There are no legal ordinances in either the City of East Saint Louis or St. Clair County that specify detention requirements or address construction within the floodplain. However, the modified rational method was used to ensure that the existing release rates were maintained under proposed conditions, per IDOT District 8 requirements.

Retrofit Objectives

The proposed Tri-Level drainage work will avoid any impacts to the existing pump station. Detention will be provided upstream of the pump station to maintain the existing 100-year release to the outlet, and to maintain the existing pump characteristics.

The total added impervious area to the Tri-Level Interchange mainline sewer system is approximately 7.86 ac. This

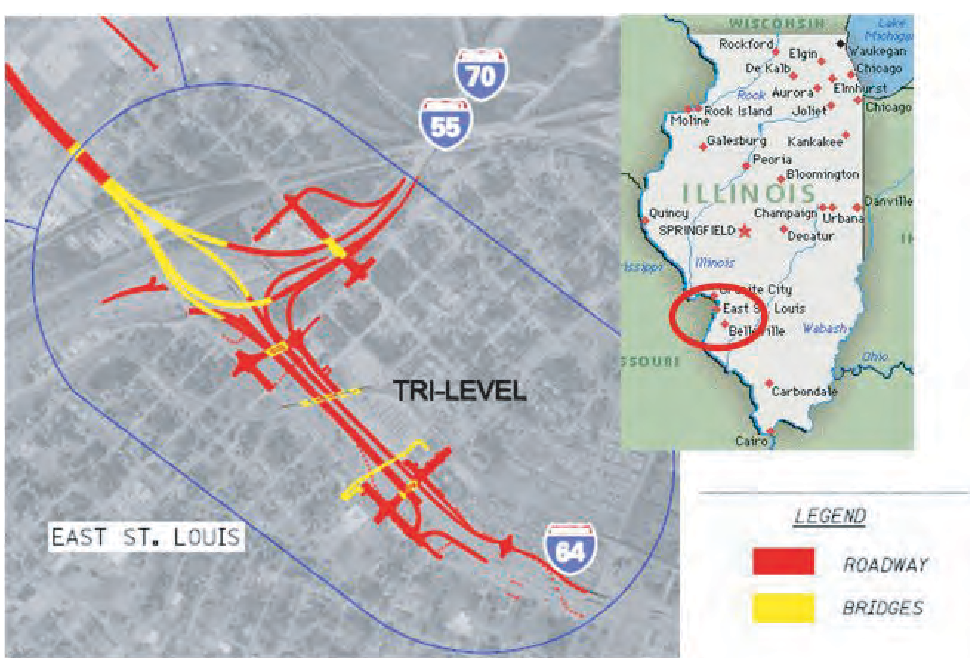


Figure 10.17. IDOT Mississippi bridge, project location.

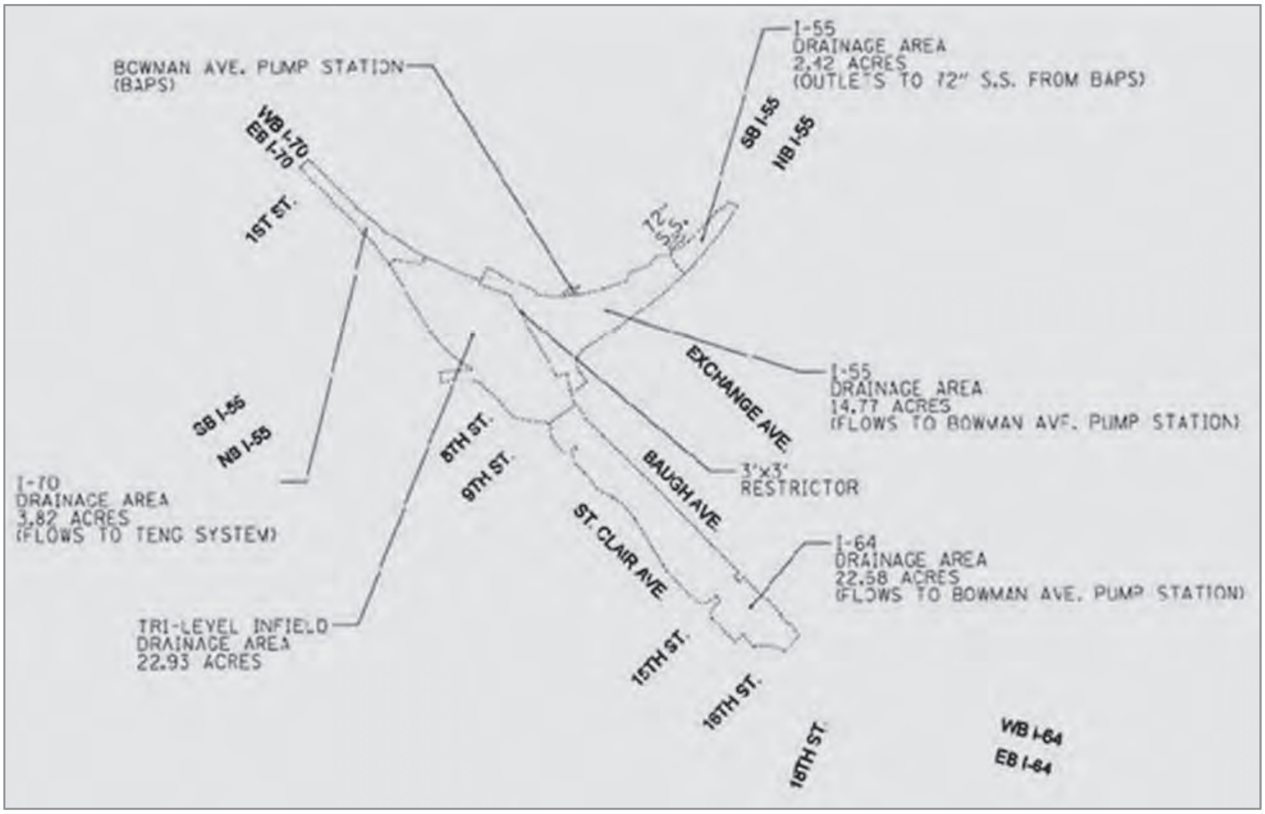


Figure 10.18. IDOT Mississippi bridge, Bowman Avenue pump station location.

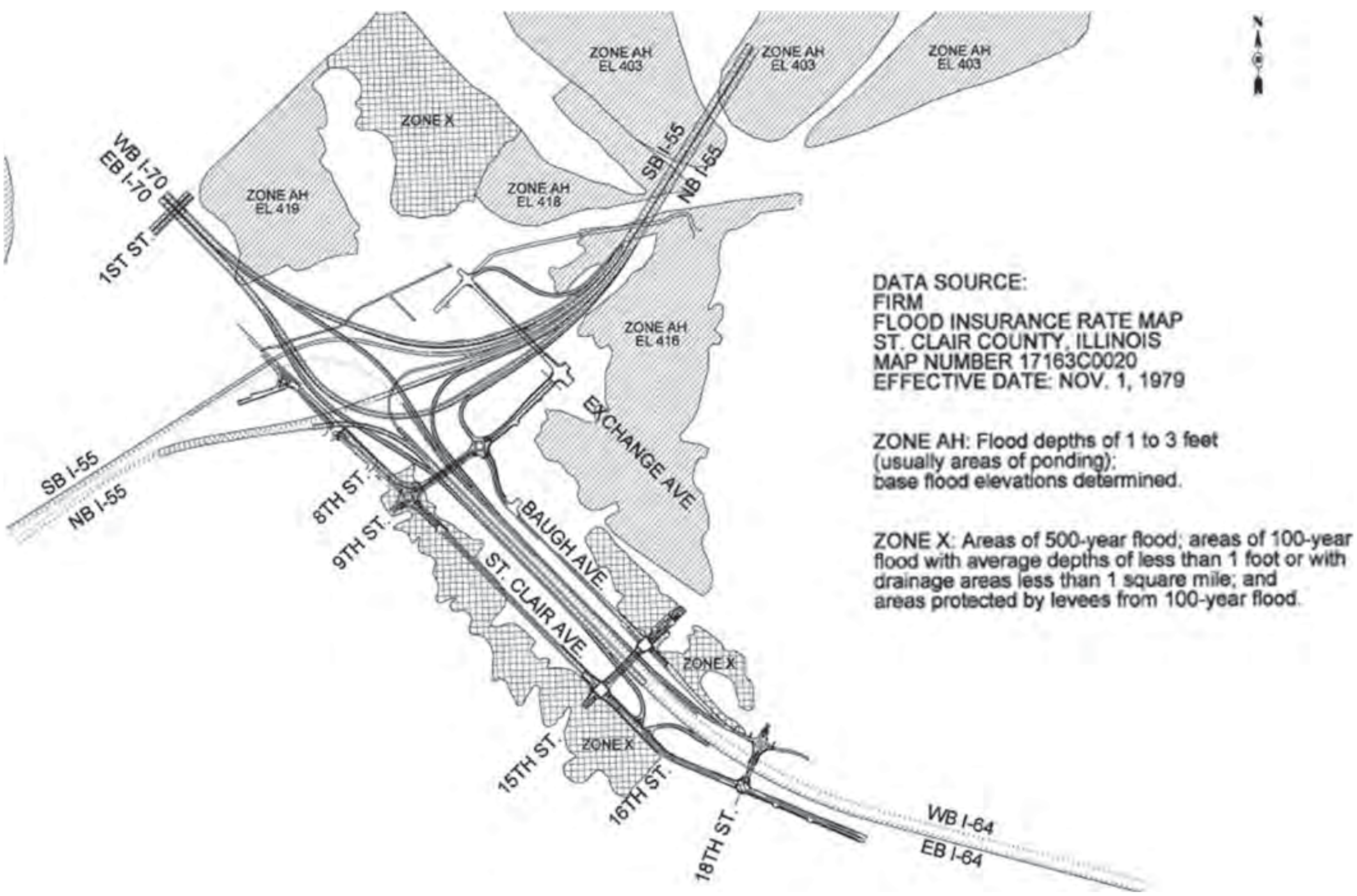


Figure 10.19. IDOT Mississippi bridge, floodplain in vicinity of project.

includes the I-70 area east of the railroad tracks, I-64, I-55, and the new or re-aligned ramps. The added impervious area results in approximately 1.64 ac-ft of detention storage volume required for the 100-year storm event. Providing detention storage to meet this volume is necessary to avoid increased runoff to the existing pump station system, while making sure that adequate freeboard is provided between the low road elevation and the design hydraulic grade line.

Step 3: Characterize Site Conditions and Constraints

Since the BAPS was recently rehabbed in 2006, the proposed Tri-Level drainage work will avoid any impacts to the existing pump station. Detention will be provided upstream of the pump station to maintain the existing 100-year release to the outlet, and to maintain the existing pump characteristics.

The fill in the 100-year floodplain volume is very minimal with the proposed Tri-Level improvements. Based on the floodplain map (Figure 10.19), some fill in the floodplain will be required for proposed WB I-70 Connector between 1st and 2nd Streets. Compensatory storage for this volume will be provided along re-graded ditches in this area.

Additional project constraints include special considerations for flyover bridges. Since these did not affect the drainage of the non-bridge area, they are not included here.

Step 4: Select BMP Retrofit Alternatives

BMP selection is primarily targeted at the goal of managing runoff volumes to maintain existing pump characteristics at the BAPS as well as providing storage for floodplain fill. Volumetric BMPs that were evaluated include the following:

- ***Utilize re-graded ditches and ditch checks along the highways and within the ramp infield areas:*** Widen some ditches from 4 ft bottom widths to 8 to 10 ft. Allow 2 to 3 ft of standing water within the ditches at the ditch check locations.
- ***Provide detention storage within the mainline storm sewer systems along the highways:*** Some lateral pipe will be constructed with the proposed improvements, but most will have small diameters and have insignificant detention storage capacity.
- ***Construct new detention basin system within the ramp infield areas:*** Two possible sites were investigated but the tributary drainage area is small and basins will not detain enough runoff to meet the 100-year release rate requirements. Diversion of some runoff was considered, but existing sewer system pipes obstruct some connections.

Step 5: Practicality Assessment of Candidate BMPs

Cost Assessment

The overall estimated cost for the Tri-Level Interchange is $186.5 million, including re-graded ditches and detention basins (IDOT, 2008). Costs for the drainage components alone were not available from the resources reviewed. Providing detention storage within the mainline storm sewer system would add major costs if the existing mainline sewers were replaced and upsized or if a parallel storage pipe were constructed.

Maintenance Assessment

These costs include cleaning and maintaining ditches and drainage structures. Herbicidal applications will also be necessary for weed control.

Sizing and Performance

The ditches are sized to fit within the right-of-way for the highway and ramps. Areas where there is not sufficient ditch capacity will have detention basins such as the infield of ramp “O” (Figure 10.20).

Discussion and Lessons Learned

This project demonstrates that BMPs just for water quantity can be just as challenging in an ultra-urban area. IDOT engineers successfully modified existing drainage components, including pipes and ditches, to provide most of the storage needed for this project. Later phases of the project should provide information currently lacking about water quality considerations.

Acknowledgments and Project Contacts

Information regarding this project was generously provided by IDOT engineers, Michael Pritchett (Michael.Pritchett@illinois.gov) and Jennifer Hunt (Jennifer.Hunt@illinois.gov).

10.5 MnDOT Crosstown/ I-35 Highway Retrofit

Step 1: Project Scope

Background

Minnesota DOT (MnDOT) is providing comprehensive improvements to the I-35W and State Highway 62 (“Crosstown”) interchange. The limits of the project area are from 66th Street on the south, 42nd Street to the north, Penn

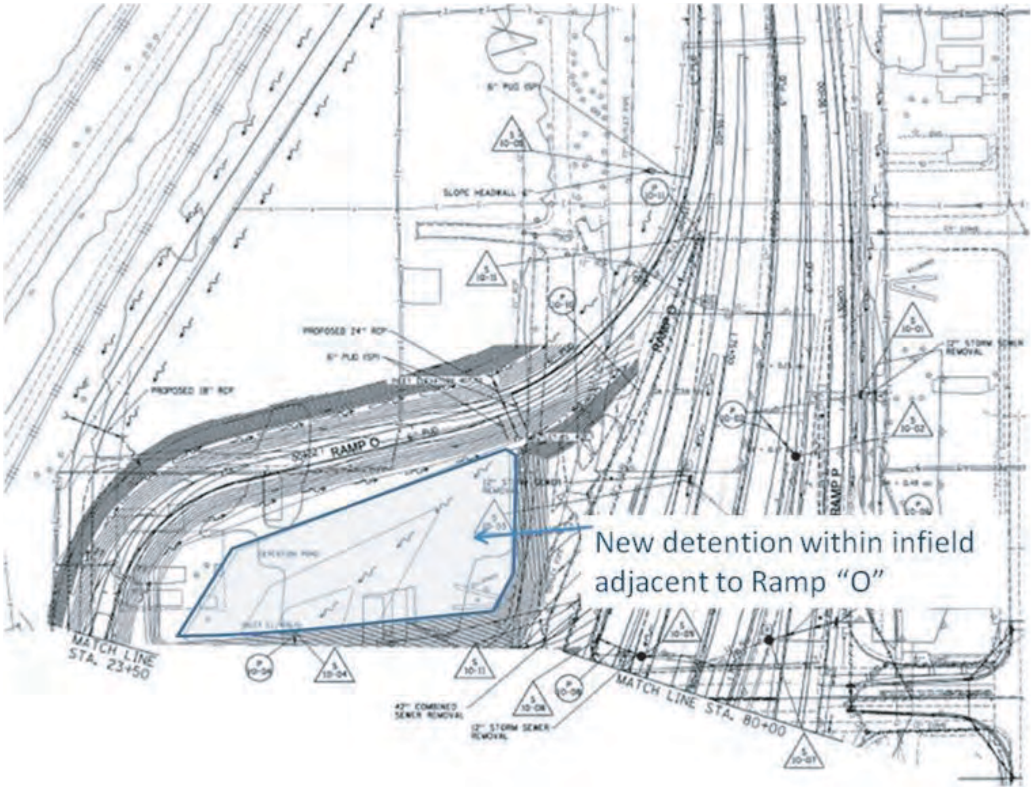


Figure 10.20. IDOT Mississippi bridge, ramp "O" infield detention basin.

Avenue to the west, and Portland Avenue to the east. The segment lies in a heavily urbanized area within and between Minneapolis and Richfield, Minnesota (Figure 10.21). This highway segment is in a suburban commuter corridor with an ADT of 130,000 to 150,000 vehicles. Land use adjacent to the highway is a mixture of residential and commercial. The goals of the project include increasing road capacity, providing continuous high-occupancy vehicle (HOV) lanes, improving safety by eliminating left-lane exits, and reducing traffic diversions to local streets.

Existing Treatment

Stormwater treatment along the highway segment is currently accomplished by routing runoff through existing urban lakes and wetlands (Figure 10.22). The lakes and wetlands provide water quality benefits but are not engineered treatment BMPs.

Water Quality Issues of Concern

The project receiving waters include Diamond Lake, Minnehaha Creek (construction stormwater runoff), Richfield Lake, Grass Lake, Legion Lake, and the Mississippi River. Several of these water bodies are impaired. While the majority of stormwater runoff entering these water bodies comes from the residential and commercial facilities, the highway runoff does contribute, and MnDOT does play a role in providing treatment from the runoff of the highway. The major water quality issue for the project receiving waters is the presence of sediment, floating debris, and phosphorus.

Regulatory Requirements

The primary regulatory drivers for water quality in this project are the CWA, Minnehaha Creek Watershed district permit compliance, and Minnesota Pollution Control Agency permit compliance. Since 1995, the design has been refined with a combined Environmental Assessment (EA) and Environmental Assessment Worksheet (EAW) document. This format is adopted when a project meets both state and federal thresholds for environmental review. The EA/EAW document consists of a completed state EAW embedded into a more detailed and comprehensive federal EA document. The EA/EAW document evaluated the physical, social, and economic impacts associated with the design plans. The key issues addressed in the EA/EAW include:

- Traffic;
- Noise;
- Air quality;
- Water resources (runoff and encroachment on water bodies);

Figure 10.21. MnDOT I-35 retrofit, project location.

- Cultural resources, including historically significant sites and buildings;
- Construction impacts;
- Right-of-way;
- Parks; and
- Visual/aesthetics.

After reviewing comments received on the EA/EAW published in July 2004, MnDOT determined that all state requirements for environmental review of the I-35W/Highway 62 reconstruction project had been met, and the FHWA approved a "Revised Record of Decision."

Step 2: Define Retrofit Objective

Treatment Objective

The regulatory compliance objective was to address sediment loading and floatable debris. To meet this objective, MnDOT sized treatment BMPs to treat all runoff from the project. The project will provide stormwater treatment for the entire roadway, which includes treatment for the new lanes and improved treatment for the existing lanes and shoulders.

Flow Control Objective

The presence of a storm tunnel that leads to the Mississippi River complicates the treatment issues as well as safety issues to the traveling public. As the tunnel fills with stormwater and flow characteristics change from open channel flow to pressure flow, a geyser occurs in the median of I-35W where access shafts to the tunnel are located. Storm tunnel surge chambers are incorporated into the project.

Step 3: Characterize Site Conditions and Constraints

Site Conditions and Constraints

MnDOT identified the following site conditions and constraints:

- Existing city roads and residential development near the highway limit the possibility of ROW acquisition on both sides of the highway.
- Proximity to lakes, streams, and wetlands limits treatment practices.
- Traffic routing through the site during construction is difficult.

Retrofit Design Constraints

To assess BMP design constraints, MnDOT designers coordinated with pavement construction and maintenance personnel. The following BMP design constraints were identified:

- Staging the project to provide through traffic and safe conditions and to maintain stormwater treatment during construction.
- Siting treatment BMPs to provide safe access for maintenance.
- Dealing with localized high water table affecting residential and commercial buildings.

Step 4: Select BMP Retrofit Alternatives, and Step 5: Practicality Assessment

Candidate Treatment BMPs

BMP selection was primarily targeted at the goal of reduced pollutant loading in highway runoff. Seven tributary areas

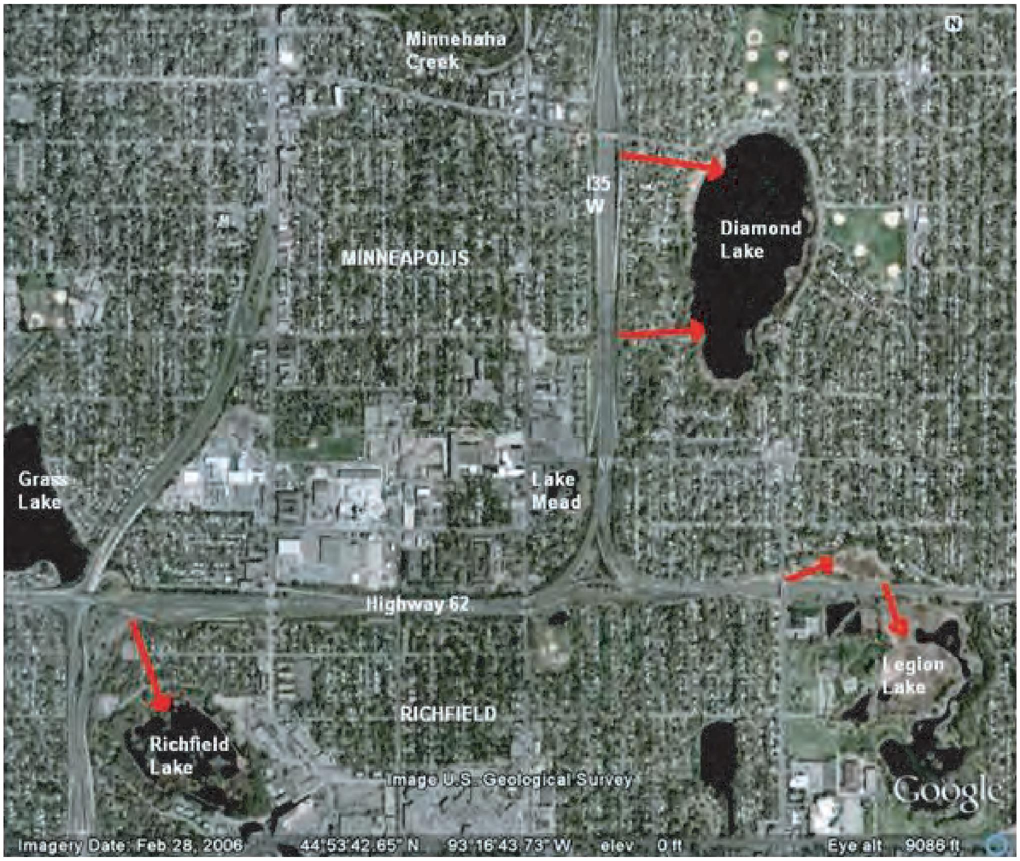


Figure 10.22. MnDOT I-35 retrofit, existing lake and wetland outfalls.

need some type of treatment prior to discharging stormwater into five water bodies. One of the practices for treatment is a partnership with the cities of Minneapolis and Richfield to build lined regional ponds and ring treatment systems upstream of the existing water bodies. Installing grit chambers to capture floating debris and larger particles, modifying wetlands to include forebays and naturalized wetland treatment systems, and modifying existing storm sewer outlets with grit chambers and forebays to capture larger sediment particles were among the other treatment practices.

Ring Ponds

Ring ponds (Figure 10.23) were designed in cooperation with the City of Richfield. This system captures sediment via a moat system that surrounds the lake. This system acts like a long linear sediment trap that provides the detention time for particles to settle from stormwater. Periodic maintenance will be needed to clean the sediments from the ring pond.

Grit/Swirl Chambers

Grit chambers are located along I-35W at 46th Street and 42nd Street to help pretreat stormwater entering the storm tunnel that leads to the Mississippi River. Three grit chambers are located on I-35W at Diamond Lake Road to pretreat stormwater entering Diamond Lake. Two of these are to capture I-35W stormwater and one is to capture City of Minneapolis stormwater. Grit chambers are located along city streets to pretreat the city's stormwater contributions to outfalls at Diamond Lake and Ferdinand Pond. The designers did not select specific designs or proprietary systems for the grit chambers. Rather, they developed detailed design attributes for selected parameters and performance specifications in the contract for the grit/swirl chambers as follows:

- The structure shall provide the means to remove and contain sediment and floatables—including buoyant objects,

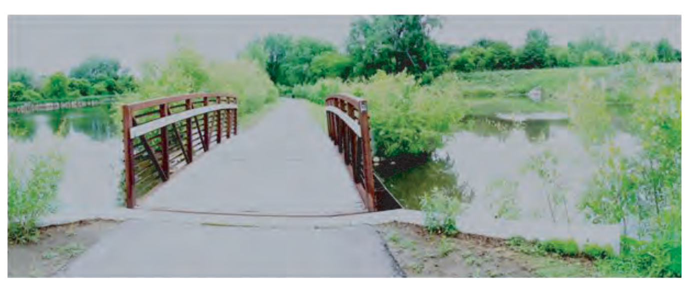


Figure 10.23. MnDOT I-35 retrofit, ring ponds in Richfield Lake.

oils, and fuels—from stormwater runoff during frequent wet weather events. The structures must be capable of 80% removal of TSS on an annual average basis based on the gradation analyses. The structures must remove oil and grease from the stormwater runoff without the use of special sorbent material.

- The units must be non-mechanical and gravity-flow driven, requiring no external power. The units must not block-clog or have a reduction in treatment capacity during normal operation. The units must treat all flows up to the treatment flow rate listed in Table 10.2 before bypassing any flow. The structures must be designed to bypass the design flow for the storm sewer system listed below without resuspension of captured material. The manufacturer shall be required to carry out a backwater analysis of each proposed installation to ensure that the head required to drive the separation process does not lead to flooding problems upstream of each unit. The manufacturer shall review the results of the backwater analysis with the project engineer.
- The structures shall be equipped so as to regulate the flow rate into the treatment chamber and convey high flows to the outlet in a manner that will not cause scour and/or resuspension of sediment materials previously collected. The sediment chambers shall not be compromised by temporary backwater conditions (e.g., trapped pollutants shall not be scoured and re-suspended during backwater conditions). The units must permanently retain all captured material for all flow conditions of the storm drain to include flood conditions, until removed through routine maintenance.
- The structures shall be designed and constructed so that they can be inspected and maintained from the surface without requiring entry into the structure. All access covers shall be clearly marked to indicate that the structures are for retaining oil and sediment.
- The storage sumps must be sized so that they are capable of storing a volume of material that would allow the units to be fully functional if cleaned only one time per year, at equal intervals. The manufacturer shall review the storage requirement of the devices with the project engineer. The storage sumps shall be designed to accommodate an amount of sediment determined by the loadings given by the Nationwide Urban Runoff Program study or the volume of litter as determined by Armitage and Rooseboom (2000), whichever results in the greater volume requirement.
- The manufacturer of the structures must submit details and shop drawings of sufficient detail for the project engineer to confirm that no available flow paths exist that would allow the passage of an object greater than 2.4 mm. The structure must remove all neutrally buoyant materials in all flows up to the treatment flow rate listed in Table 10.2 before bypassing any flow. Additionally, the manufacturer must submit a "Manufacturers Performance Certificate" certifying that the units achieve the specified removal efficiencies listed in these specifications.
- The manufacturer of the structures must guarantee the units free from defects in materials and workmanship for a period of 1-year following installation. Equipment supplied by the manufacturer must be installed and used only in the particular application for which it was specified.

Stormwater Detention Ponds

Stormwater ponds are located at the west and east commons areas of I-35W and Highway 62. The west commons pond (Figure 10.24) is surrounded by retaining walls making maintenance somewhat of a challenge. A maintenance access road is incorporated into the design that is out of traffic flow. The outfall of this pond is to Richfield Lake.

Flow diversion weirs were constructed at Grass Lake to divert low flows with the majority of the pollutant load to the west commons pond and Richfield Lake perimeter pond system for treatment but yet convey high flows into Grass Lake to largely maintain existing water balance.

East common stormwater ponds are located at the northwest quadrant of I-35W and Highway 62. These ponds were

Table 10.2. MnDOT I-35 retrofit, hydrological data.

Design Special No.	Structure No.	Location	Drainage Area (acres)	Runoff Coeff	T_c (min)	Design Bypass Event	Design Bypass Flow (ft^3/s) [treatment flow]
12	B5234	Southbound I-35W at Diamond Lake Road – south of bridge	9.9	0.84	11	10-year	41.4
13	B5296	Northbound I-35W at Diamond Lake – low point north of bridge	11.9	0.86	12	50-year	78.1
14	B5289	Municipal area southwest of I-35W/ Diamond Lake Road	15.9	0.60	14	10-year	48.7
15	C5124	Municipal area north of Ferdinand Pond	22.1	CN = 74	34	10-year	28.7
16	B5474	I-35W low point at 46th St.	28.9	0.83	14	50-year	158.8
17	B5527	I-35W low point at 42nd St.	28.6	0.80	13	50-year	158.4

Figure 10.24. MnDOT I-35 retrofit, construction of the west commons pond, located beneath an elevated highway section.

designed in cooperation with the City of Minneapolis to capture and treat city and highway stormwater runoff. These ponds were named Powell and Lake Mead. The drainage area of Powell Pond is 35 acres and Lake Mead Pond is 170 acres. These ponds are lined so that neighboring homes would not be impacted by any groundwater effects from pond water elevations and they would be isolated from suspected contaminated soils on the site. Apparently this area was prone to flooding prior to the construction of Lake Mead by the Minnehaha Creek Watershed District and Minneapolis. The outlet of these two ponds is to Diamond Lake with an overflow to Ferdinand Pond/Legion Lake.

The eastern-most pond system (Figure 10.25) is combined with a wetland enhancement for a naturalized treatment system. This system is located at the northeast quadrant of

Figure 10.25. MnDOT I-35 retrofit, stormwater pond and wetland complex.

Figure 10.26. MnDOT I-35 retrofit, treatment forebay to Diamond Lake.

Highway 62 and Portland Avenue and is named Ferdinand Pond. The drainage area for Ferdinand Pond is 72 acres. The main treatment is a forebay pond with access for maintenance. Stormwater is routed through a wetland area prior to discharge to the Legion Lake wetland area located south of Highway 62 and Portland Avenue.

A treatment forebay (Figure 10.26) is designed at the outfall to Diamond Lake and Diamond Lake Road. This treatment is to further capture sediment from stormwater before it enters the lake. The total I-35W drainage area contributing to Diamond Lake is 40 acres. Access to this forebay is provided for maintenance activities. The outlet of Diamond Lake is to Minnehaha Creek.

Surge Chambers

Two stormwater surge chambers (Figure 10.27) were constructed in the median of I-35W at 39th and 35th Streets. The purpose is to relieve stormwater pressure during storm events that create an air/water surge when the tunnel flow is transforming from open channel to pressure flow. The contributing drainage area from I-35W that has treatment from grit/swirl chambers is 54 acres. A contributing drainage area of 377 acres of surrounding city neighborhood to the 39th Street dropshaft remains untreated. The I-35W/I-94 stormwater tunnel has a total tributary area of 4.9 mi^2. The outfall of this storm tunnel is the Mississippi River located 3.8 mi north from the project.

Maintenance Requirements

MnDOT design engineers coordinated with maintenance personnel to develop a BMP design with acceptable mainte-

Figure 10.27. MnDOT I-35 retrofit, storm tunnel surge chamber construction.

nance requirements. Routine maintenance practices for the grit chamber design are anticipated to include litter pickup and vacuuming the sediment when the chamber is filled. Locations for access to ponds were coordinated with city and MnDOT maintenance staff.

Summary and Discussion

MnDOT developed a comprehensive BMP plan as part of a large highway improvement project in a space-constrained urban setting. The plan includes a variety of BMP approaches and implementation strategies to meet both water quality and hydraulic control objectives. The following activities supported development and implementation of the BMP plan:

- **Coordination with adjacent municipalities:** The most significant strategy in forming the BMP plan is the substantial use of off-site regional BMPs. MnDOT coordinated with the cities of Minneapolis and Richfield to develop BMPs that would address common water quality issues related to commingled runoff. The benefits to MnDOT from this approach were (1) the availability of off-site areas to treat highway runoff, which would otherwise have been difficult to accomplish within the highway ROW; (2) assistance and cost savings in ROW acquisition for locating BMPs; and (3) streamlining of the project due to shared water quality goals and benefits. Coordination between MnDOT and the cities was sensible and mutually beneficial. The regional BMPs helped to achieve DOT treatment objectives for new and existing highways facilities, helped to provide retrofit treatment of urban development areas, and are less costly for both installation and operation/maintenance than would have been with separate DOT and city projects.
- **Opportunistic BMP siting:** The diversity of approaches in the BMP plan suggests a willingness by MnDOT to pursue an array of BMPs opportunities, which is a key retrofitting strategy. Although infiltration techniques were considered, it was determined early on that existing groundwater table height issues made infiltration not feasible. The diversity of BMP approaches encompass:
  - *BMP development:* MnDOT worked with the City of Richfield to develop ring ponds for treating of urban and DOT runoff prior to its discharge to receiving lakes. The ring ponds are adapted to the existing space availability and runoff conveyances, providing a low-cost approach for retrofit treatment by detention and sedimentation.
  - *Enhancement of existing BMPs:* Where opportunities were identified, MnDOT modified existing BMPs to improve treatment capability and maintenance functions. These modifications included the construction of sedimentation forebays to existing detention ponds and the enhancement of existing wetland systems for water quality treatment.
  - *Construction of new surface BMPs:* MnDOT in cooperation with the City of Minneapolis acquired ROW for constructing new detention basins that would treat urban and DOT runoff.
  - *Limited use of underground BMPs as necessary:* MnDOT selected underground hydrodynamic systems for pretreatment and outfall retrofits in locations where opportunities for new surface BMPs or BMP enhancements were not practical.
- **Bid specifications for proprietary BMPs:** MnDOT's approach to selecting proprietary BMPs was to develop detailed bid specifications and then to work with manufacturers during bid selection. The advantage of this approach is that it simplifies and streamlines evaluation of BMPs to a limited number of BMP manufacturers that have assessed the specific project requirements. The bid specifications for hydrodynamic separators in this project were both stringent and comprehensive. They included (1) the ability to meet prescribed design flows and treatment performance; (2) a requirement for no resuspension and washout; (3) the ability to safely maintain the BMPs; (4) sufficient sump storage capacity to limit cleaning frequency to 1 year; and (5) certification of treatment performance.

Acknowledgments and Project Contacts

The project was designed by SRF/HDR under the direction of David Filipiak. John Griffith was the MnDOT Project Manager and the contact with the cities of Minneapolis and Richfield. Construction administration/inspection was provided by MnDOT under the direction of Steven Barrett.

Information regarding this project was provided by Brett Troyer (brett.troyer@state.mn.us) of MnDOT.

10.6 District of Columbia Department of Transportation Interchange Retrofit Evaluation

Step 1: Project Scope

Project Description and Location

This project was to develop strategies for water quality treatment and volume reduction in areas of open space within the ROW. Interchanges and cloverleafs typically have large areas of managed landscapes, woods, or grass outside of the clear, or safety, zones where BMPs can be installed as retrofits. The District of Columbia (the District) has a limited number of grade-separated interchanges due to the highly urbanized and developed area that existed prior to the development of the highway system. The District has both separate and combined storm and sanitary sewers.

The District of Columbia Department of Transportation (DDOT) stormwater management quality design and construction efforts began in 1994 as part of the requirements for the overall Phase I NPDES permit. The current NPDES permit requires District public agencies to incorporate LID techniques into their design and construction program. DDOT published design guidelines and standards for the use of LID techniques in 2004 as part of the overall Anacostia River Waterfront design standards for street construction. These standards are now being developed and incorporated into new DDOT construction projects throughout the highway system. The use of these techniques is also required for streetscape improvements on private sector land development projects.

Practically all of the construction activities for DDOT are reconstruction and rehabilitation projects in the existing ROW. The city is almost completely built out. DDOT is in the process of developing detailed specifications and standards for LID retrofits of street projects in order to meet the above-listed NPDES requirements. These standards will be based on the guidelines developed from the Anacostia Waterfront Initiative Transportation Standards (DDOT, 1994). This retrofit project is one of a series of pilot projects that DDOT has been constructing in order to develop LID retrofits standards. The project includes the implementation of non-structural practices as well.

The retrofit project is to construct non-structural and structural techniques inside a cloverleaf interchange. The project is located at the intersection of North Capital Street and Irving Street in the District. North Capital Street is a major arterial that runs north and south through the city. Irving Street is a major arterial that runs east and west in the upper portion of the city. Figure 10.28 is an aerial view of

Figure 10.28. DDOT interchange retrofit project, aerial view.

the cloverleaf during the construction of the retrofits. Figure 10.29 is a photograph of the northeast quadrant of the cloverleaf before construction. The retrofits were constructed on the northeast and southeast quadrants of the interchange. A reforestation, or the planting of trees in areas where they had not previously existed, was used as a non-structural technique in the northeast quadrant. Bioretention cells were constructed as a structural technique in the northeast and southeast quadrants.

Receiving Waters and Issues of Concern

Runoff from the District drains to the Anacostia River to the east and the Potomac River to the west. The Anacostia is one of the most heavily polluted and impaired watersheds in the United States and is affected by a wide range of chemical and biological impairments caused by urban and agricultural point source and non-point source runoff. Urban runoff from the District includes point sources from treatment plants and industrial activities, combined sewer overflows, and non-point source runoff. This includes, but is not lim-

Figure 10.29. DDOT interchange retrofit project, before construction.

ited to TSS, bacteria, metals such as copper and zinc, PCBs, and oil and grease.

Regulatory Requirements

The primary stormwater regulatory requirements are focused on compliance with the current Phase I NPDES permit, the existing long-term control plan to eliminate combined sewer overflows, and the upcoming wasteload allocations for the TMDL implementation plan that is currently being developed. The NPDES permit is the compliance document and guidance for these programs. Four public agencies are jointly responsible for the implementation of the permit: the District Department of the Environment (DDOE), the Department of Public Works, the Department of Transportation (DDOT), and the District of Columbia Water and Sewer Authority. In the NPDES permit, public construction—including DDOT projects—uses the following planning and design elements:

- A shift in focus by public agencies from the use of traditional stormwater controls, which are still allowed under the local stormwater ordinances and guidelines, to programs that encourage the use of functional landscape to enhance the aesthetic and habitat value at new parking lots and/or new developments.
- Encouragement of the use of LID practices such as improved tree boxes, infiltration trenches, porous pavements, grassy swales, and filter strips where appropriate. In addition, DDOE and DDOT are going beyond permit requirements by working together to construct green streets.
- Coordination of street sweeping and catch basin cleaning that optimizes reduction of stormwater pollutants.
- Coordination of solid waste services, including leaf collection.
- Preventative maintenance inspections for all existing stormwater management facilities.
- Development and implementation of a rain leader disconnection program, also known as downspout disconnection.
- Development of a multi-faceted approach to stormwater public education, which includes collecting pet feces and environmentally friendly fertilizing and landscaping techniques.
- Modeling of storm water impacts.
- Development of a simple method for measuring the performance of these activities.
- Strengthening of the erosion control program for new construction.

The District currently encourages the use of LID and functional landscapes in new development and encourages retrofits in existing development by working with sister agencies, federal land owners, and private commercial and industrial land owners. For residential property, DDOE has an incentive program for homeowners called "RiverSmart Homes," which encourages them to incorporate LID practices on their property. The District is working to go beyond the scope of traditional stormwater practices and is encouraging the use of functional landscape practices in all LID implementation. Mayor Adrian Fenty has authorized an aggressive tree canopy goal for the city. DDOE is working with sister agencies to construct green roofs, green streets, and green alleys on District and private property. In addition, the RiverSmart Homes program encourages homeowners to plant trees, conduct landscaping with native plants, and construct rain gardens on their properties.

Step 2: Determine the Retrofit Objectives

The retrofit objective for this project is to determine the most effective and efficient methods for the construction of two LID BMPs (bioretention and afforestation) that will be a mainstay of the DDOT stormwater management system. The project will utilize the existing storm drainage structure design standards and specifications for the construction of the BMPs. One of the challenges of retrofit projects, and with the implementation of new BMPs, is the use and/or modification of existing highway structure standards and specifications. The development of hydrologic and hydraulic design procedures, specifications for bioretention media mixtures, new plant lists, construction, inspection, and closeout procedures must all be developed for the successful use of these techniques. This project was used to document and evaluate potential modifications to existing standards or to identify the need for new standards.

Step 3: Characterize Site Conditions and Constraints

ROW Area and Utilities

The existing site is open and easily accessible for construction (Figure 10.29). There are minimal utilities in the construction area. The primary utilities are the electric lines for the lights in the cloverleafs and the existing storm drainage system.

Drainage

There are numerous storm drain inlets along the interior of the cloverleafs that are sized to properly intercept flows and reduce the spread of water across the road surface. There are three to four sets of curb inlets in each cloverleaf. Located in the interior of each cloverleaf is a yard inlet that collects runoff from the turf areas in the interchange. The runoff from these inlets is collected into a centralized system that drains to Irving Street.

Soils

The existing soils in the area are fill and are heavily compacted urban soils and clay loams. There is little capacity for rapid soil infiltration in these areas. There is virtually no organic horizon or topsoil in these areas. The grass is a sparse and poorly established typical urban bluegrass or fescue with many bare spots. This is probably the result of the poor productivity of the soils.

Design Constraints

This project has limited-space constraints, because of the large open areas and lack of utilities. The primary constraints would be the depth of the existing storm drain system and the safety and clear zones adjacent to the roadway. The site is limited for infiltration to reduce the volume of runoff for larger storm events because the facility would not have the capacity to drain and then respond to the storage and infiltration requirements for a subsequent rainfall event. Low runoff volume storm events could be accommodated through absorption of the runoff in the bioretention media, uptake of plants through evapotranspiration, or slow infiltration.

The requirement to use the existing standards for inlets, pipes, and inlet structures was the main design constraint. The current standards have deep inlets and large distances between the pipe inverts and the inlet throats. This is important because the design goal is to intercept and divert runoff to bioretention areas in the interior of the cloverleafs. Therefore, large drops in grade between the inlets and the bioretention cells can produce inflows with high erosive potential. The standard outfall protection uses large riprap that is meant to reduce velocities from larger storm drainage pipes and greater peak discharges than are meant to drain to bioretention cells.

Step 4: Select Retrofit Alternatives

There were no significant BMP alternatives evaluated for this site as the goal of this pilot study was to evaluate current design and construction standards for retrofit bioretention facilities. DDOT considers bioretention cells as a preferred structural method of treatment for small-scale open areas where space is available. There is confidence in the performance of these systems from DDOT and from the DDOE, which is the stormwater permit review agency. This confidence is based on extensive monitoring data on the effectiveness and reliability of the systems in the District and experience in the design, construction, and maintenance of the systems. Afforestation and reforestation are emerging practices in the DDOT BMP inventory. The TMDL wasteload allocation for nutrients and other programs, such as air quality, are encouraging the conversion of grass and lawn areas to woods. This strategy reduces runoff volume and, once established, the need for maintenance and mowing.

Step 5: Assessment

Bioretention Design

Figure 10.30 shows the grading plan from the inlets to the bioretention cells. Figure 10.31 shows some of the pipe profiles from the back of the inlets to the outfall at the bioretention cells. The cells are designed so that the runoff intercepted by the cell can be absorbed in smaller storms. In larger storms, or when the cell is saturated, the water is detained on the surface and then drains back into the existing drainage system. There are no underdrains.

Figure 10.32 shows the sites immediately after grading and during landscaping. The photograph shows the drop between the inlet structure and the bioretention cell and associated erosion protection and the overflow outlet that drains back to the inlet structure, completing the system, or loop.

Sizing and Performance

The District is using monitoring data to revise the standards for contributing area, pretreatment requirements, media type, and media depth. The initial bioretention design standards that were developed over 10 years ago had pretreatment areas and media depths of over 4 ft. They were also sized based on the requirement for the first inch of runoff volume from impervious area, without regard to the routing or rate of filtering of the runoff through the media. The size of riprap or outfall protection is also being reconsidered. Designs for shallow curb inlets and smaller yard inlets for the bioretention cells are also being developed.

Cost

The construction of bioretention cells and tree planting is very predictable in situations where there are no or limited space constraints and existing infrastructure/belowground contamination issues. The contingencies are typically for unmarked utilities or existing drainage structures that are in need of repair when modifying older systems. The costs of these systems are expected to be substantially reduced when the drainage structure standards are revised to reflect the hydrologic and hydraulic requirements of these small-scale systems, which have smaller pretreatment areas and media depths.

Maintenance

Minimal effort is required to provide guidance on how to operate and maintain bioretention systems. Proper plant

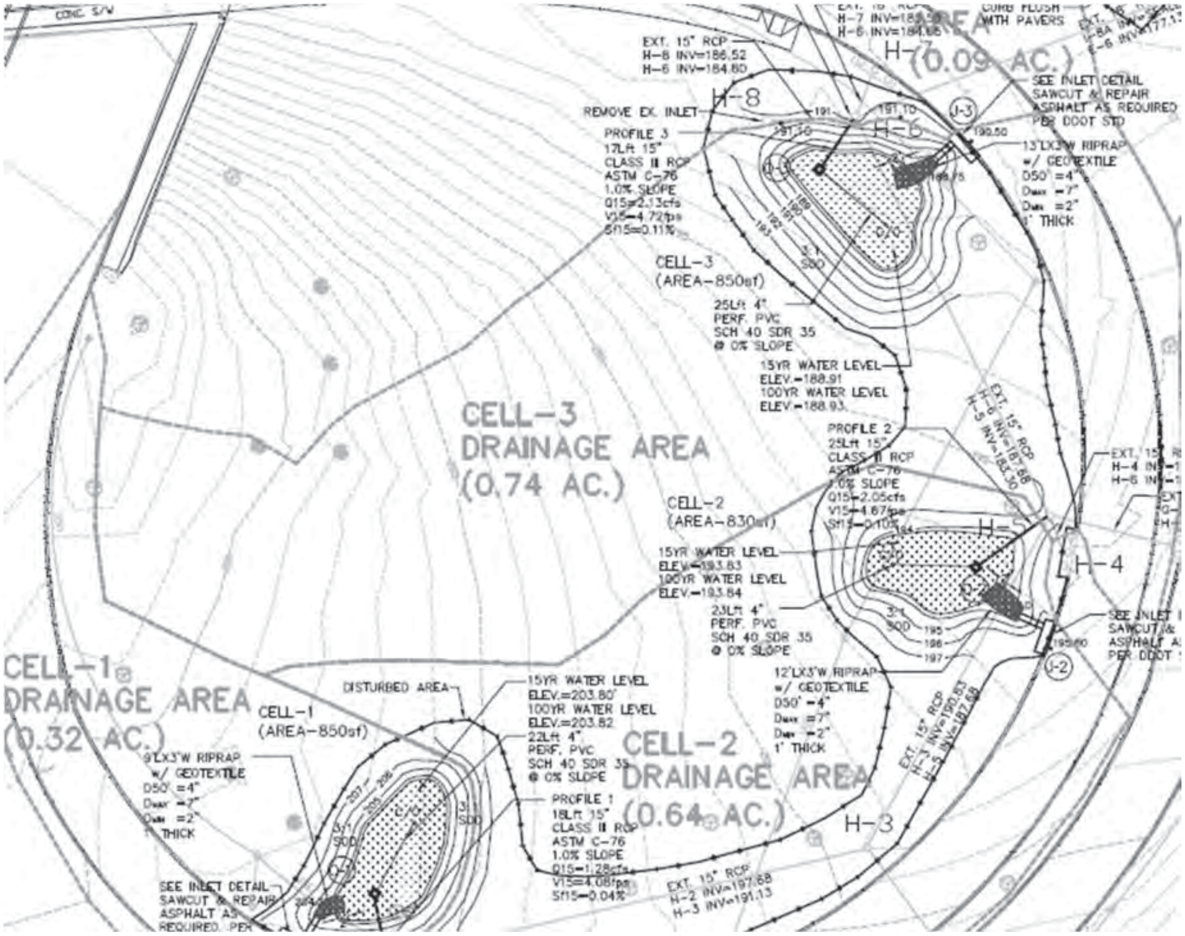


Figure 10.30. DDOT interchange retrofit project, bioretention grading plan.

selection for the establishment of wooded areas and bioretention cells is critical to establishing a healthy and regenerative self-sustaining landscape. The establishment of a stabilized contributing drainage area is also critical. Many sites fail because the vegetation on the surrounding construction is not established and sediment collects and chokes off the bioretention cells. Techniques such as compost filter berms, which can remain in place after construction, can provide longer-term sediment control protection for the facilities.

Traffic Control

One important issue in BMP retrofit construction is the maintenance of traffic and potential disruption of traffic flow and commerce. These sites were relatively accessible and did not require lane closures because of the wide ramp widths.

Discussion and Lessons Learned

The goal of the project was to evaluate the current construction processes, standards, and details. Many lessons were learned during the design and construction of the systems, particularly on erosion and sediment control issues. DDOT construction projects are typically awarded to the lowest qualified bidders. Specifications must be very explicit and the materials must be readily available. Construction inspectors must also have sufficient training and background in the identification of materials and construction procedures and sequencing. During the construction several material substitutions were made that would have significantly affected the performance of the bioretention cells. This includes media that did not meet the specifications and the use of non-permeable geotextiles in place of drainage fabric in the bioretention cells. Some of the plant species were also substituted with inferior species or improper sizes. The construction team was debriefed and potential modifications to the standard specifications were developed.

Acknowledgments

Information regarding this project was generously provided by DDOT and DDOE.

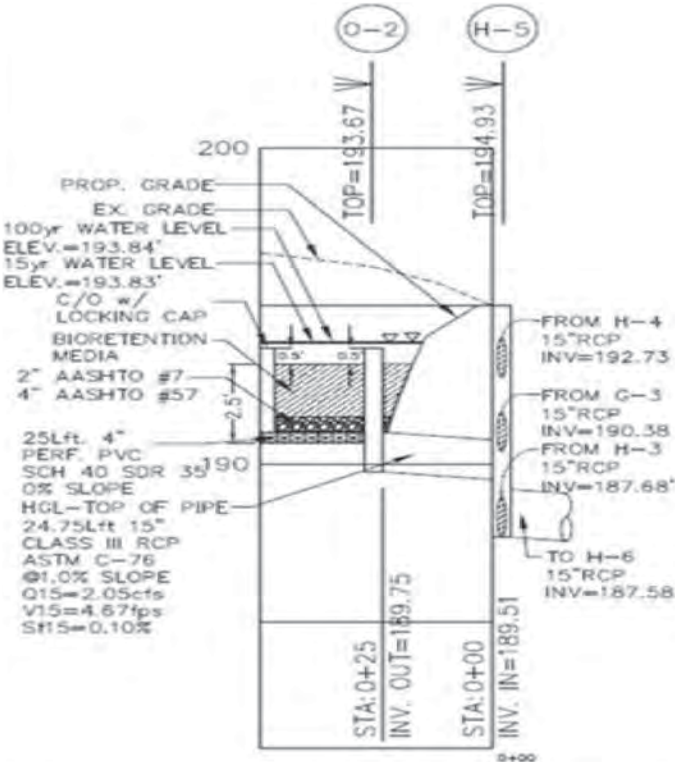


Figure 10.31. DDOT interchange retrofit project, storm drain profile.

10.7 Maryland State Highway Administration Concrete V-Ditch Conversion Pilot Study

Project Scope

Background

The Maryland SHA manages approximately 14,500 lane-miles of highway throughout the state and owns approximately 25,000 acres of impervious area. The State of Maryland Department of the Environment (MDE) is the review authority of the overall Phase I NPDES permit held by SHA and for individual construction projects. A requirement of the NPDES permit is that SHA is to provide water quality treatment for a significant amount of existing impervious area within the ROW.

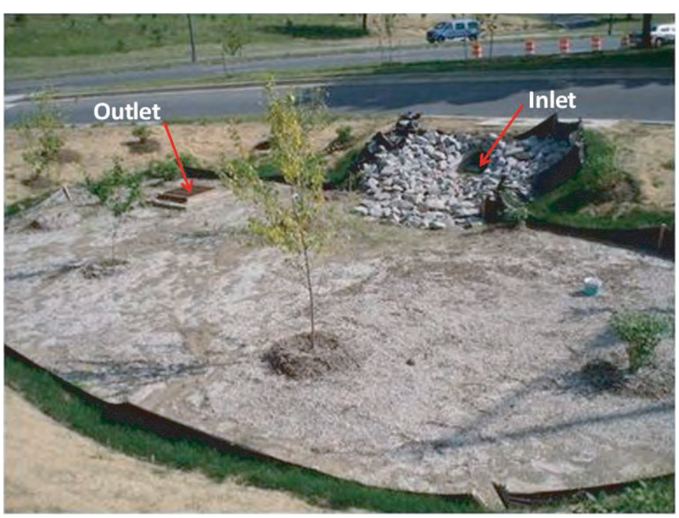


Figure 10.32. DDOT interchange retrofit project, constructed bioretention cell.

The water quality treatment standard in Maryland is 80% TSS removal and 40% TP removal for new projects. The state uses a presumptive approach for water quality compliance. The MDE stormwater handbook (MDE, 2009) gives treatment credits for the use of grass swales provided the swale has a certain drainage area and geometric characteristics. The design criteria include limitations on the tributary drainage area, a 2 ft bottom width, and a pretreatment grass filter strip. The design requirements were not specifically developed to address the unique requirements of linear highway environments.

A significant amount of runoff from SHA roads is conveyed by concrete V-ditches that outfall to streams without any water quality treatment. Conversion of the concrete ditches to grass swales can potentially achieve retrofit treatment of existing ROW required by the NPDES permit. However, the MDE design requirements for grass swales are particularly onerous for retrofit projects that have complex drainage conditions and limited ROW that are typical of ultra-urban highways. The goal of this project was to test alternative (narrower) swale designs that would achieve the water quality treatment requirements and would be more amenable for concrete V-ditch conversions in areas with typical limited width available for use as a swale.

Project Description and Location

This research project evaluated the treatment effectiveness of two swale designs within the existing highway ROW. One was based on the standard MDE design criteria. The other was based on a modified design that is suitable for retrofitting concrete V-ditches and their typical location in areas with limited width. This design includes a reduced bottom width, soil amendments, and a limited filter strip. The swales were constructed in paired watersheds, or watersheds with similar drainage and land use characteristics, in order to compare the effectiveness of the water quality treatment for each system and to determine the optimal design and construction parameters for the modified swale and the potential to use it to replace or be a substitute for existing concrete swales. To accommodate side-by-side testing of the two swale designs, the project is located within the median of Route 32; a four-lane highway in Howard County, Maryland. Figure 10.33 shows an aerial view of the project location.

Figure 10.33. SHA V-Swale testing study location.

Receiving Waters and Issues of Concern

The preservation and restoration of the Chesapeake Bay and its tributaries are the primary water quality concerns in the region. Major urban centers of concern to Maryland SHA are the Washington DC and Baltimore metropolitan areas. There are myriad potential impairments that are generated by stormwater impacts from highway drainage and runoff. These include nutrients, sediments, bacteria thermal impacts, and hydromodification. The state uses a tiered system to classify the uses of water, ranging from non-contact to high-quality water contact, and habitat preservation in order to determine water quality management strategies. There is also a number of waters listed as impaired under the §303 (d) of the Clean Water Act. TMDL strategies are now being developed for these waters. The project watershed is a tributary to the Chesapeake Bay and is listed as being impaired for cadmium, nutrients, sediments, and stream biology. It is also classified as contact recreational water and has reaches that are potential habitat for sensitive aquatic species.

Regulatory Requirements

A requirement of SHA's Phase I NPDES permit is to provide water quality treatment for a significant percentage of the existing untreated runoff from the roadway impervious areas. However, the NPDES permit includes provisions for establishing and maintaining a water quality bank, or offsets, to mitigate the impacts of new projects within a watershed when the physical constraints or ROW limitations would preclude the construction of BMPs (i.e., space constraints in ultra-urban highway). SHA has the opportunity to provide water quality treatment within the same watershed. Conversion of concrete V-ditch to grass swales in association with the water quality offset allowances is a potential approach for meeting retrofit treatment requirements in ultra-urban highways.

Pilot Study Objectives

One of the challenges for the SHA stormwater program is to design and maintain BMPs to meet NPDES requirements for TSS and TP removal and address the need to reduce pollutant loads for TMDL waste load allocations within a watershed. BMPs that can be used to reduce runoff volume (and the resultant pollutant load) and treat, or mitigate, biological, chemical, and thermal impacts with minimal operating and maintenance costs are essential. These characteristics are found in LID BMP types, such as swales, bioretention cells, and bioslopes. The challenge addressed by this project is to identify and test procedures for applying such LID practices in narrower, space-limited settings.

The objective of the pilot study is to determine if the narrow swale design can meet or exceed the treatment performance standards of the conventional swale designs (80% TSS removal and 40% TP removal). A second objective is to determine if the narrow swale design can also reduce the volume and loading of metals, stormwater volume, and energy for future TMDL compliance. The data generated from the pilot study, including design and construction procedures, will be used to develop improved design standards for swales that are applicable to new construction and V-ditch retrofits. V-ditch retrofits can potentially be used to meet NPDES retrofit requirements in ultra-urban areas through allowable water quality offsets.

Pilot Study Site Conditions and Constraints

ROW Area and Utilities

The pilot study site is located in the median between the travel lanes. There is an expansive ROW with gently sloping side slopes off the travel lanes. The area has been disturbed and graded for the road construction. There are no utilities or woody vegetation in the project area.

Soils and Vegetation

The soils are sandy or a sandy loam that has been compacted from roadway grading operations. There is a minimal depth of topsoil that was spread over the graded areas in order to establish vegetation in the project area. There is no woody vegetation in the project area. The vegetation is the standard fescue grass mix that is used by SHA for permanent stabilization. The area is mowed several times during the growing season. There are some bare spots of soil that produce TSS.

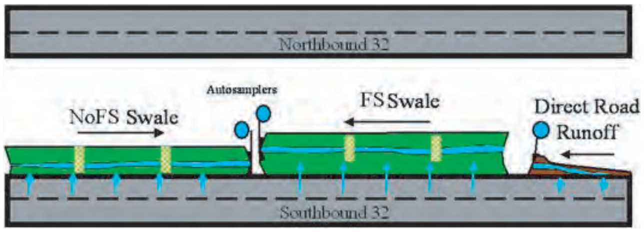


Figure 10.34. SHA swale testing study layout.

Design Constraints

This project has limited design constraints; because of the lack of utilities and wide median, many of the design constraints found in narrower ROWs are not present. Construction access and maintenance of traffic issues were also minimal.

Pilot Study Design

Layout

Figure 10.34 shows a schematic of the pilot study layout, and Figure 10.35 shows photographs of the standard swale design in the media and the modified design. The standard swale design includes a filter strip adjacent to the swale, whereas the modified design excludes the filter to produce a narrower footprint. Both swale systems include earthen check dams, which are used to slow the velocity of water and encourage infiltration.

The study layout has three water quality sampling locations shown as circles in Figure 10.34. One sampler is dedicated for water quality measurements of direct road runoff, which is assumed equivalent to the influent quality to both swale systems. The other two samplers measure the effluent quality and flow from the two swale systems.

Design and Sizing

The design of the swales and the adjacent slopes had to meet or exceed the state and AASHTO design guides for roadside landscape and geometry (AASHTO, 2006). The systems have earthen check dams with grass incorporated into the design (see Figure 10.35). Check dams are already in use in the SHA inventory. They are typically constructed out of compacted earth berms that have established grass areas from sodding or well-planned and -constructed seeding. Rock or wooden check dams are typically not used because they are more difficult to mow around and maintain.

Standard hydraulic design criteria from the SHA Highway Drainage Manual, the Maryland Department of the Environment Stormwater Management Manual (MDE, 2009) and the State of Maryland Erosion and Sediment Control Manual (MDE, 2005) were used to size the swales and the check dam spacing and size. The design criterion includes a buffer between the highest water level in the swale and the adjacent pavement

Figure 10.35. Standard swale design in the media with adjacent minimal filter strip (left); modified narrow swale design without filter strip (right).

Table 10.3. Design parameters of the study swales and channel.

Parameter	Direct Channel	Standard MDE Swale with Check Dams	SHA Modified Swale with Check Dams
Roadway drainage area (ha)	0.271	0.225	0.224
Swale area (ha)	0	0.431	0.312
Total area (ha)	0.271	0.656	0.393
Channel material	Concrete	Grass	Grass
Channel slope	0.2%	1.2%	1.6%
Channel length (m)	168	137	198
Pretreatment slope	–	6%	–
Pretreatment width (filter strip) (m)	–	15.2*	–
Number of check dam rows	–	3	3
Thickness of each check dam (m)	–	0.914	0.914
Bottom width of check dam (m)	–	0.610	0.610
Total width of check dam (m)	–	variable	variable
Distance between two check dams (m)	–	60.5	59.8

*from roadway to channel center

subgrade. Table 10.3 lists the design parameters for the direct runoff from the concrete channel, the design from the current stormwater manual standards, and the enhanced swale.

Maintenance

Minimal effort is required to operate and maintain swale systems. The swales typically require mowing a few times per year.

Enhancements

Since the goal of the project is to use the lowest cost modifications to the geometry and vegetation, additional design modifications—such as compost-amended soils, bioswale channel bottoms, and other amendments, such as oxide coated sands to bind metals—were not included in the designs. Enhancements may also include modifications to construction techniques, such as fertilization, seed mixture, aeration, and compaction. Design and construction enhancements are most applicable for areas where treatment goals require advanced treatment considerations, such as retrofits addressing TMDL wasteload allocations.

Cost

The construction of swales and modified swales with check dams is very predictable. SHA has extensive experience in the design of these systems. These modified designs may ultimately result in major cost savings because less ROW or easements are required due to the reduced cross sectional area of the "V" section instead of the trapezoid section that is currently required. The additional cost of potential design and construction enhancements is considered minimal and would require only minor changes to procurement and design specifications.

Pilot Study Monitoring and Results

Findings

Water quality samples were collected using an automated sampler for four storm events for the standard MDE swale and the SHA modified swale. Table 10.4 shows the water quality results. For the four storm events, the study demonstrates that there are significant benefits from the swales for the constituents of concern. The modified swale design, without the buffer, performs as well or better than the current MDE design standard. It should be noted that the standard MDE swale produced more TSS during the June 3, 2009, storm event than the concrete channel. This is probably because of the poorly established grass in portions of the drainage area. The swale designs also facilitate infiltration and reduction of the total mass and energy of the stormwater runoff.

Significance for Retrofits

New BMPs that are required for regulatory compliance and resource protection are extremely expensive to construct and difficult to design when using the existing prescriptive design methods and requirements. These challenges motivated engineers to consider if design adaptations that can reduce the requirements for wide pretreatment filter strips and channel bottom width are feasible and appropriate. To successfully accomplish this goal, multiple tasks were required. This included a monitoring study to initially assess water quality benefits of the modified design over the

Table 10.4. Pilot study monitoring results.

Storm Event	Total Rainfall (in.)	Location	Solids (mg/L)	Nutrients (mg/L)				Total Metals (µg/L)				Cl^- (mg/L)
			TSS	NO_3^--N	NO_2^--N	TKN	TP	Pb	Cu	Zn	Cd	Cl^-
April 29	0.12	Direct	139	0.65	0.18	9.3	0.54	17	60	320	0.4	NA
		MDE				No outflow						
		SHA				No outflow						
May 16	0.33	Direct	68	1.05	0.03	1.4	0.39	11	32	250	0.2	56
		MDE				No outflow						
		SHA				No outflow						
June 3	1.75	Direct	145	0.76	0.04	3.7	0.99	21	64	650	1.0	16
		MDE	162	0.34	0.05	1.9	0.36	21	18	24	0.2	45
		SHA	45	0.38	0.02	1.9	0.24	6.5	10	45	0.5	29
July 1	0.52	Direct	183	0.67	0.03	6.8	1.10	19	48	1200	0.9	26
		MDE	80	0.36	0.03	1.5	0.20	9.5	9.0	28	0.2	127
		SHA	15	1.95	0.04	2.2	0.28	4.8	8.1	16	0.3	65

conventional design; additional monitoring was needed to obtain statistically significant verification of the water quality benefits. The study also needed to demonstrate construction and maintenance requirements in order to make sure the new design elements could be integrated into the Environmental Management System and the SHA design manuals and standards. SHA regulatory requirements to construct innovative BMPs and the overall stewardship and management policies supported this project. The design demonstrates the combination of innovative solutions at the project and watershed scales that can be used to advance the knowledge and understanding of how to implement innovative practices into the operations of a DOT, particularly for retrofit situations where adaptability is the key attribute. The incorporation of techniques to study the reduction of pollutant loads and volumes will help to develop strategies and techniques to address TMDLs. The positive results warrant additional studies and negotiations with regulatory agencies to verify water quality benefits, to incorporate the designs into the regulatory process, and to implement these designs in highway retrofits.

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Abbreviations and acronyms used without definitions in TRB publications:

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
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