Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Nanda Srinivasan
Staff Officer
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This report provides information on long-term performance and life-cycle costs for highway-related stormwater best management practices (BMPs). The report is accompanied by a CD-ROM containing a BMP evaluation tool in a spreadsheet format as a computational aid that provides average annual performance and whole life costs for treatment BMPs. The report will be of interest to state DOT highway design and environmental practitioners.

The management of stormwater runoff from the highway network is a major concern for state departments of transportation (DOTs) and other transportation agencies. Highway stormwater runoff may affect receiving waters and ecosystems through changes in water quality and hydrology. Roadway surfaces and rights-of-way are subject to pollutants from motor vehicles, atmospheric deposition, maintenance operations, and offsite sources. Rainfall runoff and snowmelt can carry pollutants from the roadway surface into receiving waters and can be a cause for environmental concern. Preserving the quality of national waters is an important goal for highway agencies and a requirement of federal laws such as the National Environmental Policy Act, Clean Water Act (e.g., National Pollutant Discharge Elimination System and Total Maximum Daily Loads), and the Endangered Species Act.

A wide range of treatment controls (commonly known as "best management practices" or BMPs) have been developed to manage stormwater. Treatment BMPs use various processes to mitigate the impacts of pollutants and altered hydrology; for example, by attenuating the flow or reducing the volume of stormwater or by reducing pollutants with physical, biological, or chemical processes.

There have been many guides to assist agencies with the selection of the most appropriate BMPs for specific site characteristics and agency objectives. However, the guidance was typically based on limited information about the BMP's expected initial performance and installation cost. Even less information has been compiled on the long-term performance of BMPs, maintenance requirements over time, expected life span, and total life-cycle costs. Transportation agencies need guidance on how long-term considerations should influence the selection and maintenance of stormwater BMPs. Furthermore, they need guidance on how to collect long-term performance and life-cycle cost data to improve the decision-making process in the future. NCHRP Project 25-40 was conceived to provide this guidance.

The research under NCHRP Project 25-40 was performed by Scott Taylor of RBF Consulting, Dr. Michael Barrett of the University of Texas, Marc Leisenring of Geosyntec Consultants, Neil Weinstein of the Low Impact Development Center, and Marie Venner of Venner Consulting. Information was gathered via literature review, survey of DOTs, and interviews with practitioners. Information for treatment BMPs was derived from DOT studies and the International BMP Database. The International BMP Database contains performance records for treatment BMP evaluations throughout the United States. The research included conducting a large number of computer simulations using the U.S. EPA's Stormwater Management Model (SWMM) to quantify runoff volume reduction through the BMP. The report is accompanied by a CD-ROM containing a BMP evaluation tool in a spreadsheet format as a computational aid that provides average annual performance and whole life costs for treatment BMPs. A guide (Planning Tool Handbook) is provided as Appendix F to quickly orient the user to the basic functions of the tool provided on the CD-ROM.

CONTENTS

Appendices B through F are on the CD-ROM included with this report.
Appendix A is unpublished.

ACRONYMS AND ABBREVIATIONS

ASCE	American Society of Civil Engineers
BMP	Best Management Practice
BMPDB	(International Stormwater) BMP Database
BOD	Biochemical Oxygen Demand
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CIPP	Cured-In-Place Pipe
COD	Chemical Oxygen Demand
COOP	Cooperative Observer Program
CSP	Corrugated Steel Pipe
CWA	Clean Water Act
DDT	Drawdown Time
DelDOT	Delaware Department of Transportation
DOT	Department of Transportation
DP	Dissolved Phosphorus
DREE	Division Roadside Environmental Engineer
E. coli	Escherichia Coli
ENR	Engineering News Record
ET	Evapotranspiration
FC	Fecal Coliform
FHWA	Federal Highway Administration
GIS	Geographic Information System
GPS	Global Positioning System
HDPE	High-Density Polyethylene
HIDOT	Hawaii Department of Transportation
HRDB	Highway-Runoff Database
IC/ID	Illicit Connection/Illegal Discharge
IDOT	Illinois Department of Transportation
IPM	Integrated Pest Management
IRVM	Integrated Roadside Vegetative Management
IRWD	Irvine Ranch Water District
LCCA	Life-Cycle Cost Analysis
LOS	Level of Service
MAD	Median Absolute Deviation
MAP	Maintenance Accountability Process

MassDOT	Massachusetts Department of Transportation
MDOT	Michigan Department of Transportation
MDSHA	Maryland State Highway Administration
MnDOT	Minnesota Department of Transportation
MS4	Municipal Separate Storm Sewer System
MUSLE	Modified Universal Soil Loss Equation
MWD	Metropolitan Water District
NCDC	National Climatic Data Center
NCDOT	North Carolina Department of Transportation
NCEEP	North Carolina Ecosystem Enhancement Program
NCHRP	National Cooperative Highway Research Program
NJCAT	New Jersey Corporation for Advanced Technology
NMDOT	New Mexico Department of Transportation
NO_3	Nitrate
NPDES	National Pollutant Discharge Elimination System
NPV	Net Present Value
NSQD	National Stormwater Quality Database
NYSDOT	New York State Department of Transportation
NWIS	National Water Information System
O&M	Operation and Maintenance
OCWD	Orange County Water District
ODOT	Oregon Department of Transportation
OGFC	Open-Graded Friction Course
OP	Orthophosphate
PCBs	Polychlorinated Biphenyls
PFC	Permeable Friction Course
PVC	Polyvinyl Chloride
RCP	Reinforced Concrete Pipe
RIDOT	Rhode Island Department of Transportation
ROW	Right-of-Way
RUSLE	Revised Universal Soil Loss Equation
RVTS	Roadside Vegetated Treatment Study
SR	State Route
SWMM	Storm Water Management Model
TAPE	Technology Assessment Protocol Ecology
TCu	Total Copper
TDA	Tributary Drainage Area
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TPb	Total Lead
TSS	Total Suspended Solids
TxDOT	Texas Department of Transportation
TZn	Total Zinc
UDFCD	Urban Denver Drainage and Flood Control District
UOP	Unit Operations and Processes
USDA-NRCS	United States Department of Agriculture–Natural Resources Conservation Service

U.S. EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WEF	Water Environment Federation
WERF	Water Environment Research Foundation
WLC	Whole Life Cost
WSDOT	Washington State Department of Transportation

SUMMARY

Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices

The department of transportation (DOT) stormwater practitioner has the responsibility to implement a stormwater program that protects the beneficial uses of receiving waters, is compatible with public safety and transportation infrastructure, and is economically and environmentally sustainable. A variety of resources are available to develop and implement a DOT stormwater program (Center for Environmental Excellence by AASHTO, 2009). However, the art of stormwater program development is found in the pursuit of implementing the most environmentally protective measures for the lowest possible cost while not compromising public safety. There are clear methods for understanding the cost of capital improvements, but the whole life cost of capital improvements can be less clear, particularly considering uncertainties associated with future maintenance requirements and the useful life of a stormwater best management practice (BMP). These uncertainties and the number of variables involved confound efforts to use whole life cost information coupled with BMP performance as the basis for BMP selection and design. Indeed, pollutant removal performance of BMPs depends on a variety of factors, and capital and operation and maintenance costs are very site-specific. Furthermore, BMP performance is difficult to quantify for the nonstructural and public outreach portions of the stormwater program.

Nonstructural BMPs and source controls can be the most effective part of a DOT stormwater program from both a cost and benefit perspective. Measures that keep pollutants from coming into contact with stormwater runoff are usually preferable to the difficult task of trying to remove the pollutant from runoff. This preference is because of the very large volumes of stormwater to be treated and the relatively modest performance of some passive runoff treatment controls for many common pollutants of concern. In addition, DOTs may be understandably cautious about making large capital expenditures on BMPs that have a significant perpetual maintenance burden without quantification of their benefits. An optimized DOT stormwater program achieves the most effective blend of nonstructural, source control, and treatment controls that can be reliably funded.

The Interstate highway system (and most of the other state highway systems) in the United States is largely already constructed. Accordingly, the practitioner is faced with implementing a stormwater program for infrastructure that was largely planned without stormwater quality management (and rather was planned primarily for drainage management) as an objective. This research focuses on retrofit of treatment BMPs into existing highway infrastructure. Various types of retrofit may be defined: construction of a new treatment BMP as a stand-alone project, construction of a new treatment BMP as part of a larger project, enhancement of an existing BMP, or replacement of an existing BMP. Since water quality treatment requirements are typically only triggered with new development or redevelopment projects, the most common case is retrofit of a BMP as a part of a highway improvement project. The cost estimates provided by this study and in the included BMP Evaluation Tool are specifically targeted to this situation. However, the cost information and the associated defaults in the tool are easily adaptable for other BMP retrofit situations.

BMP retrofit is an important tool for the practitioner. DOT National Pollutant Discharge Elimination System (NPDES) stormwater permits may include specific requirements to implement stormwater BMPs when disturbing 1 acre or more of land or to comply with a total maximum daily load (TMDL). A water quality certification [Clean Water Act (CWA) Section 401 certification] may also impose runoff treatment requirements on a project. Regardless of the regulatory driver, retrofit of highway infrastructure with treatment controls will likely occur with increasing frequency in the future, and the practitioner must be able to perform the assessments necessary to balance the use of treatment BMPs with other available measures.

Objectives

The main objective of this research was to provide the practitioner with tools to help optimize the BMP portion of his or her DOT stormwater program. BMP performance and cost are key information needed to maximize program performance and plan for necessary resources for capital and long-term implementation. It is helpful for the practitioner to be able to quickly evaluate potential stormwater treatment scenarios to make management and implementation decisions; two primary tools are provided to assist in this regard, the BMP Evaluation Tool and information on nonstructural and source control BMPs.

This research provides operation and maintenance protocols, unit costs, and performance predictions for treatment BMPs. BMP performance in the long term is dependent on local hydrology, influent quality, and an assumed base level of maintenance. Guidance for maintenance is provided by BMP type to support the BMP functioning for the useful life of the facility as designed. Maintenance and operation protocols are provided in a consolidated maintenance guide that DOTs can use as the basis for a maintenance manual, if needed.

Nonstructural and source control BMPs can be optimized if practitioners understand the variables that are important in their implementation. Another objective of this research was to describe some of the primary nonstructural and source control BMPs used by DOTs and provide information to assist in improving their performance and reducing the implementation cost.

BMP Evaluation Tool and Use

The BMP Evaluation Tool is a spreadsheet-format computational aid that provides average annual performance and whole life costs for treatment BMPs. Pollutant concentration reduction performance information is based on the repository of BMP performance studies contained in the International Stormwater BMP Database. Statistical regressions were completed by BMP and pollutant using the database records to develop estimates for effluent pollutant concentration given the pollutant influent concentration. Highway runoff quality is generally consistent throughout the United States for many constituents since the use of the land (almost exclusively by automobiles) is consistent. Accordingly, the tool prepopulates the influent quality using values from the FHWA Highway Runoff Database and highway data contained in the National Stormwater Quality Database; however, the user is free to overwrite or modify these values if local data are available.

The tool has been developed as a series of seven Excel spreadsheet files for each of the treatment BMPs simulated: vegetated swale, vegetated strip, dry detention basin, wet pond, bioretention, permeable friction course (PFC) overlay, and sand filter. The user inputs the nearest rain gauge to the project within the contiguous United States, BMP tributary area characteristics, the design water quality volume, and a few BMP-specific design parameters.

The tool then computes the remaining BMP dimensions and provides output on pollutant effluent concentrations, load reductions, and the whole life cost. Cost per unit weight or measure of a pollutant is also provided, so the practitioner can refine selection of the BMP that has the highest removal rate for the least whole life cost for a specified pollutant of concern. A guide (Planning Tool Handbook) to quickly orient the user to the basic functions of the tool is provided as Appendix F on the CD-ROM that accompanies this report.

A significant value of the tool is the ability to estimate the volume captured and volume reduced by the BMP. Most BMPs, whether designed to explicitly include infiltration or not, have associated volume loss from infiltration to native soil and, to a lesser extent, from evapotranspiration. Volume captured and lost (through infiltration and evapotranspiration) is estimated by the tool by simulating a range of conditions (physical BMP dimensions, soil type, volume input) using the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM). A large number of simulations were run to develop hydrologic performance curves that are incorporated into the tool to account for volume and load captured and reduced.

Table S.1 provides a comparison of volume and total suspended solids (TSS) loss for BMPs sized to capture 80% of the average annual runoff volume from a hypothetical highway section in Daytona Beach, Florida, where right-of-way soils are characterized as hydrologic soil group Type C. Filter strips and PFC are assumed to capture >99.9% of the runoff, since these BMPs treat sheet flow.

The tool computes capital and long-term operation and maintenance costs to estimate a whole life cost for the BMP. Capital cost is based on user-specified design parameters and tool-computed dimensions and construction quantities. Cost output includes unitized costs by pollutant load (removed), allowing the practitioner to assess the most cost-effective option for any modeled constituent of concern. The practitioner has flexibility to modify the unit capital costs in the tool to reflect project-specific requirements or local information. Using the same hypothetical example as before, the annualized cost per unit of performance by BMP for selected pollutants is shown in Table S.2.

An example of the whole life cost summary output from the tool is shown in Table S.3.

The assumptions used to develop the tool have broad application for DOTs throughout the United States. BMP performance is generally dictated by site-specific variables affecting hydrology and hydraulics such as influent volume, soil type, and BMP dimensions. The tool accounts for these variables by incorporating the results of tens of thousands of long-term continuous simulation model runs from across the United States when estimating average annual hydrologic results. Due to the average annual timescale used, however, the results of the tool should not be viewed as applicable to any specific BMP installation for a particular

Table S.1. Percent average annual volume and TSS reductions.

BMP	Volume		Sediment
	Captured	Reduced	TSS
Swales	80%	12.9%	54%
Bioretention (without underdrain)	80%	80%	80%
Bioretention (with underdrain)	80%	25.8%	73%
Wet pond	80%	0%	65%
Filter strip	>99.9%	72.3%	93%
Dry detention	80%	17.1%	62%
PFC	>99.9%	0%	90%
Sand filter	80%	0%	71%

Table S.2. Annualized BMP cost per unit of load reduction performance.

	Pathogens ($/$10^{12}$ colonies)		Metals ($/lb)			Nutrients ($/lb)					Sed. ($/lb)
	E. Coli	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Swales	$13.29	$9.26	$26,883	$23,221	$4,117	$3,408	$1,567	$1,065	$14,574	$3,811	$6.22
Bioretention (no underdrain)	$6.33	$4.39	$41,451	$39,265	$9,113	$1,633	$746	$512	$6,923	$3,916	$12.47
Bioretention (with underdrain)	$3.97	$2.73	$33,979	$74,866	$6,490	$3,105	$1,070	$799	$13,173	$7,423	$8.30
Wet pond	$8.00	$8.51	$69,305	$50,134	$13,971	$3,991	$2,119	$1,201	$18,193	$8,563	$16.97
Filter strip	$2.44	$1.69	$12,880	$11,921	$2,732	$566	$287	$196	$2,662	$1,291	$3.74
Dry detention	$2.08	$2.13	$21,234	$16,168	$3,964	$1,450	$610	$427	$9,373	$2,346	$4.72
PFC	N/A	N/A	$69,966	$46,558	$12,264	N/A	$1,663	$1,666	N/A	$10,524	$16.09
Sand filter	$3.89	$2.64	$32,204	$19,102	$4,549	N/A	$565	$627	$13,431	$3,010	$6.03

Notes: Sed. = sediment, FC = fecal coliform, TCu = total copper, TPb = total lead, TZn = total zinc, NO_3 = nitrate, TKN = total Kjeldahl nitrogen, TN = total nitrogen, DP = dissolved phosphorus, TP = total phosphorus.

Table S.3. Whole life costs summary.

Whole Life Cycle Costs Summary			
CAPITAL COSTS	Total Cost		
Total Facility Base Cost	$12,882		
Total Associated Capital Costs (e.g., Engineering, Land, etc.)	$7,181		
Capital Costs	$20,063		
REGULAR MAINTENANCE ACTIVITIES	Years between Events	Total Cost per Visit	Total Cost per Year
Inspection, Reporting & Information Management	0.5	$180	$360
Vegetation Management with Trash & Minor Debris Removal	0.5	$1,380	$2,760
add additional activities if necessary	0	$0	$0
add additional activities if necessary	0	$0	$0
Totals, Regular Maintenance Activities			$3,120
CORRECTIVE AND INFREQUENT MAINTENANCE ACTIVITIES (Unplanned and/or >3yrs. betw. events)	Years between Events	Total Cost per Visit	Total Cost per Year
Corrective Maintenance	4	$6,740	$1,685
add additional activities if necessary	0	$0	$0
add additional activities if necessary	0	$0	$0
Totals, Corrective & Infrequent Maintenance Activities			$1,685
Capital Costing Method	Line Item Engineer's Estimate		
Assumed Level of Maintenance	H		
Estimated Capital Cost, $ (2013)	$20,063		
Estimated NPV of Design Life Maintenance Costs, $ (2013)	$92,494		
Estimated NPV of Design Life Whole Life Cycle Cost, $ (2013)	$112,557		
Estimated Annualized Whole Life Cycle Cost, $/yr (2013)	$4,502		
Totals are based on design life with routine and major maintenance.			

Note: H = high.

storm event. Instead, the tool is appropriate for planning-level analyses conducted to evaluate the relative long-term performance and costs associated with BMP implementation.

Overall, the tool can be used by practitioners to determine the optimum BMP for a particular location. The practitioner first selects the BMPs that are compatible with the physical site constraints. Then the practitioner uses the tool to develop cost and performance estimates for the selected BMPs. A comparison of performance and whole life cost can then be conducted to identify the BMP with the best performance and lowest whole life cost. Using this approach, the practitioner can document the selection process, demonstrating both environmental protection and stewardship of public funds.

The tool can also be used to estimate long-term operation and maintenance budgets to assist with asset management. The practitioner can input as-constructed dimensions of the DOT's treatment BMPs and compute an average annual operation and maintenance (O&M) budget by location. Budgets for each location can be aggregated to develop the annual budget for all BMPs for the DOT. Cost data in the tool can be refined by the user as actual costs and experience are gained, improving estimates for future years.

Specifically, the tool can be used to:

- Evaluate volume and pollutant load reduction in comparison to baseline conditions and performance targets or standards,
- Compare BMPs for planning-level studies, and
- Evaluate performance relationships and sensitivities of design parameters.

The tool can also be used indirectly to:

- Assist in the development of a stormwater program,
- Quantify local precipitation statistics, and
- Establish planning-level BMP sizing targets.

Nonstructural and Source Control BMP Information

Information on the performance and cost of nonstructural and source control BMPs can be difficult to develop. The availability of DOT personnel and equipment resources, population of the state, extent of the storm drain system, presence or absence of groundwater, and number of lane miles are some of the variables that affect the cost and effectiveness of implementation of nonstructural and source control measures.

This report provides information to assist the practitioner in improving the effectiveness of the nontreatment BMP portion of the DOT stormwater program. Chapter 8 describes managed variables for selected nonstructural BMPs to assist the practitioner in understanding the most important aspects of implementing each BMP, with the objective of maximizing performance. Information is also provided on the costs of implementation (as available), including a basic triple bottom line (TBL) analysis. Information in this chapter can be used by the practitioner to develop preliminary cost and benefit estimates by pollutant for the nonstructural portion of the DOT program. This information can be compared to the cost and benefit information from the spreadsheet tool to help formulate the desired balance of treatment controls, nonstructural controls, and source controls.

A TBL analysis assesses the factors of implementation, environmental benefit, and cost. This approach was used to assess selected nonstructural BMPs since there can be barriers to their implementation that are difficult to quantify. For example, the application of traction aides or deicers can have safety implications as well as application costs. Qualitative assessments of social and institutional factors were made and combined with implementation cost rankings to provide an overall assessment of the BMP. Nine nonstructural BMPs were assessed; the nonstructural TBL BMP analysis is summarized in Table S.4 as an overall sustainability rating.

Table S.4. Overall sustainability ratings for nonstructural BMPs.

Nonstructural BMP	Sustainability
Storm drain cleaning	Low
Traction aids and deicer application	High
Sweeping	Moderate
Irrigation runoff reduction practices	High
Smart landscaping	Moderate
Trash management programs	High
Elimination of groundwater infiltration	High
Slope stabilization	High
Channel stabilization	Moderate

The sustainability rating shown in Table S.4 is an estimated aggregate of implementation cost, effectiveness, and the potential for social disruption or implementation barriers. The practitioner can use the sustainability rating to assist in determining whether a particular measure should receive relatively more or fewer program resources when performing a program effectiveness assessment. Some measures may have a high sustainability rating but low applicability if the DOT, for example, does not use irrigation within the right-of-way.

Other Research

This report was developed to complement and build on other research completed by NCHRP. Basic BMP design information and siting constraints, as well as factors influencing BMP performance, can be found in other publications.

NCHRP Report 565: Evaluation of Best Management Practices for Highway Runoff Control provides a means for evaluating BMPs and low-impact development for stormwater quantity and quality. This report discusses hydrologic methods, BMP unit processes, pollutants of concern, regulations and regulatory requirements, and BMP selection guidance.

NCHRP Report 728: Guidelines for Evaluating and Selecting Modifications to Existing Roadway Drainage Infrastructure to Improve Water Quality in Ultra-Urban Areas provides information on procedures for evaluating and selecting modifications to existing drainage infrastructure. 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. The report discusses the constraints and challenges of retrofitting in urban areas, BMP options, evaluating BMP effectiveness, sizing and design, maintenance and monitoring, and capital cost information.

NCHRP Synthesis 444: Pollutant Load Reductions for Total Maximum Daily Loads for Highways collects information on the types of BMPs currently being used by state DOTs for meeting TMDL water quality goals for stormwater runoff. The synthesis includes information on BMP performance, cost, and design, including information on nonstructural BMPs.

The research in this report will give the practitioner information on whole life cost and BMP performance, including volume and load reductions provided by the BMP. Long-term operation and maintenance requirements are also described, including a basic BMP operation and maintenance guide. A description of nonstructural and source control BMPs helps the practitioner determine the optimum blend of nonstructural and structural solutions. This report is a valuable complement to the programmatic and BMP design information contained in the NCHRP reports just described. The practitioner is encouraged to review each of these publications to gain an understanding of state-of-the-art DOT stormwater program development and implementation.

CHAPTER 1

Introduction

1.1 Statement of Project Need and Objectives

1.1.1 Statement of Need

Departments of transportation (DOTs) are faced with increasing regulatory standards and environmental challenges that mandate better stormwater quality management outcomes, often with limited funding. Best management practices (BMPs), both nonstructural practices and structural treatment systems, play a key role in the DOT's ability to comply with the Clean Water Act (CWA) and protect water resources in the environment.

Structural BMPs remove pollutants from stormwater runoff, and they are always something less than 100% effective. Nonstructural BMPs prevent the contact of pollutants with stormwater, so they can be more effective for the source they are implemented for. Nonstructural BMPs have the potential to provide the best opportunity to prevent and reduce pollution in highway runoff for many pollutants of concern. However, there is little documentation quantifying the effectiveness of nonstructural BMPs or discussing implementation and the operational challenges of their implementation. It is also important to understand basic implementation variables of nonstructural practices so the practitioner can ensure that maximum benefit is being achieved from the BMP.

Treatment BMP selection involves a variety of assessments by the practitioner, including the pollutant of concern, physical site constraints, site access, climate, and operation and maintenance (O&M) requirements. Long-term data from the International Stormwater BMP Database and other resources can provide insight on BMP performance, but there is less information on how BMP effectiveness is affected by physical, chemical, biological, and thermal influences; maintenance; and operational practices. Further, the life-cycle cost and service life of most treatment controls are unknown and variable, making it difficult for a DOT to budget for long-term O&M of installed devices. Some DOTs have learned valuable lessons regarding real-world challenges to BMP implementation and operation. This information was gathered as a part of the literature review and DOT survey for this project.

DOTs are developing better means for data analysis and reporting that can be used to leverage limited resources in the face of increasing National Pollutant Discharge Elimination System (NPDES) permit requirements. Regulatory rules and programs such as total maximum daily loads (TMDLs), 401 certifications, and other requirements, including the Endangered Species Act and Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) projects, especially those associated with cleanups of legacy-contaminated sediments, require significant record keeping and documentation of performance. There are fundamental needs for guidance to assist agencies with these challenges, including describing conditions where nonstructural BMPs can achieve maximum benefit in a highway environment for program-level measures and providing information to assist the practitioner in evaluating treatment BMPs on a project-specific basis using performance and cost information.

The stormwater management field is rapidly evolving, and new and better data are being developed. The information provided in this report is current as of the date of publication, but the practitioner is encouraged to review new sources of data as they become available. The performance and cost information provided herein should be continuously refined by the user to maintain a contemporary stormwater assessment tool.

1.1.2 Objectives

The objective of this report is to provide information that will allow the practitioner to optimize the BMP elements (nonstructural and treatment) of a DOT stormwater program. This objective is achieved for nonstructural measures by describing the BMP, its applicability, targeted pollutants, variables that are important for implementation, implementation barriers, and effectiveness. A general discussion of costs is also provided.

For treatment BMPs, this guidance provides an evaluation tool for assisting in their selection and determining whole life costs of treatment, including the following information:

- BMP performance metrics;
- Comparative service life and long-term BMP effectiveness for enhancing water quality for typical highway runoff constituents;
- Life-cycle costs based on capital investment, maintenance, and operational expense data; and
- Constituent removal performance.

The companion tool to this document is provided on the accompanying CD-ROM in a spreadsheet format that facilitates the comparison of treatment BMPs by the practitioner. The tool may be customized by the practitioner to include local performance and cost data, or the tool default values may be used.

1.2 Scope of Report

Research for the project consisted of a literature review as well as surveys and interviews with DOT staff in all 50 states to determine DOT practices for BMPs and identify applicable grey literature that would support the objectives of the study. A precursor survey of DOTs found that they had very little actual data on life-cycle or maintenance costs of BMPs to guide BMP selection or budgeting, so individual outreach and discussions on the topic were deemed critical. Therefore, greater time was focused on discussions with DOTs compared to the literature review.

The research team developed survey questions to address the project objectives. Questions were tested and refined with various state DOT maintenance managers, NPDES program managers, and hydraulics program leads to help focus the questions and maximize their pertinence and applicability to DOTs.

The literature review was multifaceted and involved consultation with the team members as well as colleagues at research organizations and universities in the United States and abroad. Information was sought through inquiries to DOTs, via web literature searches, on the DOT Google search engine, through the University of Texas library system, and in consultations with contacts at universities, other research institutions, and TRB committees, especially the TRB Committee on Hydrology, Hydraulics and Water Quality (AFB60).

Information for nonstructural BMPs was developed from published studies, grey literature, and consultation with DOTs. The definition of nonstructural BMPs for a DOT stormwater program for this study differs somewhat from that associated with traditional development and municipal separate storm sewer system (MS4) stormwater programs. In the development context, nonstructural BMPs are commonly defined as the use of natural area conservation and buffer areas, disconnection of impervious surfaces, limited clearing of native vegetation, and minimizing the use of impervious surfaces. Highway standards dictate the extent to which these design practices can be implemented in roadway projects. Accordingly, this study focuses on operational nonstructural BMPs, reflecting the primary DOT need to manage existing infrastructure. The information was formatted in the general categories noted previously for comparability between the practices. The following nonstructural practices were evaluated as a part of this study:

- Storm drain cleaning,
- Street sweeping,
- Smart landscaping practices,
- Trash management practices,
- Elimination of groundwater infiltration,
- Slope and channel restoration,
- Winter maintenance BMPs, and
- Irrigation runoff reduction practices.

The BMPs listed are common nonstructural BMPs for a DOT stormwater program.

Information for treatment BMPs was derived from DOT studies and the International Stormwater BMP Database. The International Stormwater BMP Database contains performance records for treatment BMP evaluations throughout the United States. The BMP database is an important resource allowing the development of relationships between stormwater influent and effluent quality for a specific BMP type. The information in the database was reviewed for basic data quality, and BMP evaluation studies that were incomplete or did not meet basic quality objectives were not included in the analysis. Although many of the records in the database are for studies completed outside of the highway environment, the information is applicable to highway BMPs for the range of influent qualities that are consistent with highway data.

An important component of BMP performance is pollutant load reduction due to infiltration. Very few studies (in the database or completed by DOTs) document infiltration losses or provide information on pollutant load reduction through this mechanism. Further, measuring load reductions associated with infiltration is difficult. Identifying volume loss through a BMP requires careful measurement of influent and effluent volumes. Flow measurement for the wide range of discharge inflows that a BMP can experience during a storm event is technically daunting, and data quality is variable. To overcome the lack of high-quality load reduction data available for treatment BMPs, the hydrologic/hydraulic processes contributing to average annual BMP performance were accounted for using long-term continuous simulation via the U.S. Environmental Protection Agency (U.S. EPA) Storm Water Management Model (SWMM). SWMM simulation results were coupled with BMP performance data to provide a consistent estimate of potential BMP load reduction performance in the BMP Evaluation Tool. The BMP Evaluation Tool consists of seven individual spreadsheets for the following BMPs:

- Vegetated strips,
- Vegetated swales,
- Dry detention basins,
- Bioretention,
- Retention/wet ponds,
- Sand filters, and
- Permeable friction course (PFC).

The performance of BMPs will vary somewhat with geographic location. This is due to variability in rainfall patterns, the pH of rainfall, soil chemistry, and forms of chemicals from local pollution sources. However, the primary variables in BMP performance are rainfall-runoff characteristics, influent quality, the size and dimensions of the BMP, and the unit treatment processes (i.e., sedimentation) provided by the BMP. Accordingly, the BMP Evaluation Tool allows the users to input local values for the primary site-specific variables and accept or override various defaults developed from national data and common BMP design guidance. The performance of BMPs may also vary by season, though sufficient information does not exist to quantify this difference. The tool reports average BMP performance over the time span of the prototype studies.

The user is cautioned that the tool is not intended to be a BMP sizing tool. Instead, it is intended to allow a user to evaluate the average annual performance of a BMP that is sized according to local stormwater management requirements. Hence, the tool could be used to inform the potential revision of BMP sizing criteria.

Capital cost information for the BMPs was developed using a unit price approach. Construction items were quantified on a per-unit basis, with unit prices referenced to those provided by RS Means publications. The default cost information can be adjusted using local data or regional cost information.

O&M costs were estimated based on DOT studies that reported hours spent maintaining the BMPs, which were applied to maintenance crew costs and equipment required as a part of the maintenance task. Maintenance tasks have been defined for each BMP, and the frequency of the maintenance placed in three general categories to reflect the maintenance level at various locations throughout the United States. Areas with higher rainfall rates could generally expect to have more frequent BMP maintenance requirements due to the increased runoff volume treated and higher vegetation growth rate. However, the frequency of maintenance will be partially affected by site-specific requirements, and the practitioner can compare the description of the three maintenance levels to determine the one that is most consistent with the DOT standard.

The whole life cost estimates assume a life span for each BMP. The BMP life span was estimated by determining the useful life of the major components. When major components need to be replaced, it is appropriate to assume that the entire BMP must be reconstructed. The life span of each BMP varies, and it was used to recapitalize the facility as an input to the whole life cost calculation.

The cost information and guidance provided herein applies specifically to BMPs that are retrofit into existing DOT infrastructure as part of a highway improvement project. This is because the Interstate highway system is largely already constructed, and DOTs are faced with NPDES permit compliance in part through water quality retrofit. Costs for stand-alone retrofit projects would be higher than indicated in the tool due to fixed costs such as traffic control that cannot be spread over other work items. Performance of BMPs of the same type and size is independent of whether a BMP has been installed as a part of new construction or as a stand-alone retrofit. The costs provided in this report and the BMP Evaluation Tool represent retrofit costs as part of a larger project; the practitioner is free to replace the default cost data with data that best reflect the condition of construction of the BMP.

Retrofit of treatment BMPs, as well as enhanced installation of nonstructural and source control BMPs, will be important as DOTs continue to meet NPDES permit requirements and TMDL obligations and implement programs to ensure the protection of beneficial uses of receiving waters consistent with the goals of the CWA.

1.3 Intended Users and Uses

The results of this project are intended for use by DOT practitioners at both the programmatic and project level. Results derived from the BMP Evaluation Tool and information in the report can be used to develop BMP plans at a watershed as well as project-specific scale. They can also be used to guide inspection and maintenance practices, asset management decisions, data gathering, and reporting practices. The average annual O&M cost information will be important to assist DOTs in programming resources to ensure that they are adequate to maintain the treatment systems. The capital cost information can be used to forecast the BMP portion of capital cost budgets.

The information provided for nonstructural BMPs can be used to assist DOTs in refining the implementation of nonstructural measures in their stormwater programs. Successful implementation of nonstructural BMPs depends in part on variables that the user controls, such as the speed of the sweeper for roadway sweeping activities. The information in this report will assist the practitioner in improving the performance of nonstructural BMPs through more targeted implementation. The use of nonstructural BMPs is intended as a complement to treatment BMPs. The practitioner must determine the level of resources that are to be shared between the two that will result in a stormwater program with the highest performance for the lowest cost. The information provided in this report on nonstructural (source control) BMPs will assist the practitioner in making this determination.

1.4 Relationship with Other NCHRP Publications

This project was intended to build on the information provided within NCHRP publications from other projects. Depending on the reader's needs, those resources should be consulted in conjunction with the information provided here. Other NCHRP publications that relate to the selection of highway BMPs are:

1. *NCHRP Report 565: Evaluation of Best Management Practices for Highway Runoff Control* provides the practitioner with information regarding BMP types, treatment unit processes, highway stormwater runoff characteristics, and guidance on treatment control selection based on performance data, hydrologic factors, and site constraints. Recommendations are provided for BMP design and implementation, monitoring, and water quality modeling (Oregon State University et al., 2006).
2. *NCHRP Report 728: Guidelines for Evaluating and Selecting Modifications to Existing Roadway Drainage Infrastructure to Improve Water Quality in Ultra-Urban Areas* presents focused research on the physical characteristics and associated water quality conditions of highways within the ultra-urban environment. This report offers the reader guidance on BMP selection based on cost, performance, and maintenance considerations along with information related specifically to retrofit practices. Case studies and lessons learned that illustrate the subject matter are provided (Geosyntec Consultants et al., 2012).

Other NCHRP reports, although not directly related to the selection of water quality BMPs, offer potentially relevant information pertaining to highway water quality impacts, mitigation strategies, or general issues relating to highway costs, maintenance, asset management, or research implementation:

1. *NCHRP Report 688: Determining Highway Maintenance Costs* (Cambridge Systematics, Inc., et al., 2011).
2. *NCHRP Report 640: Construction and Maintenance Practices for Permeable Friction Courses* (Cooley, Jr., et al., 2009).
3. *NCHRP Report 632: An Asset Management Framework for the Interstate Highway System* (Cambridge Systematics, Inc., 2009).
4. *NCHRP Report 574: Guidance for Cost Estimation and Management for Highway Projects During Planning, Programming, and Pre Construction* (Anderson et al., 2007).
5. *NCHRP Report 474: Assessing the Impacts of Bridge Deck Runoff Contaminants in Receiving Waters* (Dupuis, 2002).
6. *NCHRP Synthesis 444: Pollutant Load Reductions for Total Maximum Daily Loads for Highways* (Abbasi and Koskelo, 2013).
7. *NCHRP Report 382: Facilitating the Implementation of Research Findings: A Summary Report* (Bikson et al., 1996).
8. *NCHRP Report 767: Measuring and Removing Dissolved Metals from Storm Water in Highly Urbanized Areas* (Barrett et al., 2013).

There are other NCHRP projects recently completed or currently in progress that are similar to this project that may be of value to the reader:

1. NCHRP Project 25-25/83, "Current Practice of Post-Construction Structural Stormwater Control Implementation for Highways," provides a synthesis of practices for post-construction structural stormwater control implementation measures used by state transportation agencies with information regarding selection, design criteria, operation, and maintenance for BMPs. The project includes information on recent federal or state-level research programs and projects on post-construction stormwater discharge control.
2. NCHRP Project 25-41, "Guidelines for Achieving Volume Reduction for Highway Runoff in Urban Areas," has the research objective of developing guidelines to reduce the runoff volume from highway facilities in urban areas. The guidelines are divided into two subcategories: (1) methods appropriate for new construction and (2) methods appropriate for retrofit construction. A spreadsheet tool was developed as a part of this project to assist in computing volume loss by treatment practice.

   The research considers alternative pavement systems, infiltration, and evapotranspiration methods as well as storage alternatives. Methods that are deemed to be technically and fiscally viable are refined with detailed design guidance for use by DOTs. Cost analysis methods are developed so DOTs can determine the relative costs between accomplishing volume reduction within the right-of-way or partnering with other entities to add volume reduction capacity to the developments that highways serve (e.g., commercial/residential areas, airports, and industrial parks).

3. NCHRP Project 25-42, "Bridge Stormwater Runoff Analysis and Treatment Options," is an applied research project that provides guidance for assessing potential water quality impacts and selecting BMPs for stormwater runoff from bridge decks and associated vehicle approaches. There is a growing concern that untreated runoff from bridges may be affecting receiving waters even though the bridge deck represents only a small fraction of the impervious area of the highway system, and there is not strong evidence to support the proposition that the quality of bridge deck runoff differs significantly from that of other highway runoff. The cost and environmental benefits of implementing stormwater controls for bridge deck runoff are reviewed, and a procedure is provided for the practitioner to determine the appropriate stormwater management practices for new and retrofit bridge projects. This project provides spreadsheet tools for use in BMP evaluation that are identical to those developed as a part of NCHRP Project 25-40.

CHAPTER 2

Literature Review and Survey Findings

2.1 Background

Since the NPDES program began in 1972 under Section 402 of the Clean Water Act, state DOTs have installed thousands of stormwater treatment facilities in the course of adding to the nation's capacity to meet NPDES permit requirements and other similar state laws. These structural treatment facilities are commonly referred to as treatment BMPs and are designed to control the amount of stormwater runoff pollutants and volumes discharging to receiving waters.

Maintenance of treatment BMPs is necessary to preserve their treatment and conveyance capacities as well as their intended water quality benefits. The EPA's stormwater pollution prevention fact sheet describes O&M plans as "an important part of a stormwater management program," the goal of which is "to ensure that individual and interconnected stormwater BMPs continue to meet performance and design objectives" (U.S. EPA, 2010).

2.2 BMP Effectiveness and Long-Term Performance of BMPs

2.2.1 Most Commonly Used BMPs

Treatment BMPs serve as permanent stormwater controls and typically include detention or retention ponds, constructed wetlands, and sand filters (Urbonas, 1999; Carleton et al., 2000; Middleton and Barrett, 2008). Traditional stormwater practices are designed to retain runoff and release the water slowly after the storm event has passed. This helps to decrease the peak flow rates and flow volume and improves water quality through sedimentation and infiltration.

The most common BMPs used by DOTs, based on the number of states that use them, are basin configurations including wet ponds, detention ponds, and sediment or filtration basins (Eck et al., 2010). Other common approaches are vegetated swales, filter strips, and infiltration systems. Table 2-1 indicates the percentages of state DOTs that use the listed BMPs in ultra-urban environments (Geosyntec Consultants et al., 2012). Vegetated slopes and roadside swales are more common BMPs in rural environments. Roadside ditches, if vegetated and designed with appropriate velocities for the water quality flow and of sufficient length, are BMPs and are described as "vegetated swales" in Table 2-1. Vegetated swales may be preceded by filter strips or vegetated areas that accept sheet flow. Some of the BMPs listed in Table 2-1, such as oil/water separators, porous pavements, and cisterns, are used by DOTs at maintenance facilities but generally are not used for roadways. They are listed here since they were studied under a previous NCHRP project, but non-highway treatment BMPs are not included as a part of this project.

2.2.2 Summary of Previous Studies on BMP Performance

This section summarizes previous studies on BMP performance with a primary focus on the International Stormwater BMP Database (BMPDB; http://www.bmpdatabase.org), which is the most comprehensive source of post-construction BMP performance data available in the world. The BMPDB is a collection of studies consisting primarily of BMP influent and effluent concentrations, rainfall event and runoff volumes, and ancillary test site and BMP information, such as watershed characteristics and BMP design parameters. The BMPDB, as of January 2012, contained data from over 500 BMP studies with over 15 structural BMP categories. Included within the BMPDB (in 2012) were 133 highway/roadway, park-and-ride, and maintenance station BMP research studies. These DOT studies were heavily focused on the west coast of the United States, with California accounting for approximately half of the studies (64 studies; 48%). Additionally, most of the research studies (77.5%) were highway and roadway related, followed by maintenance station (12%), then park-and-ride (10.5%). A summary of the research studies by state, BMP type, and land use can be found in Table 2-2. Because of the

Table 2-1. Percent of states reporting use of BMP type.

BMP	Number of States That Reported Using the BMP	Percent of States That Reported Using the BMP
Surface detention (Dry ED/wet/infiltration basins, wetlands)	30	81
Vegetated/rock swales	29	78
Hydrodynamic separators	23	62
Oil/water separators	22	59
Infiltration trenches	18	49
Underground detention	17	46
Catch basin inserts	16	43
Low-impact development BMPs (e.g., bioretention, amended soils)	16	43
Proprietary media filters (e.g., storm filter)	15	41
Sand filters	14	38
Filter strips	14	38
Diversion to treatment facilities	10	27
Multichambered treatment train systems	7	19
Porous pavements	7	19
Cisterns	3	8

Notes: 37 DOTs responded to this survey. ED = extended definition.
Source: Geosyntec Consultants et al., 2012

breadth and depth of data contained in the BMPDB, it was a key resource used when developing the BMP spreadsheet tools.

2.2.2.1 BMP Constituent Removal

The Water Environment Research Foundation (WERF) sponsored a comprehensive BMP technical report that included categorical performance assessments of all BMPs with sufficient water quality data in the BMPDB for statistical analysis (Geosyntec and Wright Water Engineers, 2012). The final version of that report was published in early 2012. It includes results for typical constituents of concern for state DOTs, such as total suspended solids (TSS), cadmium, copper, lead, nickel, zinc, phosphorus, and nitrogen. The median effluent concentration results are summarized in Tables 2-3 and 2-4. The tables indicate which BMPs and constituents had statistically significant differences between influent and effluent median concentrations.

Total Suspended Solid Removal. All BMP types in the WERF study demonstrated statistically significant reductions in TSS concentrations and achieved median effluent concentrations below 25 mg/L. Bioretention, media filters, and wetland basins were shown to have the lowest median effluent TSS concentrations.

Metals (Total and Dissolved). Most BMPs demonstrated significant reductions in total cadmium, copper, lead, and zinc concentrations, but the dissolved fractions of these metals are only significantly reduced by a handful of BMP types. While total metals include particles bound to sediment, and they can be removed through sedimentation and physical straining, dissolved metals are mostly only removed through sorption and biochemical processes (Strecker et al., 2005). Therefore, BMPs expected to perform the best in dissolved metal concentration reductions provide adsorptive filtration or have long hydraulic residence times to allow for microbial transformations and plant uptake. *NCHRP Report 767* (Barrett et al., 2013) explores methods for removing dissolved metals from urban runoff.

Based on the available BMP data, vegetated strips show the best performance in removing dissolved metals (significant reduction in all dissolved metal effluent concentrations except for dissolved lead, which suffers from a high percentage of non-detects). Not enough studies (<3 studies) were available to evaluate the dissolved metal performance for bioretention, wetland basins, and wetland channels. Bioswales significantly reduced effluent concentrations for dissolved cadmium, dissolved nickel, and dissolved zinc, but not for dissolved copper and dissolved lead. Swales are expected to provide similar performance to filter strips during small storms when flows are shallow and there is high contact with surface soils. However, for larger storms, as the depth of flow increases, the contact area and contact time are reduced, thereby decreasing the removal efficiency, particularly for dissolved constituents.

Nutrients (Phosphorus and Nitrogen). Retention ponds tend to perform the best in removing all forms of phosphorus

Table 2-2. Summary of transportation-related BMPDB research studies (2012).

State and BMP Type	BMP Study Count by Primary Land Use			
	Maint. Station	Park and Ride	Roads/ Highway	Total
California	**15**	**6**	**43**	**64**
Biofilter – vegetated strip	2	–	29	31
Biofilter – vegetated swale	1	–	5	6
Detention basin (dry) – concrete or lined basin with open surface	–	–	1	1
Detention basin (dry) – surface vegetated-lined basin, empties after storm	–	–	4	4
Filter – other media	1	–	–	1
Filter – peat/gravel mixed with sand	1	2	–	3
Filter – sand	3	3	1	7
Manufactured device	7	1	2	10
Retention pond (wet) - surface pond with a permanent pool	–	–	1	1
Delaware	–	–	**9**	**9**
Bioretention	–	–	1	1
Filter – sand	–	–	1	1
Manufactured device	–	–	7	7
Florida	–	–	**7**	**7**
Biofilter – vegetated swale	–	–	6	6
Retention pond (wet) – surface pond with a permanent pool	–	–	1	1
North Carolina	–	–	**14**	**14**
Biofilter – vegetated strip	–	–	2	2
Biofilter – vegetated swale	–	–	2	2
Biofilter – wetland vegetation swale	–	–	2	2
Composite – overall site BMP	–	–	4	4
Permeable friction course	–	–	3	3
Porous pavement – porous asphalt	–	–	1	1
Oregon	–	–	**1**	**1**
Manufactured device	–	–	1	1
Pennsylvania	**1**	–	–	**1**
Manufactured device	1	–	–	1
Texas	–	–	**16**	**16**
Biofilter – vegetated strip	–	–	2	2
Biofilter – vegetated swale	–	–	1	1
Detention basin (dry) - concrete or lined basin with open surface	–	–	1	1
Composite – overall site BMP	–	–	1	1
Control – no BMP/control site	–	–	2	2
Filter – gravel		–	1	1
Filter – sand	–	–	3	3
Manufactured device	–	–	1	1
Permeable friction course	–	–	3	3
Retention pond (wet) – surface pond with a permanent pool	–	–	1	1
Virginia	–	**6**	**12**	**18**
Biofilter – vegetated swale	–	–	9	9
Biofilter – vegetated strip	–	–	1	1
Detention basin (dry) – surface vegetated-lined basin, empties after storm	–	4	–	4
Wetland – basin with open water surfaces	–	–	1	1
Wetland – basin without open water (wetland meadow)	–	–	1	1
Composite – overall site BMP	–	2		2
Washington	–	–	**1**	**1**
Bioretention	–	–	1	1
Grand Total	**16**	**12**	**103**	**131**

Table 2-3. BMP median effluent concentration for constituents commonly reported in the BMPDB (continued as Table 2-4).

BMP Type	TSS, mg/L (95% CI)[a]	Dissolved Cadmium µg/L (95% CI)[a]	Total Cadmium µg/L (95% CI)[a]	Dissolved Copper µg/L (95% CI)[a]	Total Copper µg/L (95% CI)[a]	Dissolved Lead µg/L (95% CI)[a]	Total Lead µg/L (95% CI)[a]	Dissolved Nickel µg/L (95% CI)[a]	Total Nickel µg/L (95% CI)[a]
Vegetated strip	***19.1 (16.0, 21.5)***	0.09 (0.07, 0.11)	***0.18 (0.09, 0.20)***	***5.40 (4.50, 5.90)***	***7.30 (6.40, 7.90)***	0.26 (0.19, 0.35)	***1.96 (1.30, 2.20)***	***2.09 (2.00, 2.15)***	***2.92 (2.40, 3.10)***
Bioretention	***8.3 (5.0, 9.0)***	N/A[d]	***0.94 (0.25, 1.00)***	N/A[d]	***7.67 (4.60, 9.85)***	N/A[d]	2.53 (2.50, 2.50)	N/A[d]	N/A[d]
Bioswale	***13.6 (11.8, 15.3)***	***0.12 (0.09, 0.15)***	***0.31 (0.27, 0.34)***	8.02 (6.30, 9.24)	***6.54 (5.70, 7.70)***	1.08 (0.76, 1.60)	***2.02 (1.80, 2.29)***	***2.04 (2, 2.40)***	***3.16 (2.30, 4.20)***
Composite	***17.4 (12.4, 18.8)***	N/A[d]	***0.50 (0.43, 0.50)***	5.00 (5.00, 5.00)	***5.88 (5.05, 6.79)***	0.29 (0.09, 0.44)	***4.78 (3.00, 5.61)***	N/A[d]	N/A[d]
Detention basin	***24.2 (19.0, 26.0)***	***0.50[b] (0.50, 0.50)***	0.31 (0.25, 0.35)	3.52 (2.80, 4.72)	***5.67 (4.00, 6.80)***	0.66 (0.48, 0.90)	3.10 (2.15, 4.30)	2.55 (2.00, 3.00)	***3.35 (2.20, 3.75)***
Manufactured device[e]	***18.4 (15.0, 19.9)***	0.30 (0.24, 0.39)	***0.28 (0.20, 0.31)***	6.08 (4.82, 7)	***10.16 (7.94, 11.0)***	1.24 (1.00, 1.38)	***4.63 (3.80, 5.16)***	1.92 (0.44, 2.00)	4.51 (3.11, 5.00)
Media filter	***8.7 (7.4, 10.0)***	0.18 (0.11, 0.20)	***0.16 (0.10, 0.20)***	4.35 (3.58, 5.10)	***6.01 (5.10, 6.60)***	1.00 (1.00, 1.00)	***1.69 (1.30, 2.00)***	1.90 (0.99, 2.00)	***2.20 (2.00, 2.60)***
Porous pavement	***13.2 (11.0, 14.4)***	***0.04[c] (0.02, 0.05)***	0.25[c] (0.25, 0.25)	5.75 (4.90, 5.91)	***7.83 (6.80, 8.10)***	0.50[c] (0.50, 0.50)	***1.86 (1.38, 2.21)***	***0.43[c] (0.33, 0.52)***	***1.71 (1.40, 1.80)***
Retention pond	***13.5 (12.0, 15.0)***	0.10 (0.07, 0.13)	***0.23 (0.20, 0.29)***	***4.24 (4.00, 4.57)***	***4.99 (4.06, 5.00)***	0.48 (0.23, 0.96)	***2.76 (2.00, 3.00)***	2.11 (1.40, 2.53)	***2.19 (2.00, 2.60)***
Wetland basin	***9.06 (7.0, 10.9)***	N/A[d]	***0.18 (0.10, 0.20)***	N/A[d]	***3.57 (3.00, 4.00)***	N/A[d]	***1.21 (1.00, 1.55)***	N/A[d]	N/A[d]
Wetland channel	***14.3 (10.0, 16.0)***	N/A[d]	0.49 (0.19, 0.50)	N/A[d]	4.81 (3.61, 5.20)	***0.52 (0.12, 0.75)***	2.49 (1.40, 3.11)	N/A[d]	2.18 (2.00, 2.40)

Notes:

(**Bolded** and *italicized* to show statistically significant decrease between influent and effluent median concentrations.) CI = confidence interval.

a. Computed using the bias corrected and accelerated (BCa) bootstrap method by Efron and Tibishirani (1993).
b. Hypothesis testing shows statistically significant increases for this BMP category.
c. Conclusions are limited for this BMP category due to a large percentage of non-detects in the influent.
d. N/A – not available or fewer than three studies for BMP/constituent.
e. "Manufactured device" includes cartridge filters, inlet inserts, oil/grit separators, and hydrodynamic separators.

Source: Geosyntec Consultants and Wright Water Engineers, 2012.

and nitrogen, followed by wetland basins. These practices include a permanent pool, which increases the hydraulic residence time, allowing sedimentation and biochemical processes to take place while also having both aerobic and anaerobic zones to facilitate oxidation-reduction processes (e.g., nitrification and denitrification). In general, the vegetated strip, bioretention, bioswale, and wetland channel do not show a statistically significant decrease in concentrations, and some sites can show increases in phosphorus concentrations. Leaching of phosphorus from soils and planting media and resuspension or degradation of captured particulate phosphorus may be a cause of the increases observed. If soil amendments contain high concentrations of phosphorus (e.g., compost), the phosphorus could be released into the BMP effluent.

2.2.2.2 DOT BMP Constituent Long-Term Removal Studies

Unfortunately, the BMPDB contains few studies with long-term data sets—most studies span only 1 to 2 years. Studies containing more than a 4-year monitoring record constitute only 28 (21%) of the 133 DOT studies within the BMPDB. Among these 28 studies, 20 pertained to vegetated strips, three pertained to sand filters, three pertained to porous asphalt, one pertained to bioretention, and one pertained to vegetated swales.

Sites featuring some of the most commonly used transportation-related BMPs, such as swales, vegetated strips, and sand filters, are of special interest for longer-term study. Additionally, sites with new and innovative transportation BMPs, including PFC pavements and the Washington State DOT (WSDOT) ecology embankment, are also of special interest. For this reason, 10 of the 28 DOT studies were selected for further review based on the type and location of the BMP. At least one of each BMP type available in the DOT studies was chosen from highway studies containing more than 4 years of data. They were evaluated here to determine if performance changed over time and, if so, whether BMP life should be considered in the development of the BMP Evaluation Tool. Based on the analysis of the limited data sets (described in the following), it was determined that there was

Table 2-4. BMP median effluent concentration for constituents commonly reported in the BMPD (continued).

BMP Type	Dissolved Zinc µg/L (95% CI)[a]	Total Zinc µg/L (95% CI)[a]	Total Phosphorus mg/L (95% CI)[a]	Orthophosphate mg/L (95% CI)[a]	Dissolved Phosphorus mg/L (95% CI)[a]	Total Nitrogen mg/L (95% CI)[a]	Total Kjeldahl Nitrogen mg/L (95% CI)[a]	NO_x as Nitrogen mg/L (95% CI)[a]
Vegetated strip	***14.0 (10.0, 16.0)***	***24.3 (16.0, 26.0)***	0.18[b] (0.15, 0.20)	0.06[b] (0.04, 0.07)	0.25[b] (0.16, 0.26)	1.13 (1.00, 1.23)	***1.09 (0.97, 1.12)***	***0.27 (0.24, 0.31)***
Bioretention	N/A[d]	***18.3 (7.7, 25.0)***	0.09 (0.07, 0.10)	0.04[b] (0.02, 0.05)	0.13 (0.05, 0.18)	***0.90 (0.74, 0.99)***	***0.60 (0.46, 0.72)***	***0.22 (0.19, 0.25)***
Bioswale	***24.5 (21.3, 27.5)***	***22.9 (20.0, 26.6)***	0.19[b] (0.17, 0.20)	0.12[b] (0.10, 0.13)	0.07[b] (0.05, 0.11)	0.71 (0.63, 0.82)	0.62 (0.50, 0.70)	0.25 (0.20, 0.28)
Composite	***9.9 (4.4, 10.0)***	***33.0 (28.5, 39.5)***	***0.13 (0.11, 0.15)***	0.07 (0.04, 0.10)	***0.08 (0.06, 0.09)***	1.71 (1.45, 1.81)	***102 (0.88, 1.14)***	***0.40 (0.33, 0.46)***
Detention basin	11.08 (8, 17)	***29.7 (17.1, 38.2)***	***0.22 (0.19, 0.24)***	0.39 (0.24, 0.56)	0.11 (0.08, 0.12)	2.37[b] (1.75, 2.69)	1.61 (1.16, 1.78)	***0.36 (0.24, 0.45)***
Manufactured device[e]	53.3 (44.0, 64.0)	***58.5 (52.8, 63.5)***	***0.12 (0.10, 0.13)***	***0.10 (0.06, 0.13)***	0.06 (0.04, 0.07)	2.22 (1.90, 2.41)	1.48 (1.32, 1.55)	0.41 (0.35, 0.44)
Media filter	***12.2 (8.3, 17.0)***	***17.9 (15.0, 20.0)***	***0.09 (0.08, 0.10)***	***0.03 (0.02, 0.03)***	0.08 (0.06, 0.09)	***0.82 (0.68, 0.99)***	***0.57 (0.50, 0.61)***	0.51[b] (0.46, 0.57)
Porous pavement	***6.5 (4.9, 7.9)***	***15.0 (12.5, 16.8)***	***0.09 (0.08, 0.09)***	0.05 (0.04, 0.06)	0.05 (0.04, 0.05)	1.49 (1.28, 1.65)	***0.80 (0.74, 0.90)***	0.71[b] (0.59, 0.77)
Retention pond	***9.6 (5.3, 10.9)***	***21.2 (20.0, 23.0)***	***0.13 (0.12, 0.14)***	***0.04 (0.03, 0.05)***	***0.06 (0.06, 0.07)***	***1.28 (1.19, 1.36)***	***1.05 (0.98, 1.10)***	***0.18 (0.15, 0.20)***
Wetland basin	N/A[d]	***22.0 (16.7, 24.3)***	***0.08 (0.07, 0.09)***	***0.02 (0.01, 0.02)***	0.05 (0.03, 0.06)	1.19 (1.04, 1.21)	1.01 (0.92, 1.09)	***0.08 (0.05, 0.11)***
Wetland channel	9.5 (2.9, 10.0)	15.6 (11.0, 20.0)	0.14 (0.13, 0.17)	0.06[b] (0.04, 0.06)	0.09 (0.07, 0.10)	1.33 (1.05, 1.56)	***1.23 (1.10, 1.30)***	***0.19 (0.15, 0.22)***

Notes:

(**Bolded** and *italicized* to show statistically significant decrease between influent and effluent median concentrations.) CI = confidence interval.

a. Computed using the bias corrected and accelerated (BCa) bootstrap method by Efron and Tibishirani (1993).
b. Hypothesis testing shows statistically significant increases for this BMP category.
c. Conclusions are limited for this BMP category due to a large percentage of non-detects in the influent.
d. N/A – not available or fewer than three studies for BMP/constituent.
e. "Manufactured device" includes cartridge filters, inlet inserts, oil/grit separators, and hydrodynamic separators.

Source: Geosyntec Consultants and Wright Water Engineers, 2012.

no basis for adjusting performance based on BMP life. The BMPs evaluated were:

- Ecology embankment in Washington (one study),
- Vegetated swale in Texas (one study),
- Vegetated strip in California (four studies),
- Sand filter in California (three studies), and
- Permeable friction course overlay in Texas (one study).

Ecology Embankment Study. The ecology embankment study was conducted in Auburn, WA [BMP name: WA Ecology Embankment at SR (State Route) 167, MP (milepost) 16.4]. The ecology embankment is a special type of bioretention design where sheet flow runoff from the adjacent pavement surface is filtered via interflow along an engineered slope and then collected in an underdrain at the toe of the slope. Essentially, the ecology embankment is a hybrid between a filter strip and a bioretention cell containing a custom filtration media mix. The filtration media mix consists of crushed rock (screened between ⅜-in. and #10 sieve) and three amendments: dolomite, gypsum, and perlite (WSDOT, 2006). Pretreatment consists of a vegetated strip between the paved shoulder and the filtration media. WSDOT sponsored this study to analyze seven constituents of concern from August 21, 2001, to April 7, 2005. The ecology embankment was located on the shoulder of northbound SR 167 treating runoff from an approximate 0.5-acre drainage area. The drainage area consisted of two lanes of traffic and two shoulders.

Table 2-5 compares the influent and effluent medians for the ecology embankment to the 2012 categorical performance estimates for bioretention and vegetated strips for the entire BMPDB. As shown in the table, the median effluent concentrations for the ecology embankment were lower than the categorical performance estimates for total suspended solids and total phosphorus despite having higher median influent concentrations. The low total phosphorus effluent concentration achieved is likely due to sorption and precipitation of phosphorus promoted by the dolomite and gypsum amendments

Table 2-5. Median concentrations of WA ecology embankment bioretention compared to Geosyntec Consultants and Wright Water Engineers (2012) categorical BMP performance summaries.

	TSS (mg/L)		Dissolved Copper (µg/L)		Total Copper (µg/L)		TKN (mg/L)		Dissolved Phosphorus (mg/L)		Total Phosphorus (mg/L)	
WA ecology embankment at SR 167 MP 16.4	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
	96	***5***	***12.5***	***7.1***	***52***	***10***	N/A	N/A	N/A	N/A	***0.21***	***0.04***
Categorical BMP Performance (Geosyntec Consultants and Wright Water Engineers, 2012)												
Bioretention	***37.5***	***8.3***	N/A	N/A	***17***	***7.67***	***0.94***	***0.6***	0.25	0.13	0.11	0.09
Vegetated strip	***43.1***	***19.1***	***11.66***	***5.4***	***24.52***	***7.3***	***1.29***	***1.09***	0.08	0.25	0.14	0.18

Notes: **Bolded** and *italicized* values indicate effluent median that is statistically significantly less than the influent median (alpha = 0.05). TKN = total Kjeldahl nitrogen.

and the lack of any organic material in the ecology mix. While the ecology embankment effluent concentration was higher for total copper, the influent concentrations were also generally much higher (a median influent of 52 µg/L compared to 17 µg/L for the bioretention category and 25 µg/L for the vegetated strip category). The dissolved copper performance for the ecology embankment is not significantly different from that for vegetated strips.

Vegetated Swale Study, Texas. The vegetated swale study was conducted in Austin, Texas (BMP name: Brodie Lane Swale) by the City of Austin. Vegetated swales may accept flow along the entire length of the swale or may only accept flow at the upstream end, as was the case for this study. Performance is theoretically better for swales that do not operate with spatially varied flow, but in practice, the many variables that affect swale performance (depth, velocity, soil permeability) may overshadow the flow condition. The Texas DOT sponsored a highway vegetated swale study analyzing 16 constituents of concern from May 1, 2000, to May 1, 2005. The vegetated swale received runoff from an approximately 0.5-acre drainage area. The drainage area consisted of the eastern portion of Brodie Lane in Austin, Texas. (Other specific design information is missing from the BMPDB.) Two distinct monitoring periods occurred at this site: one over the 2000–2001 wet season and one over the 2004–2005 wet season. Table 2-6 provides a comparison of median influent and effluent concentrations for the Brodie Lane swale to the categorical BMP performance for TSS, dissolved copper, total copper, total Kjeldahl nitrogen (TKN), orthophosphate, and total phosphorus. The median effluent concentrations for the Brodie Lane swale were lower than the categorical performance estimates for total copper, TKN, and total phosphorus. However, the median TSS effluent concentration for the Brodie Lane swale was more than twice the categorical median performance. While the Brodie Lane swale had higher median influent TSS concentrations, the BMP was unable to achieve statistically significant reductions in TSS. Consistent with the categorical BMP performance, the Brodie Lane swale did not achieve statistically significant removal of TKN and tended to increase total phosphorus concentrations.

Table 2-6. Median concentrations from flow-weighted composite samples of Brodie Lane swale compared to Geosyntec Consultants and Wright Water Engineers (2012) categorical BMP performance summaries.

	TSS (mg/L)		Dissolved Copper (µg/L)		Total Copper (µg/L)		TKN (mg/L)		Orthophosphate as Phosphorus (mg/L)		Total Phosphorus (mg/L)	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Brodie Lane swale	56.0	43.3	N/A	N/A	***3.65***	***3.0***	0.6	0.5	N/A	N/A	*0.11*	*0.12*
Categorical BMP Performance (Geosyntec Consultants and Wright Water Engineers, 2012)												
Bioswale	***21.7***	***13.6***	11.01	8.02	***10.9***	***6.54***	0.72	0.62	*0.06*	*0.07*	*0.11*	*0.19*

Notes: **Bolded** and *italicized* values indicate effluent median is statistically significantly less than the influent median (alpha = 0.05). *Italicized*-only values indicate effluent median is statistically significantly greater than the influent median (alpha = 0.05).

Vegetated Strip Studies, California. Vegetated strip studies in California included:

1. Moreno Valley, CA (BMP name: Moreno Valley 2, average annual rainfall: 9.9 in.). Caltrans sponsored a highway vegetated strip study analyzing 27 constituents of concern from November 24, 2001, to May 22, 2006. The vegetated strip treated runoff from an approximately 0.1-acre drainage area. The drainage area consisted of an asphalt-paved eight-lane highway (eastbound Moreno Valley freeway). Three other vegetated strip studies were conducted at this location (Moreno Valley 3, Moreno Valley 4, and Moreno Valley 5).
2. Redding, CA [BMP name: Redding RVTS (roadside vegetated treatment study) 2.2 m, average annual rainfall: 34.6 in.]. Caltrans sponsored a highway vegetated strip study analyzing 31 constituents of concern from November 11, 2001, to February 23, 2008. The vegetated strip treated runoff from an approximately 0.07-acre drainage area. The drainage area consisted of an asphalt four-lane highway (eastbound 299 between Chum Creek and Old Oregon Trail). Two other vegetated strip studies were conducted at this location (Redding RVTS 4.2 m and Redding RVTS 6.2 m).
3. Sacramento, CA (BMP name: Sacramento RVTS 2, average annual rainfall: 21.1 in.). Caltrans sponsored a highway vegetated strip study analyzing 31 constituents of concern from November, 12, 2001, to February 19, 2008. The vegetated strip treated runoff from an approximately 0.1-acre drainage area. The drainage area consisted of an asphalt-paved six-lane highway (northbound of I-5 north of the Laguna St. exit). Three other vegetated strip studies were conducted at this location (Sacramento 3, Sacramento 4, and Sacramento 5).
4. Yorba Linda, CA (BMP name: Yorba Linda RVTS 2, average annual rainfall: 14.4 in.). Caltrans sponsored a highway vegetated strip study analyzing 29 constituents of concern from November 24, 2001, to February 21, 2008. The vegetated strip treated runoff from an approximately 0.2-acre drainage area. The drainage area consisted of an asphalt-paved 13-lane highway (Riverside Freeway at Woodcreek). Three other vegetated strip studies were conducted at this location (Yorba Linda RVTS 3, Yorba Linda RVTS 4, and Yorba Linda RVTS 5).

Each of these sites is located in a dry summer subtropical or Mediterranean climate. As shown in Table 2-7, Sacramento, Moreno Valley, and Yorba Linda vegetated strips did not achieve the categorical bioswale median effluent concentrations for any of the constituents analyzed, but the Redding vegetated strip did meet the effluent concentrations for TSS, dissolved copper, total copper, and TKN. All studies increased orthophosphate and total phosphorus, which is similar to what has been observed for the overall BMPDB. The sampling locations were at 1.1, 2.6, 2.3, and 2.2 m from the edge of the pavement for the Sacramento, Moreno Valley, Yorba Linda, and Redding studies, respectively. Additionally, Sacramento was located on hydrologic soil type D, and Moreno Valley and Yorba Linda vegetated strips were located on steep slopes (>10%), both factors influencing and limiting infiltration within the vegetated strip. Inhibiting infiltration reduces concentration reductions associated with sedimentation and particle retention due to greater flow depth and velocity in the strip.

Table 2-7. Median concentrations of Moreno Valley 2, Redding RVTS 2.2 m, Sacramento RVTS 2, and Yorba Linda RVTS 2 compared to Geosyntec Consultants and Wright Water Engineers (2012) categorical BMP performance summaries.

	TSS (mg/L)		Dissolved Copper (µg/L)		Total Copper (µg/L)		TKN (mg/L)		Orthophosphate as P (mg/L)		Total Phosphorus (mg/L)	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Moreno Valley 2	61.5	83	20	17.5	41.5	28.5	2.15	1.8	0.08	0.14	0.29	0.35
Redding RVTS 2.2 m	***21.5***	***8***	2.2	2.3	3.95	3.5	0.87	0.58	0.01	0.02	0.04	0.06
Sacramento RVTS 2	50	27	5.6	5.75	***15***	***12***	1.2	1.25	0.12	0.21	0.26	0.31
Yorba Linda RVTS 2	64	100	15	14	37	44	1.6	2.1	0.06	0.06	0.22	0.32
Categorical BMP Performance (Geosyntec Consultants and Wright Water Engineers, 2012)												
Vegetated strip	***43.1***	***19.1***	***11.7***	***5.4***	***24.5***	***7.3***	1.29	1.09	*0.08*	*0.25*	*0.14*	*0.18*

Notes: **Bolded** and *italicized* values indicate effluent median is statistically significantly less than the influent median (alpha = 0.05). *Italicized*-only values indicate effluent median is statistically significantly greater than the influent median (alpha = 0.05).

Moreno Valley 2 also contained the shortest vegetation, approximately 3 cm high, and the lowest vegetation coverage—average vegetation cover of less than 15%. Dense vegetation decreases runoff velocities and increases the opportunity for straining of particles, facilitating sedimentation and reduction of constituents. The Redding vegetated strip had at most 85% vegetation cover throughout the study, and the height of the vegetation was at least 5 cm, with the tallest vegetation of 28 cm. The shortest effective lengths of vegetated strips were 4.6 m, 13 m, 0 m (edge of pavement), and 4.2 m for Sacramento, Yorba Linda, Moreno Valley, and Redding, respectively (Caltrans, 2003d). Redding performed the best in terms of median effluent concentrations and had the smallest effective length. Sacramento was the only strip that achieved statistically significant removal of total copper. During the Caltrans (2003d) study, this site had high vegetative cover (80%–98%), which likely influenced the retention effectiveness at this site.

Sand Filter Studies, California. Sand filter studies in California included:

1. Redding, CA (BMP name: Mountain Gate Partial Sedimentation Austin Sand Filter). The California DOT (Caltrans, 2003a) sponsored a highway sand filter study analyzing 33 constituents of concern from February 6, 2002, to February 6, 2006. The sand filter treated runoff from an approximately 2.5-acre drainage area. The drainage area consisted of a four-lane highway (northbound and southbound I-5 near the Mountain Gate exit).
2. Shasta, CA (BMP name: Mt. Shasta Maintenance Station Sand Filter). Caltrans sponsored a maintenance station study analyzing 32 constituents of concern from November 7, 2002, to April 15, 2006. The sand filter treated runoff from an approximately 2.6-acre drainage area. The drainage area consisted of a DOT maintenance station in Shasta, CA.
3. Whittier, CA [BMP name: Eastern SF (sand filter)]. Caltrans sponsored a maintenance station study analyzing 27 constituents of concern from November 11, 2001, to April 19, 2007. The sand filter treated runoff from an approximately 1.5-acre drainage area. The drainage area consisted of a DOT maintenance station in Whittier, CA.

The California sand filter BMPs contain only sand, resulting in higher filtration rates as compared to media filters with blended compost media. Sand-only filters provide good removal of suspended solids and any constituents bound to particles, but typical filtration sand is relatively inert, and it would not be expected to reduce dissolved constituents unless an organic biofilm develops within the media bed. Biofilms may only develop in wet climates (all of these sites were relatively dry climates) where the media bed does not completely dry out between storms. Data from each of the sand filters are compared to the categorical performance estimates for media filters for the entire BMPDB.

The Redding sand filter is a partial sedimentation sand filter that does not include a sedimentation forebay, using one basin for both sedimentation and sand filtration. The Mt. Shasta maintenance station sand filter and the Whittier sand filter are full-sedimentation sand filters with dedicated basins for sedimentation that are separate from the sand filtration basin.

Table 2-8 compares the influent and effluent median values for the three sand filters to the categorical performance estimates for media filters for the entire BMPDB. As shown in the table, both the influent and effluent concentrations for the Mountain Gate sand filter were lower than the categorical performance estimates for all the constituents in the table. The comparatively lower constituent influent concentrations at the Mountain Gate sand filter may be responsible for some of the differences in effluent quality between the Mountain Gate sand filter and the categorical performance

Table 2-8. Median concentrations of Mountain Gate sand filter compared to Geosyntec Consultants and Wright Water Engineers (2012) categorical BMP performance summaries.

	TSS (mg/L)		Dissolved Copper (µg/L)		Total Copper (µg/L)		TKN (mg/L)		Orthophosphate as P (mg/L)		Total Phosphorus (mg/L)	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Mountain Gate SF	***35.2***	***4.3***	***3.6***	***1.35***	***8.8***	***2.65***	***0.78***	***0.3***	***0.03***	***0.02***	***0.09***	***0.05***
Mt. Shasta SF	***18***	***1***	0.89	1.1	***4***	***1.4***	***0.3***	***0.16***	0.02	0.01	***0.05***	***0.01***
Eastern SF	***44***	***11***	5.4	6.45	13	7.5	0.87	0.57	N/A	N/A	*0.13*	*0.09*
Categorical BMP Performance (Geosyntec Consultants and Wright Water Engineers, 2012)												
Media filter	***52.7***	***8.7***	5.37	4.35	***11.28***	***6.01***	***0.96***	***0.57***	***0.05***	***0.03***	***0.18***	***0.09***

Notes: **Bold** and *italicized* values indicate effluent median is statistically significantly less than the influent median (alpha = 0.05). *Italicized* values indicate effluent median is statistically significantly greater than the influent median (alpha = 0.05).

estimates. Other factors may be maintenance and climatic differences.

As shown in Table 2-8, both the median influent and effluent concentrations for the Mt. Shasta station sand filter were lower than the categorical performance estimates for all the constituents in the table. However, with the exception of TSS, the sand filter did not show a statistically significant difference between the effluent and the influent for any of the constituents. This site had relatively low influent concentrations compared to other sand filters in the BMPDB, with many of the constituents at or near the analytical detection limits.

Unlike the Mountain Gate and Mt. Shasta sand filters, the Eastern SF shows higher effluent concentrations for all constituents except TKN and total phosphorus compared to the categorical standards. The relatively poor performance of the Eastern SF compared to the Shasta and Mountain Gate sand filters is likely related to loading. The influent concentrations are significantly higher for the Eastern SF, resulting in higher effluent concentrations.

Other factors, such as rainfall intensities, pretreatment designs, and site characteristics, could be explored for each study to better understand the differences in median effluent concentrations between all the sites explored and the media filters in the overall BMPDB.

Permeable Friction Course Study, Texas. The permeable friction course study was conducted in Austin, Texas (BMP name: AustinTX1PFC). PFC was installed on the southbound loop of 360, approximately 1.5 km north of Lakewood Drive. The study analyzed 11 constituents of concern from April 1, 2004, to September 1, 2009, and received runoff from southbound 360.

PFC is an innovative roadway material placed in an approximately 25 to 50 mm overlay on top of regular pavement. PFC improves safety and driving conditions by allowing the road surface to drain within the porous overlay rather than on the surface of the pavement. PFC also provides water quality benefits. In this report, PFC and open-graded friction course (OGFC) are synonymous. Note that PFC and OGFC are not a full-depth permeable pavement and do not infiltrate runoff to the subgrade. Rather, runoff travels laterally through the overlay to the shoulder area, where the overlay terminates.

Table 2-9 compares the influent and effluent median concentrations for the TX1 site to the categorical performance estimates for permeable pavement for the entire BMPDB. As shown in the table, the TX1 facility shows superior TSS, TKN, and total phosphorus removal as compared to the categorical performance estimates for permeable pavement. The TX1 facility underperforms in dissolved and total copper removal as compared to the categorical estimates. PFC shows strong performance for TSS and particulate-bound pollutant removal due to shallow sedimentation and filtration/straining processes that occur as stormwater passes through the pores of the PFC material. The limited capacity for mitigating dissolved pollutants is reflected in the poor dissolved copper removal performance.

Pollutants may become attached to the PFC matrix by straining, collision, and other processes. Material that accumulates in the pore spaces of PFC is difficult to transport and may be trapped permanently. On the surface of a conventionally paved road, splashing created by tires moving through standing water can transport even large particulate matter rapidly to the edge of pavement. However, water velocities within the pore spaces of the PFC are low and likely could only transport the smallest material (Eck et al., 2010). PFC can produce TSS reductions consistent with the removal rates expected from practices such as sand filters or bioretention systems (Barrett, 2003; Hsieh and Davis, 2005; Hunt et al., 2008). Concentrations of total metals from PFC were generally significantly reduced when compared to those of conventional pavement.

2.2.2.3 BMP Water Quantity Performance (Peak Rate and Volume Reduction)

Technical Summary of Volume Reduction from BMPDB. In 2011, Geosyntec Consultants and Wright Water Engineers,

Table 2-9. Median concentrations of AustinTX1PFC to Geosyntec Consultants and Wright Water Engineers (2012) categorical BMP performance summaries.

	TSS (mg/L)		Dissolved Copper (µg/L)		Total Copper (µg/L)		TKN (mg/L)		Ortho-phosphate as P (mg/L)		Total Phosphorus (mg/L)	
AustinTX1PFC	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
	121	8	5.24	*8.7*	28.4	11.4	1.06	0.8	N/A	N/A	0.16	0.05
Categorical BMP Performance (Geosyntec Consultants and Wright Water Engineers, 2012)												
Permeable pavement	**65.3**	**13.2**	5.37	*5.75*	**13.07**	**7.83**	**1.66**	**0.8**	0.04	*0.05*	**0.15**	**0.09**

Notes: **Bold** values indicate effluent median is statistically significantly less than the influent median (alpha = 0.05). *Italicized* values indicate effluent median is statistically significantly greater than the influent median (alpha = 0.05).

Table 2-10. Relative observed volume reduction in BMPDB data set.

BMP Category	No. of Monitoring Studies	25th Percentile	Median	75th Percentile	Average
Vegetated strips	16	18%	34%	54%	38%
Vegetated swales	13	35%	42%	65%	48%
Bioretention w/underdrain	7	45%	57%	74%	61%
Grass-lined detention basin	11	26%	33%	43%	33%

Inc., performed an analysis of the BMPDB to specifically evaluate volume reduction through selected post-construction BMPs. Volume reduction is an increasingly important issue in TMDL and NPDES permit compliance; however, very little data within the BMPDB address this aspect of performance since the focus tends to be on pollutant concentration reduction. The analysis notes that when volume data were present in the database, they were often suspected to be unreliable. However, a small percentage of studies were identified as having produced reliable volume reduction data. A summary of relative volume reduction observed from these studies is shown in Table 2-10.

Normally dry vegetated BMPs (filter strips, vegetated swales, bioretention, and grass-lined detention basins) appeared to have substantial potential for volume reduction on a long-term basis, on the order of 30% for filter strips and grass-lined detention basins, 40% for grass swales, and greater than 50% for bioretention with underdrains. They also were shown to provide better volume reduction for smaller storms, which tended to occur more frequently than larger storms (Geosyntec Consultants and Wright Water Engineers, Inc., 2011).

Retention ponds, wetland basins, and channels did not appear to provide substantial volume reduction on average, and they were not recommended for projects intending to achieve appreciable volume reduction. The study did not provide specific data for BMPs (such as bioretention) that might use impermeable liners, but it was speculated that volume reduction performance would be lower compared to unlined systems subject to identical conditions (Geosyntec Consultants and Wright Water Engineers, Inc., 2011).

University of Maryland Study of Volume Loss within Lined Bioretention Systems. In 2003, the University of Maryland constructed a lined bioretention system for the specific purpose of identifying reduction impacts to peak rate and volume. The study produced data from 49 storm events. In 18% of those, the lined bioretention systems produced no discharge volume. When discharge occurred, it was observed for prolonged periods of time—sometimes several days—such that outflow hydrographs would overlap multiple storm events. Typical peak flow reduction (flow rate rather than volume) observed was on the order of 44% to 63% of the inflow peak rates (Davis, 2008).

2.3 Current Asset Management, Inspection, and Maintenance Practices

2.3.1 Asset Management and Inspection Needs

State DOTs have been devoting effort to inventorying permanent stormwater treatment facilities (by inspection of facilities) and their locations to support asset management and maintenance programs. The task takes years to complete, even with consistent, diligent effort.

Many performance problems (and associated repair costs) can be identified and addressed early through a regular inspection program. WERF describes the value of inspection and monitoring of BMPs at various stages of development (WERF, 2012, p. 429):

- Inspection during the design and construction phase helps ensure proper design, construction techniques, and sediment and erosion controls.
- Inspections following the construction phase serve to inspect, track, and help ensure that controls continue to function properly.
- Regular monitoring during operation not only ensures that maintenance activities are being carried out as specified, but also identifies any areas of potential system failure.
- Standard inspection procedures help assess the stability and function of stormwater controls.

2.3.1.1 Basic Inspection Data

The U.S. EPA advises development of inspection checklists to help determine renovation and repair needs for stormwater BMPs. EPA recommends inclusion of the following general items within BMP inspection checklists (U.S. EPA, 2012):

1. The BMP's minimum performance expectations,
2. Design criteria,

3. Structural specifications,
4. Date of initial operation,
5. Expected life span, and
6. Maintenance requirements for each BMP, to help the inspector determine if a BMP's maintenance schedule is adequate or in need of revision.

In addition, a checklist will help the inspector determine renovation or repair needs.

The WERF suggests that general BMP assessment include (WERF, 2012, p. 430):

1. Site conditions,
2. Water quality performance,
3. Structural integrity, and
4. Overall function.

2.3.1.2 As-Built Drawings

A database or geographic information system (GIS) inventory of stormwater BMP locations should include other descriptive data for each facility. Inspectors need to know where the controls are and what they should look like so they can be maintained as designed. As-built drawings offer a number of advantages for this purpose (WERF, 2012, p. 430). They:

- Provide details on components of a control that require inspection,
- Reference operation and maintenance needs in some cases,
- Reduce the potential for confusion in the field, and
- Allow the inspector to verify that all parts of the facility are functioning as designed.

Inspectors often lack ready access to as-built drawings, but agencies are increasingly investing in this access. Where as-built drawings are not available, some DOT NPDES program managers are consulting with maintenance staff to develop basic recorded information.

DOTs are also increasingly requiring contractors to provide as-built drawings in an easily storable format. For example, Colorado DOT now has a requirement on any new project that the contractor provide a surveyed, final as-built drawing in electronic format (Gay, 2012). WSDOT has new NPDES permit reporting requirements, indicating that the agency will "work with project offices to develop a procedure for ensuring field verified as-builts are provided to headquarters as part of the project closeout procedure" and that 10% of new projects will be audited annually to verify that all reported newly constructed stormwater facilities are entered into the post-construction stormwater facility database correctly (Washington State Department of Ecology, 2012).

2.3.1.3 BMPs Inspection Personnel

Responsibility for inspection of post-construction stormwater controls varies widely across states and agencies. For example:

- Regulatory agencies often have resource constraints, and consequently, routine inspections do not occur with the frequency typically recommended. In these instances, much of the regulatory response is complaint-based.
- Annual certification of performance by owner or professional engineer may be used. This is an idea that is currently being discussed in California for compliance with municipal NPDES permits.
- Colorado DOT stormwater personnel are assessing each BMP annually.
- Harris County, Texas, requires that a professional engineer selected by the facility owner certify annually that all required maintenance for a given control has been performed and that the facility is functioning properly.
- Maintenance staff or regional environmental staff performs level-of-service (LOS) condition assessments for features of stormwater facilities and other roadside assets in many states.
- Contract staff/consultants perform inventories in other states, such as Delaware.

2.3.1.4 Recording and Storing Inspection Results for Performance Assessment

While the results of inspections used to be stored on paper, they are increasingly recorded electronically for instant uploading to databases.

Life-cycle performance assessment requires detailed attribute data that describe each feature's material, defects, and repairs over time so that the reasons for failure can be understood. GIS combined with the hydraulic infrastructure database opens up a world of information about waterways, land use, and soil effects on the drainage system. At the Minnesota DOT, drainage system and water quality features are captured by Global Positioning System (GPS) field inspection or GIS tools and are accessible in a database called "HydInfra" (hydraulic infrastructure; http://www.dot.state.mn.us/bridge/hydraulics/hydinfra.html). Minnesota DOT's web-based reports identify drainage system features that need cleaning or repair. Specialized reports simplify the end-of-year MS4 reporting requirements that need maintenance (see Figure 2-1).

The HydInfra database includes inventory, inspection, and maintenance data on ponds, structural pollution control devices, MS4 outfalls, illicit discharges, pipes (culverts <10-in. span or storm drain pipes), structures (manholes, catch basins),

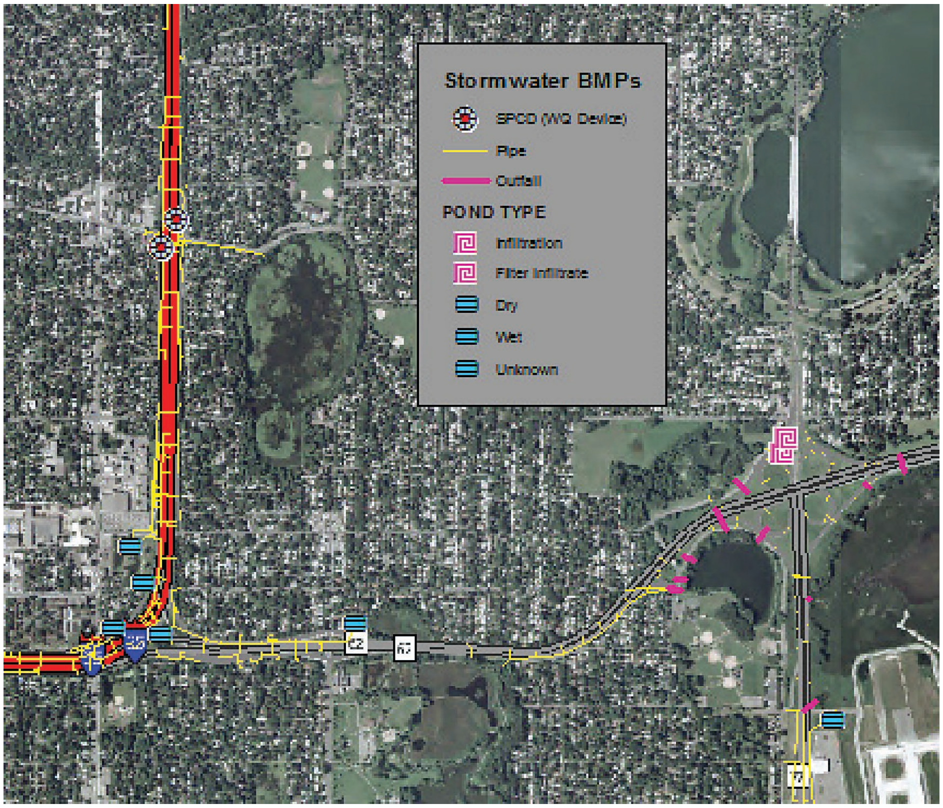


Figure 2-1. BMP information in GIS format, Minnesota Department of Transportation.

various special structures (aprons, end sections, weirs), and ditches (see Figure 2-2).

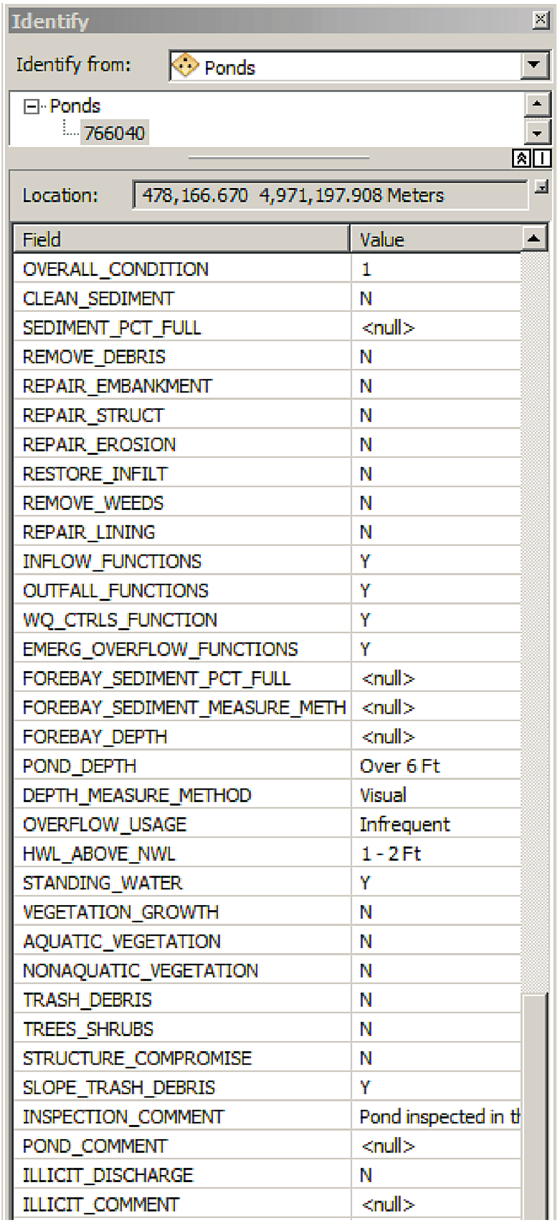
Colorado DOT's System for Recording Post-Construction BMP Assessments. Colorado DOT (CDOT) has been inspecting the full inventory of over 900 post-construction BMPs since 2010. Stormwater staff located and reviewed all BMPs in the field using information obtained from as-built plans and through consultation with maintenance staff. Stormwater staff record inspection results and reviews in the Stormwater Inspection Tool, a software application tailored to BMP types. Inspectors send results to maintenance staff to help identify labor/maintenance action needed to address identified issues. Maintenance performed and costs/labor hours are recorded in CDOT's accounting database. CDOT annually reports to the state regulatory authority on the number of post-construction water quality structures inspected, the total maintenance expenditures on each, and the results of limited, automated stormwater runoff monitoring.

The state is currently developing a new online system to store BMP data. The system is being developed in C# programming language and SQL2005 and will be moved to CDOT's virtual server as soon as it is ready (Gay, 2012).

Figure 2-2. HydInfra database information example.

Maryland State Highway Authority's Drainage Infrastructure Assessment System. The Maryland State Highway Authority (MDSHA) Drainage Infrastructure Assessment System was the first comprehensive system for recording and storing inspection results. MDSHA's system was also the first evolved system to assess conditions in a tested, duplicable way (see Figure 2-3).

MDSHA uses the system to manage the approximately 1,500 stormwater management facilities it owns, with inspection teams of trained staff who identify potential further environmental improvements. MDSHA has complemented this work by mapping the entire state for opportunities for retrofitting BMPs, enhanced pollution prevention and stream restoration, and development of a plan for systematic implementation of those improvements. The grade-based rating



Identify

Identify from: Ponds

Ponds
766040

Location: 478,166.670 4,971,197.908 Meters

Field	Value
OVERALL_CONDITION	1
CLEAN_SEDIMENT	N
SEDIMENT_PCT_FULL	<null>
REMOVE_DEBRIS	N
REPAIR_EMBANKMENT	N
REPAIR_STRUCT	N
REPAIR_EROSION	N
RESTORE_INFILT	N
REMOVE_WEEDS	N
REPAIR_LINING	N
INFLOW_FUNCTIONS	Y
OUTFALL_FUNCTIONS	Y
WQ_CTRLS_FUNCTION	Y
EMERG_OVERFLOW_FUNCTIONS	Y
FOREBAY_SEDIMENT_PCT_FULL	<null>
FOREBAY_SEDIMENT_MEASURE_METH	<null>
FOREBAY_DEPTH	<null>
POND_DEPTH	Over 6 Ft
DEPTH_MEASURE_METHOD	Visual
OVERFLOW_USAGE	Infrequent
HWL_ABOVE_NWL	1 - 2 Ft
STANDING_WATER	Y
VEGETATION_GROWTH	N
AQUATIC_VEGETATION	N
NONAQUATIC_VEGETATION	N
TRASH_DEBRIS	N
TREES_SHRUBS	N
STRUCTURE_COMPROMISE	N
SLOPE_TRASH_DEBRIS	Y
INSPECTION_COMMENT	Pond inspected in tl
POND_COMMENT	<null>
ILLICIT_DISCHARGE	N
ILLICIT_COMMENT	<null>

Figure 2-3. MDSHA infrastructure system screen shot.

system for stormwater management facilities includes an inventory, database, and photo record of all facilities statewide and their maintenance status, within a GIS. Under the rating system, those installations graded "A" or "B" are considered functionally adequate. By 2009, MDSHA had reached its long-term goal of 95% functional adequacy for its system, with that percentage being rated "A" = everything fine, working fine, and no maintenance required or "B" = minor maintenance (need mowing or trash removal), leaving only 5% needing maintenance or retrofitting to achieve functional adequacy.

MDSHA's drainage system GIS is designed to be used for planning-level computations and operations-level activities. The database is used to determine the general location of systems and drainage areas, to track maintenance activities, and to address public complaints.

Information in the drainage infrastructure database is intended to be sufficient to identify, locate, and evaluate every BMP to provide an overall assessment of MDSHA's BMP inventory. The information in the system assists the agency with decisions on inspection, maintenance, repair, and retrofit of BMP facilities, in addition to supporting compliance with MDSHA's NPDES MS4 permit. It supports GIS queries:

- By individual structure or system and BMPs (e.g., pipes, inlets, manholes, end walls, and their associated data attributes),
- By outfall (size, type, etc.),
- Within a drainage area,
- Within a watershed,
- Within a jurisdiction,
- Statewide, and
- By roadway contract.

The system has evolved to also support hydrologic analysis of the drainage systems for the preparation of estimates of the quantity and quality of stormwater runoff from the SHA right-of-way and the effects of changes in stormwater management practices. More recently, MDSHA has added visual impact-assessment components to its evaluation and remediation.

The managing for results (MFR) portion of MDSHA's business and stewardship plan was used to measure the progress and success of the NPDES program and define timelines and milestones for the numerous elements of the program. Using the MFR approach, MDSHA measured progress every month for each of the major elements and every 6 months for all the elements of the program. An example of this is the tracking of the required number of source identification efforts that needed to be completed.

By tracking BMP facilities and progress, the database has also helped in identifying BMP failures. When MDSHA inspects an infiltration BMP, it does a functional rating and assesses whether the BMP is functioning. If a filtration structure has failed, there may be an opportunity to convert the site into a structure of a different type—a wet retention facility. MDSHA has had some success with converting failed infiltration BMPs to function as wet ponds. MDSHA is trying to assess how to efficiently reassign ratings.

The database does have its limitations. While MDSHA's database was developed to enable standardized, comparable, and meaningful data, MDSHA is finding that the agency does not have the staff and analytical resources to use the information to its maximum benefit. MDSHA's system defines various filtering practices—for example, vegetated swales with subcodes for wet, dry, and other swales—but the DOT maintenance division is not able to use all of those subcodes in its record keeping or maintenance work.

Delaware Department of Transportation (DelDOT) Stormwater BMP Inspection/Maintenance Program. In 2007, DelDOT, assisted by KCI Technologies, Inc., developed a statewide stormwater BMP inspection/maintenance program with a consistent protocol for inventorying, inspecting, and maintaining BMPs, now documented in DelDOT's comprehensive *BMP Field Inspection Manual.* Field tested in 2007 with the inspection of over 300 BMPs, DelDOT's approach established four key components of a BMP inspection: site conditions, water quality, embankment, and outlet structure, each with specific evaluation parameters, differing among BMP types (Mattejat and Thompson, 2007).

North Carolina LOS Rating and Performance Reporting for Post-Construction BMPs. The North Carolina Department of Transportation (NCDOT) has a system for evaluating the LOS for post-construction BMPs. The LOS rating for stormwater control measures was created to establish a score for stormwater control measures being considered an asset to NCDOT and to gauge the maintenance needed for individual devices. A rating scale was developed from "A" to "F." An "A" rating would be given to a device that shows some aging and wear but no structural deterioration or maintenance needs, and that is functioning properly. An "F" rating would be given to a device that is no longer functional due to the general or complete failure of a major structural component or the lack of adequate maintenance. Individual LOS ratings are taken at least once a year for all stormwater control measures. These ratings are averaged for divisions, counties, and road types and provided to the asset management group within NCDOT every 2 years. In addition, based on these average ratings, the division roadside environmental engineer (DREE) from each division is given a "does not meet," "meets," or "exceeds" rating that is found on his or her individual performance dashboard appraisal. Any rating below "C" indicates to the DREE that maintenance is needed on that particular device.

NCDOT's December 2010 Maintenance Condition Assessment Report shows over 94% of facilities functioning as designed, exceeding the 90% target the agency set for itself. With over 22,000 tenth-of-a-mile sample points, NCDOT has enough points to directly manage from its sample and confidently set maintenance budgets.

Washington State DOT Maintenance Accountability Process (MAP) and LOS Rating. WSDOT has a MAP that uses outcome-based performance measures with a rating scale of "A" (best) to "F" (worst) for reporting the LOS provided. Although WSDOT does complete turbidity and other monitoring for water quality, outcomes from the MAP do not necessarily refer to water quality measures. Rather, outcomes for WSDOT refer to tasks/results accomplished by maintenance personnel. This can be a percentage of proactive or preventive maintenance performed.

WSDOT currently uses three types of assessments: operational assessment, condition assessment, and task completion. WSDOT has found task completion to be an important part of understanding what has and has not been done and whether budgets are sufficient. Operational assessment data indicate operational issues, such as how many repairs per signal were needed in a given period. Conditional assessment data are collected using statistically valid, randomly chosen sites for field surveys. Task completion data are collected from records of work required and accomplished; this metric quantifies the number of tasks needed for a specific activity each year and how many of those tasks were completed. The tasks can be preventive maintenance with a scheduled frequency or can be a list of existing deficiencies. LOS is expressed as the percentage of identified tasks that were completed. The difference between what should have been done and what was done identifies the backlog for individual maintenance activities. Reporting using the task completion component began in 2010, with eight MAP activities. The 2011–2013 bienniums will expand the use of task completion to other MAP activities. The MAP priority matrix prioritizes maintenance activities and ranks them according to their contribution to maintenance program goals.

2.3.1.5 Drivers in Inventorying and Inspecting BMPs

NPDES reporting requirements along with the additional urgency imposed by pollution reduction targets and TMDLs are driving increases in BMP inspection and maintenance to improve performance. For example, Rhode Island DOT's NPDES permit requirements for pollution prevention/good housekeeping for municipal operations state that RIDOT must "develop inspection procedures and schedules for long-term operation and maintenance (O&M) of municipal facilities, municipal structural BMPs, and the MS4." Asset management programs require basic data to allow decision makers to prioritize repair and budgeting for long-term O&M. DOTs need a record of installed BMPs, their maintenance requirements, and their maintenance history to ensure their operation at the design level.

2.3.2 Current Maintenance Practices

2.3.2.1 Current DOT BMP Maintenance Practices

Determining Maintenance Frequency. Few DOTs have systematically or programmatically budgeted for maintenance of post-construction stormwater controls. When asked, many DOTs indicated that maintenance is performed on an as-needed basis. Historically, the maintenance of stormwater BMPs included activities such as removing excess sediment, revegetating ditches and embankments, and trash removal that have occurred in response to inspection during a storm event. BMPs have also been maintained "on an emergency basis, when their hydraulic conveyance function is impaired enough to threaten the structural integrity of the highway or impair roadway safety" (WSDOT, 2005). DOT respondents reported that where formal information was not available, maintenance guidelines for stormwater BMP guidance documents were based "mostly on regulatory judgment or historical estimates of sediment accumulation, rather than empirical data" (WSDOT, 2005).

DelDOT defined remedial actions needed for each BMP after reviewing inspection results completed in 2007 and began to develop a long-term strategy for remedial actions, creating three general categories for remediation: maintenance work orders, invasive vegetation spray list, and retrofit recommendations. Sediment and vegetation buildup impeding the conveyance were the most common issues.

For maintenance work orders, starting with the BMP inspections completed in 2008, routine maintenance issues identified in the inspections (performed by a third-party consultant) were entered into DelDOT's maintenance work order system. Each DelDOT district assigned staff to receive BMP work orders and schedule tasks based on the type of work, location of the work, and severity of the issue. Work continues to be handled on a bulk rather than individual BMP basis for efficiency. For example, a labor crew might be scheduled to handle maintenance at several BMPs located in the same area, or a Vactor truck may be scheduled for removal of accumulated sediment from several BMPs.

DelDOT is performing careful tracking of invasive species, including an inventory of the approximate square footage of various invasives at each BMP and an eradication strategy. For example, DelDOT eradicates Canadian thistle regardless of the amount observed. This tracking enables DelDOT to identify the needed level of funding and effort to address the issue in a timely way.

Retrofit remedial actions are considered beyond the scope of DelDOT's maintenance districts because these projects tend to require engineering analyses to redesign and reconstruct the BMP. DelDOT categorizes remedial actions as major (complete reconstruction) and minor (only a component of a BMP that needed repair or reconstruction).

WSDOT has developed design standards for the basic BMPs used on its highway system. The standards are used for determining what and when maintenance may be required, at given (typically annual) evaluation points. WSDOT has not established design standards for nonstandard BMPs, so the agency will start with literature values as they begin inspection and maintenance (Baroga, 2012). WSDOT identified the numbers of each BMP type in its inventory, by region, and maintenance requirements. For example, the agency computes that wet/detention/infiltration ponds will need sediment clean out every 5 years, and it will take 3 days to remove 150 yd^3 of sediment.

CDOT's approach assesses BMP function per plan specifications in the field and then sends the field evaluation to the maintenance district/region for labor and equipment estimates. The evaluators "review as-builts, specs on how high the vegetation is supposed to be or what the sediment limits are, and work to restore the BMP to its intended function" (Gay, 2012).

The Minnesota Department of Transportation (MnDOT) developed a BMP resource maintenance guide (Marti et al., 2009). The guide is a supplement to the state's Stormwater Manual for inspection and maintenance activities for BMPs. It contains information for evaluating various BMPs to install based on anticipated long-term maintenance requirements.

The University of Minnesota completed a study entitled "Assessment and Maintenance of Stormwater Best Management Practices" (Gulliver and Anderson, 2008). The document provides information on the assessment, maintenance, and renovation of stormwater BMPs.

Rules of Thumb for Maintenance Schedule. DOTs and resource agencies often operate with rules of thumb regarding appropriate maintenance schedules. For example, the EPA's stormwater pollution prevention fact sheet says that in stormwater ponds, "vegetation should be harvested every 3 to 5 years, and sediment removed every 7 to 10 years" (U.S. EPA, 2010).

The New York State Department of Transportation (NYSDOT) has a GreenLITES (Leadership in Transportation Environmental Sustainability) program for maintenance and operations that indicates maintenance schedule cycle times on the following rotating schedule:

- Every 10 years for open drainage facilities—maintaining ditches, shoulder grading,
- Annual sweeping around closed conduit drainage,
- Drainage structure repair on a 10-year schedule for closed conduit drainage, and
- Capital improvements of closed drainage on a 50-year basis (NYSDOT, n.d.).

The program provides recognition for the degree to which districts place catch basin inserts and culvert/pipe replacements in order to incentivize staff. This is primarily an internal management program for NYSDOT to measure performance, recognize good practices, and identify where it needs to improve sustainability practices.

Influence of New NPDES Requirements on Maintenance Frequency. New NPDES permits are beginning to specify maintenance schedules for permanent/post-construction stormwater BMPs. For example, WSDOT's NPDES permit requires annual inspection and maintenance of stormwater BMPs (Baroga, 2012). According to the permit, BMPs must attain explicit standards, which are outlined in Chapter 5, Section 5 of WSDOT's *Highway Runoff Manual* (WSDOT, 2011).

Standard BMP Maintenance Activities. Most types of structural or vegetated BMPs share commonality in terms of the basic required maintenance activities. These activities typically include:

- Restoration of eroded areas at inlets, outlets, and slope embankments;
- Removal of invasive or excess vegetation;
- Response to burrowing or nesting wildlife;
- Response to standing water conditions or prolonged ponding;
- Removal of any obstruction to maintenance access;
- Identification and elimination of elicit discharge or other unusual occurrences in the vicinity, such as vandalism;
- Repair of structural deformation, cracking, corrosion, joint failure, or settlement;
- Removal of flow obstruction or excessive sediment buildup;
- Replacement of damaged signs, fences, or other intended barriers to pedestrians or animals; and
- Replacement of damaged or nonfunctioning irrigation systems (not typically used at most installations).

Practitioners may refer to the following sources for more detailed maintenance checklists and activities associated with post-construction BMPs:

- *Best Practices Handbook on Roadside Vegetation Management*, Minnesota DOT (http://www.lrrb.org/media/reports/200019.pdf).
- U.S. EPA BMP Inspection and Maintenance webpage (http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=factsheet_results&view=specific&bmp=91).
- *NCDENR* [North Carolina Department of Environment and Natural Resources] *Stormwater BMP Manual* (http://portal.ncdenr.org/c/document_library/get_file?uuid=7b297ecd-955a-417e-a024-56639b068f54&groupId=38364).
- *Northern Virginia BMP Handbook* (http://www.novaregion.org/DocumentCenter/Home/View/1679)
- Santa Clara Valley Urban Runoff Pollution Prevention Program Sample BMP Inspection Checklist (http://www.scvurppp-w2k.com/bmp_om_forms.htm).
- Newton, Kansas, BMP Inspection and Maintenance manual (http://www.newtonkansas.com/Modules/ShowDocument.aspx?documentid=622).
- Southeast Michigan Council of Governments BMP Maintenance Inspection Checklists (http://www.semcog.org/uploadedfiles/Programs_and_Projects/Water/Stormwater/LID/LID_Manual_appendixF.pdf).

2.3.2.2 *DOT Perceptions Regarding the Challenges of BMP Maintenance—Considerations for Design*

In *NCHRP Report 728* (Geosyntec Consultants et al., 2012), DOT practitioners shared their insights and lessons learned on the selection, design, and implementation of BMPs, especially in urban environments. Maintenance issues were among their greatest concerns and their most frequently mentioned topic:

- Retention/infiltration systems endanger groundwater or weaken pavement subgrade (Utah DOT).
- Ponding in sand filters can lead to increased mosquito breeding (DelDOT).
- It often is quite difficult to construct access roads for maintenance forces (Oregon DOT).
- Cartridge filters require trained staff and vehicle jib cranes and safe access to adequately maintain (Oregon DOT).
- Ultra-urban BMPs require constant monitoring (New Mexico DOT and CDOT).
- Accessibility for inspection and maintenance is often not considered in facility design but is essential to its life cycle, particularly for underground storage and treatment facilities. Facilities that use vegetation are often not successful due to stress of pollutants, wetness, drought, or improper species selection in conflict with desire to use native species (MDSHA).
- Standing water and vector breeding due to inadequate soil conditions (New Jersey DOT).
- Availability of training for maintenance personnel (Montana DOT and CDOT).

2.4 BMP Life-Cycle Costs

2.4.1 Life-Cycle Cost Factors for BMPs

The Center for Watershed Protection compiled cost data from 100 retrofit projects in a 2007 document, which provided guidance for estimating construction costs (Center for Watershed Protection, 2007). The data reflect all types of retrofit projects, although the center noted that cost data for highway retrofits are sparse. Retrofit is defined as a standalone project without other highway construction. New construction in this report encompasses new and reconstruction projects.

Life-cycle cost factors are described in WEF's 2012 manual, Design of Urban Stormwater Controls, which reviews and summarizes unit construction activity costs from standard civil engineering price guides, develops costing models to facilitate generic stormwater control cost estimation, compares actual and predicted costs, and outlines many cost factors, especially in BMP construction (Barrett and WEF, 2012, pp. 486–489). Size, distribution, and complexity of stormwater systems and controls also affect maintenance needs. Some of the cost factors are:

1. Stormwater controls can be built at much lower costs as part of a larger project rather than as stand-alone projects. Larger projects offer better economies of scale and do not have as large a fraction of total cost for mobilization and project initiation. It is more cost-effective to grade in extra basins or swales when a much larger development site is already being graded. Similarly, wet basins and dry basins generally have lower unit costs as facility size increases.
2. Most cost studies assume building on undeveloped land, but some retrofits are built into existing public land or easements, while others require land to be purchased and may have higher costs to get the water to drain to the facility. Many sites are not in optimal hydraulic locations due to constraints imposed by prior development. In general, the construction costs for highway BMP retrofits can be quite high (as much as 10 times more expensive than new construction) and are highly site-specific (Currier et al., 2001).
3. Regulatory requirements vary for water quality control volumes and flow rates and for structure components such as inflow structures, splitter boxes, and fencing. Specified structural components can be complex and costly or simple and inexpensive.
4. Public entities often face more requirements, bidding laws, and regulation, entailing more supervision and steps, which can raise costs. Public agencies also take on long-term maintenance of their own projects, leading to an interest in making sure the work is done right and is sustainable.
5. If an agency is able to site a facility where little grading or excavation is needed and where blasting or long-distance hauling can be avoided, that generates savings, but many projects are subject to rules and regulations that limit the DOT's ability to choose a more cost-effective site.
6. Some agencies have begun to seek partnerships with other entities (e.g., private developers or other agencies) to build stormwater controls with a better economy of scale and thus reduced cost.
7. Experienced staff and contractors are familiar with the steps involved and can suggest better, more maintainable, and cost-effective designs and projects. New requirements and technologies are relatively costly since contractors have little experience with them. Likewise, inexperienced agency staff may not be confident or knowledgeable enough to suggest cost-reducing changes in rules and designs.
8. The number of bids can depend on the state of the economy and the timing of the bid offering. If timed with many competing offerings, fewer bidders may respond, raising costs.
9. More stringent treatment requirements increase project costs. Water quality design criteria vary by jurisdiction and determine the size and complexity of the BMP that is required to meet them.
10. Geography and climate influence the design rainfall and rainfall-runoff characteristics of a site, in turn affecting drainage system component sizing.
11. The cost of land (purchase and legal costs) can outweigh design and construction costs for some controls in dense urban settings, making maintenance-intensive underground facilities seem more practical. Careful design and use of open space allocations sometimes reduces the effective cost of land allocated to surface water drainage.
12. Soil type and groundwater vulnerability dictate whether infiltration is required to treat an initial volume of runoff or whether additional storage and attenuation will be required. The soil type also dictates the level of erosion protection and vegetated reinforcement required and may influence plant selection.
13. Many stormwater control components require granular fill as the attenuation and filtering media; these costs will vary depending on the distance of the site from a potential source. Topsoil costs will also depend on source locations. Other market factors such as fuel costs to transport materials may greatly alter costs.
14. The availability of suitable plants and the required level of planting planned for a particular control component influence landscape costs, which can be substantial. In addition, landscape contractors are often required to provide a warranty for the plantings for some period, which can escalate with mortality rates of 20% to 25% for plantings.
15. Routine maintenance consists of basic tasks performed on a frequent and predictable schedule. These include inspections, vegetation management, and minor debris removal. In addition, three levels of routine maintenance can be identified, and these relate mainly to frequency of the activity being undertaken (and in WEF's estimates of life-cycle costs). These are defined as:
    a. Low/minimum—A basic level of maintenance required to maintain the function of the stormwater control;

b. Medium—The normal level of maintenance to address function and appearance; it allows for additional activities, including preventative actions, at some facilities; and
c. High—Enhanced maintenance activities required for appearance and amenity only.

16. Intermittent maintenance typically consists of more heavy-duty, unpredictable, and infrequent tasks to keep systems in working order, such as repair of structural and erosion damage, and, potentially, complete facility reconstruction. The intermittent category can include a wide range of tasks that might be required to address maintenance issues at a BMP (e.g., invasive species removal, animal burrow removal, and forebay cleanout). Intermittent maintenance is nonscheduled, occurring as needed in response to field conditions.
17. Common maintenance activities are inspections, vegetation management, and sediment removal, with frequency and thoroughness that can be affected by funding. Barrett et al. estimated that as much as 80% of total staff hours spent in the field in many jurisdictions is associated with vegetated mowing, with little effect on near-term performance, as opposed to sediment, debris and trash removal, or structural repair, though lack of routine maintenance can destroy structures in some cases, as when tree roots destroy embankments—a situation that can be avoided with periodic mowing (Barrett and WEF, 2012, p. 431). Common maintenance usually follows a regular schedule, or can if funding is available.

When other contributions are leveraged, some costs can be heavily reduced or nearly eliminated. For example, highways are designed to provide a clear recovery zone adjacent to the roadway to enable drivers to regain control before they hit a fixed object or roll over. These roadside vegetated areas are built with low slopes up to about 10-m (30-ft) wide, precisely the design criteria to optimize the water quality benefits of vegetated strips, although these benefits have only recently been recognized (Barrett and WEF, 2012, p. 502). While DOTs made these land and design investments for transportation and safety purposes, they also provide water quality benefits. WEF concludes: "For swales and filter strips, water quality benefits can effectively be considered free when compared to conventional drainage systems and when the maintenance is performed by the property owner" (Barrett and WEF, 2012, p. 509). Mowing is performed for safety/visibility and aesthetic purposes, but this is compatible with water quality objectives.

The order of BMPs in a treatment train can also greatly affect maintenance costs and can produce substantial benefits when the last facility in a train, such as filters or infiltration trenches or basins, can clog and require more expensive maintenance or rehabilitation. Again, swales or buffer strips offer an important benefit by reducing sediment upstream of a BMP that is more difficult to maintain.

2.4.2 Tracking Actual BMP Maintenance Costs

Traditionally, DOTs have made only very rough estimates of the maintenance needs and costs of roadside assets, but now they are inventorying assets, creating asset registries, and establishing and tracking costs per unit to maintain and operate those assets.

A small number of DOTs are beginning to collect information on the true, real-time costs of maintaining stormwater controls. This involves assigning maintenance codes to structures, individually identifying and attributing maintenance actions to individual BMPs located via GPS or automatic vehicle location technology, and creating the data systems and hiring staff to use them to perform the desired analyses. This information will provide the basic input data needed for finer-scale understanding and calculation of long-term performance and life-cycle costs of post-construction stormwater controls. DOTs can then follow the same process for full cost determination of permanent BMPs as for any maintenance asset, as outlined in *NCHRP Report 688: Determining Highway Maintenance Costs* (Cambridge Systematics, Inc., et al., 2011):

Step 1: Gather and classify maintenance program activities and expenditures.
Step 2: Allocate maintenance support expenditures to line activities.
Step 3: Gather and classify enterprise programs and expenditures.
Step 4: Allocate a portion of enterprise support expenditures to the maintenance program.
Step 5: Combine cost categories to derive full cost.

WSDOT developed Excel spreadsheets with assumptions on maintenance needs, which were distributed to other states in the course of project interviews. WSDOT is estimating the costs for delivering the new BMP maintenance requirements in the agency's latest NPDES permit. The NPDES permit requirements set out a clear regimen of design standards, from which WSDOT has been calculating costs. Cost projections may not be needed for BMP maintenance in the future because the agency is within months of having maintenance vehicles fully GPS capable and able to report location, activity, and hours spent for maintenance work, as well as removal quantities, such as the amount of sediment removed and cost. WSDOT staff and budget analysts anticipate that this will give the agency a better understanding of the costs of BMP maintenance (Baroga, 2012).

Table 2-11. Actual construction cost of BMP technologies (1999 dollars).

BMP Type	Cost/m^3 of the Design Storm ($)
Delaware sand filter	3,472
Multichambered treatment train	847
Wet basin	2,670
Oil–water separator	2,540
Austin sand filter	2,009
Infiltration trench	1,954
Storm filter	1,575
Swales	951
Unlined extended detention basin	877
Strips	835
Infiltration basins	639
Lined extended detention basin	348
Continuous deflective separator	220
Drain inlet inserts	33

In WSDOT's case, GPS data will be linked with the agency's Highway Asset Tracking System (HATS), a tool for managing maintenance activities by asset or roadway section. The system connects to highway features where the asset information of the agency is stored (existing asset ID, name, and location). Maintenance technicians document their work using a personal digital assistant (PDA) while simultaneously building/maintaining the inventory in HATS. When doing an inspection on an asset, staff will have the capability to add the asset or generate a pending activity, recording deficiencies that require action to be taken. The action could be anything from making a specific repair, cleaning, or making a recommendation for a larger repair. The system will track when, where, and what was inspected; if a pending activity was generated from the inspection; when the pending activity was completed; and if it remains to be completed. The system will also track multiple work activities within a section of roadway and create a pending repair for those items that cannot be completed at the time.

2.4.3 Historic Data and Studies Relating to BMP Life-Cycle Cost

2.4.3.1 Caltrans Retrofit Study

The Caltrans retrofit study included detailed accounting of BMP capital and maintenance costs, which were also subjected to independent third-party review (Caltrans, 2004). The final report points to uncertainty with regard to the location-specific nature of some costs and to how well the cost data may reflect actual costs in a large-scale retrofit program. However, the data are detailed and comprehensive, and can provide a means for comparing and ranking costs associated with various BMP technologies. Tables 2-11 and 2-12

Table 2-12. BMP actual annual maintenance effort for Caltrans BMP Retrofit Pilot Program.

BMP	Equipment and Materials ($)	Average Labor Hours
Sand filters	872	157
Extended detention basin	958	188
Wet basin	2,148	485
Infiltration basin	3,126	238
Infiltration trench	723	98
Biofiltration swales	2,236	246
Biofiltration strips	1,864	233
Storm filter	308	106
Multichambered treatment train	2,812	299
Drain inlet inserts	563	121
Oil–water separator	1,066	139
Continuous deflective separator	785	254

provide capital and maintenance information from the Caltrans study.

The practitioner may refer to the following website for other detailed BMP capital and maintenance cost information from the Caltrans retrofit study: http://www.dot.ca.gov/hq/oppd/stormwtr/Studies/BMP-Retro-fit-Report.pdf.

2.4.3.2 Highlights from WEF Life-Cycle Cost Analyses of BMPs

WEF and WERF have produced life-cycle cost analyses for a variety of BMP types (Lampe et al., 2005; Barrett and WEF, 2012, pp. 502–509). Unit whole life costs are provided in Table 2-13.

Maintenance costs of wet basins make up almost 50% of the whole life cost when basins are implemented in high-visibility locations, where aesthetics are at a premium. Dry basins tend to be easier and less expensive because there is little or no standing water in the facility. Wet and dry basins cost the same to construct if there is no pond liner for the wet basin.

The primary maintenance cost of bioretention is associated with vegetation management. The frequency of this activity was assumed to be similar to swales but with a greater cost because many bioretention facilities would require weeding, mulch replacement, and other activities beyond the mowing required for most swales.

For swales and filter strips, water quality benefits can effectively be considered free when compared to conventional drainage systems, as well as when the maintenance is performed by the property owner.

Infiltration trenches may require little routine maintenance outside of litter and debris removal. The whole life cost driver is the frequency with which the trench must be rehabilitated. Intervals of 4, 8, and 12 years were assumed based on low, medium, and high scenarios, at which time the cost is essentially the same as the original construction cost. For infiltration basins, the capital cost and routine maintenance are essentially the same as those for a dry basin, but an infiltration basin can incur much higher costs associated with maintaining sufficient infiltration rates. In addition to sediment removal, an infiltration basin may require additional activities to remove and replace clogged soils on the floor of the basin. The frequency of this activity is largely dependent on the initial soil texture and the rate at which sediment accumulates in the basin.

With PFC pavement in the same location as a conventional surface, the cost for the water quality control facility is the incremental cost difference between a conventional pavement and the pervious overlay pavement. The difference in whole life cost depends on the frequency of sweeping. DOT interest has been fostered through safety and livability co-benefits offered: better visibility and traction in storm events, reduced splash and hydroplaning, and reductions in deflected noise from highway traffic. Porous asphalt overlays (PFCs) are being used in Georgia, California, Massachusetts, and Utah. PFC was up to 8.1% of all pavements in Texas in 2010. The pavement is assumed to need replacement more frequently (every 25 years or less versus 35 and 40 years) at a cost equal to original construction. Water quality monitoring of three locations in the Austin area indicated up to a 90% reduction in pollutant discharges from PFC compared to conventional pavement. This reduction is the result of accumulation of pollutants within the pavement and the reduction in pollutants washed off vehicles during storm events (Eck et al., 2010).

2.4.3.3 Urban Denver Drainage and Flood Control District BMP-REALCOST Tool—A Predictive Tool to Estimate BMP Life-Cycle Costs

The Urban Denver Drainage and Flood Control District (UDFCD) BMP-REALCOST tool produces order-of-magnitude cost approximations for use primarily at the planning level:

- Construction costs are estimated using a parametric equation that relates costs to a physical parameter of a BMP:

Table 2-13. Whole life costs of common BMPs per cubic meter of stormwater treated (WERF, 2012).

Stormwater Control	Whole Life Cost ($/m^3)		
	Low Maintenance	Medium Maintenance	High Maintenance
Swales/strips	500	660	2,200
Wet ponds/wetlands	520	600	925
Dry extended detention basins	330	375	575
Sand filter	450	520	670
Bioretention	1,900	2,200	5,100
Infiltration trench	1,200	1,600	2,700
Infiltration basin	330	400	700
Permeable pavement	570	640	1,400

total storage volume (for storage-based BMPs), peak flow capacity (for flow-based or conveyance BMPs), or surface area (for permeable pavements).

- Maintenance costs are estimated using a derived equation that relates average annual costs to a physical parameter of the BMP.
- The additional costs of designing and permitting a new BMP are estimated as a percentage of the total construction costs. For Denver-area projects, a value of 40% is recommended if no other information is available.
- The cost of purchasing land for a BMP is estimated using a derived equation that incorporates the number of impervious acres draining to the BMP and the land use designation in which the BMP will be constructed.
- The costs of administering a stormwater management program are estimated as a percentage of the average annual maintenance costs of a BMP. For Denver-area projects, a value of 12% is recommended if no other information is available.
- After some period in operation, a BMP will require major rehabilitation. The costs of these activities (including any salvage costs or value) are estimated as a percentage of the original construction costs and applied near the end of the facility's design life. The percentages and design lives vary according to BMP (UDFCD, 2010, pp. 2–17).

UDFCD's BMP-REALCOST tool produces net present value (NPV) of the whole life costs of the BMP(s) implemented, the average annual mass of pollutant removed (lb/year), and the average annual volume of surface runoff reduced (ft/year), which can then be used to compute a unit cost per pound of pollutant or cubic feet of runoff removed over the economic life (years) of the BMP (UDFCD, 2010, pp. 2–17).

2.4.3.4 Research Funded or Supported by the Minnesota Department of Transportation

MnDOT has participated in or is aware of the development of recent studies on the cost, maintenance, and assessment of BMPs. Two of these projects are described in the following.

"The Cost and Effectiveness of Stormwater Management Practices" (Weiss et al., 2005). Stormwater management practices for treating urban rainwater runoff were evaluated for cost and effectiveness in removing suspended sediments and phosphorus. Construction and annual operating and maintenance cost data were collected and analyzed for dry detention basins, wet basins, sand filters, constructed wetlands, bioretention filters, infiltration trenches, and swales using literature that reported on existing sites with stormwater management practices across the United States. The annual operating and maintenance costs were also compiled.

"Best Management Practices Construction Costs, Maintenance Costs, and Land Requirements" (Barr Engineering Company, 2011). This report summarizes a typical range of low-impact development stormwater management BMP costs and identifies a range of construction and operating costs for eight treatment low-impact development BMP categories. The costs and the expected longevity of the BMPs were used to estimate life-cycle costs for these stormwater BMPs.

CHAPTER 3

Hydrologic Performance Assessment Methods and Data Sources

Load reduction from BMPs is a function of concentration reduction and surface runoff volume reduction. Many BMP effectiveness assessments focus only on concentration reduction for the pollutants of concern. However, BMPs that may not be as effective for concentration reductions, such as vegetated swales and dry detention basins for some pollutants, can achieve substantial surface runoff volume reduction, which thereby reduces the effective effluent load and frequency of discharge from the BMP to surface waters. Similarly, wetland BMPs, which have been shown to effectively reduce concentrations, may actually increase loads because of increased flows caused by groundwater discharge or increases in saturation overland flows.

This chapter describes the hydrologic performance assessment methods and data sources used to estimate average annual BMP performance with respect to runoff volume captured and reduced or treated and released. Chapter 4 describes the data sources and approaches used to estimate concentration reductions and how those reductions are coupled with hydrologic performance estimates to predict pollutant load reductions.

3.1 Conceptual Framework

Capture efficiency (or percent capture) is a metric that measures the percent of runoff that is captured and managed by a BMP (i.e., that does not bypass or immediately overflow). Captured stormwater may be infiltrated, evapotranspired, or treated and released. Capture efficiency is typically expressed as an average capture rate over a long period, for example, average annual percent capture. Runoff volume that is not captured by a BMP is referred to as bypass or overflow and is assumed untreated. Volume reduction by a BMP can only occur when water is captured.

When evaluating capture efficiency and volume reduction, each BMP can be considered to consist of a set of storage compartments, each with a distinct volume, discharge rate, and pathway by which water discharges [i.e., surface discharge, infiltration, evapotranspiration (ET)]. For example, a bioretention area with a raised underdrain may have storage below the underdrain that would be considered retention storage (infiltrates rather than leaving the project location via surface discharge). Ponded water and gravitational water temporarily held in the soil pore space would be considered detention storage (leaves primarily through the underdrain via surface discharge). Similarly, water not freely draining from pore spaces (e.g., plant-available water) would be considered ET storage.

Figure 3-1 illustrates how ET, retention, and detention storage compartments were modeled. When storage capacity is available in a retention or detention storage compartment, then that compartment can capture additional inflow. When storage capacity is not available in either compartment, then inflowing water overflows or bypasses the system without treatment. The capture and volume reduction performance of a BMP are primarily a function of the amount of storage volume provided and the rate at which the storage drains to volume reduction pathways and surface discharge pathways.

Two classes of storage compartments were simulated: consistent drawdown compartments (such as the retention and detention storage mentioned previously) and seasonally variable drawdown compartments (such as ET storage). The approach taken was to model a range of unit storage volumes and drawdown characteristics for each type of compartment separately and then to post-process the modeling results to estimate the performance of a specific BMP. The model simulations are described in greater detail in the following.

The conceptual representation of BMPs having discrete storage compartments allows for the development of a generalized hydrologic model that only requires two parameters, normalized storage volume and drawdown time, for estimating percent capture and volume reduction:

- **Normalized storage volume.** Expressed as an equivalent precipitation depth over the watershed that would produce

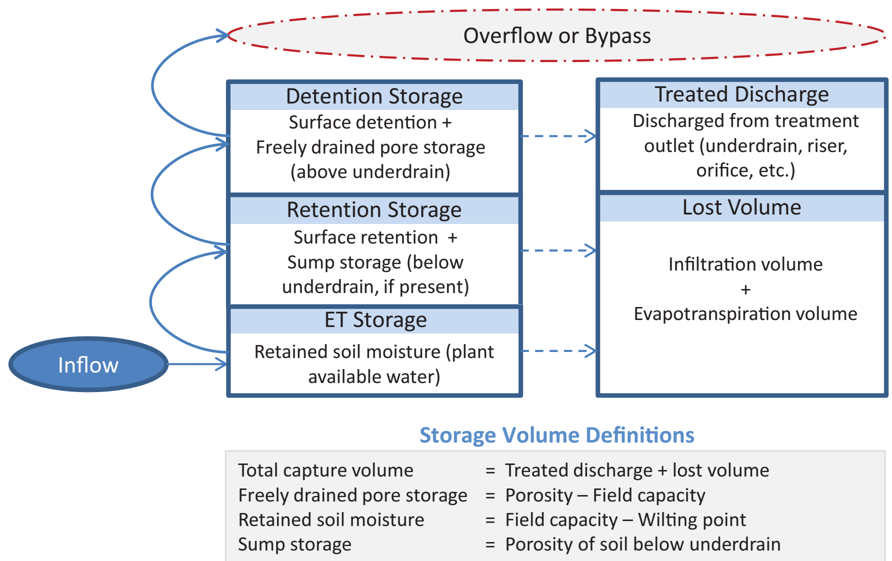


Figure 3-1. Conceptual representation of BMP storage compartments for estimating capture efficiency and volume reduction.

a runoff volume equivalent to the compartment volume. For example, a 3,000-ft^3 storage volume for a watershed that is 1 acre with a runoff coefficient of 0.9 would translate to an equivalent precipitation depth of 0.92 in. [3,000 ft^3 × 12 in./ft/(1 acre × 43,560 ft^2/acre × 0.9)]. Larger BMP sizes (storage volumes) relative to contributing area and imperviousness will provide a larger equivalent precipitation depth, which will allow them to bypass less volume (i.e., more capture).

- **Drawdown time for consistent drawdown.** For BMP storage elements with nominally consistent drawdown rates regardless of season (i.e., infiltration, filtration, orifice-controlled surface discharge), the representative drawdown time can be expressed in hours. For example, a bioretention area with a storage depth of 18 in. and an underlying design infiltration rate of 0.5 in. per hour would have a drawdown time of 36 h (18 in./0.5 in./h). Similarly, a detention basin with a 50,000 ft^3 storage volume, a 4-ft average depth, and a single 3-in. orifice will drain in approximately 60 h (based on an orifice coefficient of 0.6). BMPs with short drawdown bypass less runoff than BMPs of the same size with long drawdown times.
- **Drawdown time for seasonally variable drawdown.** For BMP storage elements with seasonally varying drawdown rates (i.e., storage drained by ET), the concept of a representative drawdown time is not applicable. In this case, the ET storage depth (i.e., the amount of potential ET that must occur for the ET storage to drain) is a more appropriate indicator of how quickly storage is recovered.

By isolating these two most important predictive variables (storage and drawdown time), a limited number of continuous simulation model runs and associated results can be used to describe the expected long-term performance of a wide range of BMP types and configurations. For example, the results of a long-term model simulation for a 0.75-in. normalized storage depth with 24-h drawdown would be representative of a wide range of different BMP configurations. The two examples that follow would both be reliably represented by this single model run:

- Example 1: A 20,000 ft^3 infiltration basin draining 8.2 acres of pavement (equates to 0.75-in. equivalent storm), with 3-ft ponding depth and a design infiltration rate of 1.5 in. per hour (equates to 24-h drawdown time).
- Example 2: A 300 ft^3 bioretention area with underdrains with a tributary area of 0.122 acres of pavement (equates to 0.75-in. equivalent storm), with 12 in. of ponding storage depth and a design media filtration rate of 0.5 in. per hour (equates to a 24-h drawdown time).

3.1.1 Continuous Hydrologic Simulation

Estimating the long-term or average annual volume captured and treated by a BMP typically requires continuous hydrologic simulation modeling (or relationships derived from continuous simulation modeling). EPA's SWMM Version 5.0.022 was used to model hundreds of long-term continuous simulation scenarios for rain gauges distributed across the contiguous United States to provide hydrologic performance results for specific BMP configurations and locations. Precipitation data used in the simulations are described in Section 3.1.2. An array of unit area storage volumes and drawdown characteristics were simulated for each rainfall record. An advantage to continuous simulation modeling for the analysis was the ability to account for the variability in the temporal frequency, distribution, and magnitude of storm events at a particular climatic region/subregion in relation to a given BMP design.

3.1.2 Precipitation Data Sources

Precipitation data were used to develop long-term BMP hydrologic performance estimates. The sources of the data used are described in the following.

Precipitation data selected for the continuous simulation model runs included 343 National Climatic Data Center (NCDC) Cooperative Observer Program (COOP) rain gauges with hourly rainfall data to cover all of the major climatic regions of the contiguous United States. A variety of unit area storage volumes and drawdown characteristics were simulated for each rainfall record. Summary statistics, including the 85th- and 95th-percentile storm event depths and the average annual rainfall depth, were computed for each rain gauge. The percentile storm events are used in the tool to scale modeling results to better match the site-specific rainfall patterns of a user's study area. The average annual rainfall depths were used to estimate the average annual runoff volume to a BMP.

In addition to the 343 COOP rain gauges, 40 Automated Surface Observing System (ASOS) rain gauges with 5-min rainfall data were analyzed. The higher temporal resolution was needed for estimating the performance of flow-based BMPs such as vegetated swales and filter strips, where the volume treated is more of a function of the design flow rate than the available storage capacity. A fine-resolution precipitation record is particularly important for small, highly impervious catchments such as highway sections to be able to understand when the BMP treatment or capture rate is exceeded or if it is not. This analysis therefore supplements continuous simulation modeling to provide a more complete estimate of the volume captured and volume reduced for flow-based BMPs.

3.1.3 Volume-Based BMPs and Volume Reduction Estimation

An array of continuous simulation runs was executed to encompass the range of normalized storage volumes and drawdown times that were needed to simulate the variety of BMP types and design configurations considered for this effort. For each combination of design variables, the percent capture was calculated as:

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

where

V_{by} = the total volume bypassed over the simulation period, and

V_c = the total runoff volume flowing into the BMP over the simulation period.

Volume reduction efficiency refers to the portion of the captured volume that is lost to infiltration, ET, or consumptive use and does not discharge directly to surface water (see Figure 3-1). The following assumptions have been made:

- For storage compartments without a surface discharge pathway (i.e., retention storage), the volume reduction efficiency was set to 100% (i.e., complete retention of all water that is captured).
- For storage compartments with surface discharge as well as significant volume loss pathways, the volume reduction efficiency is estimated by computing the average loss rate as a fraction of the average total discharge rate. For example, if the average surface discharge rate during the drawdown period is 2 in. per hour and the average infiltration plus ET loss rate during that period is 0.5 in. per hour, then the volume reduction efficiency would be estimated as 20% [0.5/(2 + 0.5)].
- For storage elements with only surface discharge pathways (i.e., lined systems with limited ET), the volume reduction efficiency is assumed to be zero. The volume estimated to be discharged from the primary treatment outlet (e.g., underdrain, riser, orifice) is assumed to be treated and having a concentration according to the estimated concentration for the particular BMP–pollutant combination (Section 3.2.2).

A large number of SWMM model runs (58,310) were completed to develop the underlying database to support the tool. Two types of modeling scenarios were conducted.

Consistent drawdown scenarios were used to represent storage compartments that draw down at a nominally constant rate throughout the year (i.e., are not influenced significantly by seasonal variations in ET or use patterns). These runs can be used to represent compartments that drain to infiltration or surface discharge. Key variables include:

- Climate station and associated precipitation,
- Normalized storage volume, and
- Drawdown time.

ET drawdown scenarios were used to represent storage compartments of BMPs that are regenerated via ET losses (i.e., are regenerated at different rates throughout the year). These runs can be used to represent the water stored in soil

Table 3-1. Summary of continuous simulation model runs.

Consistent Drawdown Model Runs (Infiltration, Surface Discharge)	
Parameter	**Number of Increments**
Climate regions	343
Modeled imperviousness of tributary area	1 (100%)
Storage volume	10
Drawdown time	10
Total – consistent drawdown runs	*34,300*
ET Drawdown Model Runs	
Parameter	**Number of Increments**
Climate regions	343
Modeled imperviousness of tributary area	1 (100%)
Storage volume	10
ET depth increments	7
Total – ET runs	*24,010*

as well as water stored in cisterns that is applied at agronomic rates. Key variables include:

- Climate station and associated precipitation and ET,
- Normalized storage volume, and
- ET drawdown depth (i.e., the amount of ET that must occur for the ET storage to drain completely).

Table 3-1 provides a summary of the tool supporting model runs.

Key results from each SWMM run were extracted to develop lookup databases indexed by the key parameters described in Table 3-1. The database consists of tabulated percent capture values for different drawdown times and design storm depths that have been normalized by the 85th-percentile storm depth for each rain gauge. This normalization is used to adjust the percent capture values to reflect higher or lower storm event depths at a study site as compared to the simulated rainfall gauge.

3.1.4 Flow-Based BMPs

For flow-based BMPs such as vegetated swales and filter strips, estimation of percent capture differs slightly from the approach used for volume-based BMPs. For volume-based BMPs, bypass occurs when the storage volume is exceeded. For flow-based BMPs, bypass or cessation of treatment occurs when the water quality design flow rate is exceeded. With percent capture being only a function of instantaneous flow rates, percent capture nomographs can be developed simply by analyzing rainfall records and expressing design flow rates in terms of design storm intensities. The volume captured by an online, flow-based BMP can be estimated by summing all flows less than or equal to the design flow rate. This assumes that once the design flow rate is reached, treatment effectively ceases. For offline BMPs, it can be assumed that a portion of all flows up to the design flow, including the design flow during the overflow, can be treated. Therefore, offline BMPs will have a higher effective percent capture than online BMPs when otherwise similar in design/sizing.

To account for different drainage area times of concentration, various averaging periods were used to aggregate the sort-duration intensities into average intensities prior to computing the volumetric percent captures. For example, if a drainage area has a 10-min time of concentration, then the percent capture nomograph associated with the 10-min averaging period would be used to estimate the capture efficiency of a flow-based BMP.

Percent capture nomographs were created for 40 ASOS rain gauges (Section 3.1.2) by analyzing 5-min rainfall data from each gauge to estimate the capture efficiency for various design intensities and times of concentration. Results were developed for both online (no treatment assumed to occur once the design flow rate exceeded) and offline BMP configurations. Each of the 343 NCDC COOP stations (Section 3.1.2) is assigned one of the ASOS gauges based on proximity.

3.2 Percent Capture Nomographs

The objective of this section is to present the results of the analyses and describe how these results have been combined to assess BMP performance for the selected BMPs. The information presented in this section forms the basis for pollutant load reductions estimated by the tool. The tool is discussed in detail in Chapter 9.

The nomographs generated from the continuous simulation modeling for percent capture for volume-based BMPs

(Section 3.2.1) and flow-based BMPs (Section 3.2.2) are described in the following sections. A description of how these nomographs can be used is provided in Section 3.2.3.

3.2.1 Volume-Based BMP Percent Capture Nomographs

An example volume-based BMP percent capture nomograph is shown in Figure 3-2. Other nomographs for other geographic locations can be found within the tool. This example is based on continuous hydrologic simulations using a 54-year rainfall record (1954–2008) from New Orleans International Airport. To use the nomograph, the design volume (in watershed inches) and drawdown time (DDT) of each of the major BMP storage volumes (detention storage, retention storage, ET storage) must be estimated. The average annual percent capture can then be estimated through visual interpolation. As indicated by the nomograph, to achieve 80% average annual runoff capture volume in New Orleans, a detention system must be sized using approximately 1.5 in. if the target drawdown time is 48 h or 1.25 in. if the target drawdown time is 24 h.

3.2.2 Flow-Based BMP Nomographs

Following are sample flow-based nomographs for the Portland International Airport rain gauge. Figure 3-3 is for an online configuration, and Figure 3-4 is for an offline configuration. Each data point on the nomographs reflects a percent of runoff captured by a BMP assuming a particular time of concentration and design intensity. Using the nomographs, the design intensity required to achieve 80% capture, assuming a 10-min time of concentration, is approximately 0.21 in./hr for an online configuration and approximately 0.12 in./hr for an offline configuration. As shown in the figures, choosing higher design intensities and times of concentration achieves higher percent capture.

3.2.3 Using the Percent Capture Nomographs

The continuous simulation modeling and post-processing described in Section 3.1 provide the basis for estimated average annual volume captured, reduced, and treated for a wide variety of climates, BMP types, and design configurations. The specific outputs from this process are summarized in Table 3-2.

The BMP Evaluation Tool queries the nomograph results associated with the selected rain gauge to estimate the approximate average annual volume treated and volume reduced for a BMP given the site location and planning-level information about the drainage area and BMP design. Example 3.1 illustrates the use of a volume-based nomograph to estimate the volume treated and reduced for a bioretention system with the major detention and retention storage compartments shown in Figure 3-5.

Example 3.1 summarizes the approach used by the tool to complete the computations given user input. The example computations use the example nomograph presented in Figure 3-2.

Figure 3-6 illustrates the process used by the tool to estimate percent capture and percent volume loss using linear interpolation of the nomograph data. The BMP design volumes are stored as unitless values that have been normalized by the 85th-percentile discrete storm event for the selected rain gauge. These normalized values can be used to scale the nomographs for the selected rain gauge to a particular location.

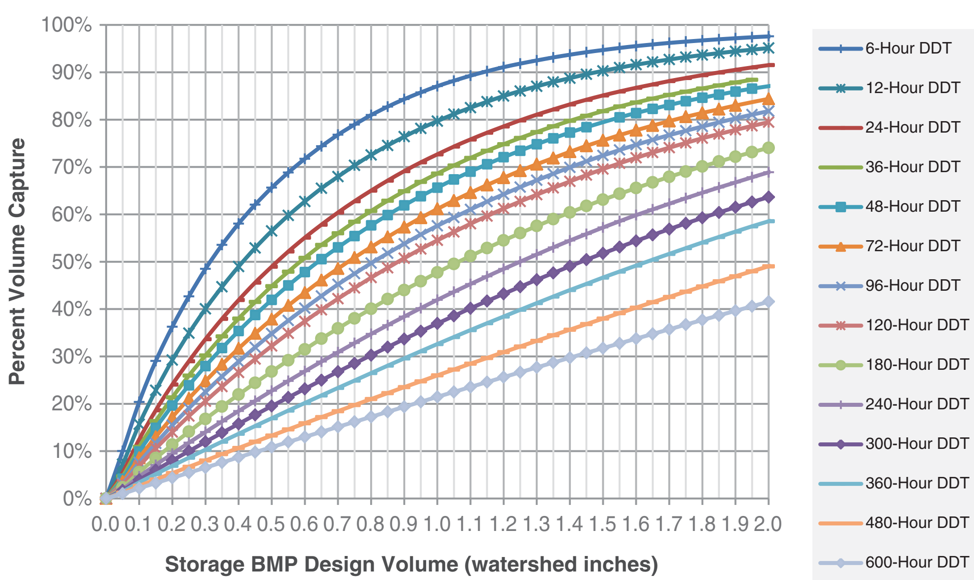


Figure 3-2. Example percent capture for volume-based BMPs (New Orleans International Airport).

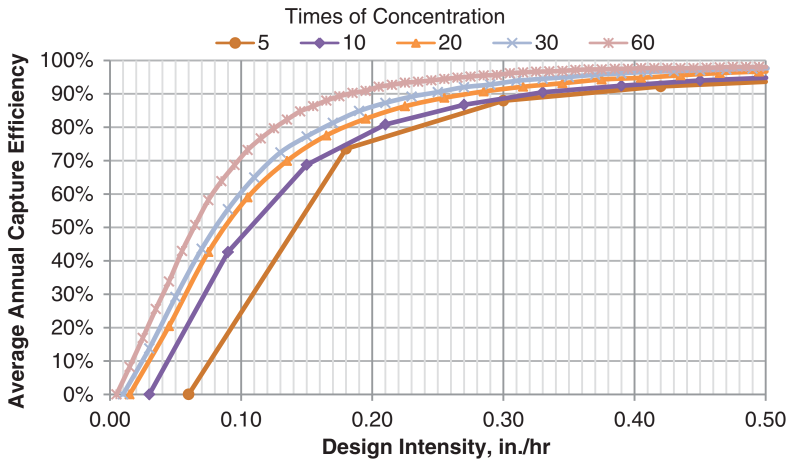


Figure 3-3. Example flow-based nomograph—online configuration (Portland International Airport).

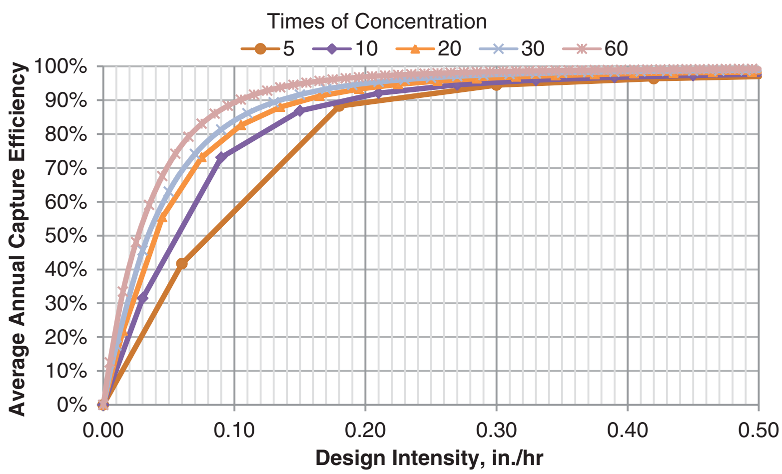


Figure 3-4. Example flow-based nomograph—offline configuration (Portland International Airport).

Table 3-2. Hydrologic analysis outputs used in calculating site-specific annual load reductions.

Information Provided for Load Reduction Estimation	Source of Information
Average annual rainfall volume	Determined from analysis of rainfall record associated with the rain gauge selected by user (or may be entered directly by the user).
Average annual runoff volume from tributary area	Calculated using tributary area (user input), imperviousness (user input), and the average annual rainfall for the project site (based on rain gauge selected, or optional user input). A volumetric runoff coefficient is computed using the following equation: $$R_v = a \cdot IMP + b$$ Where R_v is the volumetric runoff coefficient, IMP is the impervious fraction, and a and b are the parameters of the equation. The defaults for a and b are 0.225 and 0.129 when IMP < 0.55, and 1.14 and -0.371 when IMP > 0.55, based on Granato (2010).
Average annual percent capture	Determined by lookup, interpolation, and post-processing of the developed nomographs.
Average annual volume reduction (as percent of captured water)	Determined by post-processing of the developed nomographs (see Figure 3-5 and Example 3.1).

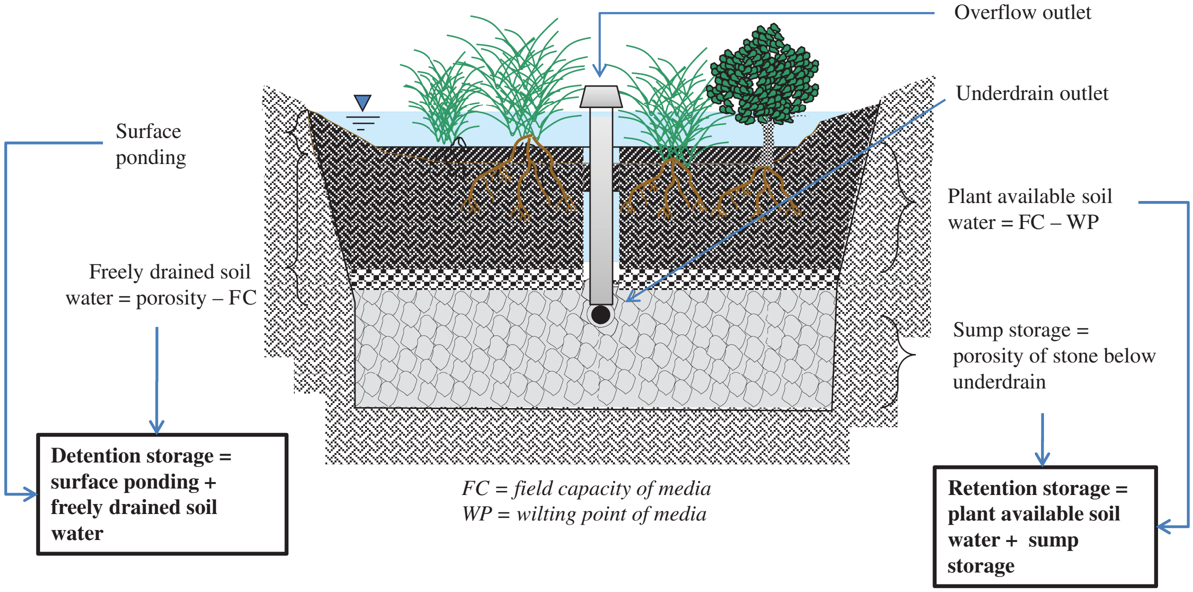


Figure 3-5. Storage compartments of a general bioretention system cross-section.

Example 3.1. Computing capture efficiency for bioretention with underdrain.

Given:

Drainage area = 1.5 acres
Runoff coefficient of drainage area = 0.86 (computed)
Effective area of bioretention = 1000 ft^2
Depth of bioretention media = 3 ft
Porosity of bioretention media = 0.4
Field capacity of bioretention media = 0.2
Wilting point of bioretention media = 0.1
Depth of surface ponding = 1 ft
Media filtration rate = 1.5 in./hr
Subsurface soil infiltration rate = 0.1 in./hr
Average evapotranspiration rate = 0.15 in./day
Negligible sump storage

Required:

Estimate the capture efficiency and percent volume loss

Solution:

Since there is an underdrain and sump storage is negligible, a significant amount of the surface storage plus the freely drained pore storage will become treated discharge. The proportion that becomes treated discharge can be estimated from the difference between the median filtration rate and the subsurface soil infiltration rate:

% of Surface Infiltrated Water That Becomes Treated Discharge = (1.5 – 0.1)/1.5 = 93%

Capture Efficiency

The major components of the storage volume are V_1, surface detention plus freely drained pore storage, and V_2, retained soil moisture.

<u>*Variables*</u>

V_1 = surface retention plus freely drained pore storage
V_2 = plant-available water
d_1 = surface retention plus freely drained pore storage as runoff storm depth in watershed inches
d_2 = plant-available water as runoff storm depth in watershed inches
D_1 = effective storage depth of surface retention plus freely drained pore storage
D_2 = effective storage depth of plant-available water
DDT_1 = brimful drawdown time of surface retention + freely drained pore storage, assuming constant rate
DDT_2 = brimful drawdown time of plant-available water

Storage Volume Calculations:

$V_1 = (1\text{ ft} \times 1000\text{ ft}^2) + [(0.4 - 0.2) \times 3\text{ ft} \times 1000\text{ ft}^2] = 1{,}600\text{ ft}^3$

$V_2 = [(0.2 - 0.1) \times 3\text{ ft} \times 1000\text{ ft}^2] = 300\text{ ft}^3$

Effective Storm Depth Calculations:

$d_1 = (1{,}600\text{ ft}^3 \times 12\text{ in./ft})/[0.86 \times 1.5\text{ acres} \times 43560\text{ ft}^2\text{/acre}] = 0.34$ watershed inches

$d_2 = (300\text{ ft}^3 \times 12\text{ in./ft})/[0.86 \times 1.5\text{ acres} \times 43560\text{ ft}^2\text{/acre}] = 0.06$ watershed inches

Effective Storage Depth Calculations:

$D_1 = 1\text{ ft} + [(0.4 - 0.2) \times 3\text{ ft}] = 1.6\text{ ft}$

$D_2 = [(0.2 - 0.1) \times 3\text{ ft}] = 0.3\text{ ft}$

Drawdown Time Calculations:

$DDT_1 = 1.6\text{ ft} \times (12\text{ in./ft})/(1.5\text{ in./hr}) = 13\text{ h}$ (controlled by media filtration rate)

$DDT_2 = 0.3\text{ ft} \times (12\text{ in./ft}) \times (24\text{ h/day})/(0.15\text{ in./day}) = 576\text{ h}$ (controlled by evapotranspiration)

Total Percent Volume Capture for V_1 plus V_2 using Figure 3-2:

1. For the plant-available water (0.06 watershed inches and 576 h DDT), the percent capture and volume lost to ET is approximately 1.3% (negligible, but included here to illustrate the process).
2. Identify the design storm depth associated with 1.3% on the 13-h DDT curve (~0.01 in.).
3. Add d_1 to this depth (0.01 in. + 0.34 in. = 0.35 in.) and find the percent capture associated with a 13-h DDT (44%). Approximately 93% of this volume is discharged as treated in the underdrain, and 7% is infiltrated.

Graphical operations supporting solution:

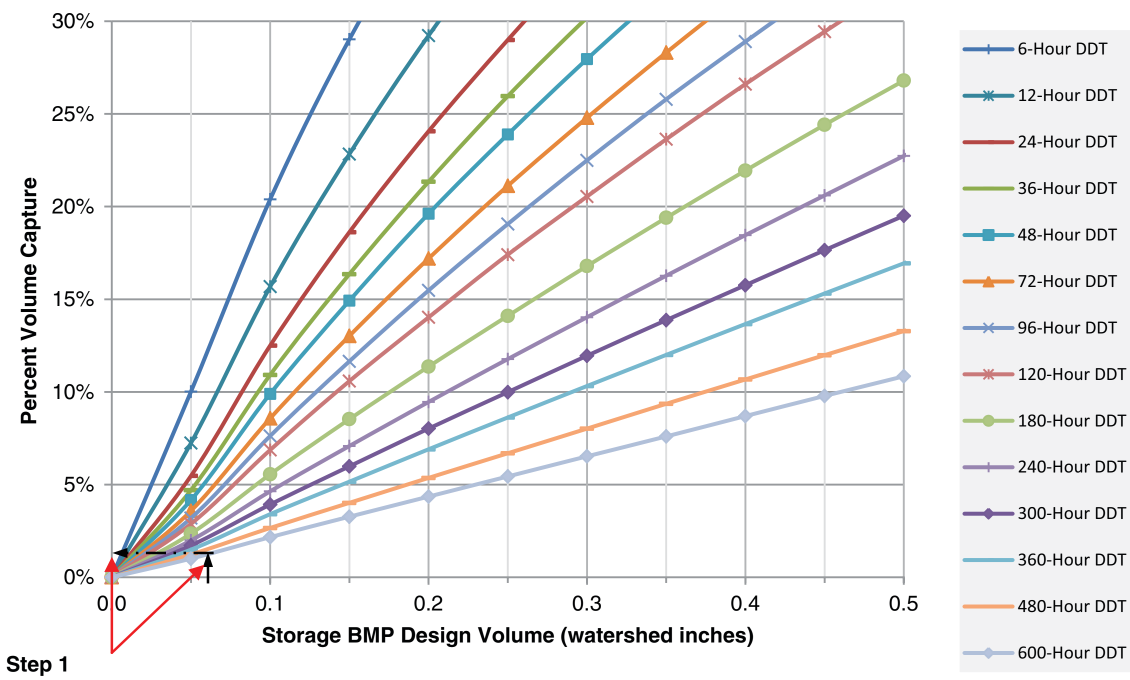
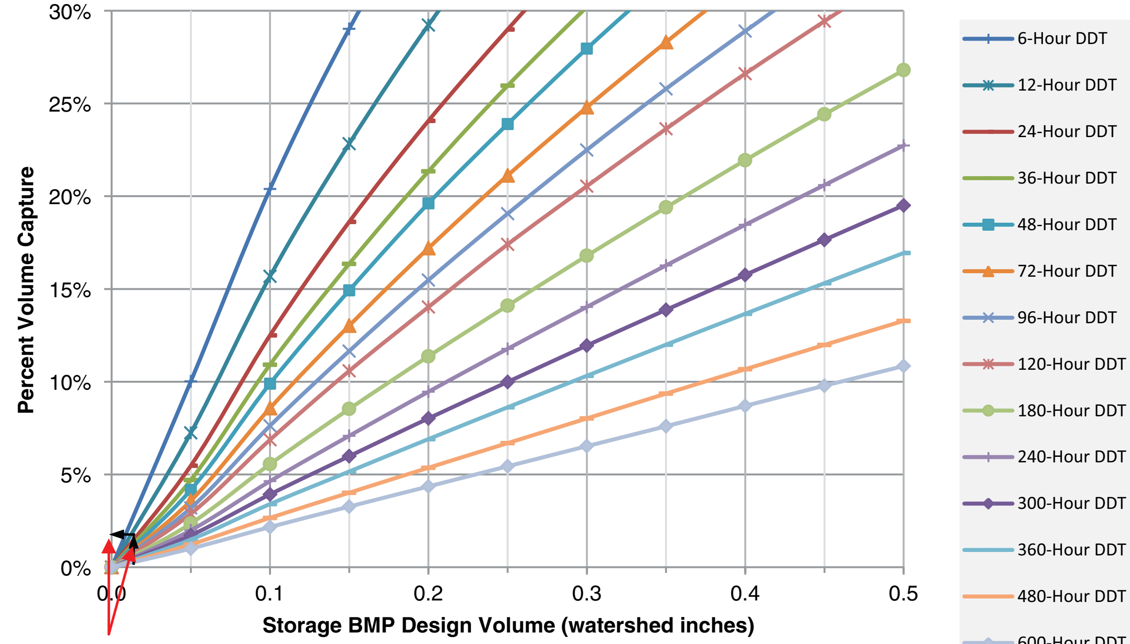
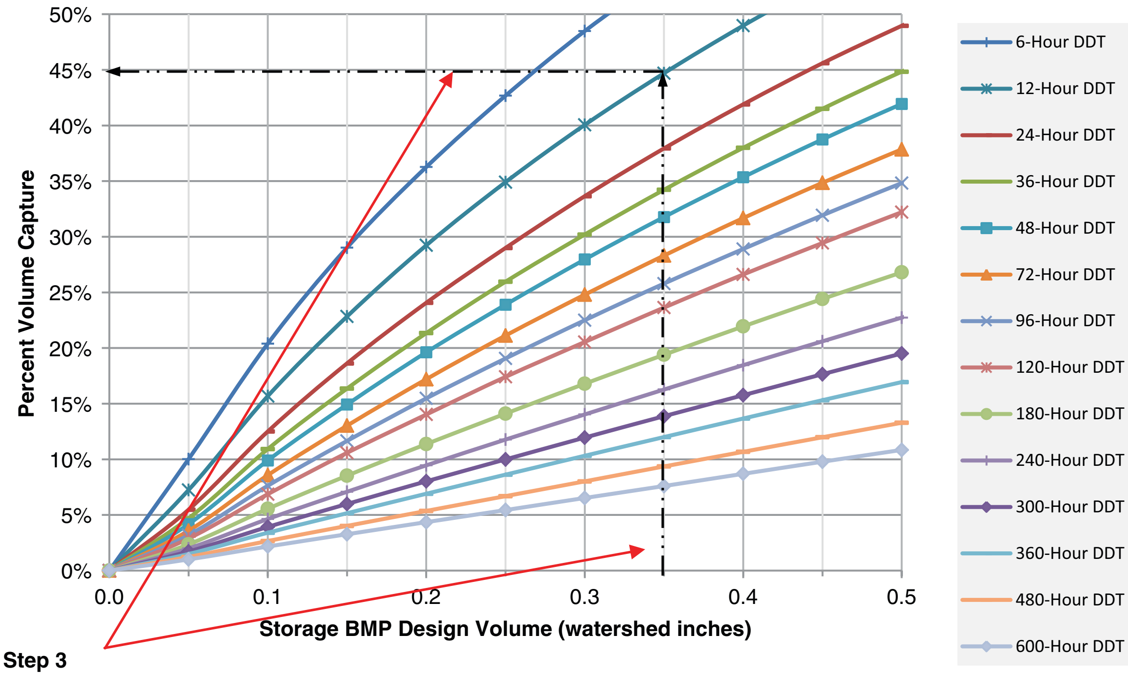


Figure 3-6. Graphical operations supporting Example 3.1.

(continued on next page)



Step 2



Step 3

Figure 3-6. (Continued).

CHAPTER 4

Water Quality Estimation Methods and Data Sources

Long-term BMP performance represents the average annual performance over the life of the BMP, which depends greatly on various BMP unit treatment processes. Pollutant removal mechanisms in BMPs are based on unit operations and processes (UOPs) and the BMP system components (e.g., forebay, vegetation, media, outlet structure) that improve or enhance those processes. UOPs can be divided according to four fundamental process categories: (1) hydrologic operations, (2) physical operations, (3) biological processes, and (4) chemical processes (Strecker et al., 2005).

- Hydrologic operations, which are essentially a subset of physical operations, include the principles of flow attenuation (e.g., peak shaving, detention) and volume reduction (e.g., infiltration, evapotranspiration).
- Physical operations include the principles of size separation and exclusion (e.g., screening, filtration), density separation (e.g., sedimentation, flotation), aeration and volatilization, and physical agent disinfection (e.g., ultraviolet light, heat).
- Biological processes include the principles of microbially mediated transformations (e.g., redox reactions resulting from microbial respiration) and uptake and storage (e.g., bioaccumulation).
- Chemical processes include the principles of sorption (e.g., ion exchange, surface complexation), coagulation and flocculation (e.g., particle agglomeration, precipitation), and chemical agent disinfection (e.g., chlorine, ozone).

Biological and chemical unit processes cannot be easily modeled due to the complex interaction of these processes with environmental variables. Thus, empirical methods based on measured data were used to evaluate these processes. Consequently, a BMP modeling approach was developed that uses a combination of long-term hydrologic simulation as described in Chapter 3 and summarized empirical data (described herein) to predict average annual load reductions for a selected suite of structural BMPs and pollutants of concern applicable to the highway environment.

4.1 BMPs and Constituents Analyzed

BMPs selected for the tool were those that are typically used by DOTs for runoff from highways that can operate passively, with extended maintenance intervals. All BMPs are proven, recognized BMPs that have had substantial study to assess pollutant removal effectiveness and whole life costs. The BMPs analyzed were:

- Vegetated swale,
- Filter strip,
- Dry detention basin,
- Bioretention,
- Wet pond,
- Sand filter, and
- PFC.

The pollutants of concern selected for the calculations in the tool were based on the types of pollutants commonly monitored and observed in highway runoff and identified in NPDES permits and other regulatory publications. Selected pollutants additionally required adequate BMP performance data for analysis. The pollutants analyzed were:

- Total zinc (TZn)
- Total lead (TPb)
- Total copper (TCu)
- Total nitrogen (TN); estimated as the sum of NO_3 and TKN
- Total phosphorus (TP)
- Nitrate (NO_3)
- TKN
- Dissolved phosphorus (DP)
- Orthophosphate (OP) as a surrogate for DP when needed

Table 4-1. Summary of available highway runoff quality data.

	NSQD	HRDB	Combined
No. of sites	43	93	136
No. of events	669	1,537	2,206
No. of sample results	3,027	8,813	11,184
No. of non-detects	41	458	499

- TSS
- Fecal coliform (FC)
- *Escherichia coli* (*E. coli*)

The sources of data used and the details of the BMP modeling approach are provided in the following sections. Additional information on BMP performance estimation methods for a variety of UOPs can be found in Strecker et al. (2005), Huber et al. (2006), and Leisenring et al. (2013).

4.2 Highway Runoff Water Quality Data

Water quality data that were used to develop long-term BMP performance estimates included highway runoff water quality and BMP influent and effluent concentrations. The sources of the data used are described in the following.

Highway runoff quality data were obtained from the Highway-Runoff Database (HRDB) (Granato and Cazenas, 2009; Smith and Granato, 2010) and the National Stormwater Quality Database (NSQD) (Pitt, 2008). Tables 4-1 and 4-2 summarize the data available for the two databases after 1986. Data before this date were excluded in the analysis because of the use of leaded gasoline that caused an unrepresentative sample of modern conditions. The HRDB provides nearly three times as much highway runoff data as the NSQD.

Table 4-2. Summary of non-detects and total samples for each constituent from the HRDB and NSQD combined.

Constituent	Non-Detects/Total Samples
TSS	11/1,713
NO_3	92/1,047
TN	0/122
TKN	49/1,408
DP	32/217
TP	120/2,022
TCu	72/1,808
TPb	102/1,683
TZn	12/2,099
FC	0/65
E. coli	0/13

4.3 BMP Influent and Effluent Concentrations

Paired BMP influent and effluent concentration data were obtained from the International Stormwater BMPDB Version 03 24 2013. Nearly all of the selected BMPs had more than three distinct studies and 20 distinct influent/effluent measurement pairs per pollutant. PFC was the only BMP with only one study in the BMPDB, and it also had no bacteria data. Filter strips had no data pairs for DP or *E. coli*, so OP and FC were used as surrogates, respectively. Similarly, sand filters had no *E. coli* data, so FC was used as the surrogate. A summary of the number of inflow/outflow data pairs per BMP and constituent is in Table 4-3.

4.3.1 Estimating Influent Concentrations

To provide representative highway runoff quality inflows for BMP treatment analysis, highway runoff mean concentrations used in the tool were developed through statistical analyses of data within the HRDB and NSQD. To assess the impact of average annual daily traffic (AADT) on constituent concentration, five AADT categories were created: 0–25,000, 25,000–50,000, 50,000–100,000, >100,000, and unknown. To improve the representativeness of the statistics generated, only data after 1986 were included in the analysis since data prior to this time are influenced by leaded gasoline and less-stringent emission control requirements on vehicles. As shown in Table 4-4, these categories provide a reasonable division of the data, with a fairly balanced distribution of the data between categories. In general, the 25,000–50,000 category has the least data. Values for TN are sparse, and TKN values were used where there was no data. Fecal coliform data are sparse in all categories, and no categorization was possible with the *E. coli* data.

Tables 4-5 and 4-6 summarize the medians and arithmetic means with 90% confidence intervals, respectively, for the pooled data sets for each AADT bin. A median is defined as the concentration where approximately 50% of the data are above and 50% of the data are below. The mean is the sum of the data divided by the number of data points. While both metrics provide an indication of the central tendency, the median is resistant to the effects of outliers. However, since the median is not a weighted metric, it can result in an

Table 4-3. Summary of available data pairs per BMP and constituent from the BMPDB.

Constituent	BMP Type						
	Bioretention	Grass Swale	Filter Strip	Wet Pond	Detention Basin	Sand Filter	PFC*
TSS	171	195	526	621	265	296	22
NO_3	19	77	414	122	105	158	22
TN	160	92	122	300	59	127	0
TKN	167	151	512	406	176	270	22
DP	21	52	16	236	117	65	22
OP	123	26	435	361	34	99	0
TP	214	191	518	586	245	286	22
TCu	67	119	382	425	191	267	22
TPb	54	138	403	465	193	248	22
TZn	110	152	412	522	209	293	22
FC	26	79	20	100	109	121	0
E. coli	54	39	0	50	32	0	0

*PFC pairs are based on paired watershed data since the influent cannot be directly sampled for this type of BMP.

underestimate of pollutant loads when data are skewed to the right (typical of water quality data). Therefore, the arithmetic means are recommended when computing pollutant loads, and the medians are recommended when comparing concentration benchmarks or thresholds.

To handle non-detects, a robust regression-on-order statistics (ROS) method as described by Helsel and Cohn (1988) was used to provide probabilistic estimates of non-detects before computing descriptive statistics. As compared to simple substitution methods [e.g., ½ detection limit (DL), DL, or zero], the ROS method reduces the potential bias caused by the presence of non-detects. Confidence intervals were generated using the bias corrected and accelerated (BCa) bootstrap method described by Efron and Tibishirani (1993). This method for computing confidence intervals is resistant to outliers and does not require any restrictive distributional assumptions common with parametric confidence intervals. Because the data were pooled for all sites, the analysis accounts for the variability at individual sites (temporal variability) as well as between sites (spatial variability). However, it is acknowledged that sites with more data points will have a larger influence on the pooled summary statistics.

As indicated in Tables 4-5 and 4-6, there does not appear to be a clear relationship between AADT and pollutant concentration

Table 4-4. Count of sample results by constituents by average annual daily traffic.

Constituent	AADT Bin					
	0–25k	25k–50k	50k–100k	100k +	Unknown	All
TSS	388	198	301	563	263	1,713
NO_3	355	151	191	350	0	1,047
TN	0	0	3	0	119	122
TKN	336	146	176	412	338	1,408
DP	46	38	28	73	32	217
TP	428	264	332	508	490	2,022
TCu	426	243	304	555	280	1,808
TPb	402	240	264	492	285	1,683
TZn	424	253	323	569	530	2,099
FC	3	0	4	19	39	65
E. coli	0	0	0	0	13	13

Table 4-5. Medians and confidence intervals for combined NSQD and HRDB data.

Constituent	Medians (90% Confidence Intervals) by AADT Bin					
	0–25k	25k–50k	50k–100k	100k+	Unknown	All
TSS (mg/L)	42.05 (33.00–45.00)	61.49 (51.00–71.00)	69.07 (57.00–72.00)	100.2 (92.00–106.0)	39.64 (34.30–44.00)	69.2 (66.00–73.44)
NO_3 (mg/L)	0.2 (0.20–0.24)	0.82 (0.71–0.89)	0.59 (0.49–0.66)	1.07 (0.86–1.16)	No data	0.6 (0.52–0.61)
TN (mg/L)	No data	No data	3.01 (2.30–5.52)	No data	3.00 (2.59–3.27)	3.00 (2.63–3.29)
TKN (mg/L)	1.00 (0.84–1.10)	1.80 (1.60–2.00)	1.55 (1.42–1.67)	2.16 (2.00–2.30)	1.64 (1.50–1.73)	1.64 (1.56–1.70)
DP (mg/L)	0.07 (0.07–0.08)	0.10 (0.05–0.13)	0.08 (0.03–0.12)	0.18 (0.15–0.20)	0.09 (0.05–0.10)	0.10 (0.07–0.10)
TP (mg/L)	0.12 (0.10–0.13)	0.16 (0.14–0.17)	0.20 (0.17–0.22)	0.24 (0.22–0.25)	0.25 (0.21–0.26)	0.20 (0.19–0.20)
TCu (ug/L)	7.95 (6.80–9.00)	18.2 (15.00–20.00)	23.48 (21.30–25.00)	48.73 (43.92–51.60)	10.89 (9.79–12.50)	22.37 (20.59–23.00)
TPb (ug/L)	3.92 (3.00–4.50)	10.51 (8.82–12.00)	7.82 (6.20–8.80)	30.7 (26.00–34.00)	56.52 (45.00–67.00)	16.02 (14.00–17.00)
TZn (ug/L)	51.64 (43.00–56.65)	90.74 (79.00–100.0)	123.8 (110.0–131.0)	220.0 (200.0–238.0)	86.04 (76.37–93.33)	116.8 (110.0–120.0)
FC (colonies /100mL)	5000 (300.0–13,000)	No data	5147 (1,100–9,500)	1626 (1,300–1,700)	2064 (492.9–2,200)	1986 (1300–2,300)
E. coli (colonies /100mL)	No data	No data	No data	No data	1971 (727.2–2,300)	1977 (680.0–2,300)

Table 4-6. Means and confidence intervals for combined NSQD and HRDB data.

Constituent	Means (90% Confidence Intervals) by AADT Bin					
	0–25k	25k–50k	50k–100k	100k+	Unknown	All
TSS (mg/L)	162.8 (136.1–190.4)	178.3 (127.1–233.8)	120.1 (95.1–150.6)	143.6 (130.6–157.1)	85.2 (72.84–98.43)	138.8 (127.4–150.3)
NO_3 (mg/L)	0.48 (0.42–0.53)	1.12 (0.94–1.32)	0.82 (0.73–0.92)	1.74 (1.51–2.02)	No data	1.06 (0.96–1.16)
TN (mg/L)	No data	No data	3.61 (2.30–4.68)	No data	3.59 (3.17–4.03)	3.59 (3.18–4.02)
TKN (mg/L)	1.62 (1.45–1.81)	2.5 (2.23–2.76)	1.9 (1.72–2.09)	3.18 (2.84–3.50)	2.11 (1.94–2.28)	2.32 (2.20–2.44)
DP (mg/L)	0.09 (0.08–0.10)	0.14 (0.11–0.17)	0.12 (0.09–0.15)	0.54 (0.32–0.81)	0.09 (0.07–0.11)	0.25 (0.17–0.34)
TP (mg/L)	0.38 (0.27–0.49)	0.46 (0.29–0.63)	0.25 (0.23–0.28)	0.39 (0.34–0.44)	0.68 (0.47–0.99)	0.44 (0.37–0.52)
TCu (ug/L)	14.92 (13.50–16.44)	26.83 (24.18–29.42)	30.79 (28.23–33.32)	82.11 (60.65–114.6)	27.11 (20.29–35.10)	41.76 (34.68–51.86)
TPb (ug/L)	18.26 (10.17–30.10)	31.29 (26.36–36.73)	26.24 (21.38–31.64)	61.6 (53.81–70.28)	77.63 (70.32–85.98)	44.08 (40.37–48.32)
TZn (ug/L)	98.0 (87.7–108.0)	152.1 (133.1–170.6)	172.7 (157.6–188.2)	329.6 (287.0–382.6)	143.0 (128.1–157.6)	189.9 (176.8–205.7)
FC (colonies/ 100mL)	6148 (300.0–10,333)	No data	5625 (1,700–8,575)	8702 (1,795–15,786)	9215 (3,520–16,607)	8700 (4,519–13,557)
E. coli (colonies/ 100mL)	No data	No data	No data	No data	5948 (1,717–12642)	6025 (1,714–12,654)

except for possibly TSS, total phosphorus, total copper, and total zinc, particularly when comparing the low traffic AADT (<25k) against the high traffic AADT (>50k). For consistency across all pollutants, the mean concentrations for all of the data combined (rightmost column in Table 4-6) are used in the tool as the default highway runoff concentrations regardless of AADT, but these defaults may be overridden if desired.

4.3.2 Estimating Effluent Concentrations

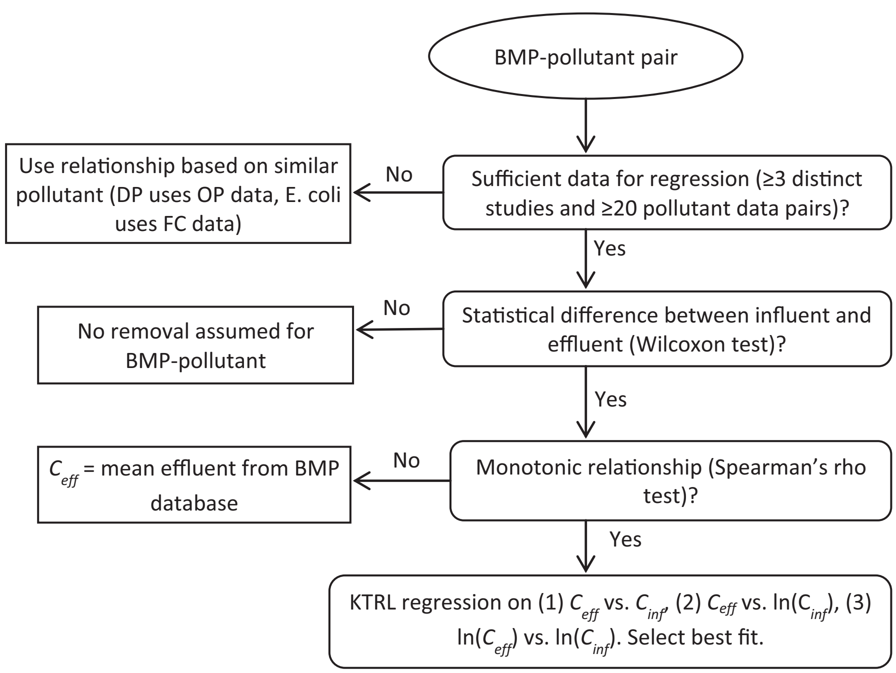
Effluent concentrations were estimated based on regression analysis of influent and effluent water quality data, when appropriate, or were simply summarized effluent data when regression analysis was not possible for the available data. BMPs are assumed to not be a source of pollutants, and thus effluent concentrations will not exceed the influent concentrations or load. While some BMPs can contribute to increased constituent concentrations, quantifying export in excess of the incoming load introduces mass balance errors that cannot be reconciled without quantifying the pollutant mass available within the BMP at the time of installation. Since this information is not typically available, the default assumption is no concentration reduction for pollutants that may in time be exported by a BMP.

The BMPDB is a repository of influent and effluent water quality data from over 500 BMP studies (as of March 2013). This database provides an avenue for a data-driven analysis of the relationship between influent concentration (C_{inf}) and effluent concentration (C_{eff}) for a wide range of BMP-pollutant combinations.

Data from the BMPDB were analyzed using a multistep process. This process is shown in Figure 4-1 and consists of five steps:

1. Determine if sufficient paired data for analysis exist in the BMPDB.
2. Determine if there is a statistical difference between C_{inf} and C_{eff}.
3. Determine if a monotonic relationship exists between C_{inf} and C_{eff}.
4. Conduct linear and log-linear regression between C_{inf} and C_{eff} and develop functional relationship.
5. Ensure that results do not show logical inconsistencies (e.g., dissolved fraction is greater than total).

Since water quality data are often highly variable and positively skewed, nonparametric statistics were selected over parametric statistics for this analysis. The Wilcoxon signed-rank test was used to evaluate whether the influent and effluent concentrations are statistically different, and the Spearman's rho correlation coefficient was used to evaluate whether a monotonic relationship exists (Helsel and Hirsch, 2002). The Wilcoxon signed-rank test assumes that the distribution of the paired differences is symmetric, so the data were log-transformed prior to conducting the test. No transformation



Note: KTRL = Kendall-Theil robust line.

Figure 4-1. Analysis process for influent-effluent regression.

was needed for the Spearman's rho computation because the correlation analysis uses the ranks of the data.

If the Wilcoxon test found a statistically significant difference between the influent and effluent concentrations, and the Spearman's rho test found that a monotonic relationship exists, regression equations were developed using the Kendall-Theil robust line procedure described by Granato (2006). Linear and log-linear relationships were evaluated, and the best-fit equation was used based on the median absolute difference. Statistical significance for all analyses was determined at a level of $\alpha = 0.10$. The analysis results are presented and discussed in the following.

4.3.3 Statistical Difference Between Influent and Effluent Quality

While some pollutants, such as TSS, are easily removed by a wide variety of BMPs, others, such as NO_3, are more difficult to remove. The nonparametric Wilcoxon signed-rank test was used to verify a statistical difference between influent and effluent quality for each BMP-pollutant pair to determine if removal of a pollutant was occurring in a BMP. Because this test requires a symmetric distribution, the data were log-transformed prior to performing the analysis. As shown in Table 4-7, most BMP-pollutant combinations involving nutrients and bacteria indicators show statistically significant concentration reductions ($p < 0.1$; bolded). For BMP-pollutant combinations that failed to show statistical significance ($p > 0.1$), no removal due to concentration changes would be assumed. Wet ponds are the only BMP type that show statistically significant removal for all analyzed pollutants.

4.3.3.1 *Monotonic Relationship Between Influent and Effluent*

The next step in this process required establishing the presence of a monotonic relationship between influent and effluent quality. To do this, the Spearman's rho test was applied to each BMP-pollutant combination. Those combinations showing a statistically significant difference between C_{inf} and C_{eff} generally exhibited a monotonic relationship between the two. The only exceptions were the swale-DP combination, the filter strip-FC combination, and all available pollutant data for PFC, where a statistically significant monotonic relationship between C_{inf} and C_{eff} was not observed. In these cases, a regression analysis was not performed. However, since the Wilcoxon test results indicated a statistically significant reduction in DP for swales and a statistically significant reduction in all pollutants except for NO_3 and DP for PFC, the arithmetic estimate of the log mean of effluent concentration data from the BMPDB was selected as an appropriate estimate of C_{eff} for these BMP-pollutant combinations. Note that when implementing constant effluent concentrations, the BMPs are assumed to never be a source of pollutants. Therefore, if C_{inf} is estimated to be less than C_{eff}, no concentration reduction is assumed.

As shown in Table 4-8, the correlation analysis for PFC indicates that the effluent concentrations for all available pollutants are not correlated with the influent concentrations. Viewing these results for PFCs with the Wilcoxon signed-rank test results, it is concluded that average effluent concentrations independent of influent concentrations are appropriate for all pollutants except for NO_3 and DP. No removal will be assumed for these two pollutants, and no removal will also be assumed for *E. coli* due to lack of data. For other constituents,

Table 4-7. Wilcoxon signed-rank test results (*p*-values).

Pollutant	Wilcoxon *p*-values by BMP Type (Bold values indicate statistically significant removals.)						
	Bio-retention	Grass Swale	Filter Strip	Wet Pond	Detention Basin	Sand Filter	PFC
TSS	**<0.001**	**0.023**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
NO_3	N/A	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.118
TKN	**0.037**	0.485	0.157	**<0.001**	**<0.001**	**<0.001**	**<0.001**
DP	**0.035**	**<0.001**	N/A	**<0.001**	0.659	**0.066**	0.239
OP	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.458	**<0.001**	**N/A**
TP	0.984	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
TCu	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
TPb	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
TZn	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
FC	**<0.001**	0.525	0.279	**<0.001**	**0.007**	**<0.001**	N/A
E. coli	**0.026**	0.128	N/A	**<0.001**	**<0.001**	N/A	N/A

Table 4-8. Spearman's rho test results (*p*-values).

Pollutant	Spearman's Rho *p*-values by BMP Type (Bold values indicate statistically significant influent/effluent correlation.)						
	Bioretention	Grass Swale	Filter Strip	Wet Pond	Detention Basin	Sand Filter	PFC
TSS	**0.30 (<0.001)**	**0.46 (<0.001)**	**0.46 (<0.001)**	**0.46 (<0.001)**	**0.55 (<0.001)**	**0.41 (<0.001)**	0.2 (0.286)
NO_3	**N/A**	**0.89 (<0.001)**	**0.65 (<0.001)**	**0.53 (<0.001)**	**0.79 (<0.001)**	**0.75 (<0.001)**	0 (0.636)
TKN	**0.57 (<0.001)**	**0.73 (<0.001)**	**0.57 (<0.001)**	**0.59 (<0.001)**	**0.70 (<0.001)**	**0.71 (<0.001)**	0.07 (0.389)
DP	-0.06 (0.786)	**0.68 (<0.001)**	**N/A**	**0.52 (<0.001)**	**0.67 (<0.001)**	**0.69 (<0.001)**	0.05 (0.416)
OP	**0.46 (<0.001)**	**0.80 (<0.001)**	**0.58 (<0.001)**	**0.57 (<0.001)**	**0.67 (<0.001)**	**0.65 (<0.001)**	N/A
TP	**0.38 (<0.001)**	**0.63 (<0.001)**	**0.46 (<0.001)**	**0.63 (<0.001)**	**0.66 (<0.001)**	**0.71 (<0.001)**	0.36 (0.207)
TCu	**0.41 (<0.001)**	**0.81 (<0.001)**	**0.70 (<0.001)**	**0.58 (<0.001)**	**0.87 (<0.001)**	**0.61 (<0.001)**	0.27 (0.245)
TPb	N/A	N/A	**0.78 (<0.001)**	**0.55 (<0.001)**	**0.90 (<0.001)**	**0.71 (<0.001)**	0.29 (0.236)
TZn	**0.49 (<0.001)**	**0.82 (<0.001)**	**0.63 (<0.001)**	**0.50 (<0.001)**	**0.72 (<0.001)**	**0.43 (<0.001)**	0.19 (0.291)
FC	**0.70 (<0.001)**	**0.83 (<0.001)**	0.31 (0.177)	**0.78 (<0.001)**	**0.65 (<0.001)**	**0.70 (<0.001)**	N/A
E. coli	**0.34 (0.012)**	**0.83 (<0.001)**	N/A	**0.78 (<0.001)**	**0.58 (<0.001)**	N/A	N/A

influent and effluent relationships that did not fail the Spearman's rho test ($p < 0.1$; bold) are shown in Table 4-8.

4.3.3.2 Regression Analysis of the Relationship Between Influent and Effluent

Based on the results of the Wilcoxon and Spearman's rho tests, several BMPs appear to provide statistically significant reductions in pollutant concentrations along with monotonic influent/effluent relationships. These results together indicate that regression analyses can be conducted to develop functional relationships that can be used to predict BMP performance.

Given the prevalence of outliers in environmental data and the strong influence these outliers can have on standard linear regression techniques, the nonparametric Kendall-Theil robust line (KTRL) regression approach was used (Granato, 2006). The KTRL was applied to the influent and effluent data in original units and after log-transformation. The regression plots are provided in Appendix C: International Stormwater BMP Database Performance Information. The KTRL method computes the median of all possible pairwise slopes between two data sets. A y-intercept is then calculated according to Equation 2.

$$Intercept = median(y) - (median\ slope) * median(x) \quad \text{(Eq. 2)}$$

Similar to linear regression, the calculation of slope (m) and intercept (b) creates a line of the form $y = mx + b$ that can be used as a generalized relationship between x and y. Kendall-Theil robust lines were calculated for three possible relationships between influent and effluent, as shown in Table 4-9.

The median absolute deviation (MAD) was used to select the best regression equation for each BMP-pollutant combination. This statistic is defined by Equation 3.

$$MAD = median\left(\left|C_{eff} - C_{predicted}\right| for\ all\ values\ of\ C_{eff}\right) \quad \text{(Eq. 3)}$$

Where $C_{predicted}$ is the value of the C_{eff} predicted by the Kendall-Theil regression line.

Best-fit regression results and plots are provided in Appendix C: International Stormwater BMP Database Performance Information.

Table 4-9. KTRL equations used for nonparametric regression.

Data Pairs Plotted for KTRL Calculations	KTRL Equation Derived
C_{eff}, C_{inf}	$C_{eff} = m * C_{inf} + b$
C_{eff}, $\ln(C_{inf})$	$C_{eff} = m * \ln(C_{inf}) + b$
$\ln(C_{eff})$, $\ln(C_{inf})$	$\ln(C_{eff}) = m * \ln(C_{inf}) + b$

4.4 Influent Highway Runoff Water Quality Methods

Influent highway runoff concentrations are calculated as described in Section 4.3.1 and are shown in the rightmost column of Table 4-6. Tool users have the option of overriding this default with a value from the table or from other monitoring data. Runoff volumes and loads are calculated as:

$$V_w = R_v \cdot A_w \cdot P \qquad \text{(Eq. 4)}$$

$$L_w = V_w \cdot C_w \qquad \text{(Eq. 5)}$$

Where, V_w is the average annual runoff volume, R_v is the long-term, volumetric runoff coefficient, A_w is watershed area, P is average annual rainfall depth, L_w is the average annual load, and C_w is the characteristic runoff concentration.

4.5 BMP Effluent Quality Performance by Pollutant

Effluent quality is estimated using the regression analysis approach described in this section. Regression equations were developed using all available storm event data pairs for each BMP-pollutant combination where both a statistically significant reduction was observed (Wilcoxon) and a monotonic relationship was found. Table 4-10 summarizes the form of equation selected for each BMP-pollutant combination based on the hypothesis test results and the best-fit regression equation.

Based on the various possible influent–effluent relationships considered in Table 4-9, a generalized equation was developed:

$$C_{eff} = \min\left[C_{inf}, \max\left(\begin{array}{c} A + B \cdot C_{inf} + C \cdot \ln(C_{inf}) \\ + D \cdot C_{inf}^{E} + e_i, DL \end{array}\right)\right] \qquad \text{(Eq. 6)}$$

where

C_{eff} is the predicted effluent concentration;
C_{inf} is the estimated influent concentration;
A, B, C, D, and E are parameters of the equation;
e_i is the bias correction factor for Equation 3; and
DL is the minimum detection limit reported for the available data sets.

This generalized equation allows for any regression equation to be used as long as the correct parameters are used and the remaining parameters have a value of zero. This equation ensures that BMPs are not a source of pollutants (e.g., C_{eff} is never greater than C_{inf}) and predicted effluent concentration is never below a reported detection limit. Tables 4-11 through 4-17

Table 4-10. Equation selection summary for BMP-pollutant combinations.

Pollutant	Bioretention	Grass Swale	Filter Strip	Wet Pond	Detention Basin	Sand Filter	PFC
TSS	3	3	3	3	3	3	8
NO_3	4	1	1	1	1	1	4
TKN	2	4	4	2	1	1	8
TN	9	9	9	9	9	9	9
DP	8	1	4	1	4	1	4
TP	4	2	2	1	2	2	8
TCu	3	3	3	3	3	3	8
TPb	4	3	1	2	1	1	8
TZn	3	3	3	3	3	3	8
FC	3	4	4	3	3	3	4
E. coli	3	4	7	3	3	7	4

1 - KTRL regression of C_{eff} vs. C_{inf}.

2 - KTRL regression of C_{eff} vs. $\ln(C_{inf})$.

3 - KTRL regression of $\ln(C_{eff})$ vs. $\ln(C_{inf})$.

4 - Failed Wilcoxon test or lack of data for analysis. No removal assumed.

5 - Insufficient data for DP analysis. KTRL line [C_{eff} vs. $\ln(C_{inf})$] based on OP data.

6 - Insufficient data for DP analysis. OP data failed Wilcoxon test. No removal assumed.

7 - Insufficient paired data for analysis. Used data for fecal coliform to develop equation parameters for this BMP.

8 - Failed Spearman's test for monotonic relationship, but passed Wilcoxon test. C_{eff} = arithmetic estimate of log mean for all available effluent data in the BMP database using regression-on-order statistics for handling non-detects followed by bootstrapping as described in Geosyntec and Wright Water Engineers (2012).

9 - To be determined by addition of NO_3 and TKN (nitrite assumed negligible).

Table 4-11. Equation parameters for predicting bioretention effluent concentrations.

Pollutant	A	B	C	D	E	e_i	DL
TSS (mg/L)	0.00	0.00	0.00	2.49	0.37	1.35	0.00
NO_3 (mg/L)	0.00	1.00	0.00	0.00	0.00	0.00	0.00
TKN (mg/L)	0.83	0.00	0.50	0.00	0.00	0.71	0.04
TN (mg/L)	← TN = TKN + NO_3 →						
DP (mg/L)	-0.82	0.00	0.00	0.00	0.00	0.00	0.03
TP (mg/L)	0.00	1.00	0.00	0.00	0.00	0.00	0.01
TCu (ug/L)	0.00	0.00	0.00	2.77	0.44	1.26	0.50
TPb (ug/L)	0.00	1.00	0.00	0.00	0.00	0.00	1.00
TZn (ug/L)	0.00	0.00	0.00	1.11	0.68	1.26	0.01
FC (colonies/100mL)	0.00	0.00	0.00	0.01	1.06	7.29	100.00
E. coli (colonies/ 100mL)	0.00	0.00	0.00	2.40	0.51	24.48	1.00

Table 4-12. Equation parameters for predicting swale effluent concentrations.

Pollutant	A	B	C	D	E	e_i	DL
TSS (mg/L)	0.00	0.00	0.00	5.74	0.45	1.35	0.50
NO_3 (mg/L)	0.02	1.07	0.00	0.00	0.00	0.00	0.10
TKN (mg/L)	0.00	1.00	0.00	0.00	0.00	0.00	0.10
TN (mg/L)	← TN = TKN + NO_3 →						
DP (mg/L)	-0.01	1.41	0.00	0.00	0.00	0.00	0.02
TP (mg/L)	0.44	0.00	0.12	0.00	0.00	0.00	0.01
TCu (ug/L)	0.00	0.00	0.00	0.85	0.88	0.92	6.00
TPb (ug/L)	0.00	0.00	0.00	0.66	0.92	0.87	3.00
TZn (ug/L)	0.00	0.00	0.00	2.99	0.56	1.21	0.01
FC (colonies/100mL)	0.00	1.00	0.00	0.00	0.00	0.00	1,000.00
E. coli (colonies/ 100mL)	0.00	1.00	0.00	0.00	0.00	0.00	0.00

Table 4-13. Equation parameters for predicting filter strip effluent concentrations.

Pollutant	A	B	C	D	E	e_i	DL
TSS (mg/L)	0.00	0.00	0.00	2.602685	0.526759	1.41	1.00
NO_3 (mg/L)	0.107391	0.608696	0.00	0.00	0.00	0.00	0.01
TKN (mg/L)	0.00	1.00	0.00	0.00	0.00	0.00	0.1
TN (mg/L)	← TN = TKN + NO_3 →						
DP (mg/L)	0.000	1.000	0.000	0.000	0.000	0.00	0.001
TP (mg/L)	0.224431	0.00	0.039056	0.00	0.00	0.00	0.001
TCu (ug/L)	0.00	0.00	0.00	1.224849	0.662004	1.29798	0.50
TPb (ug/L)	0.083685	0.300187	0.00	0.00	0.00	0.00	0.15
TZn (ug/L)	0.00	0.00	0.00	1.362558	0.679601	1.22	1.00
FC (colonies /100mL)	0.00	1.00	0.00	0.00	0.00	0.00	1.00
E. coli (colonies/ 100mL)	0.00	1.00	0.00	0.00	0.00	0.00	1.00

Table 4-14. Equation parameters for predicting wet pond effluent concentrations.

Pollutant	A	B	C	D	E	e_i	DL
TSS (mg/L)	0.00	0.00	0.00	1.62	0.51	2.33	0.50
NO_3 (mg/L)	-0.02	0.50	0.00	0.00	0.00	0.00	0.06
TKN (mg/L)	0.88	0.00	0.51	0.00	0.00	0.00	0.06
TN (mg/L)	← TN = TKN + NO_3 →						
DP (mg/L)	0.02	0.41	0.00	0.00	0.00	0.00	0.00
TP (mg/L)	0.05	0.34	0.00	0.00	0.00	0.00	0.00
TCu (ug/L)	0.00	0.00	0.00	1.41	0.55	1.22	0.01
TPb (ug/L)	-0.12	0.00	0.92	0.00	0.00	0.00	0.00
TZn (ug/L)	0.00	0.00	0.00	1.94	0.60	1.26	0.01
FC (colonies/100mL)	0.00	0.00	0.00	0.26	1.05	1.45	2.00
E. coli (colonies/ 100mL)	0.00	0.00	0.00	0.04	1.12	3.45	2.00

Table 4-15. Equation parameters for predicting detention basin effluent concentrations.

Pollutant	A	B	C	D	E	e_i	DL
TSS (mg/L)	0.00	0.00	0.00	2.16	0.59	1.42	1.00
NO_3 (mg/L)	0.13	0.73	0.00	0.00	0.00	0.00	0.10
TKN (mg/L)	0.32	0.68	0.00	0.00	0.00	0.00	0.02
TN (mg/L)	← TN = TKN + NO_3 →						
DP (mg/L)	0.00	1.00	0.00	0.00	0.00	0.00	0.02
TP (mg/L)	0.41	0.00	0.14	0.00	0.00	0.00	0.02
TCu (ug/L)	0.00	0.00	0.00	0.94	0.84	1.10	0.10
TPb (ug/L)	0.60	0.36	0.00	0.00	0.00	0.00	0.10
TZn (ug/L)	0.00	0.00	0.00	1.87	0.71	1.06	0.01
FC (colonies/100mL)	0.00	0.00	0.00	11.37	0.66	2.60	1.00
E. coli (colonies/ 100mL)	0.00	0.00	0.00	2.84	0.65	2.89	1.00

Table 4-16. Equation parameters for predicting sand filter effluent concentrations.

Pollutant	A	B	C	D	E	e_i	DL
TSS (mg/L)	0.00	0.00	0.00	1.38	0.46	1.69	0.50
NO_3 (mg/L)	0.11	1.21	0.00	0.00	0.00	0.00	0.01
TKN (mg/L)	0.19	0.35	0.00	0.00	0.00	0.00	0.10
TN (mg/L)	← TN = TKN + NO_3 →						
DP (mg/L)	0.02	0.69	0.00	0.00	0.00	0.00	0.02
TP (mg/L)	0.20	0.00	0.05	0.00	0.00	0.00	0.00
TCu (ug/L)	0.00	0.00	0.00	1.16	0.73	1.10	0.40
TPb (ug/L)	0.20	0.11	0.00	0.00	0.00	0.00	0.12
TZn (ug/L)	0.00	0.00	0.00	2.26	0.46	1.37	0.01
FC (colonies/100mL)	0.00	0.00	0.00	0.89	0.87	2.85	2.00
E. coli (colonies/ 100mL)	0.00	0.00	0.00	0.89	0.87	2.85	2.00

Table 4-17. Equation parameters for predicting PFC effluent concentrations.

Pollutant	A	B	C	D	E	DL
TSS (mg/L)	13.70	0.00	0.00	0.00	0.00	1.00
NO_3 (mg/L)	0.00	1.00	0.00	0.00	0.00	0.04
TKN (mg/L)	1.11	0.00	0.00	0.00	0.00	0.40
TN (mg/L)	← TN = TKN + NO_3 →					
DP (mg/L)	0.00	1.00	0.00	0.00	0.00	0.02
TP (mg/L)	0.086	0.00	0.00	0.00	0.00	0.02
TCu (ug/L)	13.00	0.00	0.00	0.00	0.00	2.00
TPb (ug/L)	0.84	0.00	0.00	0.00	0.00	0.50
TZn (ug/L)	25.80	0.00	0.00	0.00	0.00	5.00
FC (colonies/100mL)	0.00	1.00	0.00	0.00	0.00	1.00
E. coli (colonies/100mL)	0.00	1.00	0.00	0.00	0.00	1.00

indicate the parameters for predicting effluent concentrations for each BMP.

The regression equations are used to represent the average performance for each BMP type, not event-by-event concentrations. For a particular site, the equations are used to produce an average effluent concentration given an average influent concentration.

Example best-fit bioretention regression lines are shown in Figure 4-2 for copper and Figure 4-3 for zinc. The 95% confidence interval about the effluent median concentrations as reported in Geosyntec Consultants and Wright Water Engineers (2012) is also shown in the figures to illustrate what the estimated concentrations would be if influent concentrations were not considered in the performance estimate.

4.6 Load Reduction Assessment

Load reduction prediction in the BMP Evaluation Tool depends on three primary calculations that use the hydrologic simulation results to predict volume captured and volume reduced, as described in Chapter 3, and effluent concentration analysis methodology to provide volume and pollutant estimations. The tool reports the following: (1) annual stormwater runoff volume to the BMP, (2) amount of runoff captured and reduced by the BMP, and (3) BMP influent and effluent concentrations. Thus, the tool computes runoff loads and load reductions in a sequence of steps based on a mass balance approach, as indicated in Figure 4-4.

Runoff loads are estimated as the product of the average annual runoff volume (V_w) and the characteristic runoff

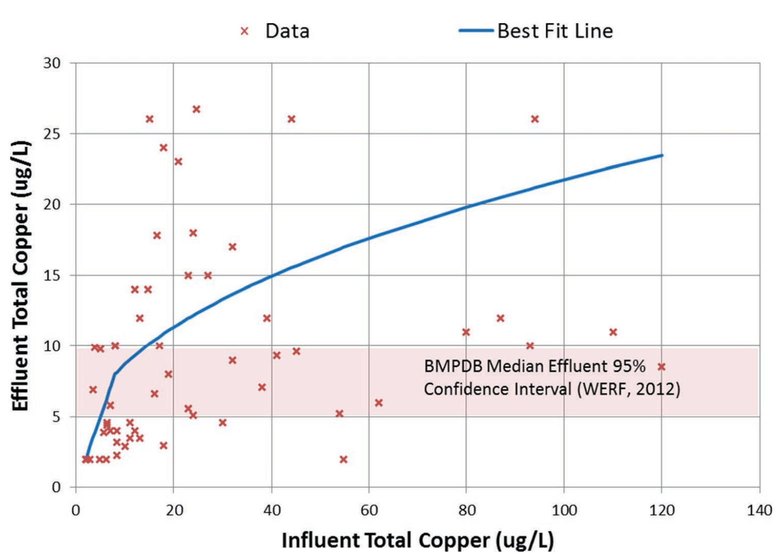


Figure 4-2. Bioretention regression line for total copper.

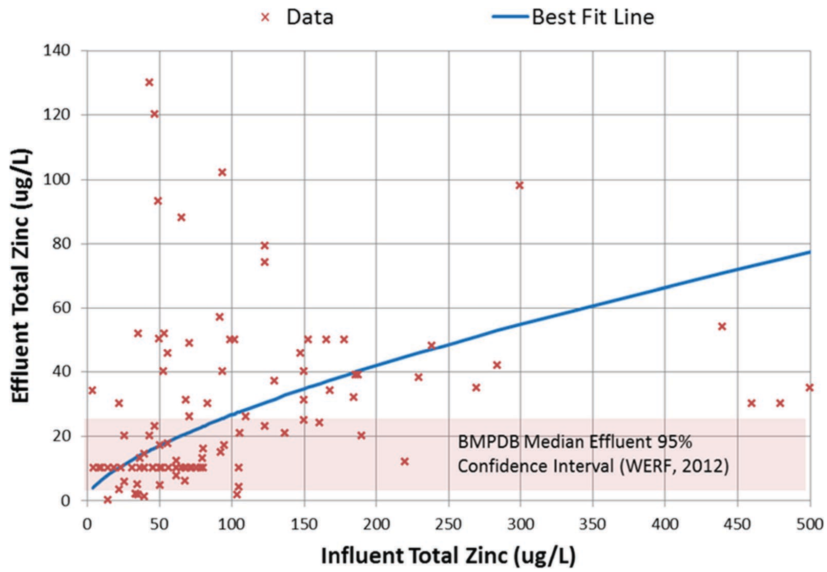


Figure 4-3. Bioretention regression line for total zinc.

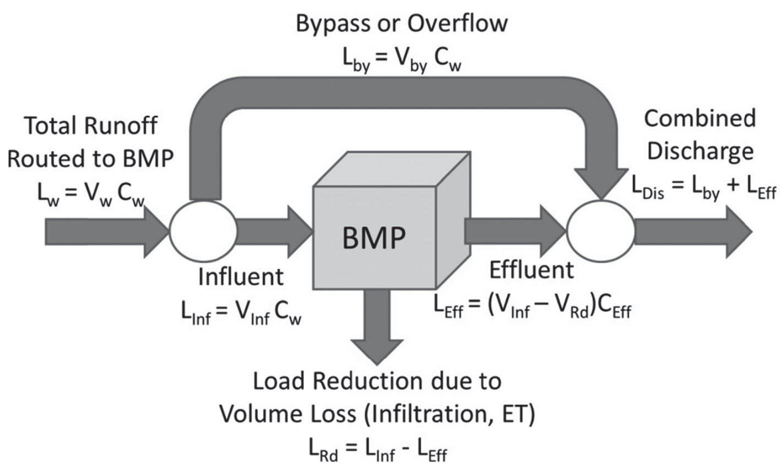


Figure 4-4. General approach for computing BMP load reductions.

concentration (C_w). The total estimated percent capture is used to determine the load bypassed ($V_{by}C_w$) and influent load ($V_{Inf}C_w$). Concentration reductions by the BMP are determined using the influent–effluent relationships described in Section 4.3 using the equation parameters for each BMP-pollutant combination shown in Tables 4-11 through 4-17. The effluent volume (V_{Eff}) is computed as the difference between the influent volume (V_{Inf}) and volume reduction estimated from the nomographs (V_{Rd}). The effluent load is then the product of the effluent volume and estimated effluent concentration (C_{Eff}). The combined discharge load and the load reductions are simply computed by applying a mass balance of the other terms. The percent average annual load reduction (%LR) is finally computed as:

$$\%LR = \frac{L_w - L_{Eff} - L_{Dis}}{L_w} \qquad \text{(Eq. 7)}$$

Where all terms are defined as previously and in Figure 4-4.

CHAPTER 5

BMP Operation and Maintenance Requirements

This chapter provides an overview of inspection protocols, maintenance triggers, and maintenance actions for the selected BMPs. Information available on maintenance practices for BMPs from DOTs around the country is assessed, and suggestions for the frequency of BMP maintenance are provided. The objective of maintenance is to ensure that BMPs function as designed over their useful lives. The information in this chapter serves as the basis for developing costs for operation and maintenance activities for use in the whole life cost tool. A review of maintenance practices across the United States shows maintenance effort to be approximately linear with the runoff volume treated by the BMP—more maintenance is needed in areas with comparatively higher rainfall (runoff). The frequency of BMP maintenance tasks was translated between geographic areas where empirical information was not available, using average annual rainfall volume (runoff) as a proxy.

Specifically, this chapter describes inspection items and frequency, maintenance triggers, vegetation management requirements, and BMP life span for the selected BMPs. The BMPs considered are vegetated swale, vegetated strip, dry detention basin, bioretention, retention or wet pond, sand filter, and permeable friction course overlay.

5.1 Background

The maintenance protocols provided in this report are based on available maintenance records and literature review of several agencies' post-construction BMP manuals, including Caltrans, Oregon DOT, Arizona DOT, Maine DOT, New York State DOT, Delaware DOT, North Carolina DOT, and Texas DOT. Caltrans completed a BMP Retrofit Pilot Program in 2004 that assessed the technical feasibility and costs of designing, building, operating, and maintaining selected treatment BMPs. This is the most comprehensive study of its kind and serves as the foundation for identifying maintenance tasks for BMPs and the time required to complete those tasks.

The information from the Caltrans pilot program was augmented by other DOT studies throughout the United States to formulate final suggestions for maintenance protocols. DelDOT has begun tracking the annual preventive maintenance performed and major maintenance that is completed by contractors. One year of data is currently available and was used to compare frequency and cost of routine maintenance. The Texas Department of Transportation (TxDOT) has inspection and maintenance schedules for the BMPs that vary from twice annually to annually to as needed. Their program is highly dependent on the specific BMP and its location. This information was also analyzed to refine suggested tasks and frequencies for the selected BMPs.

An objective of this chapter is to define a standard maintenance regimen that will ensure that the BMP functions as designed over its useful life. If BMPs are maintained, their performance generally does not decline with age, assuming the original physical dimensions and BMP influent quality remain constant. Further, the performance tool provided with this report assumes that the BMP is functioning as designed, and it will not return values for constituent concentrations in the effluent quality that exceed that for the influent quality. However, the potential exists for poorly maintained BMPs to bypass influent or, in extreme cases, contribute pollutant load to the effluent. For example, a dry detention basin that has an excessive amount of accumulated sediment may bypass a portion of the influent due to lack of storage volume, and in an extreme case, contribute sediment to the effluent due to the creation of a high-energy environment in the sedimentation area from lack of storage volume. The effluent quality from failed BMPs has not been the subject of research since it represents a condition that should not occur, but the practitioner should be aware that lack or deferred maintenance of BMPs will negatively affect the effluent water quality from the BMP.

5.2 Caltrans Prototype BMP Field Investigation

Caltrans completed a prototype-scale research program assessing the maintenance requirements of BMPs used to control runoff from highway infrastructure. This 7-year, multimillion dollar study examined the costs (life cycle) and benefits of retrofitting DOT infrastructure and developed a series of maintenance protocols, frequencies, and maintenance tasks by BMP type. There were 39 prototype installations constructed in southern California specifically for the study, all of which remain in operation today. The study sites were extensively documented during each phase of the project, from siting through design, construction, instrumentation, performance assessment (sampling), inspection, and operation and maintenance. Inspection and maintenance protocols were developed and the maintenance and operation of each site (along with the performance of each site) were documented for a minimum of a 3-year period to determine the optimum frequency for each designated maintenance task.

The results of this study were used as a primary data source to develop the maintenance costs for the tool. This study carefully developed maintenance tasks needed to ensure that BMPs operated as designed. The scopes of the maintenance tasks were refined as the study progressed, as was the frequency and time required to complete the individual tasks. As a result, this study provides a good baseline for defining the tasks and resource requirements for the tool. A description of the results of the Caltrans study is provided here as a reference for the reader to understand how the final estimates were determined. The full study report and data appendices are available on the Caltrans website at http://dot.ca.gov/hq/env/stormwater/ongoing/pilot_studies/index.htm.

The maintenance records for each site were obtained, and the research team performed field visits to determine whether the long-term inspection and maintenance protocols established under the original program were successful in ensuring BMP operation and performance at the design level. The study sites provide an opportunity to further calibrate the initially established inspection, maintenance, and operation protocols after an additional 8 years of operation beyond the formal study period. The information from the Caltrans pilot program was augmented by studies by other DOTs throughout the United States for use in this project.

Table 5-1 provides the list of Caltrans pilot program BMPs that were inspected in August 2012 and October 2012. The inspection consisted of evaluating each site in the context of the normal maintenance practices to confirm the operation and performance level.

Table 5-1. Caltrans pilot program BMP sites.

Location	Land Use	Drainage Area (acre)	Impervious Area (%)	Average Annual Site Rainfall (inches)
Vegetated Swale				
I-5/Palomar Airport Road	Highway	2.3	90	10.54
SR-78/Melrose Avenue	Highway	2.4	90	13.09
I-5/I-605	Highway	0.7	95	14.46
SR-91/Cerritos Maintenance Station	Maintenance station	0.4	95	14.46
I-605/Del Amo Avenue	Highway	0.7	95	14.46
Vegetated Strip/Infiltration Trench				
Carlsbad Maintenance Station	Maintenance station	1.7	100	10.54
Altadena Maintenance Station	Maintenance station	1.7	100	14.78
Sand Filter				
Eastern Regional Maintenance Station	Maintenance station	1.5	90	14.33
Termination Park and Ride	Park and ride	2.7	90	14.46
Foothill Maintenance Station	Maintenance station	1.7	100	17.20
Vista Park and Ride	Park and ride	0.7	80	10.54
La Costa Park and Ride	Park and ride	2.7	56	9.66
Escondido Maintenance Station	Maintenance station	0.7	85	16.22
Wet Basin/Retention Pond				
I-5/La Costa Avenue	Highway	4.2	48	9.66
Extended Detention Basin/Dry Detention				
I-5/I-605	Highway	6.8	54	14.46
I-5/Manchester	Highway	4.8	56	9.66
I-15/SR-78	Highway	13.4	28	16.22
I-605/SR-91	Highway	1.0	100	14.46
I-5/SR-56	Highway	5.3	69	10.13

Table 5-2. Vegetated swale maintenance.

Site	Vegetation Coverage %	Maintenance Records Available	Inspections Performed	Maintenance Performed	Performance
I-5/Palomar Airport Road	95	3 years	Monthly	None required	As designed
SR-78/Melrose Avenue	90	3 years	Monthly	Once/3 years vegetation trimming and removal	As designed
I-5/I-605	50	5 years	Monthly	Monthly vegetation trimming and removal	Minor erosion
SR-91/Cerritos Maintenance Station	10	5 years	Monthly for 3 years	Monthly vegetation trimming and removal for 3 years	Revegetation needed
I-605/Del Amo Avenue	90	6 years	Quarterly	Quarterly vegetation trimming and removal	As designed

5.2.1 Vegetated Swales

Five vegetated swales were inspected, as shown in Table 5-2. In four cases, the original vegetation planted at the sites had been replaced or had been taken over by vegetation from the surrounding landscape and had vegetation coverage of varying degrees. At the fifth location, there was little vegetation present, but no erosion. Three of those four vegetated locations were functioning properly regardless of vegetation height or type with no sediment buildup or evidence of erosion. The conditions of the swales supported the discharge of the design storm at velocities lower than 1 ft/s and hydraulic residence times of at least 5 min for the design storm event (design condition). The maintenance intervals for these sites were judged to be sufficient to maintain the BMP performance.

5.2.2 Vegetated Strips

Two vegetated strips located in maintenance stations were inspected, as shown in Table 5-3. The vegetated strip portion had been recently mowed at each location prior to the inspection. The vegetated strips provide pretreatment prior to flows discharging to the infiltration trenches. At both locations, the vegetated strips treat flow velocities of less than 1 ft/s during design storms. Flows are then directed to the infiltration trenches. There were no signs of overflow or sediment buildup within the infiltration trenches, and both were performing as designed. The maintenance intervals for these sites were judged to be sufficient to maintain the BMP performance.

5.2.3 Extended Detention Basin/Dry Detention Basin

Five extended detention basins were inspected, as shown in Table 5-4. Four of the basins were unlined and one had a concrete lining. Three of the four unlined basins had vegetation growth in excess of the recommended maintenance trigger of 12 in.; however, the maintenance trigger was established primarily for aesthetics (Caltrans, 2009b). These three basins were functioning as designed, with capacity for the water quality design storm. The concrete-lined basin had been recently cleaned, with all sediment deposits removed. The outlet structures were clear in all of the basins. The earthen basins did have some sediment deposits; however, all were less than 1% of the basin volume and not impairing

Table 5-3. Vegetated strip maintenance.

Site	Maintenance Records Available	Inspections Performed	Maintenance Performed	Performance
Carlsbad Maintenance Station	3 years	Monthly	Semiannually	Some channelization due to debris in spreader ditch, no erosion
Altadena Maintenance Station	5 years	Two to three times annually	Two to three times annually (mow)	As designed

Table 5-4. Extended detention basin maintenance.

Site	Maintenance Records Available	Inspections Performed	Maintenance Performed	Performance
I-5/I-605 (lined)	6 years	Quarterly	Quarterly to semiannual vegetation removal of the surrounding area (not lined basin)	As designed
I-5/Manchester	3 years	Monthly	Annual vegetation removal	As designed
I-15/SR-78	3 years	Monthly	Once/3 years vegetation removal (additional vegetation removal done for fire suppression)	As designed
I-605/SR-91	6 years	Quarterly	Quarterly to semiannual vegetation removal	As designed
I-5/SR-56	N/A	N/A	N/A	As designed

performance or requiring maintenance. The maintenance intervals for these sites were judged to be sufficient to maintain the BMP performance.

5.2.4 Wet Basin

One wet basin was inspected (Table 5-5), and it was observed that the adjacent channel was full of silt and vegetation, which allowed less dry-weather flow to enter the basin. With a reduced flow, the basin water surface elevation had dropped 1.25 ft below the design permanent pool water surface elevation. The basin had a small pool of water ranging from a couple of inches in depth to 1.75 ft in depth. This pool was 90% covered with vegetation, greater than the original design open-water criteria of 50%. The abundance of vegetation could limit the range of the mosquitofish (*Gambusia affinis*). The inlet from the highway discharging runoff to the basin was clear and free of silt. The original permanent pool design volume for this installation was twice the water quality volume. The reduced permanent pool water surface indicates that the pool volume is now about equal to the design water quality volume; thus the basin is still within the minimum design requirements. The reduced pool volume and increased extent of vegetation were not impairing the water quality performance of the facility, and no vector issues were noted during the site visit.

5.2.5 Sand Filters

Six sand filters, five Austin style and one Delaware style, were inspected, as shown in Table 5-6. Various levels of maintenance were observed and recorded in the maintenance records, with the Delaware sand filter and three Austin sand filter locations having had recent sedimentation basin cleanouts and replacement of sand media. The Vista Park and Ride Austin sand filter did not have maintenance performed within the sedimentation basin or sand bed within the last 10 years and was performing as designed. The La Costa Park and Ride location had no major maintenance needed within the sedimentation basin or sand bed within the last 3 years. Both had presence of vegetation within the sand bed. However, all sand filters were functioning with no evidence of bypass. The maintenance intervals for these sites were judged to be sufficient to maintain the BMP performance.

5.3 Literature Review

Oregon DOT maintenance and inspection practices were evaluated to review protocols for several BMPs, such as stormwater ponds, biofiltration swales, filter strips, bioslopes, detention vaults, and detention tanks. Oregon DOT also provided general maintenance requirements that are common for all types of BMPs. One of the major maintenance items consists of annual inspection to identify existing or potential operational

Table 5-5. Wet basin maintenance.

Site	Maintenance Records Available	Inspections Performed	Maintenance Performed	Performance
La Costa	3 years	Monthly	None	Increased vector monitoring due to vegetation, sufficient volume in basin to capture water quality event

Table 5-6. Sand filter maintenance.

Site	Maintenance Records Available	Inspections Performed	Maintenance Performed	Performance
Eastern Regional Maintenance Station	5 years	Annually	Every 1.5 years top 2 in. of sand replaced in sand bed*	As designed
Termination Park and Ride	5 years	Every 1.5 years	Every 1.5 years top 2 in. of sand replaced in sand bed*	As designed
Foothill Maintenance Station	5 years	Twice annually	Annually top 2 in. of sand replaced in sand bed*	As designed
Vista Park and Ride	3 years	None	None	As designed
La Costa Park and Ride	3 years	Monthly	Once/3 years top 2 in. of sand replaced in sand bed	As designed
Escondido Maintenance Station	3 years	Bimonthly	Bimonthly cleanouts	As designed

*Discussions with maintenance staff indicated that the maintenance cleanouts for all three sand filters were performed not due to poor performance but for aesthetics.

problems prior to the wet season. Other general maintenance items are limiting vegetation growth, removal of trash/debris when they inhibit BMP function, and erosion control.

NYSDOT Region 8 has developed an operations and maintenance manual to address the maintenance of permanent stormwater management BMPs. The manual provides general maintenance guidelines. It includes inspection checklists for various stormwater management BMPs, including detention basins, wet ponds, sand filters, bioretention, and swales. All BMPs require annual inspections as well as periodic vegetation repair, debris cleanout, and sediment removal (New York State Department of Transportation, Region 8, 2003).

NCDOT has an inspection and maintenance manual that specifies maintenance needs for treatment BMPs, including bioretention, filter basins, detention basin, wet basins, and swales (North Carolina Department of Transportation, 2010). The manual identifies inspection actions and recommends an annual frequency for inspection. For maintenance activities, typical actions are identified, but the manual does not address the frequency required for maintenance on many of the items. Only vegetation trimming has a recommended frequency of every 2 to 3 years.

Florida DOT has stormwater inspection of BMPs on an annual basis for the first 2 years on all new projects. After the initial 2 years, dry detention basins, retention ponds, and swales without chronic problems are inspected every 3 years and maintained as needed per the inspections. Dry detention basins with filtration but without chronic problems are inspected every 18 months. Any BMP with chronic issues is inspected annually.

DelDOT began collecting detailed maintenance cost records for its BMPs in June of 2013 for the prior 3 years of maintenance activity. The maintenance costs and number of BMP sites are shown in Table 5-7. The maintenance tasks were performed by outside contractors. The breakdown of activities performed at each BMP location is provided in Appendix D: Maintenance Field Guide. For bioswales (i.e., vegetated swales) the seven locations had excess sediment requiring nearly complete regrading of the BMPs. The sand filters all required removal of the top of the sand layer to restore permeability.

Table 5-7. DelDOT's contracted BMP maintenance costs, 2009–2012.

BMP Type	Quantity	Avg. Maint. Cost
Bioswale	7	$12,990.99
Dry pond	20	$15,779.30
Infiltration trench	1	$45,461.13
Sand filter	66	$804.57
Sediment basin	1	$5,357.95
Shallow marsh	1	$22,151.97
Wet pond	17	$30,828.49

The wet and dry ponds required sediment removal and clearing and grubbing. These costs were used as verification points for BMPs located in a medium-level maintenance region. The costs in Table 5-7 are per location and represent an average for the BMP type noted.

5.4 Vegetation and Sediment Accumulation Rates in BMPs

This section discusses the primary maintenance tasks whose frequency is based on the volume of water that the BMP treats or on the amount of vegetation management needed (also a function of rainfall). The frequencies of maintenance tasks are categorized as low, medium, or high in the spreadsheet evaluation tool. Practitioners can assess the appropriate maintenance category for their region by reviewing the suggested maintenance frequencies for each BMP (see Section 5.5) and matching the frequencies to those used locally.

Treatment BMPs are designed, constructed, and operated in part based on local climate conditions. The characteristics of storms, such as rainfall intensity, depth, inter-event time, and percentage of annual precipitation as snow or rain, are also important factors in determining inspection and maintenance frequency. The frequency of maintenance tasks typically includes sediment removal maintenance and other routine tasks appropriate to the BMP. Because the frequency of sediment and routine maintenance tasks correlates directly to the volume of runoff through the BMP, maintenance frequency is divided into the aforementioned three groups—high, medium, and low—based on the rainfall regions shown in Table 5-8.

Figure 5-1 and Table 5-8 provide the breakdown of the rainfall regions across the United States, with their average annual rainfall estimated from multiple rain gauges within each zone. Regions that received less than 20 in. of rain per year were assigned a low level of maintenance. Regions receiving between 20 and 35 in. of rain per year were assigned a medium level of maintenance, and regions receiving more than 35 in. of rainfall annually were assigned a high level of maintenance.

Inspection and maintenance activities influencing BMP operation and performance (function) for each type of BMP are described in the following sections. The maintenance functions can be divided into two categories: aesthetic and functional. These two categories can overlap. Functional maintenance is important for performance and safety reasons, while aesthetic maintenance is generally more important for public acceptance of stormwater facilities. The frequency of the maintenance action was developed as described in Sections 5.1 through 5.3.

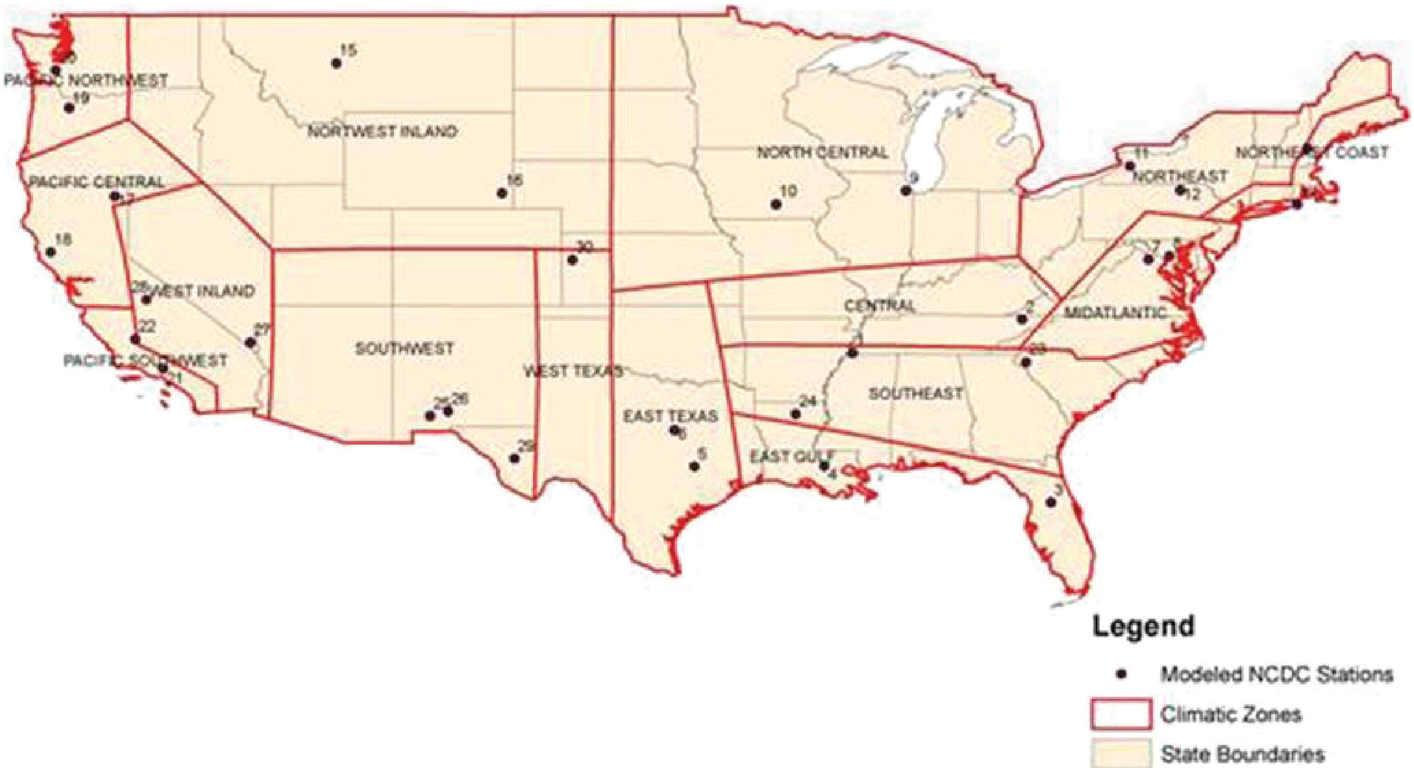
5.4.1 Vegetated Strips

Vegetated strips require vegetation to slow runoff velocity, facilitating infiltration and sedimentation of particulates. Multiple vegetated strip studies have been performed that give insight into the minimum amount of vegetated cover required for treatment. One study (Caltrans, 2003d) involved sampling

Table 5-8. Climate region rainfall data.

Climate Region	Average Regional Annual Rainfall (in.)	Maintenance Level
Central	35.57	High
East Gulf	47.56	High
East Texas	28.79	Medium
Mid-Atlantic	32.67	Medium
North Central	24.7	Medium
Northeast	30.81	Medium
Northeast Coastal	37.59	High
Northwest Inland	11.48	Low
Pacific Central	29.97	Medium
Pacific Northwest	46.03	High
Pacific Southwest	14.9	Low
Southeast	43.19	High
Southwest	10.15	Low
West Inland	11.48	Low
West Texas	14.95	Low

* Rainfall summary statistics from FHWA-HEP-09-005 (Granato, 2010).



*From FHWA-HEP-09-005 (Granato, 2010).

Figure 5-1. Climate region rainfall zones.

at different distances from the edge of the pavement to determine the effect of vegetated strip length on constituent removal. This study also evaluated vegetated cover with respect to performance for strip length. The study found that a minimum vegetative cover of about 65% is required for basic particulate concentration reduction to occur, although a decline in performance begins to occur below coverage levels of about 80% (of total area). Therefore, vegetation management is advised at least annually to ensure basic coverage of the vegetated strip. Trimming of vegetation is advised for aesthetics only, not performance. Since vegetated strips require sheet flow to function properly, erosion within the strip that would lead to channelization must be repaired to restore uniform flow.

Trash and debris that pose a hazard, inhibit the function of the strip, or that could discharge to receiving waters should be removed. The literature review of available DOT maintenance manuals indicated that trash removal is generally recommended as part of annual inspections within the vegetated strip but will usually occur more frequently in most urban areas as a part of normal operations.

Vegetated strips treat sheet flow by straining runoff through vegetation and creating conditions that promote sedimentation. Over time, as the cumulative volume from storm events passing through the vegetated strips increases, sediment will accumulate at the highway/vegetated strip interface. After an extended period of time, the sediment accumulation within the strip will need to be removed and the strip will need to be regraded to reestablish sheet flow. This period of time ranges from every 8 to 60 years based on tributary drainage area loading for the BMP and 1-in. sediment accumulation (Table 5-9).

5.4.2 Vegetated Swale

The operation of vegetated swales is similar to vegetated strips in that sedimentation is the primary unit process for pollutant removal. The results of the Caltrans pilot program study for vegetated strips indicated that a 65% vegetated coverage area was necessary for TSS concentration reduction, with 80% coverage or greater being optimal. As with vegetated strips, trimming of vegetation is advised for aesthetics, not for the performance of the swale. Trimming of vegetation may also be needed primarily for safety reasons in areas where heavy brush may block the driver's view of wildlife that may enter the highway environment and to discourage wildlife and control woody vegetation. Vegetated swales have side slopes to channel the flow, and there is a possibility for erosion of the side slopes, which must be repaired if present.

As with vegetated strips, trash and debris that pose a hazard, inhibit function, or that may discharge to receiving waters should be removed annually as part of inspections.

Table 5-9. Vegetated strip sediment maintenance frequency.

Climate Region	Annual Rainfall (in.)	Annual Stormwater Volume (ft^3/acre)	Annual Load TSS (ft^3/acre)	Time to Sediment Accumulation to Cause Concentrated Flow (years)
Central	35.57	129,119	10.11	11
East Gulf	47.56	172,643	13.52	8
East Texas	28.79	104,508	8.19	13
Mid-Atlantic	32.67	118,592	9.29	11
North Central	24.7	89,661	7.02	15
Northeast	30.81	111,840	8.76	12
Northeast Coastal	37.59	136,452	10.69	10
Northwest Inland	11.48	41,672	3.26	33
Pacific Central	29.97	108,791	8.52	13
Pacific Northwest	46.03	167,089	13.09	8
Pacific Southwest	14.9	54,087	4.24	25
Southeast	43.19	156,780	12.28	9
Southwest	10.15	36,845	2.89	37
West Inland	11.48	41,672	3.26	33
West Texas	14.95	54,269	4.25	25
TSS influent concentration = 172 mg/L, TSS effluent concentration = 31 mg/L, vegetation height = 4 in.				

The annual sediment load for a vegetated swale was estimated by rainfall region. Using average TSS values from the highway research database and TSS removal efficiency from the International Stormwater BMP Database, it takes between 12.5 and 91 years to fill the swale with sediment to the height vegetation (4 in.), as shown in Table 5-10.

5.4.3 Dry Detention Basin

Review of state DOT BMP manuals indicates that a majority of the higher-rainfall regions require a semiannual or quarterly vegetation mowing frequency. Vegetation can affect the performance of a detention basin if the vegetation volume becomes a significant portion of the basin storage volume. A calculation was performed to determine the amount of dry detention basin volume that vegetation would occupy within a fully vegetated basin: two-thirds of the surface of the basin covered with shrubs 2 ft in diameter and 1 ft in height. The shrub volume was calculated based on crown shape models that take into consideration the diameter, height, and shape of the crown (Coder, 2000). This resulted in a volume of 6%–13% of the basin, as shown in Table 5-11. Overall, vegetation should be annually inspected and maintained across all regions when the vegetation reduces the basin's volume by 10%. In high-level maintenance regions this is expected to occur every 2 years, in medium-level maintenance regions this is expected every 5 years, and in low-level maintenance regions this is expected every 10 years.

As the sediment volume from storm events accumulates, sediment will need to be removed to maintain basin storage volume. The detention basin will lose its effectiveness as sediment takes up capacity or covers the outlet. Dry detention basin studies and maintenance guides were reviewed to determine the average maintenance frequency based on sediment buildup for the identified maintenance levels. An analysis was conducted using local rainfall data to estimate the frequency of sediment cleanout assuming a standard design water quality volume (i.e., 85th-percentile design storm) and a maximum permissible sediment volume accumulation of 10% of the basin volume. The evaluation determined that a BMP with capability to capture a unit water quality volume of 2,500 cubic feet per acre will take from 20 to 150 years (depending on the rainfall region) to fill 10% of the BMP capacity with sediment. Table 5-12 provides the results of this analysis by climate (rainfall) region. Trash and debris that pose a hazard, inhibit function, or that may be discharged to receiving waters should be removed as needed or annually as part of inspections.

5.4.4 Bioretention

Vegetation is essential for the performance of a bioretention unit since the roots help promote media permeability and improve nutrient removal. The surface vegetation also

Table 5-10. Vegetated swale sediment maintenance frequency.

Climate Region	Annual Rainfall (in.)	Annual Stormwater Volume (ft^3/acre)	Annual Load TSS (ft^3/acre)	Time to Fill Swale to Vegetation Height (years)
Central	35.57	129,119	10.40	16
East Gulf	47.56	172,643	13.91	12
East Texas	28.79	104,508	8.42	20
Mid-Atlantic	32.67	118,592	9.55	17
North Central	24.7	89,661	7.22	23
Northeast	30.81	111,840	9.01	19
Northeast Coastal	37.59	136,452	10.99	15
Northwest Inland	11.48	41,672	3.36	50
Pacific Central	29.97	108,791	8.76	19
Pacific Northwest	46.03	167,089	13.46	12
Pacific Southwest	14.9	54,087	4.36	38
Southeast	43.19	156,780	12.63	13
Southwest	10.15	36,845	2.97	56
West Inland	11.48	41,672	3.36	50
West Texas	14.95	54,269	4.37	38
TSS influent concentration = 172 mg/L, TSS effluent concentration = 27 mg/L, length = 100 ft, bottom Width = 5 ft, vegetation height = 4 in.				

helps filter sediment and provides some evapotranspiration. Some of the guidance for vegetation management within a bioretention BMP is aesthetic in nature (mowing, trash removal, pruning, replacing mulch) and is not necessary for performance; these are included in the suggestions in Section 5.5. Vegetation maintenance necessary for performance of bioretention includes the replacement of dead vegetation. This is estimated to be required semiannually, annually, or every 3 years, dependent on the average annual rainfall.

A bioretention facility is a soil- and plant-based filtration system. Over time, with cumulative storm events, sediment will accumulate in the BMP. A study published in *Environmental Science & Technology* (Li and Davis, 2008) showed that heavy metals within a bioretention BMP were trapped within the top 20 centimeters of soil, and after 4.5 years did not migrate through the soil. The study bioretention unit was located in the District of Columbia, an area receiving between 20 and 35 in. of rain annually. This study aligns with the expectation of bioretention media lasting at least 20 years before need of replacement, for a medium level of maintenance. Based on the TSS loading calculations, the sediment accumulation within the bioretention media will have to be removed every 15 to 100+ years (Table 5-13). Trash and debris that pose a hazard, inhibit function, or that may discharge to receiving waters should be removed annually or as needed as part of inspection.

5.4.5 Retention/Wet Pond

Retention or wet ponds are basins that contain a permanent pool of water throughout the year. Over time, sediment will accumulate in the BMP. The sediment accumulation within the forebay of the wet pond will have to be removed every 3 to 25 years, based on annual runoff volume. Computed estimates

Table 5-11. Dry detention basin vegetation impacts.

Location	Footprint Area (ft^2)	WQV Treated (ft^3)	Total Number of Shrubs in Basin	Shrub Volume (ft^3)	Total Shrub Volume (ft^3)	% Shrub Takes up of Entire Basin Volume
605/91	608	2,472	129	1.57	202.82	8%
5/56	5,586	13,808	1186	1.57	1,863.09	13%
15/78	7,610	39,658	1616	1.57	2,537.97	6%
5/Manchester	1,896	8,935	403	1.57	632.45	7%
Shrub crown diameter = 2.0 ft, shrub height = 1.0 ft, basin coverage = 66.7%. WQV = water quality volume.						

Table 5-12. Sediment removal maintenance frequency.

Climate Region	Annual Rainfall (in.)	Annual Stormwater Volume (ft^3/acre)	Annual Load TSS (ft^3/acre)	Time to Fill 10% of Capacity (years)
Central	35.57	129,119	474	9
East Gulf	47.56	172,643	634	12
East Texas	28.79	104,508	384	8
Mid-Atlantic	32.67	118,592	436	9
North Central	24.7	89,661	329	6
Northeast	30.81	111,840	411	8
Northeast Coastal	37.59	136,452	501	10
Northwest Inland	11.48	41,672	153	3
Pacific Central	29.97	108,791	400	8
Pacific Northwest	46.03	167,089	614	12
Pacific Southwest	14.9	54,087	199	4
Southeast	43.19	156,780	576	11
Southwest	10.15	36,845	135	3
West Inland	11.48	41,672	153	3
West Texas	14.95	54,269	199	4
TSS influent concentration = 172 mg/L, TSS effluent concentration = 42 mg/L, tributary drainage area = 1 acre, basin size = 2,500 ft^3/acre tributary drainage area (TDA).				

Table 5-13. Bioretention sediment maintenance frequency.

Climate Region	Annual Rainfall (in.)	Annual Stormwater Volume (ft^3/acre)	Annual Load TSS (ft^3/acre)	Time to Fill 10% of Basin (years)
Central	35.57	129,119	12.34	20
East Gulf	47.56	172,643	16.50	15
East Texas	28.79	104,508	9.99	25
Mid-Atlantic	32.67	118,592	11.33	22
North Central	24.7	89,661	8.57	29
Northeast	30.81	111,840	10.69	23
Northeast Coastal	37.59	136,452	13.04	19
Northwest Inland	11.48	41,672	3.98	63
Pacific Central	29.97	108,791	10.40	24
Pacific Northwest	46.03	167,089	15.97	16
Pacific Southwest	14.9	54,087	5.17	48
Southeast	43.19	156,780	14.98	17
Southwest	10.15	36,845	3.52	71
West Inland	11.48	41,672	3.98	63
West Texas	14.95	54,269	5.19	48
TSS influent concentration = 172 mg/L, TSS effluent concentration = 17.7 mg/L, tributary drainage area = 1 acre, basin size= 2,500 ft^3/acre TDA.				

Table 5-14. Wet basin sediment maintenance frequency.

Climate Region	Annual Rainfall (in.)	Annual Stormwater Volume (ft^3/acre)	Annual Load TSS Retained (lb/acre)	Annual Load TSS (ft^3/acre)	Time to Fill 10% of Forebay (years)	Time to Fill 10% of Main Pool (years)
Central	35.57	129,119	1,225	10.90	4.6	25
East Gulf	47.56	172,643	1,638	14.58	3.4	19
East Texas	28.79	104,508	992	8.83	5.7	31
Mid-Atlantic	32.67	118,592	1,125	10.01	5.0	27
North Central	24.7	89,661	851	7.57	6.6	36
Northeast	30.81	111,840	1,061	9.44	5.3	29
Northeast Coastal	37.59	136,452	1,295	11.52	4.3	24
Northwest Inland	11.48	41,672	395	3.52	14.2	78
Pacific Central	29.97	108,791	1,032	9.19	5.4	30
Pacific Northwest	46.03	167,089	1,586	14.11	3.5	19
Pacific Southwest	14.9	54,087	513	4.57	10.9	60
Southeast	43.19	156,780	1,488	13.24	3.8	21
Southwest	10.15	36,845	350	3.11	16.1	88
West Inland	11.48	41,672	395	3.52	14.2	78
West Texas	14.95	54,269	515	4.58	10.9	60

TSS influent concentration = 172 mg/L, TSS effluent concentration = 20 mg/L, tributary drainage area = 1 acre, forebay size= 500 ft^3/acre TDA, main pool size = 2,750 ft^3/acre.

are as shown in Table 5-14. Similar calculations for the main pool were performed indicating 20 to 140 years before sediment accumulated to fill 10% of the main pool capacity. Experience in Florida indicates that stormwater ponds need sediment removal about every 25 years (Post, 2009). This confirms the calculations for the East Gulf that show 20 years to fill the main pool with sediment. These calculations are applicable for wet ponds receiving typical highway runoff and receiving perennial flow from a source with a stabilized upstream drainage area.

Vegetation management is the most labor-intensive task for wet ponds. A minimum of annual vegetation removal is advised to ensure that excess vegetated growth does not restrict vector control activities or obstruct the passage of mosquitofish for vector control. This suggestion is based on recommendations found in literature for North Carolina (Hunt and Lord, 2006) and the Caltrans pilot program field observations.

Some jurisdictions may choose to mow around the edge of the pond for aesthetics or to provide a habitat for geese. This is an example of how maintenance preferences and issues (geese may contribute to sanitary quality problems) can affect maintenance costs and BMP performance. The practitioner should make such site-specific assessments and determinations and can customize the values in the BMP Evaluation Tool accordingly.

5.4.6 Sand Filter

The frequency of removal of sediment from the sediment forebay or sedimentation basin of a sand filter is similar to that of a dry detention basin. Maintenance is necessary to remove the accumulated sediment when 10% of the sedimentation basin volume is filled with trapped sediment.

The sand filter bed will also occlude over time as particulates are retained in the media. The filter bed can be renewed by removing about the top 1 or 2 in. of sand from the bed, since surface filtration, rather than depth filtration, occurs with a slow sand filter. Rainfall records for 10 years were obtained from rain gauges near each of the Caltrans pilot sand filter locations. Computations were made of the volume of water and TSS loading received by each sand filter between sand bed media cleanouts. Based on a review of the maintenance records, inspection of the sand filter locations, and review of volume of water received, the estimated treatment volume to a sand filter before it clogs is 600 ft^3 of runoff per square foot of sand surface area. Table 5-15 shows the computed solids loadings for the Caltrans pilot locations. This calculated loading considers observations at the Vista Park and Ride location, which has never had a sand bed cleanout during 12 years of operation and is still functioning properly, having received 667 ft^3/ft^2 loading on an average annual basis. Other sand filter locations that show lower loading rates are the result of receiving maintenance prior to occlusion of the filter.

The volume of water expected to be treated by a sand filter in each climate region was calculated based on a unit loading over the sand filter bed to determine the length of time it takes to accumulate sufficient material within the sand media to plug the sand bed. Assuming that the sand filter was constructed with 350 ft^2 of filter area per tributary acre treated, sand media replacement would be needed between 3 and 10 years, depending on the maintenance level (high, medium, or low rainfall area).

Trash and debris that pose a hazard, inhibit function, or that may discharge to receiving waters should be removed as needed or annually as part of inspections.

5.4.7 Permeable Friction Course

Maintenance of a PFC consists of either actions to restore the permeability of the existing pavement or milling the old overlay, disposing of the used asphalt appropriately, and applying a new overlay. This is necessary as suspended solids fill the voids of the permeable layer or when the structural integrity of the overlay has become compromised. Currently, other than vacuum sweeping, there is no way to remove sediment from the PFC overlay. The efficacy of this approach and the type of equipment needed require more study. Several performance studies have been prepared on PFC overlays in a variety of climates and have been summarized in National Asphalt Pavement Association Information Series 135 (National Asphalt Pavement Association, 2009). These studies were done in Ohio, North Carolina, Illinois, New York, Indiana, and Georgia. The studies indicate that 7 to 16 years of performance can be

Table 5-15. Sand filter loading calculations.

Location	Drainage Area (acre)	Filter Bed Area (ft^2)	WQV (ft^3)	Rainfall Between Cleanouts (in.)	Runoff Volume Between Cleanouts (ft^3)	Unit Volume per Filter Bed Area (ft^3/ft^2)	TSS Loading Between Cleanouts (lb)
Vista Park and Ride*	0.7	344	3,740	112.95+	229,605+	667	1,634+
Eastern Maintenance Station	1.5	291	4,060	23.47	115,026	395	819
Eastern Maintenance Station	1.5	291	4,060	28.83	141,284	486	1,005
Eastern Maintenance Station	1.5	291	4,060	9.21	45,146	155	321
Foothill Maintenance Station	1.7	431	7,660	13.85	85,446	198	608
Foothill Maintenance Station	1.7	431	7,660	31.97	197,301	458	1,404
Foothill Maintenance Station	1.7	431	7,660	6.48	40,014	93	285
La Costa Park and Ride	2.7	775	10,100	33.24	182,440	235	1,298
Termination Park and Ride	2.7	614	7,840	10.48	92,411	151	658
Termination Park and Ride	2.7	614	7,840	10.11	89,146	145	634
Termination Park and Ride	2.7	614	7,840	32.27	284,629	464	2,026

*Vista Park and Ride has not had a maintenance cleanout.

expected for overlays placed on asphalt pavements, and 6 to 10 years of life can be expected for overlays placed on concrete pavements before they must be replaced.

5.5 Suggested Maintenance Tasks

The suggested maintenance tasks by BMP, including the hours and equipment requirements, were based on collected inspection and maintenance data from the Caltrans pilot sites and the records obtained during this study from DOTs and from the literature review. These data were standardized based on local conditions (rainfall) across the country to determine the frequency and requirements for each BMP type. The suggested maintenance tasks were developed to sustain the as-designed level of function for the BMP by maintaining the original volumes and operating parameters and material specifications within a range that would not significantly alter performance. The suggestions are based on judgment following evaluations of performance studies and field observations.

Recall that the maintenance frequency is divided into three groups—high, medium, and low—based on rainfall regions, consistent with the sediment removal task for each BMP. The inspection, reporting, and information management tasks are the same frequency (i.e., annually) for all BMP types, regardless of rainfall region. The interval for vegetation maintenance actions is based on rainfall zones throughout the United States, calibrated against frequencies that provide a basic level of service observed at prototype installations. The interval for other suggested inspection and maintenance practices is based on recommended literature values, values recommended in the DOT survey, and field observations. The tables in Appendix D: Maintenance Field Guide provide the suggested frequencies for the routine maintenance practices by BMP device.

For BMPs with vegetated maintenance requirements for aesthetics (i.e., vegetated strips, vegetated swales, sand filters, dry detention basins, and bioretention), the user may specify the level of maintenance needed based on project-specific conditions. The standard input for the tool is based on rainfall region, with more frequent maintenance in those areas with higher rainfall. The user may adjust the category of maintenance to accommodate an increased emphasis on aesthetics, or may input a custom value based on preference. Maintenance activities, frequency, and time required are summarized by BMP in the following sections.

5.5.1 Vegetated Strips

Vegetated strip maintenance activities are presented in Table 5-16. Suggested frequencies for maintenance activities are three times per year, semiannually, and annually. Intermittent maintenance tasks, defined as repair of erosion, removal of woody vegetation, and repair of any structures, are suggested to occur every 2, 5, or 10 years.

5.5.2 Vegetated Swale

Vegetated swale maintenance activities are presented in Table 5-17. Vegetation management is an aesthetic task suggested to occur three times per year, semiannually, or annually. Included in the maintenance crew hours for vegetation manage-

Table 5-16. Vegetated strip maintenance activities.

Maintenance Activity	Maintenance Frequency			Hours per Event	Crew Size	Equipment Needed	Materials and Incidentals
	Low	Medium	High				
Vegetation management for aesthetics (optional)	Annually	2 times per year	3 times per year	4	2	Utility truck, mower	–
Trash and debris	Annually	Annually	Annually	Included in vegetation management	–	–	–
Intermittent maintenance (including sediment management)	Every 10 years	Every 5 years	Every 2 years	8	2	Utility truck, loader	Disposal
Vegetation repair	Every 10 years	Every 5 years	Every 2 years	Included in intermittent maintenance	–	–	–
Erosion or rutting	Every 10 years	Every 5 years	Every 2 years	Included in intermittent maintenance	–	–	–
Inspection and reporting	Annually	Annually	Annually	1	2	Utility truck	–

Table 5-17. Vegetated swale maintenance activities.

Maintenance Activity	Maintenance Frequency			Hours per Event	Crew Size	Equipment Needed	Materials and Incidentals
	Low	Medium	High				
Vegetation management for aesthetics (optional)	Annually	2 times per year	3 times per year	4	2	Utility truck, mower	–
Trash and debris	Annually	Annually	Annually	Included in vegetation management	–	–	–
Intermittent maintenance, including sediment management	Every 10 years	Every 5 years	Every 2 years	8	2	Utility truck, loader	Disposal
Slope inspection	Every 10 years	Every 5 years	Every 2 years	Included in intermittent maintenance	–	–	–
Vegetation repair	Every 10 years	Every 5 years	Every 2 years	Included in intermittent maintenance	–	–	–
Inspection and reporting	Annually	Annually	Annually	1	2	Utility truck	–

ment is the removal of trash and debris. Intermittent maintenance, including sediment management, vegetation repair, and slope repair, is suggested to occur every 2, 5, or 10 years, based on calculations for sediment buildup within the vegetated swale.

5.5.3 Dry Detention Basin

Dry detention basin maintenance activities are presented in Table 5-18. Suggested frequencies for trash and debris removal are three times per year, semiannually, and annually, as a function of the aesthetic needs of the site. Sediment removal is suggested to occur at 20, 30, or 50 years, based on typical highway loading calculations for the three maintenance categories. Intermittent maintenance includes findings from inspection of the structures, signs of erosion, or emergence of woody vegetation requiring removal. Intermittent maintenance is suggested to occur every 2, 5, or 10 years.

Table 5-18. Dry detention basin maintenance activities.

Maintenance Activity	Maintenance Frequency			Hours per Event	Crew Size	Equipment Needed	Materials and Incidentals
	Low	Medium	High				
Vegetation management for aesthetics (optional)	Annually	2 times per year	3 times per year	3	2	Utility truck, mower	–
Trash and debris	Annually	2 times per year	3 times per year	Included in vegetation management	–	–	–
Intermittent maintenance	Every 10 years	Every 5 years	Every 2 years	8	2	Utility truck, loader	Disposal
Standing water	Every 10 years	Every 5 years	Every 2 years	Included in intermittent maintenance	–	–	–
Slope inspections	Every 10 years	Every 5 years	Every 2 years	Included in intermittent maintenance	–	–	–
Sediment management	50 years	30 years	20 years	8	4	Utility truck, loader with backhoe	Disposal
Inspection and reporting	Annually	Annually	Annually	1	2	Utility truck	–

Table 5-19. Bioretention maintenance activities.

Maintenance Activity	Maintenance Frequency			Hours per Event	Crew Size	Equipment Needed	Materials and Incidentals
	Low	Medium	High				
Vegetation repair	Every 3 years	Annually	2 times per year	8	2	Utility truck, mower	Mulch, plants
Vegetation management for aesthetics (optional)	Every 3 years	Annually	2 times per year	Included in vegetation repair	–	–	–
Mulch layer management	Every 3 years	Annually	2 times per year	Included in vegetation repair	–	–	–
Trash and debris	Every 3 years	Annually	2 times per year	Included in vegetation repair	–	–	–
Intermittent maintenance	Every 12 years	Every 8 years	Every 4 years	24	4	Utility truck, loader	Disposal
Underdrain system (if necessary)	Every 12 years	Every 8 years	Every 4 years	Included in intermittent maintenance	–	–	–
Soil repair	Every 12 years	Every 8 years	Every 4 years	Included in intermittent maintenance	–	–	–
Sediment management	Every 50 years	Every 20 years	Every 10 years	8	4	Utility truck, loader	Disposal
Inspection and reporting	Annually	Annually	Annually	1	2	Utility truck	–

5.5.4 Bioretention

Bioretention maintenance activities are presented in Table 5-19. All vegetation management tasks are included within vegetation repair and are suggested to occur semiannually, annually, or every 3 years. Intermittent maintenance frequency, including repair of erosion, underdrain system, and repair of any structures, is suggested at every 4, 8, or 12 years. Sediment removal will be required every 10, 20, or 50 years, based on rainfall area.

5.5.5 Retention/Wet Pond

Retention pond maintenance activities are presented in Table 5-20. Trash and debris removal frequency is suggested at three times per year, semiannually, or annually as a function

Table 5-20. Retention pond maintenance activities.

Maintenance Activity	Maintenance Frequency			Hours per Event	Crew Size	Equipment Needed	Materials and Incidentals
	Low	Medium	High				
Vegetation management	Annually	2 times per year	3 times per year	20	4	Utility truck, loader	Disposal
Trash and debris	Annually	2 times per year	3 times per year	Included in vegetation management	–	–	–
Intermittent maintenance	Annually	Annually	Annually	8	2	Utility truck, loader	–
Sediment management (forebay)	15 years	10 years	5 years	8	4	Utility truck, loader with backhoe	Disposal
Sediment management (main pool)	50 years	30 years	20 years	16	4	Utility truck, loader with backhoe	Disposal
Inspection and reporting	Annually	Annually	Annually	2	2	Utility truck	–

Table 5-21. Sand filter maintenance activities.

Maintenance Activity	Maintenance Frequency			Hours per Event	Crew Size	Equipment Needed	Materials and Incidentals
	Low	Medium	High				
Trash and debris	Annually	2 times per year	3 times per year	2	2	Utility truck, loader	–
Sand media maintenance	10 years	5 years	3 years	8	4	Utility truck, loader, dump truck	Disposal, replacement sand
Intermittent maintenance	Every 10 years	Every 5 years	Every 2 years	8	2	Utility truck, loader	–
Sediment management	50 years	20 years	10 years	8	4	Utility truck, loader with backhoe	Disposal
Inspection and reporting	Annually	Annually	Annually	1	2	Utility truck	–

of the aesthetic needs of the community. The hours associated with trash removal are included in vegetation management. Vegetation management is a relatively labor-intensive task, necessary to allow access to the retention pond and remove nutrients from the BMP. Depending on the volume of water received by the retention pond and, therefore, the nutrient load, vegetation removal is suggested to occur three times per year, semiannually, or annually. Sediment removal within the forebay is suggested to occur at 5, 10, or 15 years and is based on typical highway loading calculations for the three defined maintenance levels. Sediment removal within the main pool is suggested to occur at 20, 30, or 50 years. Intermittent maintenance includes findings from inspection of the structures, which is suggested to occur annually for all rainfall regions.

5.5.6 Sand Filter

Sand filter maintenance activities are presented in Table 5-21. Trash and debris removal frequency is suggested at three times per year, semiannually, or annually as a function of the aesthetic needs of the community. Sand media removal will be required every 3, 5, or 10 years. Sediment removal in the detention area will be required every 10, 20, or 50 years. Intermittent maintenance includes findings from inspection of the structures, which may include repair of erosion or removal of emergence of woody vegetation. Intermittent maintenance is suggested to occur every 2, 5, or 10 years.

5.5.7 Permeable Friction Course

Permeable friction course maintenance activities are presented in Table 5-22. Replacement or rehabilitation is suggested to occur every 10, 12, or 14 years. This frequency suggestion is based on reported literature values (Cooley et al., 2009) and was confirmed with calculations of sediment buildup within the pavement, which increases the drain time to greater than 200 seconds. Sediment buildup is dependent on the runoff volume received by the pavement within each rainfall region.

5.6 BMP Life Span

BMPs were assessed to establish a consistent approach for determining the life span of each BMP type. This information was used to compute the interval for reconstruction for use in developing the whole life cost for the device. The component that would fail first and thereby limit the life span of a BMP requiring a total facility rebuild was determined. Table 5-23 summarizes the life span of the limiting component of the BMP and the estimated BMP life span.

Table 5-22. Permeable friction course maintenance activities.

Maintenance Activity	Maintenance Frequency			Hours per Event	Crew Size	Equipment Needed	Materials and Incidentals
	Low	Medium	High				
Inspection and reporting	Every 4 years	Every 3 years	Every 2 years	2	6	Utility truck, traffic control	–
Replacement or rehabilitation of PFC	14 years	12 years	10 years	16	3	Grinder, dump truck, sweeper, paving machine, roller compacter, traffic control	Disposal, overlay

Table 5-23. BMP expected life span.

BMP Type	Life Span	Limiting Factor
Vegetated strips	8–60 years (depending on ecoregion)	Sediment accumulation
Vegetated swales	10–50 years (depending on ecoregion)	Sediment accumulation
Dry detention basin	80 years	Pipe material longevity
Bioretention	80 years	Pipe material longevity
Retention pond	80 years	Pipe material longevity
Sand filter	75 years	Concrete longevity
Permeable friction course	14 years	Sediment accumulation

5.6.1 Vegetated Strips

Sediment accumulation within the strip will need to be removed and the strip regraded to reestablish sheet flow every 8 to 60 years, based on solids loading to the BMP. This would essentially be a complete rebuild of a vegetated strip.

5.6.2 Vegetated Swale

The annual sediment load to a vegetated swale was estimated for each rainfall region. It is estimated that it would take 10, 20, or 50 years to fill the swale with sediment to the height of vegetation (4 in.), depending on annual loading, requiring regrading and replanting of the swale.

5.6.3 Dry Detention Basins

A complete rebuild of a dry detention basin, including inlets and outlets, would be dependent on the longevity of the outlet structure pipes (80 years), and at that time, the whole basin would also be regraded.

5.6.4 Bioretention

A complete rebuild of a bioretention facility, including inlets, outlets, and underdrains, would be dependent on the longevity of the subdrain pipes (estimated as 80 years).

5.6.5 Retention/Wet Pond

A complete rebuild of a wet pond, including inlets and outlets, would be dependent on the longevity of the pipes and liner (if present), which is 80 and 100+ years, respectively.

5.6.6 Sand Filters

For a concrete vault sand filter, a full structure failure will primarily depend on the longevity of concrete used to build this BMP, which is expected to be at least 75 years (AASHTO, 2010). A complete rebuild of an earthen sand filter, including inlets and outlets, would be dependent on the longevity of the subdrain pipes (estimated as 80 years).

5.6.7 Permeable Friction Course

A permeable friction course functions by enabling stormwater to drain through the porous asphalt layer to the conventional road surface below. Sediment accumulation will occur within the overlay, and it will have to be removed and rebuilt every 10 to 16 years, based on loading. Raveling and delamination are two of the most common failure mechanisms listed in literature (Cooley et al., 2009) that also affect service life. The average service life reported was about 10 years.

CHAPTER 6

Capital and Operation and Maintenance Costs

This chapter gives an overview of capital costs and reports the operation and maintenance costs based on the maintenance protocols established in Chapter 5. The costs are based on the suggested frequencies of basic BMP maintenance tasks for the user-specified rainfall region, classified into maintenance levels of low, medium, and high (see Section 5.4). Average personnel costs are used but can be replaced with user-specified values. Maintenance costs for each BMP type are consistent for a standard range of tributary areas. The standard-sized tributary areas for the BMPs are presented in Table 6-1. Some maintenance tasks have the same estimated hours regardless of BMP size (i.e., inspection); BMPs larger than the standard size will have higher maintenance costs, and a linear factor may be used to adjust the values after excluding travel cost.

For BMPs not listed in Table 6-1, capital and operation and maintenance cost data are best developed from prototype field studies or experience. It is difficult to extrapolate data for other BMP types unless the configuration and maintenance requirements are similar to those described here. The practitioner is left to make such comparisons and develop estimates of costs and long-term maintenance accordingly. Care should also be exercised in extrapolating performance data for BMPs, particularly if the unit processes are not similar.

6.1 Capital Costs

Capital costs were estimated for each of the BMPs. This was done by estimating the BMP's size and design based on the user-input information on project location, design storm, tributary drainage area, and percent impervious. The tool estimates quantities for a list of construction items relevant to each BMP. A unit cost for each construction item was applied; these unit costs are based on the estimates from RS Means data. The construction items and unit prices for each BMP are provided in Appendix E: Whole Life Cost Data. The capital cost data are for retrofit projects where the BMP is constructed along with other highway improvements. A premium cost factor, which must be determined locally, should be applied for retrofit-only projects. For new construction, the capital cost estimates may be used, but these are considered conservative.

6.2 Maintenance Costs by BMP

The activities and time requirements developed in Chapter 5 are used with average wage and equipment cost rates to determine average annual maintenance costs for the selected BMPs. A description of the wage costs, equipment costs, and material costs is included for each of the suggested maintenance activities. The practitioner may use this information to determine if the default costs used in the tool are acceptable for whole life cost estimation in his/her region; otherwise these values should be modified in the tool to reflect local rates.

6.2.1 General Inspection

All conventional BMPs should be inspected annually regardless of the maintenance level categorization; annual inspection is assumed in the whole life cost calculation in the tool. This inspection assesses the vegetation coverage, structures, and any incidence(s) of erosion. Inspections of strips and swales are scheduled for 1 hour each, including travel time. For dry detention basins, retention ponds, sand filters, and bioretention, inspections are expected to take 2 hours per site, including travel time. A crew size of two is used for safety when working in a highway environment. Vehicle cost is $30 per hour based on vehicle rental rates for a pickup truck. Therefore, general inspection cost for vegetated strips and swales is $130 per occurrence, and general inspection cost for dry detention basins, retention ponds, bioretention, and sand filters is $260 per occurrence.

6.2.2 Vegetated Strips and Swales

Vegetated strips and swales have a routine maintenance of vegetation management and trash/debris removal. This task

Table 6-1. BMP standard sizes.

BMP Type	Assumed Standard Size
Vegetated strips	Treats up to 1-acre tributary area
Vegetated swales	Treats up to 2-acre tributary area
Dry detention basin	Treats up to 10-acre tributary area
Bioretention	Treats up to 1-acre tributary area
Retention pond	Treats up to 5-acre tributary area
Sand filter	Treats up to 3-acre tributary area
Permeable friction course	N/A

requires 4 hours per event with a two-man crew. The machinery cost is estimated at $60 per hour for the rental rate of a pickup truck and mower. As discussed in Chapter 5, the levels of maintenance for this BMP are dependent on the annual rainfall. Vegetation management frequency for strips and swales ranges from three times a year to once a year. For vegetated strips and swales needing a high level of maintenance, the number of months between maintenance is four (or estimated frequency of three times per year). A medium level of maintenance is defined as vegetation and trash removal every 6 months (twice per year), and a low level of maintenance is defined as 12 months between vegetation and trash removal (annual maintenance).

Vegetated strips and swales also have intermittent maintenance tasks. These include repairing damage to inlet structures (e.g., level spreaders); regrading of erosion, rutting, or vehicle damage; and revegetation due to poor coverage. For a high level of maintenance, in areas with an excess of 35 in. of rain, this is expected to be every 2 years. A medium level of maintenance is expected to be every 5 years based on 1-in. sediment accumulation within the strip leading to rilling for areas with over 20 in. of rain per year. A low level of maintenance is expected to be every 10 years. This would be for areas with climates receiving less than 20 in. of rain per year.

Maintenance costs for vegetated strips and swales are summarized in Table 6-2.

6.2.3 Dry Detention Basins

Dry detention basins may need regular vegetation management (primarily for aesthetics) for unlined designs and trash and minor debris removal. This task requires 3 hours for a two-man crew to complete. Low-level maintenance is defined as including annual vegetation management. Medium-level maintenance is defined as twice-annual frequency, while high-level maintenance is defined as three times annually. The level of maintenance required for vegetation management and trash removal is dependent on aesthetic requirements indirectly related to annual rainfall depth. As with sand filters, the user may adjust the maintenance based on the requirements for visual appeal.

Dry detention basins require intermittent maintenance, which includes items found during routine inspection of inlet and outlet structures for damage, slope stability corrections, drain time maintenance, other structural damage, and erosion. This task requires 8 hours for a two-man crew to inspect and repair any damaged components. The frequency ranges from every 2 years for high-level maintenance to every 5 years for medium-level maintenance and every 10 years for low-level maintenance. The intermittent facility maintenance costs for dry detention basins are $60 per hour for machinery (pickup truck and mower) and $200 for materials/incidentals. These include costs for seed or an erosion control blanket if slope stability corrections are needed.

Sediment removal within the dry detention basins requires 8 hours for a four-man crew to complete. The frequency for low-level maintenance is every 50 years, is 30 years for medium-level maintenance, and is 20 years for high-level maintenance. Disposal costs are estimated as a function of the cubic yards of material, at a cost of $500/yd^3.

The excavation quantity in the spreadsheet tool is located on the capital cost tab and is calculated based on design footprint and depth or may be user input.

Maintenance costs for dry detention basins are summarized in Table 6-3.

Table 6-2. Vegetated strip and swale maintenance costs.

Maintenance Task	Maintenance Frequency			Cost
	High	Medium	Low	
General inspection, reporting, information management	Annually	Annually	Annually	$130/event
Vegetation management for aesthetics Vegetation repair Slope inspection Trash and debris	3 times per year	2 times per year	Once per year	$640/event
Intermittent/corrective maintenance	Every 2 years	Every 5 years	Every 10 years	$1,280/event

Table 6-3. Dry detention basin maintenance costs.

Maintenance Task	Maintenance Frequency			Cost
	High	Medium	Low	
General inspection, reporting, information management	Annually	Annually	Annually	$260/event
Vegetation management for aesthetics Trash and debris	3 times per year	2 times per year	Once per year	$480/event
Intermittent/corrective maintenance	Every 2 years	Every 5 years	Every 10 years	$1,480/event
Sediment removal	Every 20 years	Every 30 years	Every 50 years	$3,800/event

6.2.4 Bioretention

Bioretention maintenance includes routine management of vegetation and trash and debris removal. Vegetation management requires approximately 2 hours for a two-man crew to complete. Low-level maintenance is defined as annual vegetation management. Medium-level maintenance is defined as twice-annual frequency, while high-level maintenance is defined as three operations annually. The level of maintenance required for vegetation management and trash removal is generally dependent on aesthetic requirements and is not dependent on rainfall volume.

The mulch layer within a bioretention basin is used as a preliminary erosion stabilization treatment; therefore, this layer must be maintained annually in high-level maintenance and biannually in medium- and low-level maintenance. Maintenance of the mulch layer may include redistribution, replacement in bare areas, or complete replacement in rare instances. Mulch replacement takes 2 hours for a two-person crew to complete.

Corrective and infrequent maintenance activities for bioretention BMPs include repair of damage to structures or the underdrain system as well as repair of significant erosion. The frequency for low-level maintenance is every 12 years, for medium-level maintenance is 8 years, and for high-level maintenance is 4 years. The task takes 24 hours for a four-man crew to complete. The equipment cost for corrective maintenance of bioretention basins is $60 per hour for the utility truck and skip loader.

Maintenance costs for bioretention are summarized in Table 6-4.

6.2.5 Wet Pond or Retention Pond

Wet ponds/retention ponds need regular vegetation management as well as trash and minor debris removal. This task requires 20 hours for a four-man crew to complete. Low-level maintenance is defined as including annual vegetation management. Medium-level maintenance is defined as twice-annual frequency, while high-level maintenance is defined as three operations annually.

Wet ponds/retention ponds require intermittent maintenance, which includes routine inspection of inlet and outlet structures for damage, slope stability corrections, drain time maintenance, repair of other structural damage, and repair of erosion. This task requires 8 hours for a two-man crew to inspect and repair damaged components. The frequency for intermittent maintenance activities is annual. The intermittent

Table 6-4. Bioretention maintenance costs.

Maintenance Task	Maintenance Frequency			Cost
	High	Medium	Low	
General inspection, reporting, information management	Annually	Annually	Annually	$180/event
Vegetation management for aesthetics (optional) Vegetation repair Trash and debris Mulch layer management Soil repair	2 times per year	Annually	Every 3 years	$1,380/event
Intermittent maintenance	Every 4 years	Every 8 years	Every 12 years	$6,740/event

facility maintenance cost for wet ponds/retention ponds is $60 per hour for machinery (pickup truck and skip loader).

Sediment removal within the forebay of the wet ponds/retention ponds requires 8 hours for a four-man crew to complete. The frequency for low-level maintenance is every 15 years, it is 10 years for medium-level maintenance, and is 5 years for high-level maintenance. Disposal costs are estimated as a function of the cubic yards of material excavated, and a cost of $500/yd^3. The excavation quantity is located in the capital cost tab and is calculated based on design footprint and depth, or may be user input.

Sediment removal within the main pool of the wet ponds/retention ponds requires 8 hours for a four-man crew to complete. The frequency for low-level maintenance is every 50 years, it is 30 years for medium-level maintenance, and is 20 years for high-level maintenance.

Maintenance costs for retention ponds are summarized in Table 6-5.

6.2.6 Sand Filters

Sand filters may need regular vegetation management for earthen designs where side slopes are vegetated, as well as trash and minor debris removal. A two-man crew is required for this task. In medium- and high-level maintenance categories, 2 hours are required per event. For low-level maintenance, 3 hours are required. This is due to the reduced frequency of maintenance (i.e., annual maintenance) and the expectation of more trash removal and vegetation management being needed. Medium-level maintenance requires twice-annual frequency, while high-level maintenance requires three operations annually.

Removal of the top 1 or 2 in. of sand media is necessary after an event drain time exceeds 96 hours. When overall media depth drops to 12 in., replenishment of media is necessary, typically to a depth of 18 in., but is dependent on the original design. In regions with high rainfall amounts (greater than 35 in.), the sand media will need maintenance (i.e., removal of top 1 or 2 in.) every 3 years. In regions with medium rainfall (20 to 35 in.), the filter will require maintenance every 5 years, and in regions with low rainfall amounts (less than 20 in.), the filter will require maintenance every 10 years. This sand removal task requires 8 hours for a four-person crew to complete. The machinery cost for sand removal is $200 per hour, which includes the rental of 10-yard truck, utility truck, and backhoe. Material disposal cost is estimated at $500 per event.

Sand filters may require intermittent maintenance, which includes actions needed as noted from routine inspection of substructures for damage, and for structural damage and repair of erosion. This task requires 8 hours for a two-man crew to inspect and repair any damaged components. The frequency ranges from every 2 years for high-level maintenance, every 5 years for medium-level maintenance, and every 10 years for low-level maintenance. The intermittent facility maintenance cost for sand filters is $60 per hour for machinery (pickup truck and mower).

Sediment removal within the sedimentation chamber of the sand filter requires 8 hours for a four-man crew to complete. The frequency for low-level maintenance is every 50 years, is 20 years for medium-level maintenance, and is 10 years for high-level maintenance. Disposal costs are estimated as a function of the cubic yards of material excavated, an estimated 500 yd^3, and a disposal cost of $33/yd^3, $25/yd^3, or $10/yd^3. These costs are dependent on the proximity to a disposal site.

Maintenance costs for sand filters are summarized in Table 6-6.

6.2.7 Permeable Friction Course

PFC inspection requirements are more complex than the other BMPs. Routine inspections are performed every 2, 3, or 4 years, depending on maintenance level, and require permeability testing of the pavement. This requires a larger crew to

Table 6-5. Retention pond maintenance costs.

Maintenance Task	Maintenance Frequency			Cost
	High	Medium	Low	
General inspection, reporting, information management	Annually	Annually	Annually	$260/event
Vegetation management	3 times per year	2 times per year	Once per year	$5,200/event
Trash and debris				
Intermittent/corrective maintenance	Every 2 years	Every 5 years	Every 10 years	$1,280/event
Sediment removal (forebay)	Every 5 years	Every 10 years	Every 15 years	$12,600
Sediment removal (main pool)	Every 20 years	Every 30 years	Every 50 years	$75,600

Table 6-6. Sand filter maintenance costs.

Maintenance Task	Maintenance Frequency			Cost
	High	Medium	Low	
General inspection, reporting, information management	Annually	Annually	Annually	$260/event
Vegetation management for aesthetics Trash and debris	3 times per year	2 times per year	Once per year	$320/event
Sand removal	Every 3 years	Every 5 years	Every 10 years	$3,700/event
Intermittent/corrective maintenance	Every 2 years	Every 5 years	Every 10 years	$1,280/event
Sediment removal	Every 10 years	Every 20 years	Every 50 years	$3,800/event

Table 6-7. Permeable friction course maintenance costs.

Maintenance Task	Maintenance Frequency			Cost
	High	Medium	Low	
General inspection, reporting, information management	Biannually	Every 3 years	Every 4 years	$800/mile
Overlay replacement	Every 10 years	Every 12 years	Every 14 years	Varies

account for necessary traffic control. A six-man crew needs 2 hours to perform testing, with equipment costs of $100 per hour. Each general inspection cost for permeable friction course is $800 per occurrence.

Inspection of the PFC is suggested to occur biannually for high-level maintenance (i.e., regions with greater than 35 in. of rain). For medium-level maintenance (regions with 20 to 35 in. of rainfall), inspections are performed every 3 years, and for low-level maintenance (in a climate with less than 20 in. of rainfall), inspection is performed every 4 years. PFC replacement requires approximately 16 hours for a three-man crew to complete per segment mile. The machinery cost for replacing PFC is $150 per hour. A high rainfall region requires PFC replacement every 10 years. A medium rainfall region will require replacement every 12 years, and a low rainfall region will require replacement every 14 years (see Table 6-7).

CHAPTER 7

Whole Life Cost Model

This chapter presents the basis for the development of the whole life cost (WLC) models for the selected BMPs. The whole life models include the BMP capital cost, operation and maintenance cost, and expected life span to develop a whole life cost by rainfall region.

7.1 Whole Life Cost Tool

Whole life costing (also known as life-cycle cost analysis) involves identifying future costs and referring them back to present day costs using standard accounting techniques such as NPV. NPV is defined here as the value of a stream of benefits or costs when discounted back to the present time.

Whole life costing can be thought of as the sum of money that needs to be spent today to meet all future costs as they arise throughout the life cycle of a facility. The formula for calculating the net present value is:

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

where

NPV = net present value of O&M ($),
R_t = net O&M costs ($) at time t,
i = discount rate, and
N = number of years.

The proper discount rate for DOTs is the interest rate that the Federal Reserve Bank charges on loans to institutions that borrow money from it, and it is generally very close to the interest rate that one would receive on short-term deposits (http://www.fmsbonds.com/Market_Yields/index.asp; 4% rate based on data as of April 24, 2013). In these calculations, the underlying objective is to determine how much money would have to be deposited in an interest-bearing account to pay for all future capital and maintenance costs for a BMP installation. Consequently, NPV is very sensitive to the assumed interest and inflation rates and assumptions of future costs.

An important consideration is that maintenance costs vary over the life of the facility as labor and material costs rise. Consequently, the tool provides a cell for the user to input the rate at which these costs are expected to rise so that R_t can be estimated for each year.

An example of the calculation performed is provided in Table 7-1, which shows an initial capital cost and a series of escalating maintenance costs discounted back to their present value using a discount rate of 5%.

The benefits of developing an accurate whole life cost include:

- Improved understanding of long-term investment requirements in addition to capital costs,
- More cost-effective project choices for stormwater control selection,
- Explicit assessment and management of long-term financial risk when integrated with a planned maintenance program, and
- Better understanding of the future financial liabilities when considering acceptance of the responsibility for a system.

All expenditures incurred by the DOT, whether they are termed operational or capital, result from the requirement to manage surface water runoff. Adopting a long-term approach complements the fact that most drainage assets have a relatively long useful life, provided that appropriate management and maintenance are performed.

There are a series of stages in the life cycle of a drainage asset. A conceptual diagram of these stages is shown in Figure 7-1. These stages represent cost elements and can be defined as:

- Acquisition, which may include:
  - Feasibility studies,
  - Conceptual design,
  - Preliminary design, and
  - Detailed design and development;

Table 7-1. BMP routine maintenance tasks.

Year	Actual Cost (*Rt*)	Discounted Cost
0	100,000.00	100,000.00
1	5,000.00	4,761.90
2	5,200.00	4,716.55
3	5,400.00	4,664.72
4	5,600.00	4,607.13
NPV		**118,750.31**

- Construction (or purchase of a proprietary device);
- Use and maintenance; and
- Disposal/decommissioning.

Due to the existence of significant fixed initial costs such as travel and mobilization of staff and equipment, economies of scale can be realized as project size increases. To provide users with a better understanding of WLCs as they relate to BMP incorporation, a WLC tool with a standard framework was developed for each BMP. The following sections discuss the WLC methodology and tool.

7.2 WLC Tool Calculation Foundations

The BMP Evaluation Tool presents an estimate of average or likely costs for an assumed set of conditions and characteristics that can be reviewed and adjusted for site-specific applications. Costs can be highly variable and will depend, to a certain extent, on the size of the system being considered. The costs associated with BMPs incorporated for treatment of runoff will include both capital and maintenance costs. The methodology and issues in determining these costs are presented in the following sections.

7.2.1 Capital Costs

Capital costs for BMPs include construction costs and various associated costs. Construction costs vary widely, depending on site constraints and other factors. Most U.S. cost studies assess only part of the cost of constructing a stormwater management system, usually excluding permitting fees, engineering design, and contingency or unexpected costs. In general, these costs are expressed as a fraction of the construction costs (e.g., 30%). These costs are generally only estimates, based on the experience of designers.

The cost of land varies regionally and often depends on surrounding land use. DOTs may have surplus right-of-way (ROW) that can be used for a BMP. On the other hand, the cost of land, if surplus DOT ROW is not available, may far outweigh construction and design costs in dense urban settings. Permitting can also require a major effort, and a default value for cost is included in the BMP assessment tool as a percentage of the construction cost.

Actual capital costs for controls depend on a large number of factors. Many of these factors are site-specific and thus are difficult to estimate; there are also regional cost differences. Consequently, locally derived cost estimates are more useful than generic estimates made using national data. This report provides nationally derived values for planning purposes.

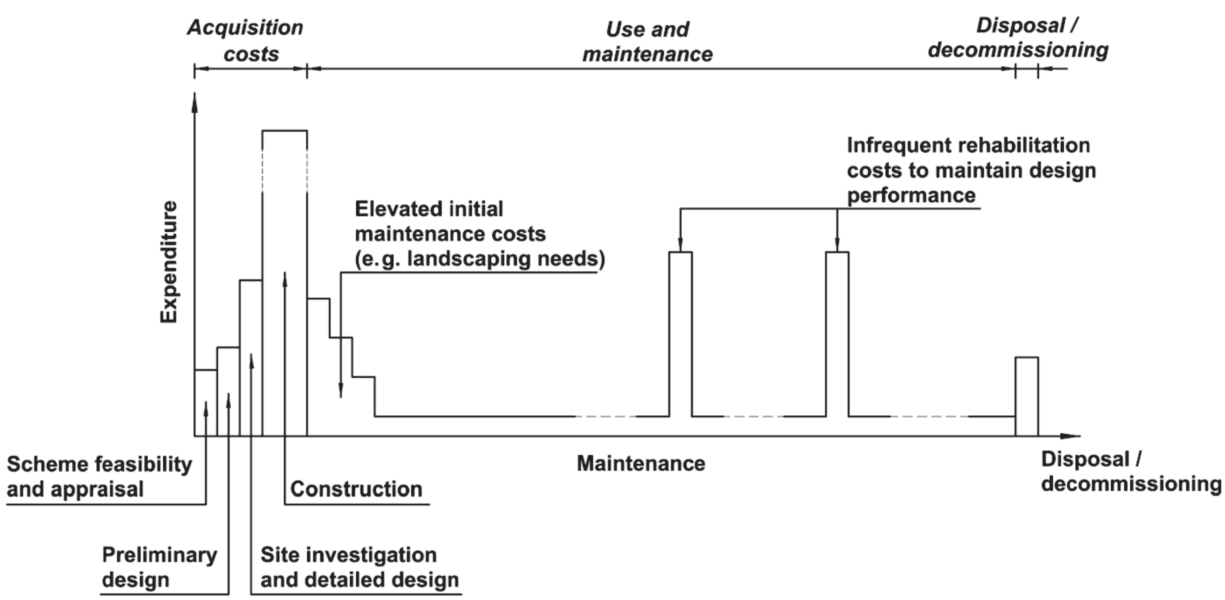


Figure 7-1. Life-cycle stages and associated costs (Lampe et al., 2005).

Following is a brief description of some major factors affecting costs:

1. *Project scale and unit costs.* Stormwater controls can be built at much lower costs as part of larger projects than as stand-alone projects.
2. *Retrofits versus new construction.* Retrofit of existing roadways with stormwater treatment controls may be required as a result of TMDLs or other factors. Retrofit in this context refers to installation of treatment controls when the roadway itself is not undergoing major improvements. Retrofit and new construction of treatment controls exhibit very different costs, with retrofit costs being much higher and uncertain.
3. *Regulatory requirements.* Each jurisdiction in the United States has varying requirements for treatment water quantity and quality.
4. *Flexibility in site selection, site suitability.* Stormwater control costs can vary considerably due to local conditions (i.e., the need for traffic control, shoring, and availability of work area, existing infrastructure, and site contamination).
5. *Level of experience of agency and contractors.* Some regions in the United States have required and constructed stormwater controls for over 20 years. In these areas, local contractors adapt to the market and learn the skills needed to build the controls.
6. *State of the economy at the time of construction.* Another consideration is the strength of the local economy when a control is bid and built. If work is plentiful, the work may be less desirable and the cost may rise due to less competition.
7. *Region.* Region may influence the design rainfall and rainfall-runoff characteristics of a site, which will in turn affect drainage system component sizing.
8. *Land allocation and costs.* The cost of land is extremely variable by location, both regionally and locally, and depending on surrounding land use.
9. *Soil type/groundwater vulnerability.* These will dictate whether infiltration is required to treat an initial volume of runoff on-site or whether additional storage and attenuation will be required.
10. *Planting.* The availability of suitable plants and required level of planting planned for a particular control component will have a significant influence on costs, as will irrigation and maintenance requirements.

Since unit costs for construction activities vary across the country and over time, the tool includes a procedure to modify the default values using information from RS Means. RS Means is a division of Reed Business Information that provides cost information to the construction industry so that contractors in the industry can provide accurate estimates and projections for their project costs. It has become a data standard for government work in terms of pricing and is widely used by the industry as a whole. RS Means data are integrated into a variety of cost-estimating software packages to allow for fast and reliable estimating. Cost information is updated annually and is available online, via CD-ROM, or in book form.

An important consideration when assessing cost is what would be constructed in lieu of the selected BMP. For instance, engineered swales are typically a much less expensive option for stormwater conveyance than the curb-and-gutter systems they replace, which leads to the conclusion that these water quality facilities are effectively free since some type of system is required for drainage purposes. Consequently, one should consider only the net cost attributable to the water quality component. It should be noted, however, that net costs could be difficult to generalize because the determination of what would be constructed in lieu of a practice can be very site-specific.

7.2.2 Maintenance Costs

Maintenance is a necessary activity required to preserve the intended water quality benefits and stormwater conveyance capacity of stormwater controls. However, there is often little planning regarding future maintenance activities and the financial and staff resources that will be needed to perform these activities. Maintenance costs, often assumed to be constant for a given type of BMP, can actually have a wide range depending on the pollutant loading rate as well as the aesthetic and safety needs of the maintenance crew and public living, driving, or working on/near them.

At many sites, vegetation management constitutes the majority of maintenance activities rather than tasks one might expect such as sediment, debris, and trash removal or structural repair. The frequency of mowing and other vegetation management activities may have little effect on stormwater control performance but result from the expected level of service by residents living near these facilities or by regulatory requirements. For example, tall vegetation can decrease the line of sight, and dry vegetation can become a fire hazard.

The frequency of maintenance has been found to depend on the surrounding land use, with more maintenance requests generated in urban areas. Consequently, the expected maintenance cost for a given type of facility can vary significantly depending on the expectations of the nearby community.

Two general maintenance categories have been established in the WLC tool: (1) routine and (2) intermittent. Routine maintenance consists of basic tasks performed on a frequent and predictable schedule. These include inspections, vegetation management, and litter and minor debris removal. In addition, three levels of routine maintenance can be identified, and these relate mainly to frequency of the activity being undertaken. These are defined as:

- Low/minimum: A basic level of maintenance required to maintain the function of the stormwater control.
- Medium: The normal level of maintenance to address function and appearance. Allows for additional activities, including preventative actions, at some facilities.
- High: Frequent maintenance activities performed as a result of high sediment loads, wet climate, and other factors such as safety and aesthetics.

Intermittent maintenance typically consists of corrective and infrequent maintenance activities. These are typically more resource-intensive and unpredictable tasks to keep systems in working order, such as repair of structural damage, sediment removal, and regrading eroded areas. In some cases, complete facility reconstruction may be required. The intermittent category can include a wide range of tasks that might be required to address maintenance issues at a BMP (invasive species removal, animal burrow removal, forebay cleanout, etc.).

The tool will calculate costs individually for routine BMP maintenance items, while corrective and infrequent items are calculated as a generalized cost since these maintenance activities are typically unplanned. For detention basins that will be used for dual-use stormwater and spill-control systems, additional costs for corrective and infrequent maintenance should be added to reflect the costs for pumping and cleanup efforts that would be incurred in the event that the basin was actually used to contain a hazardous spill. While it has not been attempted to identify possible corrective and infrequent (unplanned) maintenance activities for each BMP, routine (planned) maintenance activities have been identified in Table 7-2.

Table 7-2. BMP routine maintenance tasks.

BMP and Components	Routine Maintenance Tasks	
Swale	• Remove sediment accumulation in swale bottom	• Remove trash and debris
	• Check for standing water and repair	• Remove clogging if necessary
	• Restore vegetative cover where required	• Repair check dams
	• Mow to maintain ideal grass height	• Remove invasive and woody vegetation
	• Repair minor erosion/scour	• Till swale bottom
Dry detention basin	• Remove sediment accumulation in basin	• Remove trash and debris
	• Check for embankment erosion	• Check for animal burrows and repair
	• Remove invasive and woody vegetation	• Mow to maintain ideal grass height
	• Check for standing water and repair	• Check for settling of berm and repair
	• Check inlets/outlets for obstructions	• Restore vegetative cover where required
	• Stabilize banks and channels	• Check for erosion on spillway and repair rip rap
	• Ensure low flow channel is clear of obstructions	
Bioretention	• Remove sediment accumulation in basin	• Remove trash and debris
	• Fertilize and maintain basin vegetation	• Repair minor erosion/scour
	• Check for standing water and repair	• Check inlets/outlets for obstructions
	• Add mulch if necessary	• Remove invasive and woody vegetation
Sand filter	• Remove sediment buildup in filter bed	• Remove trash and debris
	• Check for leaks and noticeable odors	• Inspect condition of structural components
	• Remove invasive and woody vegetation	• Check for standing water and repair
	• Check inlets/outlets for obstructions	
Drain inlet	• Remove trash and debris	• Remove sediment
	• Visual inspection of damage and repair	
Open-graded friction course overlay (PFC)	• High pressure air/water or vehicles to unclog pores or mill and replace	• Check for permeability of the overlay course

(continued)

Table 7-2. (Continued).

BMP and Components	Routine Maintenance Tasks	
Vegetative filter strip	• Remove sediment accumulation if water accumulates on pavement • Restore vegetative cover where required • Mow to maintain ideal grass height	• Remove trash and debris • Remove invasive and woody vegetation • Repair minor erosion/scour
Pipes	• Check for obstructions/sediment and flush	• Check for leaks and repair
	• Check fittings and connections and repair	• Check for pipe settling and repair
Berms and baffles	• Check for damage or misplacement	• Replace (baffles) or repair (berms) when required
Skimmers and booms	• Check for damage or misplacement	• Replace or repair skimmer when required
	• Replace absorbent boom when capacity is reached	
Valve controls	• Remove sediment	• Remove trash and debris
	• Inspect all components	• Lubricate as required
	• Check for leaks	• Test operation
Liners	• Visual inspection for holes and other irregularities	• Inspect backfill for settling
	• Check for potential animal/vegetation damage	• Check anchors and seams if applicable
Real-time controls	• Remove sediment/debris from sensors or valve	• Remove trash and debris
	• Replace small parts	• Repair valves/other equipment
	• Inspect all components	• Web/monitoring services
	• Troubleshooting	
Wet ponds	• Remove sediment accumulation in basin • Check for embankment erosion • Remove invasive and woody vegetation • Check inlets/outlets for obstructions • Stabilize banks and channels • Ensure low flow channel is clear of obstructions	• Remove trash and debris • Check for animal burrows and repair • Mow to maintain ideal grass height • Check for settling of berm and repair • Restore vegetative cover where required • Check for erosion on spillway and repair rip rap

New Versus Retrofit Costs

In a report prepared by the URS Corporation (2012) for the NCDOT entitled *Stormwater Runoff from Bridges: Final Report to Joint Legislation Transportation Oversight Committee*, URS evaluates the adjustment required when estimating costs for stormwater retrofit projects for bridges compared to new construction of the same design. To provide a comparison, URS evaluated 16 NCDOT retrofit projects and determined the percent increase in cost compared to an identical new construction project.

The retrofit-specific costs were project costs that would have likely been absorbed by a new construction project, including mobilization, surveying, and traffic control. These retrofit-specific costs were deducted from the total retrofit cost to develop an estimated new construction cost. From these 16 retrofit projects (construction costs ranged between $7,336 and $246,780), the increase of cost due to retrofits was found to be 17% on average, with a range of between 8% and 33% (URS Corporation, 2012).

The same methodology used in the 2012 URS report to determine the percentage increase due to retrofit was applied to the Center Street and Marion Street bridge stormwater retrofit project that began construction in 2013 in Salem, OR. This project's total estimated construction cost was $802,206, and the stormwater retrofit-specific costs were estimated to be $102,040, resulting in a 13% increase from the estimated new construction cost due to the project being built as a retrofit. This lower percent difference from the average found in the URS report is likely due to the fact that this is a much larger retrofit project compared to the 16 projects evaluated for the URS report, with corresponding lower unit prices.

In general, retrofits have higher costs associated with them because retrofit projects are usually smaller, and unit prices are typically higher for smaller material quantities. Additionally, design costs for retrofits were estimated at 150% of new construction costs primarily because retrofits are designed as separate, individual projects including their own site visits, surveying, utility relocations, and bidding processes. Retrofits can also have unforeseen costs such as difficult site drainage or other difficulties that may not be encountered with a new construction project (URS Corporation, 2012).

From evaluation of the URS report and application of the report methodology to a recent bridge stormwater retrofit project, it appears that 10% to 30% of the new construction cost is a reasonable range to represent the additional costs attributed specifically to stormwater retrofit projects.

7.2.3 WLC Tool Calculator Guide

The WLC computations are included in a series of Excel spreadsheets for a variety of stormwater treatment practices that are integrated into the BMP Evaluation Tool. The development of the original WLC spreadsheets was initially supported by WERF and described by Lampe et al. (2005) and Pomeroy (2009). The spreadsheets have been revised for this project by including DOT-specific values for many of the required fields.

The WLC spreadsheets provide a framework for the calculation of capital and long-term maintenance costs associated with individual BMPs based on national averages. Local data can be used to adjust the estimates by the user. Multi-system and regional solutions will generally be built up from a number of different components, from source control to site and regional control facilities. Several spreadsheets may then be required, and costs will be built up by adding together outputs. Care should be taken to include all—but not duplicate any—relevant costs between individual BMP spreadsheets. Costs for improvements that would have otherwise been required for an operational facility had the BMP not been built should also be computed and subtracted as appropriate from the final BMP WLC.

Costs are calculated using unit prices developed from DOT bid tabulations that reflect average values of costs and that were normalized to an RS Means value of 100. This option is a first cut for cost analysis, and it should be used cautiously and as a starting point. Users are encouraged to substitute local values, where known, so that the estimates more accurately reflect actual site conditions.

Basic cost dynamics are made apparent by this application, such as the relative importance of capital costs versus maintenance costs for different BMPs. In addition, the tool provides estimates of the annual outlay, so agencies responsible for maintenance will be able to estimate future resource needs and maintain these facilities in proper working order.

For practitioners that are using the tool to compare BMPs, many of the potential problematic assumptions or errors will be canceled. Consequently, the best use of the cost tool is to compare the WLC of various options rather than to compute explicit costs and values for capital or O&M budget purposes. Using this approach, various practices can easily be compared to determine the most cost-effective option for improving stormwater runoff quality.

Each spreadsheet tool includes several sheets for the user to input information on the design, capital costs, and maintenance costs. The contents of the sheets are discussed in Table 7-3.

7.2.4 WLC Tool Inputs

The BMP Evaluation Tool user will likely want to start with a basic, default scenario and then build in user-entered, site-specific information as available. Again, given the significant differences in system design requirements and regional cost variables (e.g., labor costs, frequency of maintenance due to variation in climate), it is difficult to generalize for the entire United States using default values. When parametric equations are used to drive capital cost estimates, the regions of the original cost data are listed in each tool's respective design and cost information sheet.

The user can also enter custom values for virtually every component tracked by the spreadsheet: system design and sizing, capital costs, and maintenance costs. This option best reflects costs for a given geographical area and site conditions. The user can employ a combination of default and user-entered values as desired.

Site-specific costs and characteristics should be entered into the spreadsheet when available. As an example, all references to RS Means costs assume the RS Means 100 cost. RS Means 100 is a representation of cost based on the historical national average of construction costs that can be adjusted to a specific location and time by multiplying the RS Means 100 cost by location and time factors. A first step in improving the accuracy of a user-created cost estimate would be for the user to multiply these unit costs by the appropriate location factor, adjust to the current year using a similar factor, then enter the product in the User Entered column. At a minimum, the assumptions and cost components should be reviewed for appropriateness prior to model application.

Example 7-1 provides a sample worksheet for bioretention systems. Cells with yellow shading provide fields for the model user to input site-specific information for the various model parameters. In the tool, the parameters are imported automatically from the BMP performance spreadsheets. The level of maintenance is a function of sediment load and climatic conditions for the site of interest.

Table 7-3. Data-entry requirements of each spreadsheet section.

Sheet Title	Spreadsheet Description
Project Options	Requires inputs needed for the parametric cost estimations and WLC calculations. For example, the BMP Evaluation Tool required input includes: • Local RS Means scaling factor to adjust for regional cost differences, • Expected level of maintenance (high, medium, low), • Design life (years), • Discount rate (used in the WLC computation), • Inflation rate for labor and materials, • Sales tax, and • User option to display capital and maintenance cost inputs, which are hidden by default. All of these inputs are essential user-entry. Model default values are available for all cells but should be overridden with site-specific data wherever possible.
Capital Costs	Display this sheet by selecting "yes" in the "Would you like to view/edit capital cost inputs?" section on the Project Options tab. It calculates the facility base costs and associated capital costs (e.g., engineering, land) based on the design parameters provided on the Project Design tab. Default values are provided for unit costs; however, the user can also enter specific unit costs and quantities.
Maintenance Costs	Display this sheet by selecting "yes" in the "Would you like to view/edit maintenance cost inputs?" on the Project Options tab. Calculates the ongoing costs associated with the operation of the system. The following costs are included: • Routine, scheduled maintenance • Corrective maintenance (e.g., periodic repair) • Infrequent maintenance (e.g., sediment removal) Users can adjust existing categories and create new ones.
Whole Life Costs	This sheet is hidden by default, but the user can open it by right clicking on any tab and selecting "unhide." The sheet presents a time series of the costs for the system and computes the present value of these costs. These annual costs can be useful for budgeting for future maintenance requirements.
Whole Life Cost Summary	This sheet summarizes the maintenance and capital cost inputs and provides the present value of cost over time as a graph, along with cumulative discounted cost and discounted cost over time.

Example 7-2 presents the worksheet used to estimate capital costs for the facility. The default baseline unit costs were developed by examining DOT bid tabulations and adjusting to an RS Means value of 100. The adjusted unit cost is the default baseline adjusted for the RS Means value at the project location. The quantities of each element are calculated automatically based on the size and design of the facility specified in the BMP performance worksheets. Associated capital costs are calculated as a fraction of the construction cost.

The worksheet in Example 7-3 allows the user to adjust default maintenance parameters, such as task frequency, crew size, hourly rate, and other factors. The lower portion of the worksheet is a lookup table (currently hidden in rows 58 to 69) that provides the default values that depend on the expected level of maintenance.

Whole Life Cost Tool Outputs

The WLC model summarizes the expected annual costs on the whole life cost worksheet (hidden by default), as shown in Example 7-4. This sheet allows the user to budget future expenditures. Cumulative costs are tabulated up to a 50-year life. If a user selects a BMP life span of less than 50 years, the appropriate present value is retrieved from the table and reported in the results summary report.

The whole life cost summary sheet provides the capital costs and the cost per year for maintenance activities, as shown in Example 7-5. It also provides graphs depicting the net present value of time-related expenditures in terms of annual and cumulative WLC discounted, as shown in Figures 7-2 and 7-3, respectively. The WLCs for a variety of BMPs can then be calculated and compared to determine the lowest-cost alternative for a given scenario.

Example 7-1. Project options worksheet.

NCHRP Bioretention Evaluation Tool

Project Title	Test Run
Project Location	Portland, OR
Company	Geosyntec Consultants

PROJECT LOCATION AND CLIMATE SELECTION | PROJECT OPTIONS | TRIBUTARY AREA ATTRIBUTES | BMP PARAMETERS | RESULTS SUMMARY REPORT | SUPPORTING DATA | WHOLE LIFE CYCLE COSTS SUMMARY

Project Options

Key

User Steps	Default Data (editable)
Headings and Descriptions	Guidance
User Entered Data	

Step 1: View/Edit Highway Runoff Concentrations

Pollutant Loads

Would you like to view/edit the highway runoff concentrations for the project?	no

Step 2: Select Primary Cost Inputs

Cost Inputs	Value	Guidance	
Location Adjustment Factor (100 = nationwide average)	100	Enter the location scaling factor from RSMeans or other reference to adjust for local costs as a percentage of nationwide	http://www.rsmeansonline.com/
Expected Level of Maintenance (H = High, M =	M	Enter the level of maintenance expected to be	
Design Life (years)	20	Enter the design life of the BMP in years.	
Discount Rate (%)	5	Enter the discount rate to be used in whole lifecycle cost analysis.	
Inflation Rate for labor and materials (%)	5	Enter the inflation rate to be used in whole lifecycle cost analysis.	
Local Sales Tax (%)	9.25	Enter the local sales tax, including state and	
Would you like to view/edit the capital cost inputs?	no	Selecting Yes will expose the Capital Cost input tab for optional user override of default	
Would you like to view/edit the maintenance cost inputs?	no	Selecting Yes will expose the Maintenance Cost input tab for optional user override of	

Read Me | Project Location | Project Options | Project Design | Results Summary Report | Supporting Data | Whole Life Costs Summary

Example 7-2. Example capital cost worksheet.

User-Entered Engineer's Estimate Costs	Unit	Default Baseline	User-Entered Baseline Unit	Baseline Unit Cost used in	Adjusted Unit Cost	Default Quantity	User-Entered	Quantity used in Calculations	Cost	Guidance
Mobilization	LS	$1,171		$1,171	$1,171	1		1	$1,171	
Clearing & Grubbing	SY	$1		$1	$1	115		115	$110	
Planting Media	CY	$43		$43	$43	50		50	$2,135	
Pea Gravel	CY	$129		$129	$129	6		6	$800	
Gravel	CY	$27		$27	$27	25		25	$670	
Mulch	CY	$71		$71	$71	6		6	$443	
Slotted PVC Underdrain Pipe	LF	$8		$8	$8	37		37	$286	
Excavation/Grading	BCY	$9		$9	$9	163		163	$1,540	
Haul/Dispose of Excavated Material	CY	$10		$10	$10	163		163	$1,679	
Finish Grading (SY):	SY	$2		$2	$2	115		115	$228	
Bioretention Vegetation (SF)	SF	$2		$2	$2	74		74	$169	
Hydroseed (SF):	SF	$0		$0	$0	3		3	$0	Enter project-specific values in the blue "User Entered Data" cells if applicable and the calculations will automatically update to override the default value. If a value is not provided, the default value will be used in the cost calculations
18" Square Trench (LF)	LF	$1		$1	$1	37		37	$29	
Dewatering	DAY	$1,200		$1,200	$1,200	0		0	$0	
Inflow Structure(s)	LS	$2,200		$2,200	$2,200	1		1	$2,200	
Overflow Structure (concrete or rock riprap)	CY	$125		$125	$125	7		7	$926	
Metal Beam Guard Rail	LF	$58		$58	$58	9		9	$496	
Conveyance	LF			$0	$0			0	$0	
Other				$0	$0			0	$0	
Other				$0	$0			0	$0	
Other				$0	$0			0	$0	
Other				$0	$0			0	$0	
Other				$0	$0			0	$0	
Total Facility Base Cost									$12,882	

(continued on next page)

Example 7-2. (Continued).

Associated Capital Costs	Default Baseline	User-Entered	Baseline Unit Cost used in	Default Quantity	User-Entered Quantity	Quantity used in	Cost	Guidance
Project Management	$644		$644	1		1	$644	Enter project-specific values in the blue "User Entered Data" cells if applicable and the calculations will automatically update to override the default value. If a value is not provided, the default value will be used in the cost calculations.
Engineering: Preliminary	$1,288		$1,288	1		1	$1,288	
Engineering: Final Design	$644		$644	1		1	$644	
Topographic Survey	$322		$322	1		1	$322	
Geotechnical			$0	1		1	$0	
Landscape Design	$258		$258	1		1	$258	
Land Acquisition (site, easements, etc.)			$0			0	$0	
Utility Relocation			$0	1		1	$0	
Legal Services	$129		$129	1		1	$129	
Permitting & Construction Inspection	$129		$129	1		1	$129	
Sales Tax	$1,192		$1,192	1		1	$1,192	
Contingency (e.g., 20%)	$2,576		$2,576	1		1	$2,576	
						Total Associated Capital Costs	$7,181	
						Total Facility Cost	$20,063	

Example 7-3. Example maintenance worksheet.

ROUTINE MAINTENANCE ACTIVITIES (Frequent, scheduled events)

Cost Item	Frequency (months betw. maint. events)			Hours per Event			Average Labor Crew Size			Avg. (Pro-Rated) Labor Rate/Hr. ($)			Machinery Cost/Hour ($)			Materials & Inciden-tals Cost/Event ($)			Total cost per visit ($)		
	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Default Total	User	Total with User Overrides where entered
Inspection, Reporting & Information Management	12		12	2		2	2		2	50		50	40		40	0		0	280		280
Vegetation Management with Trash & Minor Debris Removal	12		12	8		8	2		2	50		50	60		60	100		100	1,380		1,380
add additional activities if necessary	0		0	0		0	0		0	0		0	0		0	0		0	0		0
add additional activities if necessary	0		0	0		0	0		0	0		0	0		0	0		0	0		0

CORRECTIVE AND INFREQUENT MAINTENANCE ACTIVITIES (Unplanned and/or > 3 yrs. betw. events)

Cost Item	Frequency (months betw. maint. events)			Hours per Event			Average Labor Crew Size			Avg. (Pro-Rated) Labor Rate/Hr. ($)			Machinery Cost/Hour ($)			Materials & Inciden-tals Cost/Event ($)			Total cost per visit ($)		
	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Model	User	Input	Default Total	User	Total with User Overrides where entered
Corrective Maintenance	96		96	24		24	4		4	50		50	60		60	500		500	6,740		6,740
Sediment Management	300		300	8		8	4		4	50		50	60		60	500		500	2,580		2,580
add additional activities if necessary	0		0	0		0	0		0	0		0	0		0	0		0	0		0

Guidance

Note: For facilities judged to require larger or smaller amounts of maintenance (due to land area, etc.), consider multiplying the Model output in Column U by a multiplier (e.g., 120%) in Column V.
Another quick means of adjustment would be to multiply the number of Hours per Event by a multiplier in the User Input field.

HIGH, MEDIUM, AND LOW (MINIMUM) MAINTENANCE COST TABLES

Cost Item	Frequency (months betw. maint. events)			Hours per Event			Average Labor Crew Size			Avg. (Pro-Rated) Labor Rate/Hr. ($)			Machinery Cost/Hour ($)			Materials & Incidentals Cost/Event ($)			Total cost per visit ($)		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
ROUTINE MAINTENANCE ACTIVITIES (Frequent, scheduled)																					
Inspection, Reporting & Information Management	12	12	12	2	2	2	2.0	2.0	2.0	50.00	50.00	50.00	40	40	40	0	0	0	**280**	**280**	**280**
Vegetation Management with Trash & Minor Debris Removal	36	12	6	8	8	8	2.0	2.0	2.0	50.00	50.00	50.00	60	60	60	100	100	100	**1,380**	**1,380**	**1,380**
add additional activities if necessary																					
add additional activities if necessary																					
CORRECTIVE AND INFREQUENT MAINTENANCE ACTIVITIES (Unplanned and/or > 3 yrs. betw. events)																					
Corrective Maintenance	144	96	48	24	24	24	4.0	4.0	4.0	50.00	50.00	50.00	60	60	60	500	500	500	**6,740**	**6,740**	**6,740**
Sediment Management	600	300	120	8	8	8	4.0	4.0	4.0	50.00	50.00	50.00	60	60	60	500	500	500	**2,580**	**2,580**	**2,580**
add additional activities if necessary																					

Example 7-4. Example whole life cost.

Whole Life Costs

Year	Discount Factor	Cost Escalation	Capital & Assoc. Costs	Regular Maint. Costs	Base Corrective Maint.	Escalated Maint. Cost	Total Costs	Present Value of Costs	Cumulative Costs	
									Cash	Present Value
Cash Sum ($)							**571864.78**	**170119.50**		
0.00	1.00		**20063.04**				20063.04	20063.04	20063.04	20063.04
1.00	0.95	1.03	0.00	**3120.00**	0.00	3213.60	3213.60	3060.57	23276.64	23123.62
2.00	0.91	1.06	0.00	3120.00	0.00	3310.01	3310.01	3002.27	26586.65	26125.89
3.00	0.86	1.09	0.00	3120.00	0.00	3409.31	3409.31	2945.09	29995.96	29070.98
4.00	0.82	1.13	0.00	3120.00	6740.00	11097.52	11097.52	9129.95	41093.48	38200.93
5.00	0.78	1.16	0.00	3120.00	0.00	3616.94	3616.94	2833.96	44710.41	41034.90
6.00	0.75	1.19	0.00	3120.00	0.00	3725.44	3725.44	2779.98	48435.86	43814.88
7.00	0.71	1.23	0.00	3120.00	0.00	3837.21	3837.21	2727.03	52273.06	46541.91
8.00	0.68	1.27	0.00	3120.00	6740.00	12490.35	12490.35	8453.96	64763.42	54995.87
9.00	0.64	1.30	0.00	3120.00	0.00	4070.89	4070.89	2624.13	68834.31	57620.01
10.00	0.61	1.34	0.00	3120.00	0.00	4193.02	4193.02	2574.15	73027.33	60194.16
11.00	0.58	1.38	0.00	3120.00	0.00	4318.81	4318.81	2525.12	77346.14	62719.28
12.00	0.56	1.43	0.00	3120.00	6740.00	14058.00	14058.00	7828.02	91404.14	70547.30
13.00	0.53	1.47	0.00	3120.00	0.00	4581.83	4581.83	2429.84	95985.96	72977.14
14.00	0.51	1.51	0.00	3120.00	0.00	4719.28	4719.28	2383.56	100705.24	75360.69
15.00	0.48	1.56	0.00	3120.00	0.00	4860.86	4860.86	2338.16	105566.10	77698.85
16.00	0.46	1.60	0.00	3120.00	6740.00	15822.41	15822.41	7248.43	121388.51	84947.28
17.00	0.44	1.65	0.00	3120.00	0.00	5156.88	5156.88	2249.93	126545.39	87197.21
18.00	0.42	1.70	0.00	3120.00	0.00	5311.59	5311.59	2207.08	131856.98	89404.28
19.00	0.40	1.75	0.00	3120.00	0.00	5470.94	5470.94	2165.04	137327.92	91569.32
20.00	0.38	1.81	0.00	3120.00	6740.00	17808.26	17808.26	6711.74	155136.18	98281.07
21.00	0.36	1.86	0.00	3120.00	0.00	5804.12	5804.12	2083.34	160940.30	100364.41
22.00	0.34	1.92	0.00	3120.00	0.00	5978.24	5978.24	2043.66	166918.54	102408.07
23.00	0.33	1.97	0.00	3120.00	0.00	6157.59	6157.59	2004.73	173076.13	104412.81
24.00	0.31	2.03	0.00	3120.00	6740.00	20043.35	20043.35	6214.80	193119.48	110627.61
25.00	0.30	2.09	0.00	3120.00	0.00	6532.59	6532.59	1929.09	199652.07	112556.70
26.00	0.28	2.16	0.00	3120.00	0.00	6728.56	6728.56	1892.35	206380.63	114449.04
27.00	0.27	2.22	0.00	3120.00	0.00	6930.42	6930.42	1856.30	213311.05	116305.34
28.00	0.26	2.29	0.00	3120.00	6740.00	22558.97	22558.97	5754.65	235870.02	122059.99
29.00	0.24	2.36	0.00	3120.00	0.00	7352.48	7352.48	1786.26	243222.51	123846.25
30.00	0.23	2.43	0.00	3120.00	0.00	7573.06	7573.06	1752.24	250795.56	125598.49
31.00	0.22	2.50	0.00	3120.00	0.00	7800.25	7800.25	1718.86	258595.82	127317.35
32.00	0.21	2.58	0.00	3120.00	6740.00	25390.32	25390.32	5328.57	283986.13	132645.91
33.00	0.20	2.65	0.00	3120.00	0.00	8275.29	8275.29	1654.00	292261.42	134299.92
34.00	0.19	2.73	0.00	3120.00	0.00	8523.54	8523.54	1622.50	300784.96	135922.41
35.00	0.18	2.81	0.00	3120.00	0.00	8779.25	8779.25	1591.59	309564.21	137514.01
36.00	0.17	2.90	0.00	3120.00	6740.00	28577.02	28577.02	4934.04	338141.24	142448.04
37.00	0.16	2.99	0.00	3120.00	0.00	9313.91	9313.91	1531.54	347455.14	143979.58
38.00	0.16	3.07	0.00	3120.00	0.00	9593.32	9593.32	1502.37	357048.47	145481.95
39.00	0.15	3.17	0.00	3120.00	0.00	9881.12	9881.12	1473.75	366929.59	146955.70
40.00	0.14	3.26	0.00	3120.00	6740.00	32163.69	32163.69	4568.71	399093.29	151524.41
41.00	0.14	3.36	0.00	3120.00	0.00	10482.88	10482.88	1418.14	409576.17	152942.55
42.00	0.13	3.46	0.00	3120.00	0.00	10797.37	10797.37	1391.13	420373.54	154333.68
43.00	0.12	3.56	0.00	3120.00	0.00	11121.29	11121.29	1364.63	431494.83	155698.31
44.00	0.12	3.67	0.00	3120.00	6740.00	36200.52	36200.52	4230.44	467695.35	159928.75
45.00	0.11	3.78	0.00	3120.00	0.00	11798.58	11798.58	1313.14	479493.93	161241.89
46.00	0.11	3.90	0.00	3120.00	0.00	12152.54	12152.54	1288.13	491646.47	162530.02
47.00	0.10	4.01	0.00	3120.00	0.00	12517.11	12517.11	1263.59	504163.58	163793.62
48.00	0.10	4.13	0.00	3120.00	6740.00	40744.00	40744.00	3917.21	544907.58	167710.83
49.00	0.09	4.26	0.00	3120.00	0.00	13279.40	13279.40	1215.91	558186.99	168926.74
50.00	0.09	4.38	1.00	3120.00	0.00	13677.79	13677.79	1192.75	571864.78	170119.50

Example 7-5. Example whole life cost summary.

Whole Life Cycle Costs Summary

CAPITAL COSTS	Total Cost
Total Facility Base Cost	$12,882
Total Associated Capital Costs (e.g., Engineering, Land, etc.)	$7,181
Capital Costs	$20,063

REGULAR MAINTENANCE ACTIVITIES	Years between Events	Total Cost per Visit	Total Cost per Year
Inspection, Reporting & Information Management	0.5	$180	$360
Vegetation Management with Trash & Minor Debris Removal	0.5	$1,380	$2,760
add additional activities if necessary	0	$0	$0
add additional activities if necessary	0	$0	$0
Totals, Regular Maintenance Activities			$3,120

CORRECTIVE AND INFREQUENT MAINTENANCE ACTIVITIES (Unplanned and/or >3yrs. betw. events)	Years between Events	Total Cost per Visit	Total Cost per Year
Corrective Maintenance	4	$6,740	$1,685
add additional activities if necessary	0	$0	$0
add additional activities if necessary	0	$0	$0
Totals, Corrective & Infrequent Maintenance Activities			$1,685

Capital Costing Method	Line Item Engineer's Estimate
Assumed Level of Maintenance	H
Estimated Capital Cost, $ (2013)	$20,063
Estimated NPV of Design Life Maintenance Costs, $ (2013)	$92,494
Estimated NPV of Design Life Whole Life Cycle Cost, $ (2013)	$112,557
Estimated Annualized Whole Life Cycle Cost, $/yr (2013)	$4,502

Totals are based on design life with routine and major maintenance.

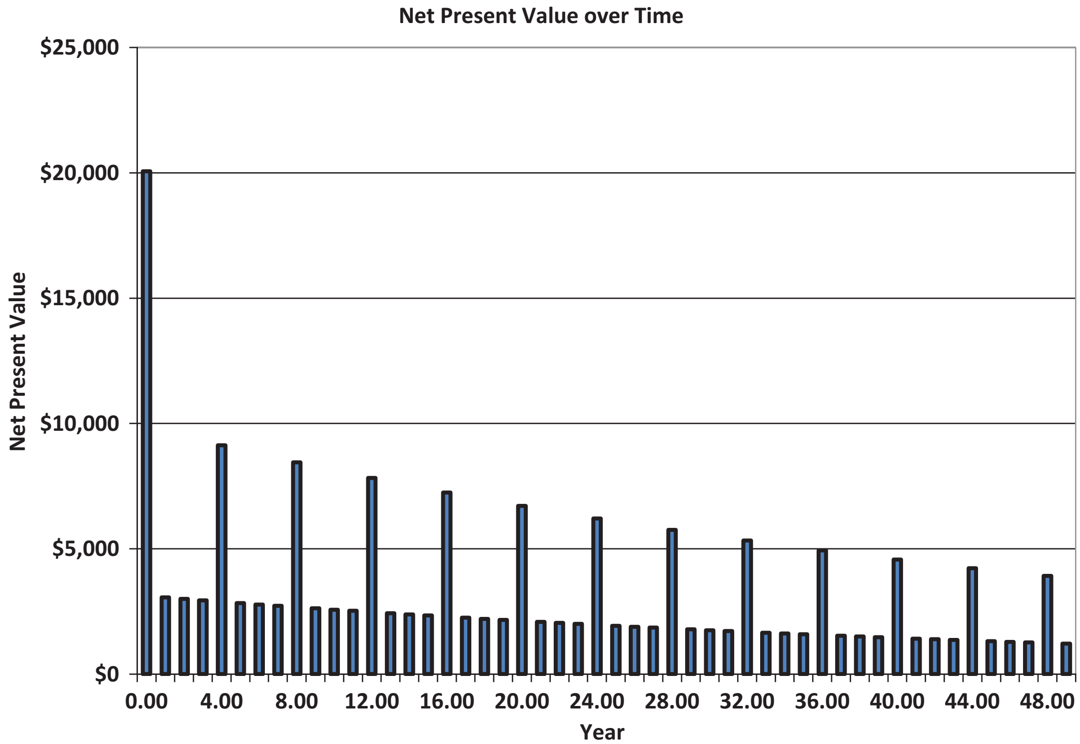


Figure 7-2. Example net present value of costs graph.

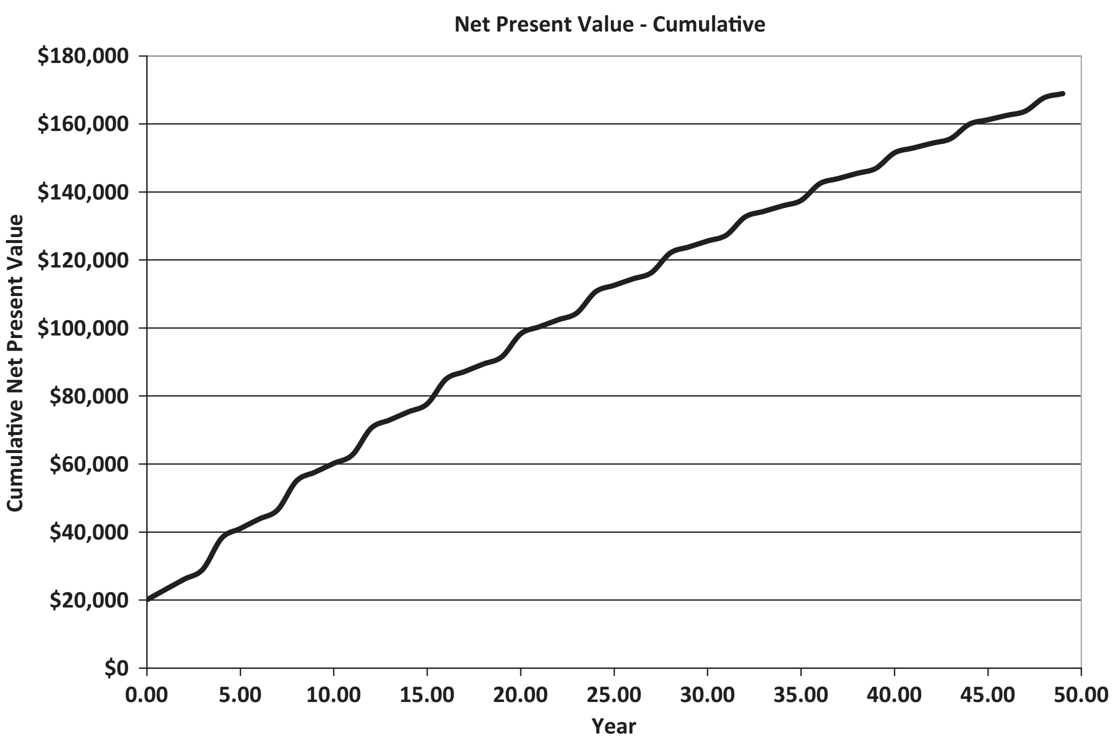


Figure 7-3. Example cumulative discounted costs graph.

CHAPTER 8

Performance of Nonstructural BMPs

8.1 Introduction

Nonstructural and source control BMPs (nonstructural BMPs) play a significant role in compliance with a DOT's municipal stormwater permit (NPDES MS4), TMDLs, and other water quality regulations. Nonstructural BMPs are typically based on pollution avoidance rather than pollutant removal, making analysis of benefits distinct from structural control measures. The authors have focused the definition of nonstructural BMPs for a DOT stormwater program for this study on operational rather than site design approaches. In the site-design context, nonstructural BMPs are commonly defined as the use of natural area conservation and buffer areas, disconnection of impervious surfaces, limited clearing of native vegetation, and minimized use of impervious surfaces. Highway standards limit the extent to which these design practices can be implemented in projects. Because the Interstate highway system is largely completed, this study focuses on operational nonstructural BMPs, reflecting the primary DOT need to manage existing infrastructure.

This chapter presents the basis for optimizing the selection nonstructural BMPs and identifies the program variables that DOTs can manage to improve their effectiveness and reduce whole life costs. This chapter also looks at the often-overlooked aspect of social and institutional challenges associated with implementing nonstructural BMPs that go beyond traditional cost–benefit analysis. Through collective consideration of whole life cost, BMP efficiency, and social/institutional barriers, the practitioner can gain insight into the overall sustainability for each of the most common nonstructural BMPs used by DOTs. A triple bottom line (TBL) analysis can be used by the practitioner to prioritize control measures based on available funding, potential social impacts, and performance. A TBL analysis assesses the factors of implementation, environmental benefit, and cost. It was originally defined with three dimensions: social, environmental (or ecological), and financial. These three TBL dimensions are also commonly called the three Ps: people, planet, and profits. The technique can be effectively applied to evaluate management options with aspects that are not easily monetized, such as nonstructural BMPs.

A comprehensive stormwater program that has been optimized will include a blend of treatment and nonstructural BMPs. The nonstructural BMPs that are qualitatively assessed within this chapter are:

- Storm drain cleaning,
- Street sweeping,
- Smart landscaping practices,
- Trash management practices,
- Elimination of groundwater inflow to storm drains,
- Slope and channel stabilization,
- Winter maintenance BMPs, and
- Irrigation runoff reduction practices.

The discussion of each nonstructural BMP includes the topics in the following subsections, which are pertinent to arriving at a determination of the TBL/sustainability rating.

8.1.1 Control Description

The BMP control description section discusses the operational and maintenance practices performed by DOTs that offer the potential to reduce stormwater impacts as well as the parties (or target audiences) typically responsible for implementation. It also discusses the locations or circumstances in which the practice might be applicable as well as significant pollutant constituents that could be reduced. The control description considers and differentiates between managed and external variables that are known or believed to potentially affect performance. Managed variables are assumed to be within the control or influence of the DOT—as opposed to an external variable, which requires substantial cooperation and coordination with an outside party to influence the intended outcome. Enforcement of anti-littering laws is an example of an external variable, since a DOT cannot implement this approach without cooperation and commitment from law enforcement agencies. Managed variables include factors such as the frequency or extent of implementing a practice and other technical details related to operational methods. The control description also includes a summary table highlighting performance characteristics and whole life-cycle cost factors.

Some of the BMPs discussed in this chapter are effective in reducing the discharge of legacy pollutants if they are associated with unstabilized areas or groundwater that discharges into or from the DOT MS4. Controlling the source of legacy pollutants is an important tool for the practitioner, and it should be considered, as needed, with treatment controls.

8.1.2 BMP Efficiency

BMP efficiency can be assessed based on research and pilot studies performed by DOTs, but in many instances it would be best assessed by the DOT based on site-specific conditions. Available information that correlates the extent to which managed variables affect performance can be used to develop and implement more sustainable stormwater programs. Performance can be assessed by reduction of runoff, reduction in measured pollutant load, and other qualitative observations. For example, if groundwater infiltration is eliminated by the DOT by sealing the storm drain, the average annual pollutant reduction load can be estimated by determining the volume of inflow eliminated and assessing the pollutant concentration of the influent.

8.1.3 Whole Life Costs

Whole life costs for nonstructural measures are considered to include the costs of DOT labor, outside contractors or consultants, materials, equipment, and education and training. The cost of equipment includes an initial capital investment and long-term maintenance.

8.1.4 Social, Institutional, or Other Barriers

Social and institutional barriers include potential human resistance to change and other DOT operational characteristics that inhibit a particular BMP from being effectively implemented, independent of cost or pollutant reduction potential. Examples include inadequate availability of staff, inability to properly implement the BMP due to lack of understanding, and a perceived conflict with other DOT objectives such as traffic safety and flood management.

8.1.5 Sustainability Rating and Suggestions

Each of the most common nonstructural control measures can be evaluated (quantitatively or qualitatively) using three criteria: (1) pollution avoidance or pollutant removal effectiveness and BMP efficiency (e.g., potential to reduce pollutant loads or change behavior/knowledge in target populations), (2) cost of implementation, and (3) social/institutional impacts of implementation.

The TBL sustainability ratings are described as low, moderate, or high. A low rating is characteristic of a BMP that should be considered a low priority for additional resources in the DOT stormwater program. A moderate or high rating is characteristic of a BMP that is more effective and sustainable using conventional practices or through reasonable adaptation of managed variables. BMPs with a moderate or high rating also suggest that strategic enhancement or expansion would be cost-effective in attaining overall stormwater program goals. Suggestions are provided where applicable to assist DOTs with adaptation and enhancement of their nonstructural stormwater management practices.

8.2 Storm Drain Cleaning

8.2.1 Control Description

8.2.1.1 General

This BMP encompasses the cleaning of highway storm drainage infrastructure. Activities are performed by DOT staff to maintain the conveyance capacity and structural integrity of storm drain pipes, catch basins, inlets, open channels, or other components and to remove potential pollutants from the system. The most commonly performed activity in this category is the cleaning of trash and debris from catch basins and drain inlets. Material removal is most often performed using a Vactor truck, although Massachusetts DOT uses a small clamshell excavator for cleanouts.

Many DOTs implement a schedule of baseline inspection and maintenance activities for storm drainage facilities to maintain hydraulic capacity and ensure safe operation during flood conditions. Some, like Caltrans, also conduct enhanced inspection and storm drain cleaning as part their NPDES implementation plan (Caltrans, 2003b). Annual activities conducted by Caltrans as part of this program include:

- Inventory and prioritization,
- Inspection,
- Cleaning and disposal of wastes removed, and
- Record keeping of maintenance and cleaning, including of amounts removed.

8.2.1.2 Applicability to Sources and Target Audiences

Storm drain cleaning is intended to remove accumulated sediment, trash, and organic debris before it can be discharged into receiving waters. Studies indicate that the highest accumulation rates occur downstream of urbanized areas (Center for Watershed Protection, 2008). Storm drain cleaning activities involve:

- The storm drain system,
- DOT staff, and
- Independent contractors.

8.2.1.3 Opportunity and Pollutants Addressed

Overall, the opportunity for water quality improvement with this BMP is low, as summarized in the following:

- Cleaning the drain inlets was found, by several studies, to have a negligible impact on the measured quality of runoff discharged. No statistically significant difference was found in the concentrations of runoff, likely due to the small change in runoff quality improvement (Caltrans, 2003b).
- Most pollutants pass through the inlets to the drainage system during runoff events, when material is typically flushed from, not deposited in, the inlet drop structure. Inlets used by many DOTs and public agencies are typically designed to be self-cleaning, with all portions of the inlet sloped to the outlet pipe.
- Accumulation of material is largely incidental and most frequently the result of localized dry weather deposition. The majority of inlets in any given catchment typically accumulate low to negligible deposition of materials (Caltrans, 2003c).

Drainage inlets or catch basins that are specifically designed to retain debris may have higher efficiency for retaining solids. To the extent that the DOT standard incorporates this type of design, the DOT may wish to assign a higher effectiveness rating for this practice.

Pollutants addressed are:

- Sediment and pollutants associated with sediment,
- Organic debris such as leaves, and
- Trash.

Secondary pollutants associated with sediment and likely to be reduced include:

- Bacteria,
- Heavy metals,
- Nutrients (phosphorus),
- Oil and grease, and
- Pesticides (Center for Watershed Protection, 2008; Jang et al., 2010).

8.2.1.4 Managed Variables

The key variables that can be managed to more effectively affect pollutant load reduction include the frequency and timing of cleaning, the location, and the equipment and techniques that are used.

Accumulation of materials in drain inlets and pipes occurs primarily through dry weather deposition and during storm events when the quantity of flow is insufficient to achieve downstream hydraulic transport. Flow that is insufficient for hydraulic transport can occur during the receding limb of a storm or as a result of system blockage or inadequate slope on the conveyance system. When flows within the system increase as a result of heightened runoff, accumulated trash and sediment are prone to resuspension and downstream transport to the receiving water. The processes of sedimentation and transport of sediment/solids are influenced by the rate of flow, the size of accumulated material, and the physical characteristics of the conveyance (including shape, size, and slope). However, there are diminishing returns as the frequency of cleaning events increases beyond the optimum, since for higher frequencies, less total accumulation between events is expected. The time required for trash, sediment, and organic debris buildup in the system will be site-specific and vary as a function of land use, watershed size, precipitation patterns/amount, concentrated flow path, and topography (among others). In terms of timing, a cleaning that occurs prior to a rainfall event may effectively prevent material stored in the system from being transferred to the receiving water and therefore have the most benefit for receiving water quality, having avoided transport of material that has had a relatively longer time to accumulate.

Storm drain cleaning is one of the BMPs that may be useful to reduce the discharge of legacy pollutants from the DOT MS4. If soils in the surrounding watershed are contaminated, material that accumulates in the system may also be contaminated. The practitioner should evaluate whether removal of legacy pollutants is an added benefit for applications of this BMP.

Storm drain systems use conduit materials that are sometimes rough, frequently in contact with water, and prone to contact with nutrients, making them conducive to the formation of biofilm habitats (Ferguson, n.d.). The City of San Diego found that for effective bacteria reduction, power washing of inlets and closed conduits is required (Roberts, 2010). This is not a practical control method since the biofilm tends to reappear on system surfaces with the occurrence of the next storm event.

Physical and Other External Variables. There are several factors associated with this BMP that are not under the control of DOT maintenance staff. These factors are likely to affect the accumulation of sediments in the system, including localized physical and regulatory constraints, and consequently affect the schedule and cost for cleaning. They include:

- Pollutant accumulation volume constraint by the design and size of the catch basin;
- Coarse sediment retention with bypass of finer-grained sediments (potentially with higher concentrations of pollutants of concern);
- Cost of cleaning activities related to the design of the system and type of facility being cleaned and the need for traffic control or confined-space entry;
- Land use contributing to drainage facility and the type of materials captured;
- Access issues (including easements and traffic);
- Resource permit requirements (habitat, channel cleaning, etc.); and
- Disposal costs.

Table 8-1 shows the life-cycle cost factors for storm drain cleaning.

8.2.2 BMP Efficiency

8.2.2.1 BMP Efficacy

Pollutant reduction benefits can be estimated by measuring the amount of material removed from the system after each cleaning and comparing to the total estimated average annual load for the system. Trash and sediment should be reported by mass. Additional analysis would be required to estimate the loads removed for other pollutants of concern in the highway environment, such as metals or oils and grease. The efficacy of storm drain cleaning should be assessed and compared to removals that can be achieved by other BMPs, acknowledging also that material in the storm drain system may or may not be transportable to the receiving water (as described previously in the Managed Variables section). Storm drain system cleaning is difficult to perform and probably has one of the higher unit costs per pound of material (solids) removed (about \$0.25/lb, Caltrans, 2003c). Caltrans also estimated a cost of about \$42,000/kg/year of copper removed through inlet cleaning.

Drain Inlet Cleaning. Studies show that storm drain cleaning has a higher effectiveness for the reduction of TSS than for nutrients, metals, volatile and semi-volatile organic compounds, and pesticides (Center for Watershed Protection,

Table 8-1. Summary of performance and whole life-cycle cost factors for storm drain cleaning.

Performance Factors for Storm Drain Cleaning				
Pollutants Addressed	**Internal DOT Variables Influencing Performance**	**Performance Range**	**Advantages**	**Disadvantages**
✓ Sediments ✓ Trash ✓ Organic debris ✓ Bacteria ✓ Heavy metals ✓ Nutrients ✓ Oils ✓ Grease	✓ Frequency of cleaning ✓ Timing of cleaning relative to storm activity ✓ Type of equipment used	(Refer to Table 8-2)	✓ Low institutional barriers	✓ Low to modest reduction of targeted constituents ✓ High costs associated with labor, equipment, disposal, and traffic control ✓ Potential permitting and regulatory constraints ✓ Potential physical and access constraints

Whole Life-Cycle Cost Factors for Storm Drain Cleaning			
Planning and Implementation	**Labor**	**Equipment**	**Other**
✓ Location and frequency of cleaning ✓ System prioritization	✓ Type of labor (i.e., DOT staff versus contractor)	✓ Capital equipment purchase (Vactor truck typical) ✓ Fuel ✓ Equipment maintenance and depreciation	✓ Inspection ✓ Record keeping and reporting ✓ Traffic control (potentially) ✓ Disposal costs ✓ Regulatory permitting (potentially)

Table 8-2. Pollutant load reduction from storm drain cleaning.

Constituent	Effectiveness		Load Reduction (Average)
	Average	Range	
Sediment[a,c]	35%	14%–56%	500 lb/acre
Bacteria[a]	X	1%–2%	X
Nutrients[a,b]	X	5%–10%	X
Trash[a,b]	X	X	X
Metals[a,b]	X	5%–10%	X

Notes:

[a] Center for Watershed Protection, 2006 (nutrients reported as nitrogen).

[b] Pitt,1985 (metals reported as zinc).

[c] Pitt and Voorhees, 1995.

2008; Jang et al., 2010). A literature review performed by the Center for Watershed Protection also found that catch basin cleaning can reduce TSS by 29% if performed annually and by 56% if performed semiannually, total phosphorus by 1% (annual frequency) to 2% (semiannual frequency), and total nitrogen by 5% (annual frequency) to 10% (semiannual frequency) (Center for Watershed Protection, 2006). Pitt and Clark (2010) found that material captured in catch basins is not effectively transported through the drainage system, and it will likely accumulate before discharge to receiving waters. (Note: "catch basins" is used in the Pitt and Clark study to refer to structures that are designed with a storage area for debris, unlike drain inlets that are designed without a sump.) The study found that the effectiveness depends on inlet design and conditions, the frequency of cleanout events, and the pollutant of concern (Pitt and Clark, 2008). Pitt (1985) estimated that removal rates for cleaning catch basins at a frequency of twice per year for total solids was 25%, and for chemical oxygen demand (COD), nutrients, and zinc ranged from 5% to 10%. Other data provided by local municipal agencies in the San Diego region indicate that the amount of material removed averaged about 0.2 tons per drain inlet cleaned. Summary data for the effectiveness and pollutant load reduction from storm drain cleaning are shown in Table 8-2.

8.2.2.2 Whole Life Costs of Implementation

Costs depend on the frequency and type of MS4 cleaning as well as traffic control and access constraints. Estimated costs should include personnel, equipment, fuel, material testing, disposal, and (if applicable) regulatory permitting.

Caltrans (2003c) has extensively documented the costs of drain inlet cleaning along highways. The costs include inlet inspection and traffic control. Cleaning was accomplished using a Vactor truck. The most recent data (2002) indicate a cost of about $550 per drain inlet for annual cleaning. Review of other literature suggests that costs could be reduced to $350 using a dump truck and front loader.

8.2.3 Social/Institutional Barriers

Most DOTs are already conducting baseline storm drain cleaning to the extent necessary to maintain hydraulic performance and safe operation of the storm drain system. For this reason, enhanced cleaning of the storm drain system for water quality purposes has a relatively low level of anticipated social and institutional impact. The institutional impact includes the additional personnel hours required to operate machinery. The material that is removed from the storm drain system must be appropriately managed, transported, and disposed of to protect human health and the environment. In addition, access to the storm drain facilities may be limited, and traffic control and resource agency permits may be required.

Potential impacts from storm drain cleaning include energy and emissions from equipment and disposal of material removed. Habitat can also be disturbed in open channel areas during cleaning operations.

8.2.4 Sustainability and Suggestions for Practitioners

The overall sustainability and TBL rating of storm drain cleaning is considered to be low (see Table 8-3). Studies conducted by Caltrans suggest modest reduction of TSS and negligible reduction of other constituents of concern to the highway environment. Despite a limited reduction of pollutants, storm drain cleaning requires considerable financial resources and involves additional complications associated with traffic control issues as well as physical and regulatory constraints. Social and institutional impacts associated with storm drain cleaning are not significant, since most if not all

Table 8-3. Storm drain cleaning sustainability rating.

Effectiveness					Cost per Location[a]	Social/Institutional Impacts	Sustainability Rating
Bacteria	Nutrients	Sediment	Trash	Metals			
Low	Low	Low-medium	Medium	Low	$550 to $2100	Low	Low

[a] Cost per setup of Vactor equipment at either a drain inlet or a section of storm drain to be cleaned. Cost includes traffic control.

DOTs are already performing baseline storm drain cleaning to maintain hydraulic performance during flood events. Unless required to do so as part of an NPDES program, an enhanced cleaning program intended specifically for pollutant load reduction is not advised. If enhanced cleaning is required, DOTs could perform prioritized inspection and pre-storm cleaning activities where historical hotspot areas are in close proximity to open receiving water. When historical data are lacking, strategic prioritization should be performed using physical characteristics of the watershed and drainage system to determine the locations that have the highest combined pollutant generation rate and hydraulic transport potential to the receiving water.

8.3 Street Sweeping

8.3.1 Control Description

8.3.1.1 General

Street sweeping is a practice that DOTs have implemented for some time as a requirement of NPDES programs to remove accumulated trash and debris along curbs, shoulder areas, and median edges. As the technology of street sweeping has improved, sweepers have become much more effective at removing sediment as well. Consequently, many DOTs have begun to evaluate whether enhanced street-sweeping programs would offer a cost-effective means to improve stormwater runoff quality.

The main factors for street sweeping are:

1. The type of equipment used and its speed,
2. The frequency and timing of sweeping, and
3. The condition of the roadway being swept.

The presence of a curb may also increase the amount of material collected. If the cross-section drains to a shoulder without a curb, which is also directly connected to the storm drain system, it may be beneficial to sweep the shoulder area for removing fines. It is always beneficial to sweep for removing gross solids.

8.3.1.2 Applicability to Sources and Target Audiences

Street sweeping may reduce the discharge of pollutants from:

- Highway shoulder areas;
- Parking lots for rest stops, welcome centers, and office and administration buildings;
- Maintenance yards; and
- Other large impervious surfaces.

8.3.1.3 Opportunity and Pollutants Addressed

The opportunity for enhanced implementation of this BMP is modest. Gains beyond what is currently being achieved with the sweeper program for most DOTs will be marginal and would be achieved with improved equipment and timing relative to rain events.

The most likely pollutants to be addressed through these actions are:

- Sediment,
- Organic debris,
- Trash/litter, and
- Phosphorus.

Secondary pollutants associated with sediment and likely to be reduced include:

- Bacteria and
- Heavy metals

8.3.1.4 Managed Variables

The important managed variables in street sweeping include:

- Selection of equipment and speed,
- Frequency of sweeping,
- Time of day,
- Time to rain event,
- Posted versus non-posted routes (somewhat related to frequency of sweeping),
- Selection of which areas to sweep (i.e., parking lots, shoulder areas, median edge, etc.), and
- Condition of the roadway.

Type of Equipment. There are three principal types of street sweepers currently available: mechanical, regenerative air, and vacuum. Modern mechanical sweepers are equipped with water tanks and sprayers used to loosen particles and reduce dust. Mechanical brooms gather debris under the sweeper, and the vacuum system pumps debris into the hopper. Part of the impetus for the advent of these sweepers was the recognition that the majority of debris, especially the heavy debris, is collected within 36 in. of the curb line. Mechanical sweepers are designed to do an effective job of cleaning within this area. Even though this type of sweeper typically uses water-based dust-suppression systems, they exhaust a high level of particulates into the atmosphere on a continual basis during operation.

Regenerative air systems are more environmentally friendly than mechanical sweepers (Sutherland, 2011). Several factors contribute to this. Regenerative air sweepers employ a closed-loop cyclonic effect to clean. They are similar to vacuum sweepers in that there is a vacuum inlet located on one side of the sweeping head. Unlike vacuum machines, however, regenerative air sweepers constantly recirculate (regenerate) their air supply internally. Regenerative air technology has become widely seen as having a number of advantages, such as cleaning a wider path, removing small particles more effectively, and limiting the amount of dust-laden air that is exhausted back into the atmosphere. Since these machines air blast the pavement across the entire width of the sweeping head, regenerative air sweepers tend to do a more effective job of cleaning over the entire pavement surface covered.

Vacuum-assisted street sweepers use a high-powered vacuum to suction debris directly from the road surface and transfer the debris to a hopper. Research has shown that these machines are significantly more effective at removing sediment, nutrients, and metals than standard mechanical sweepers.

Frequency and Timing. According to EOA and Geosyntec Consultants (2011), the frequency of sweeping for maximum benefit is discussed extensively in the literature, although there does not appear to be full agreement on the issue. Most sources conducted sweeping tests with a biweekly or weekly schedule, although one study examined a frequency of three times per week (Pitt and Bissonette, 1985) and another examined a frequency of five times per week (Pitt and Shawley, 1981). A study by the City of San Diego (Weston Solutions, 2010) found that increasing sweeping from once to twice per week with a vacuum sweeper substantially increased the amount of material collected; however, this was not the case for mechanical sweepers. By contrast, in the Caltrans litter management pilot study, it was noted that increasing the frequency of street sweeping did not effectively reduce trash within the stormwater discharges monitored (Lippner et al., 2001).

The ideal goal is to sweep prior to a forecasted storm with as little lag time as possible, but this is difficult given logistical and resource constraints. Some references suggest that the frequency of sweeping should be, on average, one or two sweepings between storms. In semi-arid climates such as southern California, some references recommended more intensive sweeping prior to the onset of the wet season. Street sweeping is most effective when there is free access to the curb, where the most pollutants commonly accumulate. The optimum interval between sweeping events is likely when the material accumulated in the sweeper begins to decline as the interval between events is shortened.

Table 8-4 shows the life-cycle cost factors for street sweeping.

Table 8-4. Summary of performance and whole life-cycle cost factors for street sweeping.

Performance Factors for Street Sweeping				
Pollutants Addressed	**Internal DOT Variables Influencing Performance**	**Performance Range**	**Advantages**	**Disadvantages**
✓ Sediments ✓ Trash ✓ Organic debris ✓ Bacteria ✓ Heavy metals	✓ Type of equipment used (vacuum, mechanical, etc.) ✓ Equipment speed ✓ Frequency and location of cleaning ✓ Route posting ✓ Timing of cleaning relative to storm activity ✓ Time of day cleaning is performed ✓ Time of year first sweeping after thaw is completed	(See Table 8-5)	✓ Low institutional barriers	✓ Low to modest reduction of targeted constituents ✓ Costs associated with labor, equipment, disposal, and traffic control ✓ Potential physical and access constraints

Whole Life-Cycle Cost Factors for Street Sweeping			
Planning and Implementation	**Labor**	**Equipment**	**Other**
✓ Choice of equipment ✓ Location, timing, and frequency of cleaning ✓ System prioritization	✓ Type of labor (i.e., DOT staff versus contractor)	✓ Capital equipment purchase ($100k to $300k) ✓ Fuel ✓ Maintenance and depreciation (5- to 10-year life span)	✓ Inspection ✓ Record keeping and reporting ✓ Disposal costs ✓ Potential to compost

8.3.2 BMP Efficiency

8.3.2.1 BMP Efficacy

There are two main areas of research regarding street sweeping effectiveness. The first of these is the amount of material removed from the street and the factors that influence sweeping effectiveness. The second area of research focuses on whether removal of street dirt and associated pollutants has any impact on runoff quality.

Type of Equipment. EOA and Geosyntec Consultants (2011) reviewed a number of street sweeping studies and developed Figure 8-1 to compare the observed removal efficiencies. Removal efficiencies of the material accumulated on the street varied from about 20% to 70%, depending on the type of sweeper evaluated and the pavement condition. Other factors being equal, the regenerative air sweepers and advanced vacuum-assisted sweepers were shown to be more effective. These results were confirmed in a study by the City of San Diego (Weston Solutions, 2010).

The removal of sediment is important, but other pollutants of concern are bacteria and metals. No studies were identified that examined street sweeping as a practice to remove bacteria from paved surfaces. In the environment, bacteria are generally associated with the smallest-size fraction of particles, which are the least effectively removed by street sweeping programs. Consequently, removal efficiency may be only 10% to 50% of that observed for sediment.

Several studies were identified that evaluated removal of other pollutants through street sweeping. Kurahashi & Associates (1997) reported 45% to 65% removal of total suspended solids, 30% to 55% of total phosphorus, 35% to 60% of total lead, 25% to 50% of total zinc, and 30% to 55% of total copper. The Montgomery County Department of Environmental Protection (2002) provides removal effectiveness data from studies performed by the Center for Watershed Protection. TSS reduction ranged from 5% (major road) and 30% (residential street) for mechanical sweepers to 22% and 64% respectively for regenerative air and 79% to 78% respectively for high-efficiency vacuum sweepers. Law et al. (2008) developed the estimates shown in Table 8-5 for total solids and nutrient removal.

Frequency and Timing. Despite the reported substantial reduction of pollutants on the street surface, these values cannot be used to predict directly the improvement that would

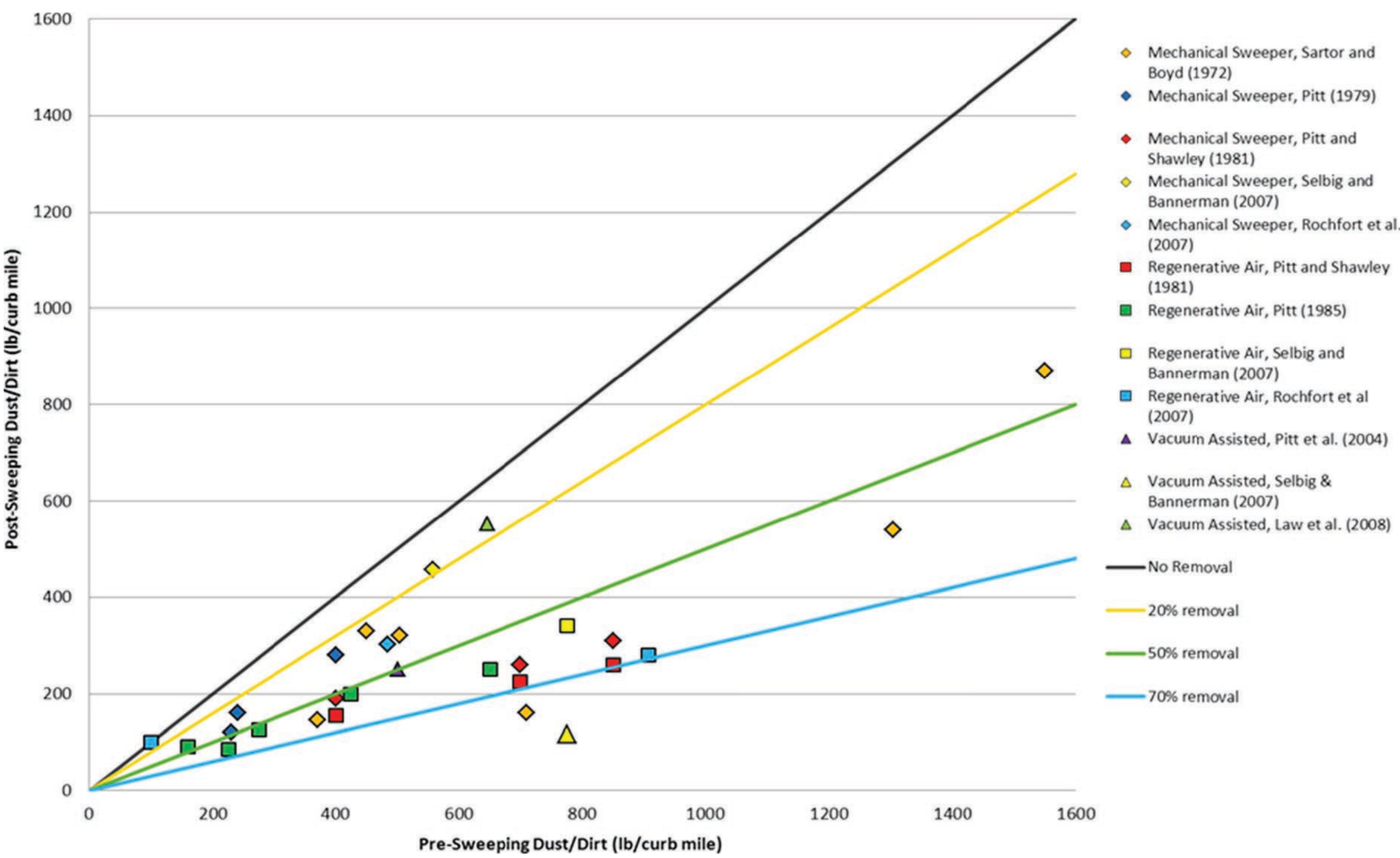


Figure 8-1. Comparison of pre- and post-sweeping solids data (in the form of pounds of solids per curb-mile) from the various street-sweeping studies reviewed (EOA and Geosyntec Consultants, 2011).

Table 8-5. Percent removal of nutrients from street sweeping.

Frequency	Technology	TS	TP	TN
Monthly	Mechanical	9	3	3
	Regenerative air/vacuum	22	4	4
Weekly	Mechanical	13	5	6
	Regenerative air/vacuum	31	8	7

Note: TS = total solids.

be expected in runoff quality. The basic problem is that pollutants start to build up on the road surface immediately after the sweeper passes. Pollutants will continue to accumulate on the road surface for approximately 1 to 3 weeks until steady-state concentration is reached. According to data collected by Sartor and Boyd (1972) and presented in Figure 8-2, the pollutant buildup process in residential and commercial land uses will replace more than half of the removed material in as little as 2 days. Sweeping in industrial areas would be expected to have a larger impact on water quality since the ultimate pollutant load on the road surface is greater, and it builds up over a longer period. Studies have not focused on cold climate areas and the timing of sweeping after roadways have thawed and traction aides are available to be removed by sweeping operations. It is likely that performing sweeping as soon as possible after roadways have thawed for the season would be beneficial. Conditions as dry as possible would be optimal if vacuum equipment is used.

This replacement of the removed material also indicates the difficulty in observing any impact on water quality despite many attempts. Kang et al. (2009) reviewed 15 datasets in 13 locations from four previous studies of this type and only identified a single study that observed any significant improvement in water quality as a result of sweeping. On the other hand, the City of San Diego documented a substantial decrease in pollutant concentrations in the first flush of runoff following weekly sweeping (Weston Solutions, 2010). Mean concentrations of total copper, lead, and zinc in runoff collected from the vacuum-swept street segment had 35% less TSS, 34% less total copper, 59% less total lead, and 26% less total zinc than the mean concentration from the mechanically swept street segment. In addition, concentrations from the vacuum-swept street had 85% less TSS, 71% less copper, 83% less lead, and 70% less zinc than the un-swept street. Extrapolation of these results for use in water quality modeling is probably not warranted because of the small number

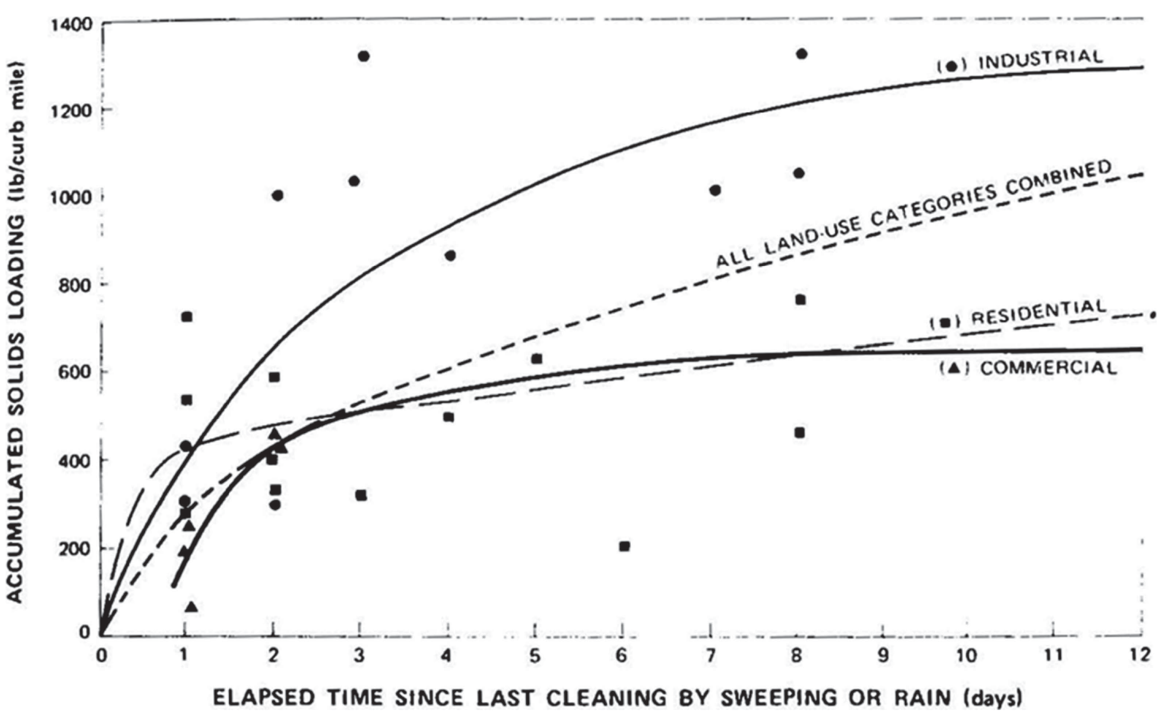


Figure 8-2. Accumulation curves developed by Sartor and Boyd (1972).

of events and the fact that only a small fraction of each storm was sampled.

8.3.2.2 Whole Life Costs of Implementation

Type of Equipment. EOA and Geosyntec Consultants (2011) conducted a literature review to assess the cost of street sweeping programs, and their summary is provided here. Literature sources that addressed costs often addressed life-cycle costs on a dollar per curb-mile-swept basis. Schilling (2005) indicated that life-cycle cost for mechanical sweepers was approximately $40 in 2005 dollars per curb-mile swept, and about $20 for a vacuum sweeper. Although this author did not address the reason for the difference, another report indicated that vacuum sweepers have fewer wearing parts than mechanical broom sweepers. Schilling quoted a capital cost of approximately $100,000 for a mechanical sweeper compared to over $200,000 for a vacuum sweeper. However, the City of San Diego reports that the cost difference between a mechanical sweeper and a vacuum sweeper is minimal—$193,000 versus $203,000 (URS Corporation, 2011). The life of the mechanical sweeper was given as 5 years compared to 8 years for the vacuum sweeper.

In an evaluation of street sweepers, Blosser for the City of Olympia, Washington, estimated the cost of a Schwarze EV-1 vacuum sweeper at $300,000, annual operation and maintenance costs at $50,000, and annual capital replacement costs at $30,000 (although he stated that the latter figure was conservative). If it is assumed that the equipment is operated 40 hours/week at 4 mph, the total distance travelled per year would be about 8,300 miles. Assuming that 80% of those miles are associated with cleaning would yield about 6,500 curb-miles swept per year. If, as indicated by Blosser, the total capital and O&M costs are about $80,000 per year, the O&M costs on a per curb-mile-swept basis would be about $12.

Phone inquiries were made to three major sweeper manufacturers by EOA and Geosyntec Consultants requesting current cost information for their products. One manufacturer responded that the purchase price for regenerative air sweepers ranges from $170,000 to $200,000, depending on options. Dustless regenerative air sweepers, which comply with the most stringent air quality requirements, range in price from $250,000 to $280,000.

Discussions with the City of San Jose and City of Oakland by EOA and Geosyntec Consultants (2011) also provided some insight into two Bay Area street-sweeping programs. The City of Oakland relies primarily on mechanical broom sweepers, whereas the City of San Jose is moving more toward regenerative air sweepers. According to the contact at the City of San Jose, a typical sweeper might sweep about 28 curb-miles per day, 5 days a week, and 50 weeks a year, for approximately 7,000 curb-miles swept per year. Using an estimated life-cycle cost of $40/curb-mile based on several references results in a life-cycle cost of about $280,000 per year. Sweeper life depends on numerous factors, but a rough estimate might be about 10 years, during which time a sweeper would have swept about 70,000 curb-miles. If the capital cost of a sweeper is $300,000, the capital cost per curb-mile is about $4, or about 10% of the overall life-cycle cost of operating a sweeper.

8.3.3 Physical Barriers

The following barriers to the effectiveness of street sweeping have been identified by Sutherland (2011). Pavement conditions are known to significantly affect the pickup performance of street cleaners (Sartor and Boyd, 1972). Street sweepers have considerable difficulty effectively picking up particulate material from streets whose pavements are classified as poor, because this usually indicates the presence of significant surface cracks and deep depressions where dirt can accumulate. The uneven surfaces that accompany poor pavement conditions make it difficult for the sweepers to operate effectively, especially the newer air machines. Research has shown that when sweeping poor-pavement-condition streets, a large portion of the material removed could be the street pavement itself. To realize the benefits of better street-sweeping pickup performance, proper pavement maintenance activities are needed to maintain a minimum pavement condition rating of "fair," with a preference for "good." In addition, all cracks should be sealed on a regular and ongoing basis.

Barriers such as street curbs or concrete barriers are known to significantly improve the ability of street cleaners to effectively pick up the accumulated material. The City of San Diego has also demonstrated that substantial accumulation and removal can occur by sweeping curbed medians (URS Corporation, 2010).

Pitt (1979) notes that if a smooth street has extensive on-street parking 24 hours a day (such as in a high-density residential neighborhood), most of the street surface particulates would not be able to accumulate next to the curb, which is the area usually cleaned by street cleaning equipment. If the percentage of curb length occupied by parked cars exceeds about 80% for extensive 24-hour parking conditions, this study indicates that the results would be best if the parked cars remained and the street cleaner swept around the cars.

The forward speed of a street cleaner while sweeping will significantly affect its ability to pick up particulate material. Other factors being equal, the pickup effectiveness increases as the forward speed decreases (Sartor and Boyd, 1972); however, the URS Corporation study (2011) did not find that speed had a significant influence on material pickup for mechanical sweepers. The optimum average forward sweep-

Table 8-6. Street sweeping sustainability rating.

Effectiveness					Cost per Mile	Social/Institutional Impacts	Sustainability Rating
Bacteria	Nutrients	Sediment	Trash	Metals			
Low	Low	Low-medium	Medium	Low	$40	Low	Moderate

ing speed is believed to be approximately 5 miles per hour. This is good balance for the trade-off between pickup performance effectiveness and the need to sweep a reasonable number of streets in a given day.

8.3.4 Sustainability and Suggestions for Practitioners

For DOTs, street sweeping continues as a necessary function to satisfy current NPDES requirements. However, it is apparent that the improvement in runoff quality from conventional street-sweeping practices must be modest, since there have been a number of studies that have attempted to quantify the improvement but with little success. Studies performed by municipalities and DOTs for enhanced street-sweeping programs show mixed results for reduction of pollutant discharge.

Most of the research to date has focused on the effectiveness of different types of sweepers for the removal of material from streets and parking lots. The data related to improvements in water quality are much more limited. Nevertheless, weekly sweeping during the rainy periods with high-efficiency vacuum sweepers does appear to provide the potential for significant stormwater quality improvement. Future research should focus on the water quality benefits and include the use of automatic samplers in selected test watersheds to evaluate the change in event mean concentrations that might be achieved for the pollutants of concern. The list of pollutants to be tested should be increased to cover the suite of common stormwater constituents of concern within the highway environment, including metals, TSS, and oils and grease.

The focus of any enhanced street-sweeping program should be on roadways that are curbed or have other barriers. Uncurbed roadways could be swept on occasion, potentially in response to a windstorm where a significant amount of vegetative debris has accumulated.

Despite the mixed results pertaining to enhanced programs, street sweeping, as an alternative to structural BMPs such as wet ponds, media filtration systems, and hydrodynamic separators, should be considered cost-effective. Median costs for pounds removed of TN, TP, and gross solids were shown in a University of Florida study to be substantially less compared to other structural options (Berretta et al., 2011).

Considering the relative cost and modest (if not questionable) effectiveness compared to other management options, as well as the social and institutional impacts, street sweeping practices are considered to have a moderate overall sustainability rating (see Table 8-6).

8.4 Smart Landscaping Practices

8.4.1 Control Description

8.4.1.1 General

Smart landscaping practices include a broad range of activities. As a best management practice for stormwater, smart landscaping includes two main objectives:

- Reduction or elimination of the use of potential pollutants (primarily fertilizers, herbicides, and pesticides) that could be discharged to the storm drain system and receiving waters; and
- Reduction of irrigation rates and prevention of irrigation runoff (irrigation excess).

This section focuses on alternative landscaping and vegetation management practices to reduce the need for irrigation and the reduction or elimination of potential pollutants, including sediment. Programs can be implemented by DOTs at median and slope areas, rest stops, welcome centers, weigh stations, and other landscaped areas.

- Smart landscaping focuses on the use of native plants, inert landscape materials, and other integrated roadside vegetative management (IRVM) practices. Compared to native plants, nonnative plants frequently require additional irrigation, additional nutrients, and protection from local pests. The use of nutrients, herbicides, and pesticides to protect nonnative plants can create a condition where these materials come in contact with stormwater runoff and are transported to the storm drain.
- IRVM practices include the use of automated equipment, GPS systems, drift-resistant nozzles, and other technological advances to focus and reduce herbicide applications. The U.S. Department of Agriculture is conducting a biological control program that involves importing and propagating insects and pathogens as an alternative to the use of chemical suppressants and mechanical controls used to prevent noxious weed growth. Several DOTs have become very active in the use of biological controls, including

Caltrans, MnDOT, New Hampshire Department of Transportation, and the Vermont Agency of Transportation. The use of biological control practices and other IRVM practices is discussed in detail in NCHRP Project 20-05, Topic 33-04 (Berger, 2005). The New Mexico State Highway and Transportation Department developed a pilot project along a 6-mile stretch of road in Taos County that used goats for noxious weed control (Berger, 2005).

- A more aggressive approach is to attempt to introduce bans on the use of pesticides and fertilizers, particularly in watersheds with water bodies that are impaired.
- The FHWA has several publications focused on smart landscaping for DOTs. Information on the use of native plants and managing invasive species can be found at http://environment.fhwa.dot.gov/ecosystems/vegmgmt_row.asp. The FHWA recently released the publication, "Vegetation Management: An Ecoregional Approach," Publication number FHWA-HEP-13-043.

8.4.1.2 Applicability to Sources and Target Audiences

The audience for this BMP includes DOT staff members and contractors that maintain landscaped areas within:

- Median and slope areas,
- Rest stops,
- Weigh stations,
- Agricultural check points, and
- Welcome centers.

8.4.1.3 Opportunity

- Opportunities for this BMP are moderately high. The use of nonnative plants requires the use of pesticides and fertilizers to maintain healthy vegetation. Education of DOT staff to avoid the use of nonnatives has good potential to reduce the use of pesticides.
- Studies have been performed on the concentrations of pesticides in stormwater runoff from southern California. One study detected Diazinon in 93% of samples, including 12 of 13 site-events. (Diazinon has now been banned for non-licensed application but serves as a useful proxy for other commercially available pesticides targeting the same pests, such as pyrethroids.) Chlorpyrifos, which is registered only for agricultural use, was detected at much lower rates (12% of samples). Mixed agricultural land use had the highest Diazinon concentrations and a flow-weighted mean concentration of 4,076 ng/L (4.08 μg/L). Commercial land use had the second highest with 324 ng/L, and high-density residential had the third highest with 99 ng/L (Schiff and Sutula, 2001). Pesticides that are in current use include pyrethroids (and synergists such as piperonyl butoxide) and Fipronil.

8.4.1.4 Pollutants Addressed

The pollutants of concern here are associated primarily with fertilizers and chemicals that are used in landscaped areas to control pests or unwanted plants and support the healthy growth of nonnative plants. By switching to alternative products that are safer for use (that degrade rapidly in the environment or do not easily transport), the potential for stormwater pollution is reduced. Sediment discharge from unstabilized areas is also a concern. The primary pollutants of concern are:

- Pesticides,
- Herbicides,
- Fertilizers (nutrients, metals), and
- Sediment.

For most pesticides, less than a pound of ingredient will render 1 million gallons of discharge toxic to aquatic life.

8.4.1.5 Managed Variables

The managed variables for smart landscaping practices depend on the type of practices implemented. The variables that can be adjusted to achieve the most effective outcome for DOTs include:

- The type and extent of staff training.
- The implementation of IRVM practices and biocontrols.
- Automated control systems, drift-resistant spray nozzles, and robotic and smart spray systems.
- Timing and location of the application of pesticides, herbicides, and fertilizer (exposed area, impervious/pervious surface, proximity to the storm drain, time prior to rain event).

Options that are included in this BMP category are:

- Integrated pest management (IPM) and IRVM. Extensive information is available at http://www.fhwa.dot.gov/context/practitionersguide/reference/Use_of_Herbicides_in_Roadside_Environments.pdf, http://www.projectcleanwater.org/html/ipm.html and http://www.ipm.ucdavis.edu/IPMPROJECT/freepublications.html (see publication ANR 8093—guide for public agencies to establish integrated IPM programs).
- Public education to teach users how to properly apply pesticides and alternatives to pesticides, herbicides, and fertilizers.

- Hydrozoning—a landscape practice that groups plants with similar water requirements together in an effort to conserve water.
- Xeriscaping:
  - Selecting plant species that require less water, such as native species (more information at http://cnps.org/).
  - Replacing turfgrass with artificial turf, low-water use plants, or permeable materials.
  - Using mulch or compost to retain soil moisture and increase water penetration.

Table 8-7 shows the life-cycle cost factors for smart landscaping.

8.4.2 Physical/Institutional Barriers

Potential barriers may be the costs associated with new, automated equipment, additional labor, and additional staff training.

8.4.3 BMP/Control Evaluation

8.4.3.1 BMP Efficacy

Little information is available to estimate the effectiveness of smart landscaping practices on stormwater runoff or surface water quality.

- The U.S. EPA has initiated requirements and limitations for the use of pesticides, so concentrations and types of pesticides in runoff change as regulation is introduced. However, the toxicity found from pesticides in receiving waters indicates the potential for high levels of pesticide-related pollutants in runoff.
- The water quality objectives established by the California Department of Fish and Game freshwater quality criteria for Diazinon (now banned) are 80 ng/L (0.08 µg/L) for short-term exposure (acute criterion) and 50 ng/L (0.05 µg/L) for long-term conditions (chronic criterion) (San Diego

Table 8-7. Summary of performance and whole life-cycle cost factors for smart landscaping.

Performance Factors for Smart Landscaping				
Pollutants Addressed	**Internal DOT Variables Influencing Performance**	**Performance Range**	**Advantages**	**Disadvantages**
✓ Pesticides ✓ Herbicides ✓ Fertilizers (nutrients, metals) ✓ Sediment	✓ Staff training ✓ IRVM, IPM, hydrozoning and biocontrol practices ✓ Timing and application of pesticides and fertilizers ✓ Robotic and smart spray systems ✓ Refer also to irrigation runoff reduction practices	✓ N/A – insufficient data	✓ Low social and institutional impacts	✓ Unknown potential pathogen impacts resulting from application of biocontrols ✓ Applicability of some automated variable rate pesticide/herbicide/fertilizer control systems to highway environment not known

Whole Life-Cycle Cost Factors for Smart Landscaping			
Planning and Implementation	**Labor**	**Equipment**	**Other**
✓ Choice and application method of pesticides, herbicides, and fertilizers ✓ Choice of IRVM, IPM, hydrozoning, and biocontrol practices ✓ Evaluation and choice of variable rate equipment and control systems ✓ Staff training and education	✓ Type of labor (i.e., DOT staff versus contractor)	✓ Capital costs for installation of landscape and irrigation ✓ Capital costs for automated variable rate control systems ✓ Irrigation system maintenance ✓ Pesticide, herbicide, and fertilizer control system maintenance ✓ Landscape maintenance/replacement	✓ Targeted inspection program ✓ Record keeping and reporting

Regional Water Quality Control Board, 2002). Criteria for most other pesticides do not exist; rather, a narrative standard exists that generally translates to "no toxics in toxic amounts" for receiving waters. A very rough estimate of the expected reduction in toxicity for small drainage areas could be obtained by assuming an equivalent reduction in toxic units to the percent reduction in the amount of pesticides used on exposed impervious surfaces. Hanzas et al. (2011) report a chemical loss of up to 0.6% of applied Bifenthrin (to turf) with over-irrigation.

- Similarly, the reduction in application of fertilizer that ultimately enters the storm drain system should have direct benefit for eutrophication and dissolved oxygen problems in receiving waters. Few studies were found measuring fertilizer use in urban areas and impacts to receiving waters. In a Baltimore, Maryland, study, Groffman et al. (2004) measured increased nitrate losses from urban and suburban watersheds (approximately 2 to 7 lb per acre per year of nitrogen) compared with a forested watershed (less than 1 lb per acre per year of nitrogen). These researchers also noted high retention (75%) of nitrogen inputs in the urban watersheds, mostly consisting of fertilizer and atmospheric deposition.
- There are studies of a similar nature for agriculture, which is a reasonable proxy. RIVM (1992) calculated that European agriculture is responsible for 60% of the total riverine flux of nitrogen to the North Sea and 25% of the total phosphorus loading. A study by Ryding (1986) in Sweden demonstrated how lakes that were unaffected by industrial or municipal point sources underwent a long-term change in nutrient status because of agricultural activities in the watershed. Over the period of 1973 to 1981, the nutrient status of Lake Oren increased from 780 to 1000 mg/m^3 for total nitrogen and from 10 to 45 mg/m^3 for total phosphorus. Lake transparency declined from 6.2 to 2.6 m and suffered periodic (heavy) algal blooms.
- Researchers established water quality sampling stations in the Huron River watershed in southeastern Michigan (Lehman et al., 2009). Sampling was conducted under the jurisdiction of the Ann Arbor, Michigan, fertilizer ordinance and upstream in a geographic area not under the city ordinance. Phosphorus concentrations in the water were compared for 2008 data against older data collected before the ordinance was enacted. Phosphorus concentrations in the river were lower in 2008 compared to the period prior to the ordinance and lower for the Ann Arbor sampling sites compared to upstream sites. The ordinance not only controlled phosphorus fertilization but also included strong education programs about proper fertilizer management. The study showed a positive relationship between phosphorus reduction in the water with the implementation of the ordinance BMPs, but the authors acknowledged that it was impossible to determine if the controls on fertilizer solely led to the reductions in phosphorus. Other components of the overall program, such as fertilizer-management education, may have also played a role.

8.4.3.2 Costs of Implementation

There is highly limited information regarding costs associated with IRVM and biocontrol programs.

- Data from *NCHRP Synthesis 341* indicates a cost range per site-application of biocontrols from $2 to $200. By contrast, selective herbicide applications range from as little as $2.45 per acre of application to as high as $455 per acre of application, while hand removal of vegetation is reported to be as high as $2,000 per acre per visit (Berger, 2005).
- Publications and technical resources available from the agricultural community may offer the best sources of cost information related to variable rate equipment and control systems for use in applying pesticides and herbicides (e.g., Clemson Cooperative Extension, http://www.clemson.edu/extension/rowcrops/precision_agriculture.html). However, the adaptability of these systems to the transportation environment and associated costs are not known. Anticipated capital expenditures associated with automated control systems and additional labor and training are intuitively assumed to be moderate when compared to annual DOT costs for conventional landscaping, vegetation, and pest management programs. Additional research is required to assess the relative cost-effectiveness of such systems.

8.4.3.3 Sustainability Rating

Smart landscaping practices, including IPM and IRVM, seem to offer potential for moderate pollutant load reduction by reducing the need for irrigation and allowing for more controlled application of fertilizers and pesticides. In some instances, implementation of such practices could potentially eliminate the need for irrigation, herbicides, and pesticides. Biocontrol practices also offer potential for substantive reduction of pesticides, herbicides, and nutrients. However, the effect of biocontrols on generation of pathogens is unknown. Based on the potentially moderate to high level of effectiveness for pesticides and nutrients, the relatively low institutional impacts, and moderate assumed whole life costs, smart landscaping is considered to have a moderate sustainability rating (see Table 8-8).

The primary pollutants that would be addressed through a program are nutrients, pesticides, and, to a lesser extent, sediment. Pilot programs are a good idea before a large-scale program is enacted in order to evaluate the effectiveness and level of participation since there is not a great deal of information on the effectiveness of smart landscaping programs

Table 8-8. Smart landscaping practices rating.

Effectiveness						Cost per Mile	Social/ Institutional Impacts	Sustainability Rating
Pesticides	Bacteria	Nutrients	Sediment	Trash	Metals			
Medium-high	Low	Medium	Low-medium	Low	Low	Varies	Low	Moderate

available for DOTs. Separate pilot programs should examine the effectiveness of biocontrols and adaptation of precision agriculture techniques to the highway environment. Programs should focus on watersheds where there is a pesticide- or nutrient-related impairment. The program should also evaluate whole life costs compared to traditional landscape, vegetation, and pest management practices used by DOTs.

Until more detailed information is available on the costs and extent of pollutant load reductions that could be realized, DOTs can implement these smart landscaping measures aimed at improving water quality:

- Update landscaping design standards to favor, if not require, the use of native landscape species. Native species can reduce or eliminate the need for irrigation. Cultural controls specified as part of the design can be used to strategically minimize the potential for invasive vegetation and weeds.
- Conduct training for DOT staff in the appropriate application of fertilizers and herbicides. Require private companies selected for maintenance contracts to possess appropriate licenses for application of fertilizers and herbicides.
- Utilize hand removal of vegetation wherever economically and physically feasible or in watersheds suffering nutrient-, pesticide-, or herbicide-related impairment. Some DOTs have used volunteer workers from environmental stewardship groups for the removal of trash. This concept would seem to have applicability for the removal of noxious weeds and invasive vegetation as well.

8.5 Trash Management Practices

8.5.1 Control Description

8.5.1.1 General

Trash management practices include a broad range of options to prevent the discharge of trash into the storm drain system or receiving waters. Caltrans defines litter (trash) as manufactured material that can be retained by a ¼-in. mesh (Caltrans, 2000). The main factors contributing to trash entering the storm drain system are:

- Littering by the public,
- Trash blowing from uncovered/partially covered loads from trucks within the right-of-way, and
- Wind picking up trash from sources such as landfills and uncovered containers and depositing it into the right-of-way.

The primary focus of trash management is to prevent trash and other potential pollutants from being dispersed outside of dedicated trash facilities (into receiving waters). This is accomplished by changing people's habits to reduce littering as well as through cleanup and abatement programs.

Education and outreach programs can be implemented by DOTs to encourage good waste management practices and discourage littering. These programs can also be supplemented through external enforcement of anti-littering laws, political efforts to ban products of concern, and advancing the design of more environmentally friendly packaging materials.

Several actions can be taken as part of a DOT trash management/control program:

- Create public education campaigns (e.g., "Don't Mess with Texas" by TxDOT and Adopt-a-Highway litter pickup).
- Increase the number and convenience of trash storage receptacles at rest areas, weigh stations, welcome centers, and so forth.
- Ensure that trash receptacles have operable lids that are closed and secure.
- Prioritize the cleanup of trash and material from areas that are more likely to have high rates of dispersal and receive run-on.
- Work with local and state officials to increase the enforcement of littering laws within DOT right-of-way areas. Work with other stakeholders to advance the design of environmentally friendly packaging materials and ban other materials considered critical to trash management (e.g., plastic bags, fast food cartons).
- Provide additional signage to inform the public of littering laws and mandatory fines.
- Maintain storm drain signage if required by an NPDES permit.
- Create alternative configuration of inlet grates to exclude trash.

Trash management can also be accomplished through trash pickup and sweeping. Trash pickup programs can use DOT staff as well as other volunteers interested in environmental stewardship. This guidance focuses on prevention activities as the most effective BMP—true source control.

8.5.1.2 Applicability to Sources and Target Audiences

People easily associate litter with stormwater pollution, suggesting that this behavior (i.e., not littering or picking litter up) would be a good topic for outreach efforts (Goodwin, 2009). Target audiences include:

- 18- to 25-year-old males,
- Persons transporting trash on roadways, and
- Smokers in vehicles.

Target locations include:

- Within shoulder areas and along right-of-way fencing;
- Storm drain inlets, conveyance systems, and outfalls;
- On- and off-ramp areas;
- Welcome centers;
- Rest stops; and
- Weigh stations.

8.5.1.3 Opportunity and Pollutants Addressed

The greatest trash reduction benefit will be achieved by focusing on high-priority areas—areas with the most severe litter problem. Keep America Beautiful (2009) estimates that there are 51.2 billion pieces of litter on roadways nationwide, and of this, the majority (91%, or 46.6 billion pieces) is less than 4 in. in size. This estimate translates into 6,729 pieces of litter per centerline mile of roadway, or greater than one piece of litter per centerline foot. Clearly, there is opportunity to reduce roadside litter.

Keep America Beautiful also notes that smokers are a significant source of litter (cigarette butts, which are disposed of improperly 57% of the time) and that as much as 85% of littering behavior can be attributed to the individual (and conversely, 15% to the context—the presence of existing litter). The results from their nationwide telephone survey showed that 15% of Americans reported littering in the past month, down from 50% in 1968.

Trash is a general category, but the term is inclusive of other items that could be considered pollutants in other categories, such as grease and organic material. The Statewide Waste Characterization Study for 2008 by the California Integrated Waste Management Board characterized the material classes of trash disposed of in California and found that about 32% was organic material (California Environmental Protection Agency, 2009). Organic material is likely to have high levels of nutrients, and it could cause algal blooms, resulting in low dissolved oxygen levels in receiving waters. In addition, the organic material could attract wildlife and cause high levels of bacterial indicators. Other constituents of concern found in the waste characterization study are metal (5%) and electronics (0.5%). The metals are not likely to be in a form that would affect water quality, but over time could be problematic. The primary pollutants of concern were:

- Paper/wood/cardboard,
- Organics,
- Nutrients, and
- Pathogens.

Caltrans characterized trash collected in the Los Angeles area (air dried, by weight) as shown in Figure 8-3.

8.5.1.4 Managed Variables

The managed variables for trash practices depend on the target audience and the type of litter to be managed. General items to consider include:

- The extent and nature of education and outreach efforts (including media and advertising).
- The level of enforcement of littering ordinances and fines.
- The level of effort for inspections.
- Public trash receptacle numbers and the frequency of emptying. Littering rates decrease as the convenience of using a proper receptacle increases, and more trash receptacles lead to less littering.
- Frequency of sweeping.
- Frequency of manual trash pickup.
- Source of labor (e.g., DOT staff, contractors, volunteers).

External Variables. A literature review and study identified additional variables that should be considered when developing a plan to reduce littering (Action Research, 2009). They do not show whether some of these variables are more important for trash reduction than others.

- The condition of the physical surroundings has a substantial impact on a person's decision to litter. People were more likely to litter in areas with higher amounts of existing litter (context).
- Social norms play a large role in the propensity to litter; males aged 18 to 25 years are the most likely demographic.
- Public outreach and awareness campaigns effectively reduce littering.
- Enforcement (the threat of fines or violations from local or state police).

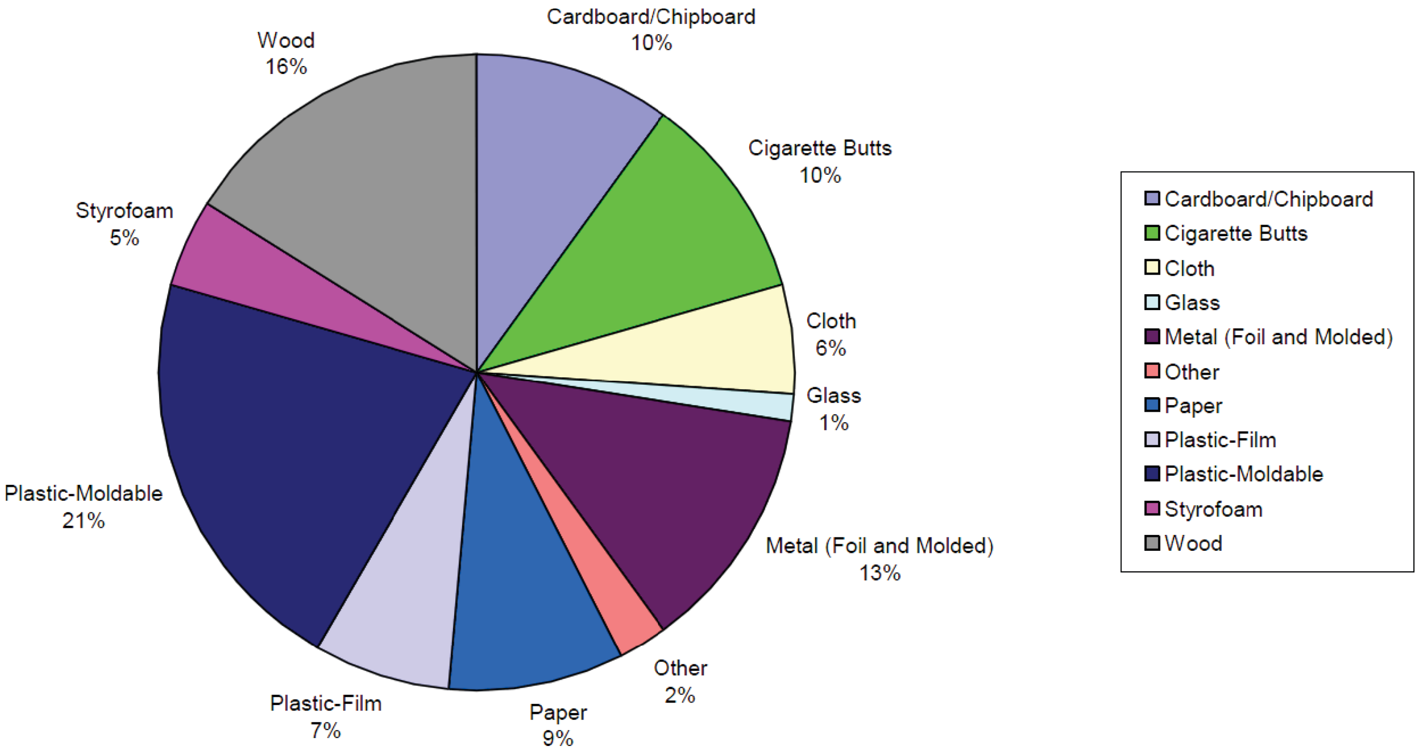


Figure 8-3. Caltrans characterization of trash collected in the Los Angeles Area (Caltrans, 2000).

- Litter type/activity source. The type of activity a person is involved in (or trash associated with the activity) can result in higher incidences of litter. Table 8-9 shows the types of litter that are most often disposed of improperly (Keep America Beautiful, 2009).

Table 8-10 shows the life-cycle cost factors for trash management.

8.5.2 BMP Efficiency

8.5.2.1 BMP Efficacy

Measuring and Estimating BMP Efficacy. The effectiveness of various types of trash management strategies, such as public education and the Adopt-a-Highway program, has been studied and quantified. However, the effectiveness of other types of management practices, such as covering trash

Table 8-9. Types of litter (Keep America Beautiful, 2009).

Item	Proper	Improper	Percent Littered
Cigarette butt	146	194	57
Combo/mixed trash	325	12	4
Paper	251	20	7
Beverage cup	180	5	3
Napkin/tissue	110	9	8
Beverage bottle: plastic	100	5	5
Food remnants	65	16	20
Food wrapper	85	14	14
Beverage can	59	8	12
Food container	57	1	2
Plastic bag	38	2	5
Beverage bottle: glass	11	0	0
Unknown	116	10	8
Other	77	46	37
TOTAL	**1,620**	**342**	**17**

Table 8-10. Summary of performance and whole life-cycle cost factors for trash management.

Performance Factors for Trash Management				
Pollutants Addressed	**Internal DOT Variables Influencing Performance**	**Performance Range**	**Advantages**	**Disadvantages**
✓ Paper/wood /cardboard ✓ Organics ✓ Nutrients ✓ Pathogens	✓ Extent and nature of education and outreach ✓ Level and nature of inspection ✓ Availability of public trash receptacles ✓ Trash pickup frequency ✓ Source of labor (e.g., DOT staff, contractors, volunteers)	✓ Long-term education and outreach varies up to 35% (Keep America Beautiful, 2009) ✓ Trash reduction at outfalls from increased pickup, or inlet grate modification varies up to 30% (Caltrans, 2000)	✓ Potentially high levels of pollutant reduction for targeted constituents	✓ Education and outreach effectiveness influenced by behavioral modification, enforcement, and other external variables

Whole Life-Cycle Cost Factors for Trash Management			
Planning and Implementation	**Labor**	**Equipment**	**Other**
✓ Trash pickup time, location ✓ Modification to standard inlet grate design	✓ Type of labor (e.g., DOT staff, contractor, or volunteer)	✓ Additional trash receptacles	✓ Targeted inspection program ✓ Record keeping and reporting ✓ Media and outreach programs (TV, radio, print, etc.)

bins or providing signage, is more difficult to assess accurately. Studies that evaluate the impact of trash management programs often provide estimates of the total volume and mass of litter but not the material composition of the trash captured or collected. The Don't Trash California stormwater public education campaign was estimated to have secured an annual benefit of about $2.25 million (Caltrans, 2011a).

Past Studies Regarding Public Litter Control Programs.

Keep America Beautiful. The results from studies conducted by Keep America Beautiful indicate that individuals are the key source of litter (Keep America Beautiful, 2009). Study results found that 81% of observed littering acts were intentional. Keep America Beautiful found that younger individuals are more likely to litter (and report littering) than older individuals. This group presents the most important segment for focused messaging and education campaigns.

Passive media and messaging campaigns may be useful, but Keep America Beautiful also indicates that there is a need to actively involve youth in cleanup and beautification activities to raise their awareness about litter as an issue and to increase their commitment to preventing litter.

Another important variable affecting litter program effectiveness is the presence of existing litter and its correlation with enforcement measures. Individuals are much more likely to litter in littered environments (as seen in the observational studies), and they are less likely to report littering in beautified environments (Keep America Beautiful, 2009). Interestingly, Keep America Beautiful noted that posting litter-prevention messages or signs in already-littered environments is likely to exacerbate the littering problem rather than fix it. In such cases, cleanup is necessary as the first step, followed by enforcement.

Don't Trash California. Caltrans has performed several studies to evaluate the effectiveness of the Don't Trash California stormwater public education campaign. The public education campaign in the Los Angeles River watershed was estimated to reduce littering by an annual average of 2,592 ft^3 (Caltrans, 2011a).

Adopt-a-Highway. The efficacy of trash collection programs has also been evaluated. Caltrans has implemented several programs. Within Los Angeles County, maintenance crews removed over 1.1 million ft^3 of trash from the freeway over a 1-year period. The Adopt-a-Highway program was also successful at removing large amounts of trash. Caltrans collected over 130,000 ft^3 for the Adopt-a-Highway program and 20,547 ft^3 of debris left by the homeless during a 1-year period (Caltrans, 2008).

Don't Mess with Texas. In 2013, the Texas Department of Transportation conducted telephone and online surveys of statewide residents to better understand attitudes and develop strategies to reduce littering on highways. The surveys, in part, were conducted to measure recall of the Don't Mess with Texas advertising slogan. Public recollection of the slogan was shown to be very high, at 98%, with 62% of residents recalling specific advertisements or public service announcements using it within the previous year. Despite the high recall, one-third of the residents surveyed admitted to having littered within the previous month. The most commonly reported types of litter were food and organic material and small pieces of paper (such as receipts and gum wrappers). Those who reported littering had generally less knowledge that littering was illegal in all cases. That same group also reported driving more miles per day compared to those who had not reported littering within the previous month. Around 30% of current and former smokers reported throwing cigarette butts from their car windows. Although most agreed that this action constituted a form of littering, the action was typically justified as a habit or as the only convenient way for disposal. No results were reported correlating the Don't Mess with Texas advertising campaign with measured quantities of reduced trash or pollutant load (Decision Analyst, Inc., and Sherry Matthews Advocacy Marketing, 2013).

Caltrans Summary of Effectiveness. BMP effectiveness and other study results reported by Caltrans (2000) are:

- Increasing the frequency of sweeping from monthly to weekly had no statistical significance on the total system load recorded at storm drain outfalls.
- Increasing the frequency of litter pickup from monthly to weekly reduced the quantity of litter seen at storm drain outfalls by 30% by weight.
- Modifying storm drain inlets with a grate (maximum openings 0.25 in. in diameter) reduced the quantity of litter at storm drain outfalls by 26% by weight.
- A reduction in trash (through the implementation of litter BMPs) did not affect the concentration of chemical constituents in stormwater runoff.
- There was no relationship between litter at the pipe outfall and rainfall intensity, peak flow, total flow, or antecedent dry period.

It is also worth noting that the California Highway Patrol reported making over 8,500 citations for littering in 2008. This included trash from vehicles, as well as from unsecured loads within or near the Caltrans right-of-way (Caltrans, 2009a).

Wind-Transported Trash. No studies were found quantifying the amount of trash transported by wind events. Loss of trash can be prevented by covering trash containers and other sources of trash such as recycling bins.

8.5.2.2 Whole Life Costs of Implementation

Abatement and Cleanup. Estimates show that $11.5 billion is spent on abatement and cleanup activities nationally each year (Keep America Beautiful, 2009). In California, the estimates are:

- $62 million to pick up roadside litter (non-state ROW), and
- $375.2 million for public agency abatement of litter.

Caltrans estimates the cost of the Adopt-a-Highway program as $4.8 million annually. As noted previously, the total cost to collect roadside litter (maintenance crews, Adopt-a-Highway, sweeping) is $62 million/year. Caltrans operates about 15,000 centerline miles of highway.

A 2009 news release from Caltrans District 2 reported annual costs of $57 million for Caltrans statewide efforts related to litter pickup and disposal. These efforts resulted in the removal of 182,000 yds^3 of trash from the Caltrans right-of-way (Caltrans, 2009a).

Education and Outreach Campaigns. The majority of the trash management program that is focused on the public would likely take place through education. The costs to implement public education campaigns vary widely. The campaigns may include the media, such as through television and radio ad space, information pamphlets, and other distributable items that can carry the message. The costs for a particular item are often negotiated and dependent on the number of items purchased. As a point of reference, the Don't Trash California campaign by Caltrans cost about $3.5 million per year in the first 2 years of operation.

Enforcement Efforts for Uncovered Loads. Reducing trash blowing from uncovered loads could be managed through enforcement effort. Costs for education programs are cited previously; marginal enforcement costs for citing drivers with uncovered loads would likely have net positive revenue.

8.5.3 Social/Institutional Considerations

Anti-litter campaigns are well established, having been in place for decades. However, the success of the public trash management campaigns depends highly on the willingness of the target audience to take action. Even with these programs, there is likely to be some level of illegal littering.

Additional regulation or enforcement may be viewed negatively. To move to the next level of effectiveness, stepped up enforcement of anti-littering laws will be necessary. For this reason, it is important to clearly quantify the benefits of additional regulation or enforcement to secure political and public acceptance.

8.5.4 Sustainability and Suggestions for Practitioners

Implementation of this BMP has a moderate to high sustainability rating for projects, primarily due to the potential reduction that could be achieved through the relatively large opportunity and low to moderate overall cost. The specific type of trash management practice chosen is likely to have a large effect on cost–benefit relationship. Pickup and abatement programs that involve the use of volunteer labor, like the Caltrans Adopt-a-Highway program, appear to offer the greatest degree of cost-effectiveness in terms of dollars spent per cubic yard of removal. Management programs involving pickup and disposal using DOT staff are considerably less cost-effective. Pickup and abatement programs appear to be most effective when targeted toward historic problem areas and used in conjunction with additional enforcement.

Engineered structural solutions within the right-of-way, such as modification of standard grate inlet design, appear also to offer sustainable long-term opportunities based on the reduction of trash at storm drain outfalls cited by Caltrans in the litter management pilot study from 2000. However, DOTs could benefit from additional research that weighs cost savings from reduction of trash at storm drain outfalls (and the associated environmental benefit) versus the added cost to retrofit existing systems and design of new systems to achieve equivalent hydraulic performance, as well as the potential maintenance concerns with alternative grate designs.

In the short term, education and outreach programs would also seem comparatively less cost-effective when compared to programs like Adopt-a-Highway. However, education and outreach programs appear greatly more sustainable when viewed within the context of contributing toward long-term behavioral changes—as shown by the large reduction in per capita littering rates cited by Keep America Beautiful since 1968. If undertaken, education and outreach programs should be targeted toward the demographics most likely to be involved with littering (e.g., younger people 18 to 24, males, smokers). In addition to stressing the environmental consequences of littering, education and outreach programs should include suggestions for effective transportation habits, such as carrying a small trash bag in the vehicle and adequately covering exposed loads.

Social/institutional impacts are likely to be modest for most practices, but moderate to high with specific regard to the use of additional enforcement measures or product bans (see Table 8-11). These key social barriers can only be overcome by DOTs through cooperative involvement with external organizations such as law enforcement agencies, as well as political representatives and lawmakers. Over the long term, additional enforcement efforts, development of biodegradable fast food packaging, or product bans (e.g., cigarettes, plastic bags) appear to offer substantial opportunity to increase the sustainability of trash management practices.

8.6 Elimination of Groundwater Inflow to Storm Drains

8.6.1 Control Description

8.6.1.1 General

Groundwater inflow to the storm sewer system creates perennial flow that may contain or pick up pollutants prior to discharge to receiving waters. Groundwater inflow can occur when the storm drain pipes lie below the groundwater table. Storm drain pipes provide a conveyance pathway to the receiving water that may not otherwise exist, or if conveyance would naturally occur through interflow, may increase the discharge rate compared to natural conditions.

The USGS National Water Information System (NWIS) is an extensive database that includes data on groundwater contamination nationwide. It can be used by DOTs to identify areas of concern applicable to their rights-of-way. The NWIS database is set up for automated sharing of information with the U.S. EPA (U.S. Geological Survey, n.d.). Some NPDES

Table 8-11. Trash management rating.

Effectiveness					Cost	Social/ Institutional Impacts	Sustainability Rating
Bacteria	Nutrients	Sediment	Trash	Metals			
Low	Medium	Low	High	Low	Low/medium	Medium	Moderate/high

permits prohibit the discharge of contaminated groundwater from storm drain systems. Once discharged from the storm drain, DOTs can be accountable for any and all contamination transported to the receiving water. The main factors influencing groundwater inflow to storm drains are:

- Presence of a high groundwater table near a storm drain system, and
- Type of storm drain joint construction.

DOTs can implement a variety of practices and controls to identify and prevent groundwater inflow to the storm drain system. These include dry weather screening, subsurface condition assessment to identify the presence of groundwater inflow, and retrofit of existing pipes and connection joints. Dry weather screening should involve analysis for any constituent of concern identified using the USGS NWIS or similar source of information.

Preventing future groundwater inflow to the storm drain can be achieved by ensuring appropriate specifications during the design and construction processes. Once identified, groundwater inflow can be controlled by sealing/grouting pipe joints (reinforced concrete pipe) or slip lining (corrugated metal and plastic pipe).

8.6.1.2 Applicability to Sources and Target Audiences

The sources of groundwater pollution are many and varied and may include industry, the military, and agriculture, or be naturally occurring. Damaged sewer pipes that pass over storm drain systems may also contribute polluted infiltration. Groundwater that infiltrates into the storm drain may pick up pollution, particularly pathogens, which tend to be sustained in the absence of light and with sources such as vectors, and transport them to receiving waters.

8.6.1.3 Opportunity

The opportunity for this BMP is very good in locations where the groundwater table free surface is higher than the local storm drain system. The practice of constructing storm drains with watertight joints varies from region to region.

8.6.1.4 Pollutants Addressed

The primary pollutants addressed by controlling groundwater inflow to the MS4 are:

- Nitrate, phosphorus,
- Total dissolved solids (TDS), and
- Bacteria (picked up in the system as flow passes through).

Secondary pollutants addressed include:

- Pesticides and
- Organic compounds.

Other pollutants may contaminate groundwater, such as selenium, arsenic, and iron from natural or anthropogenic sources.

8.6.1.5 Managed Variables

High Groundwater and Joint Construction. The managed variables for controlling groundwater infiltration into storm drains depend on whether the control project will be for new construction or as a retrofit. For new construction, options include:

- Specify watertight joints for the pipe,
- Use pipe materials with watertight joint systems, and
- Elevate the conduit profile above the ground water phreatic surface.

For retrofit construction, options include:

- Cured-in-place pipe (CIPP) lining,
- Slip lining,
- Sealing joints,
- Lowering the groundwater table, and
- Separating slope drains from storm drain system and discharge to sanitary sewer.

With new construction projects, the engineer has the option of specifying watertight joints as a part of the plans, specifications, and estimate package. There are four primary pipe materials commonly used for storm drain systems: poly vinyl chloride (PVC), high-density polyethylene (HDPE), corrugated or spiral rib steel, and reinforced concrete pipe (RCP). Each of these pipe materials either has a watertight joint as a part of standard construction or can be modified to include a watertight joint.

- PVC. PVC pipe joints are watertight for standard installations. The engineer should determine the maximum external head to be placed on the joint and verify with the pipe manufacturer that the joint design is sufficient.
- HDPE. HDPE pipe joints are watertight for standard installations. The engineer should determine the maximum external head to be placed on the joint and verify with the pipe manufacturer that the joint design is sufficient.
- Corrugated steel pipe (CSP). CSP or steel spiral rib pipe (may also be corrugated aluminum) is available with watertight joints. CSPs may abrade in the pipe invert due

to coarse material carried by flow over time or due to corrosion. Pipe joints can also separate on slopes or in high-velocity areas. If holes or gaps form, the pipe will no longer be watertight.

- RCP. Standard RCP joints may involve the use of watertight joints. A double-gasket or mortar joint should be specified, and each joint should be air tested during construction.

For retrofit construction, the approach to creating a watertight storm drain system is different. There are three approaches available to retrofit conduits:

- Chemical grouting of pipe joints. Chemical grout is injected in the pipe joint; access to the interior of the pipe is necessary. This method is primarily used for larger-diameter (30 in. and greater) reinforced concrete pipe.
- CIPP. This method may be used for pipes up to about 42 in. in diameter for any pipe material. Beyond this pipe size, slip lining is more economical.
- Slip lining. Slip lining is completed by installing a smaller carrier pipe into a larger host pipe, grouting the annular space between the two pipes, and sealing the ends.

Table 8-12 shows the life-cycle cost factors for elimination of groundwater infiltration.

8.6.2 Physical, Social, and Institutional Barriers

8.6.2.1 Physical Barriers

The following barriers may exist for storm drain sealing retrofit projects:

1. Identification of storm drain reaches with infiltration. The most effective way to identify locations with infiltration of groundwater into the storm drain system is by video camera. The cost for video of storm drain conduit ranges from $3 to $15 per linear foot (Harris, 2011). Variables significant in determining the cost include requirements for traffic control, ease of access to the beginning and ending reaches of the pipe segment, and quantity (length) of pipe to be surveyed.
2. Complexity of the storm drain profile. If the storm drain has many changes in the vertical profile, pipe laterals, junctions, and changes in conduit diameter, the cost and complexity of the sealing operation will increase. Access to the subject pipe segment is also a key determination of cost.
3. Condition of the storm drain pipe. For badly deteriorated pipes, slip lining may be the only viable option for sealing the conduit. Slip lining may reduce the capacity of the system, which may be at a premium for older storm drains.
4. If infiltration is identified as resulting from a leaking sewer pipe, coordination with the entity responsible for maintenance of the sewer system to correct the deficiency will be required.

For new construction, awareness is the primary barrier. Plan check personnel must be aware that groundwater inflow to the storm drain system should be avoided. Geotechnical information locating the season high groundwater table should be shown on the plans or discussed in design reports. Based on that information, design engineers should specify the use of watertight joints for storm drain pipe where the free surface is at or above the invert of the storm drain system.

Social and Institutional Considerations. There are few substantial social or institutional considerations associated with this BMP. Impacts to the public are likely to be limited to traffic control for some projects for access to the storm drain (or sewer) system. Cost for both investigation and completion of the work is a significant consideration.

A geotechnical engineer also should be consulted to determine the potential consequences of eliminating the drawdown of the shallow aquifer by sealing the storm drain system. It is possible that there could be secondary impacts (rising groundwater) associated with this type of project. It is also possible that habitat that has developed because of perennial flow could be altered with a reduction in dry weather flow. Local resource agencies should be consulted regarding habitat impacts if this potential exists.

Benefits from implementation of this BMP are likely to be substantial, particularly for receiving waters with a recreational beneficial use that receive infiltrated groundwater runoff from a storm drain system. Sanitary quality during dry weather conditions should be improved in the receiving water to the extent that the storm drain was a primary source of bacteria. The source of other constituents, if present in the groundwater, would also be reduced or eliminated using this BMP.

The service life of the storm drain system should be significantly extended for CIPP and slip lined projects. Permits from resource agencies will not be required to perform the work, and inconvenience to the public will be minimal in most cases.

8.6.3 BMP/Control Efficiency

8.6.3.1 BMP Efficacy

High Ground Water. The efficacy of this BMP is directly related to the presence of high groundwater that contains constituents of concern or the potential for dry weather flows to violate sanitary standards from pathogens resident in storm drain systems.

Table 8-12. Summary of performance and whole life-cycle cost factors for elimination of groundwater infiltration.

Performance Factors for Elimination of Groundwater Infiltration				
Pollutants Addressed	**Internal DOT Variables Influencing Performance**	**Performance Range**	**Advantages**	**Disadvantages**
✓ Nitrate ✓ TDS ✓ Bacteria ✓ Pesticides ✓ Organic compounds	✓ Use of watertight joints, watertight joint systems, or CIPP ✓ Elevation of the pipe profile ✓ Slip lining ✓ Lowering the groundwater table	✓ Up to 100% of pollutants originating from groundwater source, assuming proper adequacy of joints ✓ Up to 100% of pollutants originating from groundwater source, assuming proper elevation of pipe relative to groundwater table ✓ Impact on receiving water requires site-specific assessment that considers dry weather flow volume and constituent concentration	✓ High levels of dry weather pollutant reduction for targeted constituents ✓ Low social/ institutional barriers	✓ Potential physical barriers associated with inaccessible, complicated, or deteriorated existing pipe systems

Whole Life-Cycle Cost Factors for Elimination of Groundwater Infiltration			
Planning and Implementation	**Labor**	**Materials/Equipment**	**Other**
✓ Initial screening for pipes with groundwater infiltration and associated constituents ✓ Televised pipe condition assessment ✓ Research and geotechnical testing ✓ Development of prioritized implementation strategy	✓ Type of labor (i.e., DOT staff or contractor) ✓ Laboratory testing for non-visible constituents	✓ Pipe materials, liners, watertight joint systems ✓ Pump systems	✓ Targeted inspection program ✓ Record keeping and reporting

Joint Construction. Elimination of dry weather flow in systems dominated by groundwater infiltration due to non-watertight joints would be a highly effective BMP. Load reduction estimation requires a site-specific assessment of average daily flow and the concentration of the constituent of concern. For systems with groundwater infiltration, water quality improvement during non-storm periods should be high if other sources of dry weather flow are eliminated.

8.6.3.2 Costs of Implementation

Joint Construction. Costs for each of the approaches discussed previously vary based on the quantity of pipe to be sealed, access to the pipe segment(s), and pipe diameter. Table 8-13 provides a general range of prices that can be used for planning purposes for construction; these are in addition to investigation and design costs. Since the extent

Table 8-13. Estimated costs for retrofit sealing of pipe.

Method	Manhole Rehab (4-ft diameter)	Laterals (20 ft)	8 in.	10 in.	12 in.	15 in.	18 in.	21 in.	24 in.	48 in.	84 in.
Sancon's Cost Estimates*											
AM-Liner	N/A	N/A	$35	$41	$52	N/A	N/A	N/A	N/A	N/A	N/A
Sancon/CIPP	N/A	N/A	$40	$43	$52	$85	$110	$125	$141	N/A	N/A
HDPE slip lining	N/A	N/A	$25	$30	$35	$50	$60	$70	$85	N/A	N/A
Danby	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$342	$633
CIPP spot repairs	N/A	20-ft long	$3,500	$4,000	$5,000	$5,200	$6,000	$7,000	N/A	N/A	N/A
Link pipe/spot repairs	N/A	3-ft long	$2,000	$2,000	$2,200	$2,500	$3,000	$3,300	$3,500	$5,500	N/A
Lateral lining	N/A	$5,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Manhole Sancon 100	$250/ft	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Manhole Sancon 200	$375/ft	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Manhole Linabond	$525/ft	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* Data from personal communication with Mr. Chuck Parsons, Sancon Engineering, Huntington Beach, CA.

Cost factors to consider:

Pipe lining is based on 250-ft run lengths with five laterals included (additional laterals $250/each, normal cleaning included, CCTV included).

Manhole rehabilitation is based on 10-ft-deep manholes (3 manholes/callout); normal traffic control is included.

of infiltration into storm drain systems is not known, it is not possible to calculate area-wide remediation costs.

8.6.4 Sustainability Rating

Implementation of this BMP has a high sustainability rating for projects that meet basic criteria (see Table 8-14). Investigation must be completed to document the presence of groundwater infiltration into the storm drain system, as well as the quality of the discharge at the receiving water. Storm drain systems receiving infiltrated groundwater of poor quality or that become contaminated through the storm drain system are candidates for implementation of this BMP.

DOTs might consider an infiltration screening program for highway storm drain systems considered to be at risk of receiving contaminated groundwater or thought to be a source of pathogens. The basic screening process could consist of:

1. Review NWIS and other available local data to identify systems with flow and constituents indicative of a groundwater source (high TDS, nitrate, or, potentially, bacteria and hydrocarbons).
2. Perform field inspections to screen systems without flow data and verify the source of dry weather flow when detected.
3. Review available depth to groundwater data to screen for candidate systems.
4. Review storm drain construction drawings and area geotechnical investigations.
5. Video storm drain systems with a high probability of groundwater infiltration (based on steps 1 to 4) to confirm infiltration and the lineal extent of the infiltration along the system.
6. Estimate the relative magnitude of groundwater infiltration to storm drain systems versus surface dry-weather flow sources for areas of interest.

If groundwater infiltration to the storm drain system is determined to be a significant cause of impairment, and other options for limiting inflow have been explored, repair projects could be prioritized based on the following hierarchy:

1. Systems discharging to water bodies with a TMDL for a constituent present in the dry weather discharge.

Table 8-14. Storm drain groundwater inflow sustainability rating—dry weather.

Effectiveness					Cost per Mile	Social/ Institutional Impacts	Sustainability Rating
Bacteria	Nutrients	Sediment	Trash	Metals			
High	High	Low-medium	Low	Low	Varies	Low	High

2. Systems discharging to U.S. EPA's 303(d) list of impaired water bodies for a constituent present in the dry weather discharge.
3. Systems discharging to water bodies with known exceedances for a constituent present in the dry weather discharge.
4. Systems discharging to another permitted entity.
5. All other systems.

8.7 Slope and Channel Stabilization

8.7.1 Control Description

8.7.1.1 General

Channel and slope stabilization consists generally of a range of structural and nonstructural BMPs aimed at reducing or eliminating artificially accelerated rates of erosion and sedimentation. This section will focus on nonstructural sub-controls that can be used to correct degraded streams crossing or flowing longitudinally to DOT right-of-way areas, inadequately maintained slopes created from highway embankments, and cut areas.

The major factors contributing to the need for channel and slope stabilization are:

1. Highway and drainage design standards, and
2. Section 404/401 of the Clean Water Act permitting and associated channel and riparian restoration consisting of:
   a. Improvement to channel alignment and cross-section,
   b. Revegetation and habitat management,
   c. Individual erosion and sediment control best management practices (BMPs for slope areas), and
   d. Inspection and maintenance programs.

8.7.1.2 Target Audiences

The target audience for this BMP consists of:

- DOT engineers, environmental planners, design consultants;
- Regulators within resource agencies; and
- DOT inspection and maintenance staff.

8.7.1.3 Opportunity and Pollutants Addressed

The opportunities to use this BMP will vary by location depending on the number of natural or unlined channels, the degree of urbanization, and the intensity of precipitation. Location can also affect the opportunity to implement channel and slope stabilization BMPs based on the potential for occurrence of natural wildfire. The National Interagency Fire Center maintains extensive statistical information regarding the location and occurrence of wildfires dating back to 1960. In 2013, 4.4 million acres of land were damaged by wildfire, with the loss of surface vegetation resulting in substantial increase of erosion. In years past, the nationwide total has approached or exceeded 9 million acres (National Interagency Fire Center, 2014). Fire risk is particularly relevant for DOTs situated within arid and semi-arid climates of the southwestern United States.

Pollutants and indicators addressed by this BMP are:

- TSS, which also acts as a proxy for:
  - Total metals. [TSS also correlates well with COD, biochemical oxygen demand (BOD), total phosphorus, polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (commonly, DDT), dioxin, mercury, phthalates, chlordane, and dieldrin.]
  - Natural channel form.
- Flow rate and volume (through enhanced infiltration), which can affect:
  - Pathogens and nutrients.
- Other natural stream attributes:
  - Temperature.
  - Aquatic food sources.
  - Obstructions to aquatic migration.

8.7.1.4 Managed Variables

Update of Drainage Design Standards. Creation and implementation of new design standards should be done to the extent necessary to adequately address new regulations targeting the effects of hydromodification management and receiving water impairments/TMDLs for turbidity, TSS, and other pollutants associated with degrading channels and slopes.

Channel and Riparian Restoration. Channel restoration projects can involve many different aspects, both structural and nonstructural, and can involve improvement within the banks or riparian areas. Nonstructural aspects can have varying impacts on water quality improvement, depending on their specific nature and extent. Channels that are eroding at an increased rate relative to natural conditions degrade habitat in both the eroding reach and downstream where eroded materials are deposited.

- Type and extent of revegetation—Herrera Environmental Consultants et al. (2006) credit revegetation practices as being effective in terms of volume management. Volume can be considered a good general proxy for the overall load of urban pollutants and pathogens (suspended, partially suspended, and soluble). Volume also has significance in contributing toward hydromodification effects in urbanized areas. Revegetation is also considered significant in terms of controlling flow rate. All factors created equal, projects that involve longer, denser revegetation components will result in better overall flow rate and volume management. Vegetation is also an important component of high-quality habitat.

- Extent of alignment and cross-section improvements—Extensive research and publication of data and design criteria have been done that relate channel alignment (horizontal and vertical), cross-section, bed material size, and flow rate with likelihood of long-term stability. Stormwater managers usually have little to no control over watershed flow rate or natural channel bed material, but from a design perspective, they have some control on the ability to balance these with properly determined alignment meanders, cross-section changes, and grade adjustments. (Grade control structures are not specifically addressed here but could be a tool for the stormwater manager.) All factors being equal, projects that adhere more closely to established alluvial channel design criteria will achieve better results controlling flow rate and sediment discharge. A stable channel cross-section with riffle–pool sequences is important for high-quality habitat and spawning and the presence of macroinvertebrates.
- Size of channel/stream—Herrera Environmental Consultants et al. (2006) discuss variability in water quality effectiveness of stream restoration projects as a function of individual design elements versus stream size. Restoration of riparian areas is cited as most effective in smaller streams. Addition of habitat structure or root wads, logs, and so forth is discussed as most effective in small to mid-sized streams. All factors being equal, projects that involve restoration of riparian areas will achieve greater beneficial impact on channel form, temperature, and pollutants when applied to smaller streams or sloughs.

Individual Erosion and Sediment Control BMPs for Slope Areas. The City of Portland, Oregon, conducted a study in 2006 that evaluated the effectiveness of a wide range of structural and nonstructural BMPs (Herrera Environmental Consultants et al., 2006). Among the nonstructural BMPs considered most effective were those that involved revegetation practices, protection of stream buffers, erosion control, and development regulation. These BMP sub-controls were deemed highly effective in terms of flow reduction, volume reduction, habitat improvement, temperature management, and TSS removal.

Inspection Frequency and Location. Channel inspections should identify, among other issues, long-term incision or sedimentation within streams that can result from urbanization, lateral highway encroachment, and highway crossing. All factors being equal, increased inspections by properly trained personnel should result in a lower percentage of surface waters suffering from bed and bank destabilization. However, this is only true if suitable corrective measures are identified and implemented in a timely manner.

Table 8-15 shows the life-cycle cost factors for slope and channel restoration.

8.7.2 Physical, Social, and Institutional Barriers

Barriers to this BMP are:

- Limitations in right-of-way/easements;
- Physical limitation in access to stream and slope areas;
- Resource agency permitting and related requirements;
- DOT staff resources for inspection; and
- Financial resources to design, construct, and monitor stream stabilization projects.

Social/Institutional Considerations

Social considerations related to this BMP are:

- Temporary impacts on stakeholder use (channels and riparian areas),
  - Temporary discontinuation of use during construction,
- Permanent stakeholder benefits (channels and riparian areas),
  - Recreational,
  - Aesthetic,
- Inherent staff resistance to changes/increased design standards, as well as the associated need for related training, and
- Positive citizen reaction from avoiding property damage associated with slope failure.

8.7.3 BMP Efficiency

8.7.3.1 BMP Efficacy

Update of Drainage Design Standards. This practice would be applicable for DOT design and retrofit projects. DOTs could face increasingly stringent NPDES standards related to flow duration, sediment supply, and volume impacts. In California, these impacts are collectively known as "hydromodification." No known data correlate the effectiveness of engineering hydromodification management standards to abatement of artificially accelerated channel erosion and sedimentation. In San Diego County, CA, a regional hydromodification monitoring program has been developed to increase the accuracy of recently updated engineering design standards and to reduce the gap between theoretical and actual performance of hydromodification BMPs. The stringency of hydromodification management standards created through MS4 NPDES permit requirements in California is consid-

Table 8-15. Summary of performance and whole life-cycle cost factors for slope and channel restoration.

Performance Factors for Slope and Channel Restoration				
Pollutants Addressed	**Internal DOT Variables Influencing Performance**	**Performance Range**	**Advantages**	**Disadvantages**
✓ TSS and associated proxies ✓ Flow rate and volume	✓ Channel restoration projects – alignment, vegetation, stable geometry, etc. ✓ Erosion and sediment control BMPs – rolled erosion control products, grade controls, etc. ✓ Nature, frequency, and location of inspection ✓ Appropriate design standards	✓ Channel restoration – TSS and associated proxies varies up to 60% ✓ Erosion and sediment control BMPs – TSS and associated proxies varies up to 90%	✓ Long-term aesthetic and recreational benefits to riparian areas ✓ Reduced property damage from slope failures	✓ Potential institutional barriers associated with changing/more stringent design standards for DOT staff ✓ Potential physical conflicts with insufficient right-of-way or access to stream and slope areas ✓ Regulatory permitting and processing for channel improvement projects ✓ Potential temporary impacts to channel and riparian areas

Whole Life-Cycle Cost Factors for Slope and Channel Restoration			
Planning and Implementation	**Labor**	**Materials/Equipment**	**Other**
✓ Staff training ✓ Development of prioritized implementation strategy	✓ Type of labor (i.e., DOT staff or contractor) ✓ Post-project monitoring and sampling	✓ Landscaping, native revegetation ✓ Grade control structures ✓ Erosion and sediment control BMPs and associated equipment (hydroseed spray trucks, etc.) ✓ Earthwork, grading equipment ✓ Fuel, equipment maintenance, and depreciation	✓ Targeted inspection program ✓ Record keeping and reporting

ered very effective at maintaining current stream alignment and cross-section. As a restorative means to address streams already degraded by urbanization, the effectiveness of adopting hydromodification management standards can only be assessed through long-term monitoring programs.

Channel and Riparian Restoration. Alluvial channels that have been affected or that are undergoing change as a result of increased imperviousness in the watershed may benefit from in-channel restoration projects.

- Improvement to channel alignment and cross-section—It is assumed that modification to channel alignment and cross-section would be re-engineered to a dynamically stable condition, whereby sediment transport into a given reach generally equals that which is exiting. Consequently, it is reasonable to anticipate that accelerated levels of erosion and sedimentation could be reduced.
- Riparian restoration is considered to have little to no effectiveness on flow rate or volume management (Herrera Environmental Consultants et al., 2006). The Herrera study does indicate, however, a moderate effect on TSS and other pollutant proxies in small to medium-sized streams.
- Integration of multiple restoration elements—It is common for channel stabilization or restoration projects to include multiple nonstructural elements such as geometric improvement, revegetation, and riparian restoration. Projects that include some or all of these elements would be expected to have increased water quality benefits compared to projects that incorporate only a single aspect. However, very little information exists on directly measured benefits resulting from stream restoration.

A 2002 study conducted by the Chesapeake Bay Laboratory and the University of Michigan performed in-depth reviews of approximately 37,000 channel restoration projects (Burks, n.d.). The study found that less than 10% of the projects involved monitoring or assessment. Among the 10% of those projects that did involve monitoring, most focused on implementation rather than ecological benefit. A limited study conducted by the University of Maryland on six streams in Anne Arundel County concluded that the restorations were not effective at retaining or reducing nutrient loads (http://chesapeake.news21.com/water/stream-restoration). The study authors were emphatically cautious about applying any conclusions from these six sites to other projects due to the inherently dynamic nature of streams. Within the San Diego region, the Chollas Creek enhancement project at Youth Park was assessed in a study prepared by Weston Solutions (Weston Solutions, n.d.). The monitoring conducted as part of this project consisted of two seasons of pre-project wet-weather data and limited post-construction information. The study concluded that there was a general decrease in the concentration of metals. The study also anticipated a further reduction in TSS and associated pollutants as vegetation continues to mature. Based on the aforementioned factors, the following overall range of effectiveness is assumed for stabilized channel reaches, before and after a project:

- TSS and pollutant proxies (PCBs, trash, metals)—40% to 60% removal.
- Bacteria and nutrients—10% to 25% removal.

Individual Erosion and Sediment Control BMPs for Slope Areas. These practices are considered highly effective in controlling flow rate and sediment discharge. Standard engineering methods [e.g., Revised Universal Soil Loss Equation (RUSLE), Modified Universal Soil Equation (MUSLE), rational method hydrology] are available to quantify the specific reduction. Research conducted by the United States Department of Agriculture—Natural Resources Conservation Service (USDA-NRCS) over the course of several decades indicates that properly implemented erosion control measures can reduce average annual sediment loss by more than 90% compared to bare soil. Sediment control measures, by contrast, are substantially less effective when solely implemented without the benefit of erosion control.

8.7.3.2 Whole Life Costs of Implementation

Update of Drainage Design Standards. The cost of implementing hydromodification management standards by DOTs has not been studied in detail but is expected to be substantial based on known impacts from private development in California. Hydromodification management standards affect the traditional stormwater management design approach by necessitating enhanced attenuation, infiltration, and avoidance of coarse sediment areas. In a typical highway fill prism, infiltration is rarely suitable as a BMP, and if it is, only at a nominal rate. Bioretention is a structural BMP particularly well suited to addressing hydromodification impacts. However, construction in a highway environment would likely have impacts to right-of-way needs and would necessitate the use of permeable liners, subdrains, and select soil backfill. In California, municipal hydromodification management standards often necessitate bioretention sizing on the order of 8% to 15% of the contributing area, though this will vary from project to project based on precipitation frequency, soil, topography, and other climate conditions. Costs can be on the order of $15 per square foot or higher.

Channel and Riparian Restoration. The costs associated with implementation of (nonstructural) channel stabilization projects consist of design, permitting, construction, and, in some instances, land acquisition and monitoring. Construction includes items such as earthwork, temporary and permanent revegetation, varying forms of natural structures, and, in some instances, acquisition of easements or right-of-way. Since the 1980s, the State of Maryland has conducted approximately 221 stream restoration/nonstructural stabilization projects, through either the state highway agency or the state environmental agency. The total cost of these 221 projects was approximately $110 million, or an average of about $0.5 million each. Other project-specific data suggest costs in the range of $1.5 to $5 million per mile, depending on the extent and nature of the restoration. Basic stability monitoring can cost as little as $5k to $10k annually. More intricate water chemistry and biological monitoring can add significantly to overall project cost. However, the value of chemical and biological monitoring must be assessed on a project-by-project basis in the context of the project goals and requirements. Available data for chemical and biological monitoring suggests costs of $40k to 50k on an annual basis for a typical project. These costs could vary significantly for atypically large or small projects.

The North Carolina Ecosystem Enhancement Program (NCEEP) in-lieu fee program assesses a charge of $338 per foot of affected stream based on the current fee schedule for higher fee cataloging units (effective July 1, 2010; North Carolina Ecosystem Enhancement Program, 2010). The rate represents the average cost for stream restoration projects and includes planning, design, construction, land acquisition, maintenance, and monitoring. However, the cost of restoration efforts at a particular location is dependent on the intensity of management measures recommended and the level of degradation. NCEEP has addressed this dependence by applying the mitigation credit ratios by management type to the $338 per foot rate to differentiate the approximate costs (Robin Hoffman, North Carolina Ecosystem Enhancement Program, personal communication, July 26, 2010).

Project costs for buffer restoration projects are typically based on the square feet to be restored and the fee schedule of $0.96 per square foot. Cost determinations for reaches recommended for only buffer restoration will require more detailed on-site assessments to more accurately determine areas of needed restoration; therefore, they were not considered in the cost–benefit analysis. Preservation/protection sites were also excluded from the analysis.

Individual Erosion and Sediment Control BMPs for Slope Areas. The costs associated with slope stabilization measures are fairly well documented in publications from the California Stormwater Quality Association and Caltrans since they involve employment of traditional erosion and sediment control BMPs as well as permanent stabilization measures used in construction and development. The measures include vegetated approaches such as permanent landscaping, temporary hydroseed, and bonded fiber matrices. Additionally, these could include rolled erosion control products, binding agents, and standard sediment control measures suitable for use on slopes, such as silt fences and straw waddle. Major slope re-stabilization can also involve structural elements such as grading and buttressing of keyway areas. Erosion and sediment control BMPs for exposed slope areas generally range on the order of $15k to $25k per acre.

Another point of reference for DOTs pertaining to the cost of under-vegetated or destabilized slope areas can be found within the Caltrans Stormwater Program Annual Report for Fiscal Year 2012–2013 (http://dot.ca.gov/hq/env/stormwater/annual_report/index.htm). Of the 9,678 miles of shoulder area inspected, only 55 major problem areas were identified, along with 378 minor problems. The cost for major problem projects is defined as requiring funds in excess of $1,000 per site or $15,000 per mile. Minor problem projects are defined as being less than this lower cost threshold.

8.7.4 Sustainability and Suggestions for Practitioners

Implementing slope stabilization programs by DOTs would be cost-effective for reducing sediment discharge to receiving waters. Many DOTs, like Caltrans, are currently performing slope stabilization activities in limited areas as a response to erosion failures, wildfires, and so forth. In situations where slope areas constitute 50% of the right-of-way, an enhanced slope stabilization program could reduce TSS from DOT sources on the order of 50 lb per acre annually, or 25%. These values of course would vary from location to location throughout the United States as a function of slope topography, length, rainfall intensity, and the adequacy of current vegetative cover. Slope revegetation is also attractive when viewed from a whole life cost perspective since efforts at a particular site are assumed not to involve annual reoccurrence, as would be expected with maintenance of a structural BMP. Enhanced slope stabilization programs should prioritize and target roadways in TMDL watersheds where current vegetative cover is minimal or where slopes constitute greater percentages of the right-of-way. Increased effectiveness of enhanced stabilization programs can be achieved in high-priority target areas by coupling slope revegetation with other practices aimed at reducing TSS from the roadway surface. A strategically prioritized program involving enhanced slope stabilization is considered to have a high sustainability rating given the whole life costs, ability to significantly contribute to meeting TMDL waste load allocations, and low institutional barriers.

Given both the documented and intuitive effectiveness of stream restoration with respect to TSS, proxy pollutants, and (to a lesser extent) stormwater volume, it is clear that substantial portions of many urbanized watersheds could benefit from wide-scale implementation. However, capital costs would be high, but these types of projects result in other ecological, aesthetic, and recreational benefits that extend beyond the objectives of the NPDES permit and TMDL programs. Consequently, many would likely receive support from citizens and nongovernmental organizations. Some channel restoration projects may be eligible for grant funding or cost sharing with other agencies and organizations.

Inspection resources can be leveraged most effectively by accurately identifying susceptible channel reaches before they reach a point of significant failure. This is particularly true in watersheds that have experienced significant development in the previous 10 years without the protection from newer design standards or targeted management practices. These critical watersheds are likely still within the lag period in which hydromodification symptoms have not fully emerged. It is suggested that GIS-based rapid screening programs be developed in conjunction with routine inspections to prioritize channel reaches that can benefit the most from restorative projects, and in doing so, also contribute toward effective numeric reduction of other urban pollutants. To provide value, it is critical that the staff who conduct these inspections be trained on geomorphic processes and be capable of recognizing the preliminary signs of artificially triggered changes. It is suggested that methods such as the Rosgen Stream classification method be included in training for highway inspection teams.

Table 8-16. Channel and slope stabilization sustainability ratings.

Effectiveness of Integrated Channel Stabilization					Cost per Mile	Social/Institutional Impacts	Sustainability Rating
Bacteria	Nutrients	Sediment	Trash	Metals			
Low-medium	Low	Medium-medium/high	High	Medium	$1.5 to $5 million	Low	Moderate
Effectiveness of Slope Stabilization					**Cost per Acre**	**Social/Institutional Impacts**	**Sustainability Rating**
Bacteria	**Nutrients**	**Sediment**	**Trash**	**Metals**			
Low-medium	Low	High	Medium-high	Medium	$15 to $25 thousand	Low	High

A regionally prioritized approach is the most appropriate for wide-scale implementation. Given their technical effectiveness at a regional level, their capital investment requirements, their publicly desirable nature, and their potential for limited post-construction costs over the whole life, stream stabilization projects have been given a "moderate" overall sustainability rating for channel stabilization (see Table 8-16).

8.8 Winter Maintenance BMPs

8.8.1 Control Description

DOTs are responsible for maintaining passable and safe roadways during winter. Current methods to accomplish this involve the use of plow blades working in conjunction with the use of abrasives and chemical anti-icing and deicing agents. Application of these materials is sometimes controlled using GPS and computer automation (Alwan and Casey, 2014).

Abrasives function during winter conditions by creating friction between tires and the road surface; they require certain characteristics to function properly, including high breakdown strength and minimal potential to generate fine particles. However, sand is not effective at keeping snow and ice from adhering to the pavement. The use of deicing chemicals can accomplish this and hasten the melting process. The use of abrasives such as sand or ash, and deicing chemicals such as salt, can represent a threat to receiving water quality. Studies have found that at highway speeds, the majority of sand applied to the road is blown off by only a handful of vehicles. A direct relationship between the use of roadway abrasives and particulate matter emissions from highway traffic has also been documented in previous research. In some western states such as South Dakota, Montana, Idaho, Colorado, and Nevada, sand application and snow control activities are considered a significant contributor to particulate air quality problems (Barbaro, 2006).

8.8.1.1 General

The major factors for winter BMPs for traction aides and deicers are:

- Choice of materials used as abrasives and ice control agents;
- Material storage;
- Rate and technique used during application of abrasives and chemical agents;
- Temperature and weather conditions during application of abrasives and chemicals agents;
- Use of automatic vehicle location systems, application sensors, and high-efficiency equipment (intelligent control systems);
- Operator training; and
- Timing and method of post-season cleanup efforts (refer to Street Sweeping section).

8.8.1.2 Target Audiences

The target audience for this BMP consists of DOT road maintenance staff and maintenance contractors, including plow operators and employees at material storage yard areas.

8.8.1.3 Opportunity and Pollutants Addressed

Pollutants addressed are:

- TSS;
- Sedimentation;
- Eutrophication (Barbaro, 2006);
- Phosphorus (Barbaro, 2006);
- Sodium chloride (Barbaro, 2006);
- Calcium chloride (Barbaro, 2006);
- Magnesium chloride (Barbaro, 2006);
- Sulfate (Smith and Granato, 2010);
- Total metals (Smith and Granato, 2010); and

- Other adverse impacts, such as increased flooding potential, impacts to aquatic habitat, and proliferation of invasive species (Barbaro, 2006).

A study of highway runoff water quality conducted in Massachusetts found a substantial increase in concentration for nearly all constituents measured between composite samples taken during winter months compared to samples taken during non-winter months. Total phosphorus, total metals, and suspended sediment, for example, were found during the winter at levels 3 to 11 times the average concentration during the non-winter period. Differences in snow removal techniques and the presence of snow embankments along the highway were identified as among the variables that potentially affect the winter concentration of metals and organic compounds. These differences in concentration between winter and non-winter periods tended to be greater for highways with less traffic. Snow embankments were also shown to have the potential of entraining large amounts of highway-related particulates near the shoulder, capable of being washed downstream during the spring rains (Smith and Granato, 2010).

8.8.1.4 Managed Variables

Salt Application Rates. The application of traction aides and deicers can increase the sediment or chloride (salt) load in highway runoff. Chloride is extremely mobile and soluble, and once it has been introduced to the environment, it is nearly impossible to remove without advanced treatment. The only practical control option is to minimize the use of salt. Sand on highways can be removed through an aggressive street-sweeping program (see the Street Sweeping section).

A balanced approach should be used during application of salt for snow and ice control (The Salt Institute, 2007). This will result in providing the necessary level of safety for traffic while minimizing the potential for transport of pollutant constituents that results from overapplication. Determining a properly calibrated application rate in conjunction with the use of automated spreader control systems can keep the amount of salt needed for adequate traffic protection to a minimum. Proper application rates will take into consideration variations in road surface temperature, type of precipitation, and the tendency for accumulation. The practitioner should keep in mind that there is no direct correlation between yearly snowfall and the total quantity of salt required for effective traffic protection. The type of storm dictates the frequency of application and total amount of salt necessary. For example, a short-term freezing rain or ice storm may require large amounts of salt, perhaps even more than a prolonged snowstorm. Table 8-17 illustrates the relationship between road temperature, meteorological condition, ideal salt application rate, and resulting coverage per two-lane mile of highway.

Table 8-17. Salt application guidelines.

Condition	Suggested Application Rate	Coverage of Salt Per Two-Lane Mile (yd^3)
Temperature near 30°F Precipitation: snow, sleet, or freezing rain Bridge surface wet	If snow or sleet, apply salt at 500 lb per two-lane mile. If snow or sleet continues and accumulates, plow and salt simultaneously. If freezing rain, apply salt at 200 lb per two-lane mile. If rain continues to freeze, re-apply salt at 200 lb per two-lane mile. Consider anti-icing procedures.	Snow/sleet – 4 Freezing rain – 10
Temperature below 30°F or falling Precipitation: snow, sleet, or freezing rain Bridge surface wet or sticky	Apply salt at 300 to 800 lb per two-lane mile, depending on accumulation rate. As snowfall continues and accumulates, plow and repeat salt application. If freezing rain, apply salt at 200-400 lb per two-lane mile. Consider anti-icing and deicing procedures as warranted.	Snow – 6 to 2½ Freezing rain – 10 to 5
Temperature below 20°F and falling Precipitation: dry snow Bridge surface dry	Plow as soon as possible. Do not apply salt. Continue to plow and patrol to check for wet, packed, or icy spots; treat only those areas with salt applications.	N/A
Temperature below 20°F Precipitation: snow, sleet, or freezing rain Bridge surface wet	Apply salt at 600 to 800 lb per two-lane mile, as required. If snow or sleet continues and accumulates, plow and salt simultaneously. If temperature starts to rise, apply salt at 500 to 600 lb per two-lane mile and wait for salt to react before plowing. Continue until safe pavement is obtained.	Snow or sleet – 4 to 2½
Temperature below 10°F Precipitation: snow or freezing rain Bridge surface accumulation of packed snow or ice	Apply salt at a rate of 800 lb per two-lane mile or salt-treated abrasives at rate of 1,500 to 2,000 lb per two-lane mile. When snow or ice becomes mealy or slushy, plow. Repeat application and plowing as necessary.	Snow or freezing rain – 2½

Source: The Salt Institute, 2007.

It is important to note that typically available temperature information from traditional meteorological sources is measured at 30 ft above the ground (The Salt Institute, 2007). Determining the optimal salt application rate for a highway should be based on the actual roadway temperature as opposed to the air temperature. Obtaining this type of information requires road sensoring systems or having access to a road weather information system (RWIS) (The Salt Institute, 2007).

Calibration of material spreaders is critical in ensuring that the planned application rate achieves the actual application rate. Calibration involves calculating the pounds per mile actually discharged at various spreader control settings and truck speeds. It is carried out by counting the number of auger or conveyor shaft revolutions per minute, measuring the salt discharged in one revolution, multiplying the two, and finally multiplying the discharge rate by the minutes it takes to travel 1 mile. An example of a calibration chart in a spreadsheet format can be found on the Salt Institute website at http://www.saltinstitute.org/images/calibrationchart.xls.

Another work effort aimed at producing practical outcomes and optimizing winter maintenance activities such as the application of salt and deicing agents is the Clear Roads Highway Operations Pooled Fund (the Clear Roads project). The Clear Roads project is a cooperative effort consisting of 14 state DOTs that leverages membership contributions to identify and conduct research relating to emerging technology, performance, cost, and environmental impact, among other topics (Alwan and Casey, 2014). For more information on research efforts being conducted by the Clear Roads project, refer to http://www.clearroads.org/research-projects.html.

Salt and Sand Application Techniques for Pollutant Minimization. Several techniques can be observed when applying salt. These techniques include pre-wetting, determining the proper spread width, consideration of wind effects, consideration of plow timing relative to salt application, and how plowing influences the need for re-application.

Pre-wetting salt with brine speeds the reaction time of the salt and keeps it from bouncing off the road so more of it is available to melt the ice and snow. This effect also helps minimize the salt's transport potential. However, brine use should include careful consideration of how varying concentration and temperature influence the effectiveness in deicing and snowmelt. Brine will only be effective on highways with a temperature of between –6 degrees and 30 degrees Fahrenheit and in concentrations of 5% to 23% salt by weight (The Salt Institute, 2007). Various material alternatives to brine exist for use in pre-wetting. A tool has been developed to evaluate relative trade-offs between cost, performance, and environmental impact of brine application that can be used by DOT practitioners. Refer to the following website for a copy of the tool and additional information regarding the selection of environmentally sensitive pre-wetting materials: www.saltinstitute.org/snowfighting/index.html.

Salt spreading on highways is typically done by applying a windrow of salt in a 4- to 8-ft strip along the centerline. This technique is effective on two-lane pavements with a low to medium traffic count (The Salt Institute, 2007). Less salt is required with this pattern and quickly gives vehicles clear pavement under the wheel areas. Traffic will soon move some salt off the centerline, and the salt brine will move toward both shoulders for added melting across the entire road width. It is important in this scenario to remove remaining snow from the shoulder area as quick as possible, since when snowmelt occurs, it will potentially refreeze and necessitate re-application. As snow melts within the shoulder area, the use of salting directly into drains should be avoided or minimized.

Consciousness of wind conditions is also an important aspect when spreading salt. A strong wind blowing across the roadway can cause salt to drift as it comes out of the spreader, pushing it onto the shoulder area where drains are located. This is particularly true in rural areas where there are few windbreaks. How the wind affects spreading depends on both velocity and pavement conditions. The operator or application crew should avoid areas where high wind has the potential to blow salt to the shoulder.

It is important also to know when to plow and re-apply salt. Salt use can be minimized by giving it appropriate time to work. Plowing operations should be timed to allow maximum melting by salt. The need for another salt application can be determined by watching melting snow kicked out behind the vehicle tires. If the slush is soft and fans out like water, the salt is still effective. Salt should only be re-applied once the slush begins to stiffen and is thrown directly to the rear of vehicle tires (The Salt Institute, 2007).

Application of sand is most effective when the weather is too cold (under 5 degrees Fahrenheit) for chemical deicers. Some agencies, such as MassDOT, use a mixture of salt and sand in limited conditions such as exceptionally low temperature, on steep grades, and at sharp curves and intersections. Their policy of strategic reduced winter sand use was effective at lowering the ratio relative to salt from an average of 1:3 to 1:10. Use of chemical brine solutions is a common method also used in the application of abrasives such as sand. Other modestly effective alternatives to brine use include heating the abrasive or mixing it with hot water (Barbaro, 2006). Another emerging approach aimed at reducing environmental impact and cost involves expansion of the use of directly applied liquid deicers, although field testing to date is highly limited (Alwan and Casey, 2014).

Post-Winter Cleanup. The timing of post-winter cleanup of sand and salt is important because the removal of accumulated material in the spring creates less opportunity for transport during spring and summer rain events. Sand cleanup removes only a small portion of the total sand applied each winter. In high-speed roads, traffic tends to throw sand particles away from the travelled way. On lower-speed roads, pulverizing effects from traffic can hamper the effectiveness of street sweepers. The majority of the sand remains in the environment, where it degrades water bodies and air quality (Barbaro, 2006).

Table 8-18 shows the life-cycle cost factors for winter maintenance.

8.8.2 Social and Institutional Barriers

Social and institutional barriers associated with modifying traditional winter maintenance activities are well described within Barbaro's "Environmental Concerns of Sand," a portion of which is cited here:

"Some public works officials believe that the use of contractors for snow and ice control services results in excessive application of deicing materials due to contractors typically hiring temporary drivers who, compared to year-round maintenance staff, lack operational experience and knowledge in the application of deicing materials.

In addition, sand may be over-applied in some communities due, in part, to the visual and psychological benefits of the roads being treated. In these cases, when citizens see an agency working on controlling roadway snow and ice, namely by spreading sand, they get a sense of safety (although perhaps a false sense), while the agency gets a public relations benefit. This is especially true because sand provides visible

Table 8-18. Summary of performance and whole life-cycle cost factors for winter maintenance BMPs.

Performance Factors for Winter Maintenance BMPs				
Pollutants Addressed	**Internal DOT Variables Influencing Performance**	**Performance Range**	**Advantages**	**Disadvantages**
✓ TSS ✓ Sedimentation ✓ Eutrophication ✓ Phosphorus ✓ Sodium chloride ✓ Calcium chloride ✓ Magnesium chloride ✓ Total metals ✓ Particulate matter (PM-10)	✓ Choice of materials used for abrasives, deicers, anti-icing, and pre-wetting agents ✓ Application techniques ✓ Use and type of intelligent control systems ✓ Nature and timing of post-winter season cleanup ✓ Staff training, contractor qualifications	✓ Reduction of sand and PM-10 varies up to 70% ✓ Reduction of salt varies up to 600 lb per two-lane mile	✓ Reduced material cost ✓ Reduced pollutant load in receiving water ✓ Reduced post-season cleanup	✓ Potential political/public perception of reduced response ✓ Constraints from single-vendor suppliers and proprietary technology with intelligent controlled systems ✓ Environmental impact of some emerging material substitutes unknown (e.g., glass-based abrasives, directly applied liquid deicers)

Whole Life-Cycle Cost Factors for Winter Maintenance BMPs			
Planning and Implementation	**Labor**	**Materials/Equipment**	**Other**
✓ Staff training ✓ Development of modified maintenance strategy based on Salt Institute guidance, Clear Roads project, etc. ✓ Evaluation and selection of intelligent control system technology	✓ Type of labor (i.e., DOT staff or contractor) ✓ Extent/effectiveness of post-winter cleanup	✓ Intelligent control systems ✓ Materials such as salt, sand, pre-wetting agents, and other suitable material substitutes	N/A

evidence of snow and ice control work, whereas salt is less visible because it dissolves. The EPA corroborated this dynamic through a recent study, which found that abrasives are frequently applied at loadings well above recommended levels due to public perception" (Barbaro, 2006).

8.8.3 BMP Efficiency

8.8.3.1 Efficacy of Reduced Sand and Salt Application

Several noteworthy studies show the relationship between winter maintenance activities and sedimentation effects within receiving waters. For example, researchers studying North Fish Creek in Wisconsin found that 94% of sediments enter during snowmelt or storm runoff, and up to 60% of the sediments can be sand-sized particles (Barbaro, 2006). The Massachusetts Division of Marine Fisheries has determined that sedimentation is usually immediately adjacent to a road and observed normally within a range of 10 to 30 m. In 1995, the Lake Tahoe Regional Planning Agency mandated reduced sand application on SR 28. Up to 70% of sand entering the lake was shown to be from snow and ice control. Sand was being carried by rain and snowmelt into culverts that drained into the lake. In response, the Nevada DOT spent $3 million to retrofit a 1.5-mile stretch of SR 28 with structural control measures. They later emphasized the use of anti-icing chemicals, which cut the use of sand by over 70% (Barbaro, 2006).

Studies also show that 50% to 90% of sand remains in the environment after cleanup. A study of highways in Switzerland indicated that overall impacts to the environment from the use of sand are considerably greater than from the use of salt (Barbaro, 2006).

8.8.3.2 Efficacy of Alternative Material Specification

South Dakota studied sand application and set a mandatory statewide minimum hardness rating on abrasives used for snow and ice control. The quartz sand used by MassDOT has a hardness of 7 on the Mohs scale. Relatively harder particles have been shown to not break down as easily under typical transportation conditions. Colorado and Nevada have also set minimum hardness ratings for abrasives and have seen positive results. These minimum ratings are used in conjunction with limits on the places sand can be used (slower traffic areas, curves, etc.) and have been shown to reduce particulate matter (PM-10) air pollution by 50% to 75%. The City of Denver reduced sanding in experimental areas by 30% to 75% and saw significant reduction in PM-10 emissions. An alternative to sand, a type of glass-based abrasive, was examined by the State University of New York in Cooperstown to reduce phosphorus loading. Although the glass has higher phosphorus content, the phosphorus remains out of solution, leading to a lower nutrient impact relative to sand. At this time, glass-based abrasives have only been used in small-scale experimental areas (Barbaro, 2006).

Another abrasive alternative that has been studied is Realite Plus. Studies performed in Colorado have shown a potential reduction in PM-10 dust loading of 70% by using this material. It was studied by Rapid City, South Dakota, in 1996 and was found to be harder and retain its structure longer than sand. Realite Plus also led to reduced silt loading in a nearby creek, reductions in chloride standard violations, and a lower salt application rate. This material also is only being used on a small scale and needs to be studied further (Barbaro, 2006).

8.8.3.3 Whole Life Costs of Implementation

The cost of winter maintenance BMPs includes material purchase, storage, equipment and application costs, and cleanup and disposal. Research indicates that reduced use or elimination of sand is the most significant means to reduce winter-season operational costs due to the impact on cleanup and disposal (Barbaro, 2006).

In 2008, the Clear Roads project evaluated manual control systems for the application of sand and deicing agents versus open- and closed-loop ground-speed control systems. Open-loop systems monitor truck speed during application, while closed-loop systems monitor truck speed and spreader discharge. The closed-loop systems also adjust the spreader speed to optimize material use. Their study found that automated ground-speed control systems were superior to manual application, with closed-loop systems achieving as much as a 47% material savings at an application rate of 400 lb of salt per mile (Alwan and Casey, 2014).

Many DOT winter maintenance fleets use some sort of intelligent control system that incorporates GPS with automated sensors that track and adjust the application rate of sand, deicers, and anti-icing agents. Iowa DOT has determined from analysis that the single act of outfitting snowplows with GPS yielded a benefit–cost ratio of as high as 10:1. However, implementing intelligent systems can raise unanticipated cost issues associated with varying proprietary communication protocols and data format constraints. Many state DOTs deal with this challenge with a single-vendor contracting approach, established under a low-bid procurement process. Advances in industry that promote plug-and-play technology and a seamless interface between the equipment of differing manufacturers will allow for reductions in the cost of intelligent control systems (Alwan and Casey, 2014).

Assistance from private contractors using substandard equipment or employees that are not properly trained can contribute to unnecessary costs (Barbaro, 2006).

8.8.4 Sustainability and Suggestions for Practitioners

Implementing sustainable winter maintenance BMPs requires careful selection of traction and deicing materials, application techniques, and use of intelligent control systems.

Due to the difficulty of post-winter cleanup and documented environmental impact, the use of sand should be kept to a minimum. If necessitated based on extreme cold or roadway characteristics such as unusually steep gradient or tight curvature, the use of sand should involve mixing with salt or brine to limit the overall quantity required. Additionally, DOTs might develop and implement material specifications for the use of sand that require a minimum hardness, or consider alternatives such as glass-based substitutes or Realite Plus. This approach will promote easier cleanup and limit the potential for environmental transport. The evaluation tool discussed in Chapter 9 can help DOTs evaluate and select pre-wetting agents that are more cost-effective and environmentally friendly than current practices.

DOTs can consider or conduct pilot assessment of emerging practices involving substitution or elimination of traditional winter maintenance materials. With respect to abrasives such as sand, this could include heating it or mixing it with hot water as an alternative to traditional chemical brine solutions. Another approach that could prove beneficial is the use of directly applied liquid deicers as an alternative to salt. However, additional research is necessary to further explore the effectiveness, practicality, and environmental impacts of this approach. Most of the alternative products available to DOTs for use as deicing or anti-icing agents have trade-offs between cost, environmental impact, and other potential safety impacts to the road surface. Since no product has risen above the others as the clearly preferable alternative, the only practical approach is optimization of use.

Michigan DOT (MDOT) has been conducting pilot projects involving emerging technologies in winter road maintenance that could be considered for adaptation by other states. On U.S. 131, the roadway and bridge decks have been outfitted with 175 automated spray nozzles that distribute anti-icing chemicals. Another project, at the U.S. 127 bridge over Looking Glass River, involved the use of SafeLane surface overlay. This patented combination of epoxy and aggregate acts like a rigid sponge to store and safely release anti-icing agents over multiple winter storm events. MDOT also emphasizes the use of anti-icing agents as opposed to deicing agents, since they are a preventative rather than a reactive measure (MDOT Storm Water Management Team and Tetra Tech, 2006).

A pilot project similar to the one on U.S. 131 was studied at the A2 Jubilee Way Bridge in the United Kingdom. It featured a fixed automated spray technology (FAST) system for automated release of anti-icing agents by a series of sensor-activated spray nozzles. The study concluded that the cost of the FAST system was comparable to similar systems in North America and Europe and was significantly more compared to traditional salt spreading. Despite this fact, benefits could be achieved in areas of unusually high traffic or on roads that were particularly difficult to maintain by vehicles during severe weather (Plumb and Edwards, 2011). The specific long-term impacts to stormwater runoff from emerging technologies such as SafeLane, FAST, and similar spray nozzle systems requires further analysis.

Guidance from the Salt Institute and research findings from the Clear Roads project could be considered to modify techniques used to apply traditional abrasives and deicing agents such as sand and salt. Modified application techniques should take into consideration factors such as surface temperature, wind speed and direction, type of precipitation, traffic speed, and other physical characteristics such as roadway gradient and curvature and proximity to receiving water or conveyance system. Proper calibration is also an important part of applying salt at the optimum rate. Use of roadway abrasives and deicers should help avoid the social and political pressure associated with overapplication in high-visibility locations. Public education and outreach campaigns may be an effective means of reducing these social and political pressures over the long term.

Research conducted by the Clear Roads project, Iowa DOT, and others indicates that application of winter maintenance materials can be optimized most effectively using intelligent control systems, as opposed to manual spreading. Intelligent control systems that incorporate GPS, state-of-the-art ground-speed control, and access to a RWIS are well documented in their ability to minimize the use of winter maintenance chemicals that become a source of pollutant load. DOTs could consider use of such systems if they are not already in place. Purchase of intelligent control systems will involve capital expenditure and long-term maintenance, as well as additional staff training. Care should be to taken whenever possible to purchase systems that are upgradable, expandable, and that function well with other proprietary technologies. Additionally, the use of private contractors to provide assistance with winter maintenance should be limited only to those that possess appropriate qualifications and have proof that staff members are adequately trained.

Despite the capital costs for intelligent control systems and staff/contractor training, the reduction in materials used offers high opportunity to reduce pollutant load to receiving waters. The capital costs are also offset by reduced long-term material use and post-season cleanup by street sweeping. Social and institutional impacts are considered to generally be low to moderate. Because of the relatively high cost-effectiveness combined with low social barriers, use of winter maintenance BMPs has a high overall sustainability rating (see Table 8-19).

Table 8-19. Winter maintenance BMP effectiveness and sustainability ratings.

Effectiveness of Winter Maintenance BMPs					Cost per Mile	Social/ Institutional Impacts	Sustainability Rating
Bacteria	Nutrients	Sediment	Trash	Metals			
Low	Medium	High	Low	Medium	Varies based on choice of technology and fleet size	Low	High

8.9 Irrigation Runoff Reduction Practices

8.9.1 Control Description

8.9.1.1 General

Irrigation runoff (excess irrigation) may account for a large portion of dry-weather flows entering highway storm drain systems. The major factors contributing to irrigation runoff are:

- The existence of landscapes heavily reliant on irrigation systems;
- The configuration and function of irrigation systems as well as excess runtime; and
- The lack of adequate maintenance, repair, or service of irrigation systems.

A variety of practices and controls can be employed to reduce irrigation runoff. DOTs can implement the practices and controls described in the following within the right-of-way area as well as at facility locations such as administration buildings and other offices. DOTs can also facilitate implementation of appropriate irrigation management by staff and contractors through development and enforcement of standard operational procedures, training, and contract specifications for work relating to the installation and maintenance of irrigation.

8.9.1.2 Applicability to Sources and Target Audiences

The potential for irrigation runoff exists across all developed areas, including areas with transportation land uses. The greatest benefit for the effort and cost will be achieved by working with staff and contractors that manage or can influence the management of the largest landscaped areas where irrigation might occur:

- Median and right-of-way landscaped areas,
- DOT office and administration buildings,
- Park-and-ride facilities,
- Maintenance stations,
- Weigh stations,
- Agricultural checkpoints,
- Wayside parks, and
- Welcome stations.

8.9.1.3 Opportunity and Pollutants Addressed

In addition to concerns regarding impacts to the limited water supply as well as the erosive effect of excess flows on receiving waters, irrigation runoff has the potential to transport pollutants of concern that are associated with fertilizers and chemicals commonly used in irrigated areas, as well as pollutants from roadways or other portions of the storm drain system. Numerous studies have shown high bacterial indicator concentrations associated with dry-weather flow in storm drain systems. The primary pollutants of concern are:

- Fertilizers (nutrients, metals),
- Pesticides and herbicides,
- Bacterial indicators, and
- Pollutants commonly found in gutters (TSS and metals, trash).

8.9.1.4 Managed Variables

The managed variables for irrigation runoff reduction practices relate to how irrigation controls, maintenance, or staff education efforts are implemented. The options for the DOTs include:

- Retrofit of existing irrigation control devices or replacement of existing vegetation with drought-tolerant native species;
- System maintenance—frequency and level of effort to detect broken lines or facilities that are not working properly;
- Use of design standards and contract specifications to require use of smart controllers, drip irrigation, and other similar landscape management practices; and
- Development of standard inspection procedures to identify and reduce over-irrigation.

Landscape Selection. Development in some areas of the country (southern California, for example) uses nonnative landscaping requiring irrigation. Replacing existing vegetation with native species and requiring native landscaping are prudent options to reduce irrigation excess. Some agencies, such as Florida DOT, are requiring the use of locally friendly landscaping that minimizes the potential for erosion and maintains compatibility with the storm drain system, other utilities, and intelligent transportation system (ITS) devices (Florida DOT, 2013).

Selection of Irrigation Systems. Irrigation control devices have been developed that can be used to reduce over-irrigation. Common irrigation control devices include:

- Weather-based irrigation controllers,
  - Climate-based (Performance summaries and technical reports for numerous devices are available at http://www.irrigation.org/swat/control_climate.)
  - Sensor-based (Calibration summaries of numerous devices are available at http://www.irrigation.org/swat/control_sensor.)
- Drip irrigation systems,
- ET controllers, and
- Smart controllers/pressure drop sensors.

Arizona DOT publishes an approved-products list that includes specific irrigation control systems that have automated alarm systems, include rain sensors, or are capable of remote monitoring via tablets or smart phones (Arizona DOT, 2014). Florida DOT design standards promote the use of smart irrigation technology and require system design methods that prevent overspray onto roadways and other paved surfaces (Florida DOT, 2013). The Caltrans Landscape Architecture Program, Research Program Strategic Plan and Gap Analysis establishes water conservation and reduction of irrigation life-cycle costs as a stated goal and identifies potential funding sources for further research (Caltrans, 2011c).

Irrigation System Service and Maintenance. Irrigation facilities must be maintained to ensure that they are functioning properly. The City of San Diego study conducted on minimization of irrigation runoff from municipal parks found several potential concerns with irrigation systems at parks. In some cases, sprinklers at parks were spraying on impervious surfaces, creating runoff. In other cases, off-site irrigation was entering the municipal park boundary, or irrigation system operation was leading to flow onto impervious sources (City of San Diego, 2010). System pressure drop sensors can be used to shut off the system when leaks or broken lines are detected.

Table 8-20 shows the life-cycle cost factors for irrigation runoff reduction.

8.9.2 Social/Institutional Barriers to Better Irrigation Runoff Management

Development of an irrigation runoff reduction program should include several institutional considerations. There may be resistance to irrigation reduction procedures due to a perception that unreasonable requirements or limitations are being placed on existing staff resources. For example, internal documents within the City of San Diego indicate that staff resources for parks are already considered limited and irrigation systems have been described as old (City of San Diego, 2010).

Finally, implementation of irrigation reduction within the right-of-way area may bring up equity issues among different maintenance practices. For example, activities related to bridge washing (or similar) should also be restricted to the same standard or the implementation of strict irrigation controls will be controversial.

8.9.3 BMP Efficiency

8.9.3.1 BMP Efficacy

There is a relatively large body of information available from municipal and institutional sources on the impact of irrigation control. Studies have estimated the impacts of various irrigation runoff reduction practices on runoff volume. Study results have not shown a correlative reduction in pollutant concentrations; however, if runoff volume is reduced, there is likely to be an equivalent reduction in pollutant load for dry-weather flows. Dry-weather flows may pick up contaminates as they travel through the MS4 system, so it is difficult to characterize the final quality of irrigation excess until it is discharged to the receiving water. An added benefit of irrigation runoff reduction practices is potential reduction in water usage. Studies in southern California have shown reductions of up to 70% of dry-weather flow from implementation of irrigation runoff programs [Orange County Water District (OCWD) and Irvine Ranch Water District (IRWD), 2004].

Landscapes Requiring Irrigation. The Water Conservation Garden, located on the Cuyamaca College campus in El Cajon, Calif., near San Diego, is a public garden that demonstrates xeriscape principles applicable to residential and commercial landscapes. The garden is operated by a joint power authority whose members include the Grossmont-Cuyamaca Community College District, Helix Water District, Otay Water District, Padre Dam Water District, City of San Diego, and San Diego County Water Authority. Conversion of turf to xeriscape can result in irrigation demand reductions of up to 75% (http://sdchamber-members.org/Business Online 2009-10/Business Action Online April 2010/Business Action Online April Story 2.html). Xeriscape landscape areas are less

Table 8-20. Summary of performance and whole life-cycle cost factors for irrigation runoff reduction.

Performance Factors for Irrigation Runoff Reduction				
Pollutants Addressed	**Internal DOT Variables Influencing Performance**	**Performance Range**	**Advantages**	**Disadvantages**
✓ Fertilizers (nutrients, metals) ✓ Pesticides and herbicides ✓ Bacterial indicators ✓ TSS and metals, trash	✓ Retrofit of existing irrigation ✓ Drought-tolerant or landscape native species ✓ System maintenance frequency ✓ Use of smart controllers, drip irrigation, and so forth ✓ Targeted inspection ✓ Staff education	✓ Drought-tolerant/native plants varies up to 75% ✓ Smart controllers 25% to 50%	✓ Reduced water usage	✓ Potentially moderate institutional impacts ✓ Potentially high costs

Whole Life-Cycle Cost Factors for Irrigation Runoff Reduction			
Planning and Implementation	**Labor**	**Equipment**	**Other**
✓ Choice of irrigation controller system ✓ Choice of irrigation type (e.g., spray, drip) ✓ Staff training and education	✓ Type of labor (i.e., DOT staff versus contractor)	✓ Capital installation of landscape and irrigation ✓ Irrigation system maintenance ✓ Landscape maintenance/replacement	✓ Targeted inspection program ✓ Record keeping and reporting

likely to have irrigation excess since the applied irrigation is less, and spray irrigation practices are typically not used in favor of drip irrigation systems.

Irrigation Systems. In 2004 to 2006, the OCWD performed a study where approximately 4,100 smart timers were installed in residential and commercial settings throughout Orange County. The OCWD smart timer study estimated a reduction of approximately 175 gallons per day per acre (25% to 50% of the total runoff from the areas tested) in runoff from the Buck Gully watershed due to installation of smart timers. The total runoff flow varied seasonally and by area during the study, ranging from 669 to 476 gallons per day per acre in the control area of Buck Gully. In the retrofit area, runoff flow varied from 545 to 175 gallons per day per acre. (The authors of the study attributed 175 gallons per day per acre to the implementation of irrigation control devices and the rest to other factors.) The study also measured a large reduction in a second area evaluated, Portola Hills; however, there was no control area set up to quantify the reduction due to installation of smart timers. The study authors were not able to make definite conclusions from water quality analyses of two areas tested about the water quality benefit; however, Jakubowski reported that total loads for conductivity, nitrate/nitrite, and TKN were lowered. By use of the smart timer devices, there was also a water savings of 18.3 gallons per day for 899 water accounts evaluated and 170 gallons per irrigated acre (Berg et al., 2009; Jakubowski, 2008).

A study in Orange County found a significant reduction in urban runoff from residential areas that had ET controllers implemented. The study design did not allow direct comparison of runoff between the pre- and post-installation of ET controllers because seasonal changes, precipitation, and other variables were not accounted for. However, the area where ET controllers were installed had a 50% reduction in dry-weather runoff, while a control area with no implementation of controllers had a 70% increase in runoff over the same period. Over this same time, an area with irrigation reduction education experienced an increase in runoff of 37% (OCWD and IRWD, 2004).

8.9.3.2 Whole Life Costs of Implementation

Costs for capital improvement, retrofit, and maintenance of existing DOT facilities and for staff education and outreach programs are also a barrier, particularly without the benefit of information showing that transportation sources are a significant portion of the dry-weather flow problem.

Table 8-21. Irrigation runoff reduction rating.

Effectiveness					Cost per Mile	Social/ Institutional Impacts	Sustainability Rating
Bacteria	Nutrients	Sediment	Trash	Metals			
Medium-high	High	Low-medium	Low	Low	Varies	Moderate	High

To estimate the cost of implementation of irrigation reduction practices, it is important to compare the cost of implementation activities to the potential savings that could be achieved by reducing water usage over the long term. In some instances, retail water supply agencies offer incentives and rebates for water conservation practices and smart irrigation retrofits.

Landscapes Requiring Irrigation. The City of San Diego estimated that the water cost for irrigation is approximately $4.94 per 1,000 gallons of water used, and an average dry-year irrigation uses 3 acre-feet (980,000 gallons) of water per developed acre. This calculates to a cost of $4,840 per developed acre per year.

Irrigation Systems. Irrigation controllers range from about $50 to $2,000, depending on the type, features, number of stations, and complexity of the device. As noted previously, the OCWD smart timer study found that the water saved by use of these controls averaged 170 gallons per day per acre. That is a cost savings of $306 per acre per year.

Irrigation System Service and Maintenance. The costs to maintain smart controllers are noted to be higher than conventional, less-sophisticated equipment. Sensors for moisture, system pressure drop, and rain and equipment to wirelessly connect with weather services must all be upgraded and maintained periodically.

8.9.4 Sustainability and Suggestions for Practitioners

Implementation of this BMP has a high sustainability rating for DOTs (see Table 8-21), primarily due to the environmental benefits that could be achieved from smart irrigation retrofit, diligent maintenance and inspection programs that target reduction and elimination of dry-weather flow, and increased emphasis on native landscaping choices. However, social/institutional impacts are likely to be moderate since these management practices can be viewed inherently as a drain on existing staff and financial resources, already considered inadequate. As a consequence, these costs should be viewed against opportunities to better attain water quality objectives, meet NPDES and TMDL regulatory standards, and return on investment potential from long-term savings on irrigation water.

CHAPTER 9

DOT BMP Planning Tool

This chapter discusses the use of the BMP Evaluation Tool (located on the CD-ROM that accompanies this report) that can be used for planning-level estimates of BMP treatment performance and whole life costs. The tool is packaged as a collection of Excel workbooks (one for each BMP type) that can be used for BMP evaluation or to optimize BMP selection. An example is provided to show how the tool can be used to quickly compare the performance and cost of candidate BMPs to treat runoff from a highway site.

9.1 BMP Evaluation Tool Overview

This section provides an overview of the functions, calculation methodology, inputs, and results and interpretations that are common to each BMP workbook.

9.1.1 Tool Assessment Functions

The tool assessment functions are to provide stormwater volumes, stormwater pollutant loads and concentrations, and costs.

Stormwater Volumes. Provides an estimate of key stormwater volumes, including:

- Annual stormwater runoff volume generated by the drainage area to the BMP;
- Stormwater runoff volume that bypasses the BMP;
- Stormwater runoff that is captured, reduced, and released as treated effluent by the BMP; and
- Total combined stormwater volume discharged to the receiving water body.

Figure 9-1 illustrates a typical BMP and the relationship of these key stormwater volumes to the BMP.

Stormwater Pollutant Loads and Concentrations. Provides an estimate of key stormwater pollutant loads and concentrations, including:

- Annual stormwater runoff pollutant load generated by the drainage area to the BMP;
- Stormwater runoff pollutant load that bypasses the BMP;
- Stormwater runoff pollutant load captured, reduced, and released as treated effluent by the BMP;
- Total combined stormwater pollutant load discharged to the receiving water body;
- Total annual stormwater pollutant load reduction; and
- Annual influent, treated, and combined effluent concentrations.

Costs. Provides an estimate of whole life costs, including:

- Direct and associated capital costs of designing and installing the BMP,
- Regular and corrective maintenance costs of the BMP, and
- Annualized whole life costs per annual load removed.

9.1.2 Tool Inputs

The tool inputs include user-specific climate data based on closest available rain gauge, highway tributary area characteristics, and the treatment BMP design features/configuration. Rain gauges are selected based on the NCDC climate divisions (Figure 9-2). User-friendly features of the tool include a navigation bar to navigate to key input forms via one button click, a color-coded key to identify cell content application (i.e., instructions, headings, user data, and reference data), drop-down menus for select inputs, and built-in guidance information located directly adjacent to design values for ease of customization.

Default values for climate and BMP design parameters are provided for ease of use. Section 9.3 discusses how most

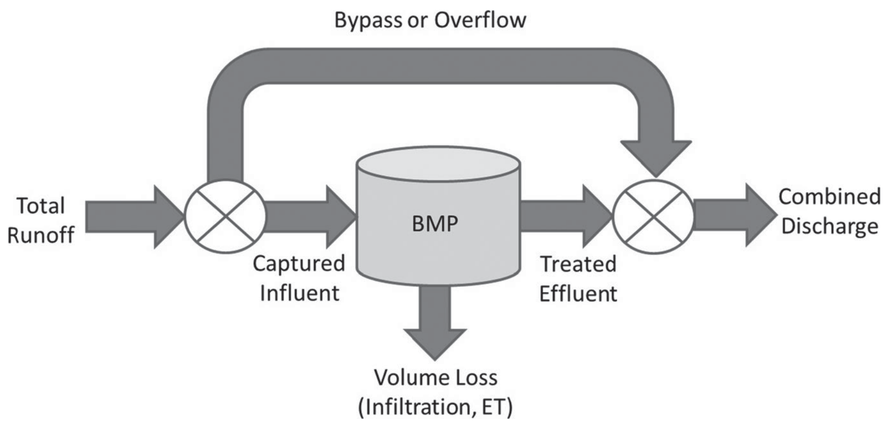


Figure 9-1. General BMP stormwater volume routing schematic.

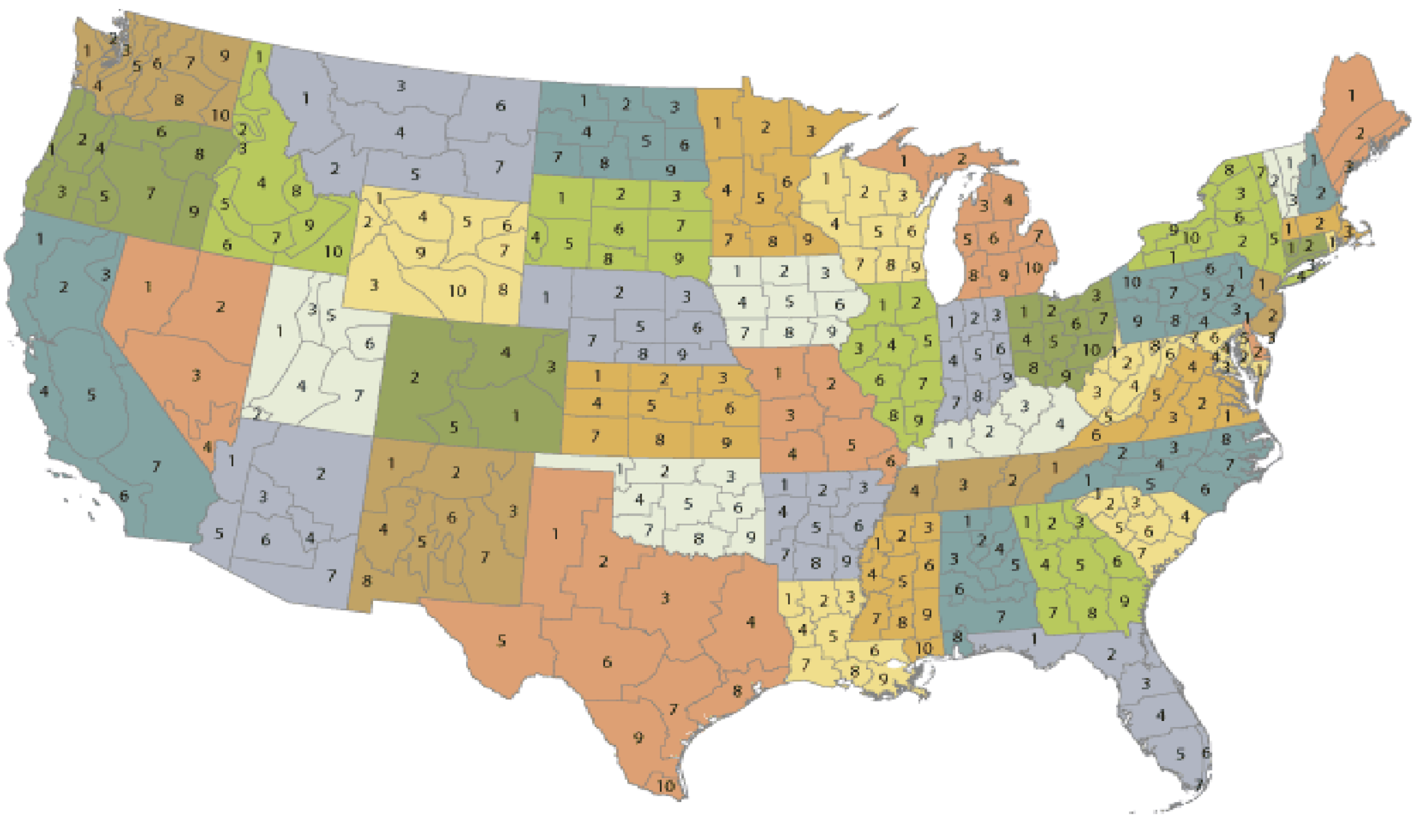


Figure 9-2. NCDC climate divisions for tool rain gauge selection.

defaults are customizable by the user to adapt to site-specific needs. Appendix F: Planning Tool Handbook provides detailed information on tool organization, project set up, entering project data, and general information such as saving, editing, and printing multiple scenarios.

9.1.3 Tool Results and Interpretations

Tool results are presented in a single worksheet and include:

- Summary of the modeled scenario (tributary area, BMP type, rain gauge location, and precipitation depth),
- Summary of design parameters (BMP type and configuration data),
- Summary of whole life costs (capital and maintenance costs as well as WLC per load removed),
- Tabular and graphical summary of volume performance (see Section 9.1.3.1),
- Tabular and graphical summary of pollutant load performance (see Section 9.1.3.2), and
- Tabular summary of water quality concentrations (see Section 9.1.3.3).

Appendix F: Planning Tool Handbook provides detailed information on viewing and interpreting results.

9.1.3.1 Volume Performance Results

The following volume performance results are provided by the tool:

- Baseline Average Annual Runoff Volume—The total volume of annual runoff for the site (highway) based on climatic region/subregion, drainage area, imperviousness, and soil type.
- BMP Captured Volume—The volume of annual runoff captured by the BMP.
- BMP Effluent Volume—The volume of annual runoff that is treated and released from the BMP.
- Runoff Bypassed (Overflow) Volume—The volume of annual runoff not captured by the treatment BMP that bypasses or overflows directly to the receiving water body. Note that the tool conservatively assumes that overflow receives no treatment even though some limited treatment of this volume may occur.
- Total Discharge Volume—The volume of annual runoff discharged to the receiving water body. This is calculated by adding the bypassed and effluent volumes.
- Total Volume Reduction—The volume of annual runoff lost by the BMP through infiltration and ET.

9.1.3.2 Pollutant Load Performance Results

The following pollutant load performance results are provided by the tool:

- Baseline Average Annual Runoff Load—The total annual pollutant load for the site (highway). This is calculated by multiplying total annual runoff volume by the characteristic highway runoff mean concentration.
- BMP Captured Load—The annual pollutant load captured by the treatment BMP. This is calculated as the difference between the baseline average annual runoff load and the bypassed load.
- BMP Effluent Load—The annual pollutant load from the BMP to the receiving water body. This is calculated by multiplying the BMP effluent volume by the treatment BMP pollutant mean effluent concentration (computed based on influent–effluent concentration relationship).
- BMP Load Reduction—The total annual pollutant load removed by the BMP. This is calculated by subtracting the BMP effluent load from the BMP captured load.
- Bypassed Load—The annual pollutant load not captured by the treatment BMP and discharged directly to the receiving water body. This is calculated by multiplying the BMP bypassed volume by the characteristic highway runoff mean concentration.
- Percent Annual BMP Load Removal—The percentage of annual pollutant load removed by the BMP. This is calculated by dividing the total BMP load reduction by the baseline average annual runoff load.
- Total Discharge Load—The total annual pollutant load to the receiving water body. This is calculated by adding the bypassed load to the BMP effluent load.
- Total Volume Reduction Load—The annual pollutant load removed via infiltration and ET. This is calculated by multiplying the baseline average annual runoff load by the percentage of total annual volume reduced.
- Treatment Reduction Load—The annual pollutant load removed by the BMP by non-volume loss treatment processes that reduce concentrations, including adsorption, filtration, settling, decomposition, and plant uptake. This is calculated by subtracting both the total volume reduction load and the BMP effluent load from the BMP captured load.

9.1.3.3 Water Quality Concentrations

The following water quality concentrations are provided by the tool:

- Influent Concentration—The pollutant concentration in the BMP influent, given as default highway runoff concentrations unless modified by the user.

- Treated Effluent Concentration—The pollutant concentration in the BMP effluent, calculated using influent/effluent performance curves.
- Whole Effluent Concentration—The pollutant concentration for the total discharge to the receiving water body, calculated by dividing the total discharge load by the total discharge volume.

9.1.4 Tool Supporting Data

The tool provides underlying supporting data used to produce the hydrologic and water quality estimates. For example, nomographs that summarize the long-term continuous simulation model results specific to the user-selected rain gauge are provided. These nomographs could be used outside of the tool for additional BMP sizing and assessment purposes. Appendix F: Planning Tool Handbook provides information on viewing supporting data.

9.2 Worked Example of Tool

This section applies the BMP Evaluation Tool to evaluate seven types of BMPs for a hypothetical site. Since physical site properties and climatic data are needed, the hypothetical site is assumed to be located in Daytona Beach, FL. The tool will be used to evaluate and compare seven different kinds of the BMPs assumed to be treating a 1,150-ft stretch of state highway. The design criteria are based on mitigating the difference between the pre- and post-development, 2-year, 24-hour rainfall event, which is assumed to follow an NRCS Type III distribution. The relevant physical characteristics of the drainage area are shown in Table 9-1. All BMPs are assumed to be installed in the median between the east- and westbound travel lanes with the exception of the PFC and filter strip BMPs.

A 1,150-ft section of SR 400 (Beville Road) just south of the Daytona Beach International Airport constitutes the drainage area for this example. The drainage area is approximately 100-ft wide on average and consists of four 12-ft travel lanes and two approximately 5-ft-wide shoulders and a median of variable width, located between the east- and westbound travel lanes. For the purposes of this example, the average width of the median is approximated as 40 ft. The site has an assumed average slope of 3%. The combined pre-developed imperviousness of the ROW is approximately 60%, and site soils are assumed to be predominantly NRCS Hydrologic Soil Group C soils.

Seven candidate BMP types were evaluated in this hypothetical example: swales, bioretention, a wet pond, filter strips, a dry detention basin, permeable friction course overlay, and a sand filter. Cost and performance results are summarized and compared for each BMP type, as described in the following sections.

9.2.1 BMP Evaluation

The corresponding spreadsheet tool for each BMP type was used, and the following BMP evaluation steps are repeated for each BMP type:

1. Project Location Selection
   The first step of the evaluation consists of filling out project description fields in the tool for the BMP under evaluation

Table 9-1. Worked example site properties.

Variables	Assumed Values	Units
Location	Daytona Beach Intl Airport, FL	–
Candidate treatment alternatives under evaluation	Swale, bioretention, dry detention basin, wet pond, filter strip, permeable friction course, and sand filter	–
Rain gauge ID	307167	–
Climate division and name	[3] NORTH CENTRAL - DAYTONA BEACH INTL AP	–
Elevation, feet	31	ft
85th-percentile, 24-hour storm depth	1.20	in.
95th-percentile, 24-hour storm depth	2.03	in.
Average annual precipitation	49.1	in.
Average slope	0.03	ft/ft
Soil type	Hydrologic Soil Group C	–
Zoning	Commercial/industrial	–
Local design standard (90th-percentile rainfall)	0.85	in.
Imperviousness	60	%
Drainage area length	1,150	ft
Average drainage area width (8 travel lanes, 4 shoulders, 1 median)	100	ft
Drainage area size	2.6	acre

and then selecting the project location by clicking on the region where the site under consideration is located.

2. State and Rain Gauge Selection
The next step is to select the state where the site is located from a filtered list of states in the region that was selected in the previous step. For this example Florida was selected, and the available rain gauges in Florida became available in the adjacent rain gauge drop-down menu. Daytona Beach International Airport gauge was then selected.

   Section 5.3.2 of the 2014 Florida DOT Drainage Manual (Florida DOT, 2014) specifies either the modified rational method (for facilities with time of concentration of 15 min or less) or the Soil Conservation Service (SCS) Unit Hydrograph Method for the design of stormwater management facilities. Florida DOT also provides intensity–duration–frequency (IDF) curves and custom precipitation distributions for multiple durations. To simplify the calculations for the purposes of this example, the default NRCS Type III distribution for Volusia County, Florida, (where Daytona Beach is located) from the watershed hydrology modeling program WinTR-55 (http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1042901) was used to determine the design peak flow and volume for the pre- and post-development conditions. The key inputs and outputs from TR-55 are shown in Table 9-2.

3. Optional Design Storm Override
The next step in the process gives the user the ability to override the 85th-percentile rainfall depth for cases where the nearest gauge is still not representative of the site conditions. The site used for this example is right next to the airport where the rain gauge is located and is, therefore, a suitable location to apply values from the Daytona Beach International Airport gauge. Note that the 85th-percentile rainfall depth reported in the tool is not used in the actual evaluation of the BMP within the tool. It is included for information purposes and to allow users to apply an adjustment ratio based on the 85th-percentile depth of their specific rain gauge to adjust the volumetric percent capture results generated from the tool.

4. Project Options
Beyond Step 3, the individual BMP evaluation tools contain sensible defaults that need to be checked for the site under evaluation. For this example, all the values in the Project Options worksheet were left at their default entries except for sales tax under the Cost Inputs section, which was changed to reflect the 6.5% sales tax rate for Florida.

5. Project Design
The Project Design worksheet contains input parameters for individual BMPs. For each of the seven candidate BMPs under consideration for this site, BMP-specific input parameters were developed and entered into the appropriate BMP evaluation tool for that BMP. The input values used for each BMP are discussed in the subsections that follow.

9.2.2 Swales

For swales, the available project area for the installation of swales was assumed to be the highway median, which was estimated to be approximately 1,150-ft long and 40-ft wide. It was assumed that one long swale could be installed in the

Table 9-2. WinTR-55 inputs and outputs.

Inputs*	
Rainfall distribution	Type III**
Land use category	Urban
Subarea 1 – median (open space, fair condition grass cover 50%–70%) (acres)	1.1
Subarea 2 – paved (acres)	1.5
Time of concentration (hours)	0.25
Total area (acres)	2.6
Weighted curve number	90
Outputs*	
2-year pre-developed peak flow (cfs)	5.75
2-year pre-developed volume (watershed in.)	2.79
2-year pre-developed volume (ft^3)	314,769
2-year post-developed peak flow (cfs)	8.4
2-year post-developed volume (watershed in.)	3.9
2-year post-developed volume (ft^3)	441,698

*Available online: http://www.dot.state.fl.us/rddesign/Hydraulics/files/IDFCurves.pdf.

**The Type III rainfall distribution is used here to demonstrate that the default runoff coefficients in the tool can be overridden.

Table 9-3. Vegetated swale design inputs.

Water quality design flow rate (cfs)	8.4
Bottom length (ft)	150
Effective amended soil depth (in.)	6
Underlying soil design infiltration rate (in./hr)	0.2
Fraction of runoff as lateral inflow (%)	0
Longitudinal slope (ft/ft)	0.03
Online versus offline	Offline
Time of concentration (min)	15
Manning's friction coefficient (n)	0.35
Horizontal/vertical side slope ratio (H:1V)	3
Water quality flow depth (in.)	4
Maximum depth (ft)	1
Freeboard depth (ft)	1

median parallel to the travel lanes with outlet structures installed in the swale every 150 ft to collect treated runoff. This layout is effectively equivalent to having 8 individual swale segments (total length of 1,150/150 = 8 swales). The water quality design flow rate was assumed to be the 2-year post-development peak flow rate (8.4 cfs). The Swale Evaluation Tool does not directly support the evaluation of multiple swales, so the total bottom width computed by the tool should be assumed to equal the combined bottom width of the 8 swales. The input assumptions for this example are shown in Table 9-3.

Recall that the total water quality design flow (2-year peak flow) for the site was estimated to be 8.4 cfs. Therefore, the effective design flow for each individual segment of the swale is 1.05 cfs. Based on a design flow of 1.05 cfs, the dimensions of each segment needed to meet the design criteria (flow depth less than 4 in.) are shown in Table 9-4.

9.2.3 Bioretention

For the candidate bioretention area, the post-development design volume computed for the site was 441,698 ft^3, and the pre-development design volume was 314,769 ft^3. The difference of 126,929 ft^3 was therefore entered into the Project Design worksheet of the Bioretention Evaluation Tool to obtain the results for the bioretention alternative. An additional design requirement constrained the total design depth of the BMP (combined ponding depth, planning media thickness, and stone storage layer thickness) to 3 ft. A ponding depth of 0.5 ft, a planting media depth thickness of 2 ft, and a stone reservoir thickness of 0.5 ft were used. In reality, this bioretention area represents the aggregate total of multiple smaller bioretention areas that would be installed in the available area of the median.

Table 9-4. Individual swale segment properties.

Bottom width (ft)	8.9
Bottom length (ft)	150
Calculated flow depth (in.)	4
Calculated velocity (ft/s)	0.35

However, note that this is a very large volume for complete infiltration and would require an excessively large footprint in Type C soils (~46% of the drainage area with an assumed 1-ft ponding depth, 2 ft of media, and 1-ft gravel storage layer). Underdrains would likely be appropriate for this site. However, unless routing-based sizing is used, the footprint would not change. The effects of routing-based sizing are presented and discussed in Section 9.2.10.

9.2.4 Wet Pond or Retention Pond

For the candidate wet pond BMP, the BMP is sized for the attenuation volume, which is the difference between the pre- and post-developed volumes. The difference of 126,929 ft^3 was therefore entered into the Project Design worksheet of the Wet Pond Evaluation Tool to obtain the evaluation results for the wet pond alternative. The wet pond was assumed to have a 3-ft permanent pool and a 1-ft water quality surcharge depth. Other values were left at their defaults.

9.2.5 Vegetated Filter Strips

Filter strip sizing is often dependent on the available area adjacent to the project right-of-way. For the purpose of this example, the Filter Strip BMP was sized to be comparable to the area used for swales. Thus, the length of the filter strip extends the length of the highway section of 1,150 ft. The width of the filter strip was calculated to achieve a hydraulic residence time greater than 10 min using Excel's Goal Seek function. This width was calculated as 36 ft, and for comparison, is of a similar size to the highway median. The Filter Strip Tool assumes 100% capture of the tributary runoff.

9.2.6 Dry Detention Basins

For the candidate dry detention BMP, the BMP is sized for the attenuation volume, which is the difference between the pre- and post-developed volumes. The difference of 126,929 ft^3 was therefore entered into the Project Design worksheet of the Dry Detention Evaluation Tool to obtain the evaluation results for the dry detention pond alternative. A maximum water quality design depth of 3 ft was assumed for the dry detention basin.

9.2.7 PFC Overlay

For this site, PFC is considered an opportunistic BMP and is controlled by the available space as opposed to a required size. The PFC was assumed to be installed over the four 12-ft travel lanes for an approximate total installed footprint area of 1.26 acres (55,200 ft^2). In this instance, the tributary area is assumed as 1.26 acres, or the total area of the highway, as no runoff is expected to enter the BMP from the median and shoulders. For this reason, it would be inappropriate to use the total tributary area of 2.6 acres for this BMP. An assumed overlay depth of 3 in. and a footprint area of 55,200 ft^2 were entered into the Project Design worksheet of the PFC Evaluation Tool to obtain the evaluation results for the PFC alternative.

9.2.8 Sand Filter

The 2004 Florida DOT Drainage Handbook: Stormwater Management Facility (Florida DOT, 2004) specifies a design hydraulic conductivity (K) of 6 in./hr for sand filters (Section 4.4.3.1 of the handbook). Assuming the design criterion is to treat the change in runoff from pre- to post-developed conditions, the design peak flow (Q) for the sand filter is 2.6 cfs (post-development flow of 8.4 cfs minus pre-development flow 5.8 cfs). Assuming a media bed thickness (L) of 2 ft and an allowable ponding depth (d) of 2 ft above the media, the surface area was then calculated using Darcy's equation.

The footprint area of the sand filter based on Darcy's law is approximately 12,960 ft^2. The design hydraulic conductivity (K) of 6 in./hr, the maximum ponding depth (d) of 2 ft, and the media thickness (L) of 2 ft were entered into the Project Design worksheet of the Sand Filter Evaluation Tool. Then, the footprint area of 12,960 was achieved by using the Goal Seek function to calculate the appropriate storage volume to obtain the evaluation results for the sand filter alternative.

9.2.9 Comparison of Results

The volume and load reduction results for the seven BMP evaluation scenarios described previously are provided in Table 9-5 through Table 9-15. Table 9-12 compares the average annual percent capture volumes as well as volume and load reductions for each. As shown, the percent capture volumes for all BMPs are above 95%, indicating that these are oversized for water quality when using the design assumptions described previously. The bioretention alternative provides the highest volume reduction and highest associated load reductions for all modeled pollutants. In this worked example, swales and dry detention basins have the lowest estimated load reduction performance. Bioretention provides the most volume reduction (96.9%), followed by filter strips (72.3%) and swales (37.5%). Wet ponds, PFC overlay, and sand filters would not be expected to provide any significant volume reduction.

Table 9-13 summarizes the annualized life-cycle costs per unit of volume and load reduction performance. Filter strips are estimated to have the lowest cost per cubic foot of volume reduction and are estimated to have the lowest cost per pound of pollutant removed for all modeled pollutants, followed by swales. Bioretention has the highest unit annualized cost per pollutant load reduced for most pollutants, but as indicated in Table 9-12, bioretention provides the most

Table 9-5. Swale volume and pollutant load performance.

	Average Annual Volume (f^3/year)	Percent of Baseline Runoff Volume	Average Annual Pollutant Loads										
			Pathogens (colonies /year)		Metals (lb/year)			Nutrients (lb/year)					Sediment (lb/year)
			E. Coli	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Baseline average annual runoff	144,970	–	2.474E+15	3.572E+15	0.3780	0.3989	1.7190	9.59	21.00	30.59	2.26	4.00	1256.6
Runoff bypassed	2,160	1.5%	3.690E+13	5.330E+13	0.0056	0.0060	0.0257	0.14	0.31	0.46	0.03	0.06	18.8
BMP captured	142,800	98.5%	2.437E+15	3.518E+15	0.3723	0.3930	1.6934	9.45	20.68	30.14	2.23	3.94	1237.9
Total volume reduction	54,330	37.5%	9.271E+14	1.339E+15	0.1417	0.1495	0.6443	3.60	7.87	11.47	0.85	1.50	471.0
ET reduction	2,510	1.7%	–	–	–	–	–	–	–	–	–	–	–
Infiltration reduction	51,820	35.7%	–	–	–	–	–	–	–	–	–	–	–
Treatment reduction	–	–	0.000E+00	0.000E+00	0.0987	0.1185	0.7331	0.00	0.01	0.00	0.00	0.54	469.9
BMP effluent	88,470	61.0%	1.510E+15	2.180E+15	0.132	0.125	0.316	5.85	12.80	18.70	1.38	1.90	297.0
Total discharge	90,630	62.5%	1.547E+15	2.233E+15	0.1376	0.1310	0.3417	5.99	13.11	19.16	1.41	1.96	315.8
BMP load reduction	–	–	9.266E+14	1.338E+15	0.2403	0.2680	1.3774	3.60	7.88	11.44	0.85	2.04	940.9
Percent annual BMP load reduction[1]	–	–	37%	37%	64%	67%	80%	38%	38%	37%	38%	51%	75%

[1] Computed as the total volume reduction loads plus the treatment reduction loads divided by the baseline average runoff loads.

Table 9-6. Bioretention area volume and pollutant load performance.

	Average Annual Volume (f^3/year)	Percent of Baseline Runoff Volume	Average Annual Pollutant Loads										
			Pathogens (colonies /year)		Metals (lb/year)			Nutrients (lb/year)					Sediment (lb/year)
			E. Coli	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Baseline average annual runoff	144,980	–	2.474E+15	3.571E+15	0.378	0.399	1.719	9.59	21.00	30.59	2.26	4.00	1256.6
Runoff bypassed	4,540	3.1%	7.750E+13	1.120E+14	0.012	0.013	0.054	0.30	0.66	0.96	0.07	0.13	39.4
BMP captured	140,440	96.9%	2.396E+15	3.459E+15	0.366	0.386	1.665	9.29	20.34	29.63	2.19	3.87	1217.2
Total volume reduction	140,440	96.9%	2.396E+15	3.459E+15	0.366	0.386	1.665	9.29	20.34	29.63	2.19	3.87	1217.2
ET reduction	90,340	62.3%	–	–	–	–	–	–	–	–	–	–	–
Infiltration reduction	50,100	34.6%	–	–	–	–	–	–	–	–	–	–	–
Treatment reduction	–	–	0.000E+00	0.000E+00	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.0
BMP effluent	0	0.0%	0.000E+00	0.000E+00	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.0
Total discharge	4,540	3.1%	7.750E+13	1.120E+14	0.012	0.013	0.054	0.30	0.66	0.96	0.07	0.13	39.4
BMP load reduction	–	–	2.396E+15	3.459E+15	0.366	0.386	1.665	9.29	20.34	29.63	2.19	3.87	1217.2
Percent annual BMP load reduction[1]	–	–	97%	97%	97%	97%	97%	97%	97%	97%	97%	97%	97%

[1] Computed as the total volume reduction loads plus the treatment reduction loads divided by the baseline average runoff loads.

significant volume reductions and treatment for all evaluated pollutants.

The final selection of a BMP depends on the pollutants and hydrologic conditions of concern for the project along with physical and financial constraints. If bacteria and dissolved nutrients are not a concern at the site, PFC overlay could be a very cost-effective option if implemented as part of a planned pavement rehabilitation project. PFC combined with swales would be expected to have a lower combined annualized cost per volume and load reduced than bioretention alone, while still reducing 40% or more of all pollutants. However, this example only evaluates volume and load reductions. If there are effluent concentration targets for some of the pollutants, then the BMP that achieves the target while also providing the

Table 9-7. Wet pond volume and pollutant load performance.

	Average Annual Volume (f^3/year)	Percent of Baseline Runoff Volume	Average Annual Pollutant Loads										
			Pathogens (colonies /year)		Metals (lb/year)			Nutrients (lb/year)					Sediment (lb/year)
			E. Coli	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Baseline average annual runoff	145,000	–	2.474E+15	3.572E+15	0.378	0.398	1.720	9.60	21.00	32.50	2.26	3.98	1258.2
Runoff bypassed	1,660	1.1%	2.833E+13	4.090E+13	0.004	0.005	0.020	0.11	0.24	0.37	0.03	0.05	14.4
BMP captured	143,340	98.9%	2.446E+15	3.531E+15	0.374	0.394	1.700	9.49	20.76	32.12	2.24	3.94	1243.8
Total volume reduction	0	0.0%	0.000E+00	0.000E+00	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.0
ET reduction	0	0.0%	–	–	–	–	–	–	–	–	–	–	–
Infiltration reduction	0	0.0%	–	–	–	–	–	–	–	–	–	–	–
Treatment reduction	140,360	96.8%	2.736E+14	1.416E+15	0.107	0.029	0.407	4.47	11.47	15.94	1.07	1.75	196.2
BMP effluent	2,979	2.1%	7.160E+12	3.730E+13	0.004	0.003	0.015	0.17	0.35	0.52	0.05	0.05	7.5
Total discharge	144,999	100.0%	3.091E+14	1.494E+15	0.116	0.037	0.442	4.75	12.07	16.83	1.15	1.85	218.2
BMP load reduction	–	–	2.165E+15	2.078E+15	0.263	0.361	1.278	4.85	8.94	15.66	1.12	2.13	1040.1
Percent annual BMP load reduction[1]	–	–	88%	58%	69%	91%	74%	51%	43%	48%	49%	54%	83%

[1] Computed as the total volume reduction loads plus the treatment reduction loads divided by the baseline average runoff loads.

Table 9-8. Filter strip volume and pollutant load performance.

	Average Annual Volume (f^3/year)	Percent of Baseline Runoff Volume	Average Annual Pollutant Loads										
			Pathogens (colonies /year)		Metals (lb/year)			Nutrients (lb/year)					Sediment (lb/year)
			E. Coli	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Baseline average annual runoff	144,974	–	2.473E+15	3.571E+15	0.378	0.399	1.719	9.59	21.00	29.94	2.26	4.00	1256.6
Runoff bypassed	0	0.0%	0.000E+00	0.000E+00	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.0
BMP captured	144,974	>99.9%	2.473E+15	3.571E+15	0.378	0.399	1.719	9.59	21.00	29.94	2.26	4.00	1256.6
Total volume reduction	104,840	72.3%	1.788E+15	2.582E+15	0.273	0.288	1.243	6.94	15.19	21.65	1.64	2.89	908.7
ET reduction	6,450	4.4%	–	–	–	–	–	–	–	–	–	–	–
Infiltration reduction	98,390	67.9%	–	–	–	–	–	–	–	–	–	–	–
Treatment reduction	–	–	0.000E+00	0.000E+00	0.065	0.077	0.352	0.77	0.00	0.59	0.00	0.48	256.7
BMP effluent	40,134	27.7%	6.850E+14	9.890E+14	0.040	0.033	0.124	1.89	5.81	7.70	0.63	0.63	91.2
Total discharge	40,134	27.7%	6.850E+14	9.890E+14	0.040	0.033	0.124	1.89	5.81	7.70	0.63	0.63	91.2
BMP load reduction	–	–	1.788E+15	2.582E+15	0.338	0.366	1.595	7.70	15.19	22.24	1.64	3.37	1165.4
Percent annual BMP load reduction[1]	–	–	72%	72%	90%	92%	93%	80%	72%	74%	72%	84%	93%

[1] Computed as the total volume reduction loads plus the treatment reduction loads divided by the baseline average runoff loads.

lowest unit cost may be the preferred solution. Also, the sizing and related costs of the BMPs are not completely equitable because hydrologic routing was not performed. Hydrologic routing allows for BMPs to be sized to treat a target volume of runoff rather than simply requiring complete storage of a water quality event. For example, the effects of routing can be evaluated by using continuous simulation to size BMPs based on a minimum percent capture (e.g., 80%) of the average annual runoff volume. As described in the following, BMPs sized in this way result in more comparable performance and life-cycle costs.

9.2.10 Effects of Routing

Most BMPs capture and treat a significant quantity of flows during a storm event. Static sizing approaches that do

Table 9-9. Dry detention volume and pollutant load performance.

	Average Annual Volume (f^3/year)	Percent of Baseline Runoff Volume	Average Annual Pollutant Loads										
			Pathogens (colonies /year)		Metals (lb/year)			Nutrients (lb/year)					Sediment (lb/year)
			E. Coli	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Baseline average annual runoff	144,972	–	2.474E+15	3.572E+15	0.378	0.399	1.719	9.59	21.00	30.59	2.26	4.00	1256.6
Runoff bypassed	1,660	1.1%	2.830E+13	4.090E+13	0.004	0.005	0.020	0.11	0.24	0.35	0.03	0.05	14.4
BMP captured	143,312	98.9%	2.445E+15	3.531E+15	0.374	0.394	1.699	9.48	20.76	30.24	2.24	3.95	1242.2
Total volume reduction	17,810	12.3%	3.039E+14	4.388E+14	0.046	0.049	0.211	1.18	2.58	3.76	0.28	0.49	154.4
ET reduction	0	0.0%	–	–	–	–	–	–	–	–	–	–	–
Infiltration reduction	17,810	12.3%	–	–	–	–	–	–	–	–	–	–	–
Treatment reduction	–	–	1.839E+15	1.522E+15	0.149	0.217	0.865	1.21	3.28	4.58	0.00	1.20	771.8
BMP effluent	125,502	86.6%	3.020E+14	1.570E+15	0.178	0.128	0.623	7.09	14.90	21.90	1.96	2.26	316.0
Total discharge	127,162	87.7%	3.300E+14	1.610E+15	0.183	0.132	0.642	7.20	15.10	22.30	1.98	2.31	331.0
BMP load reduction	–	–	2.143E+15	1.961E+15	0.196	0.266	1.076	2.39	5.86	8.34	0.28	1.69	926.2
Percent annual BMP load reduction[1]	–	–	87%	55%	52%	67%	63%	25%	28%	27%	12%	42%	74%

[1] Computed as the total volume reduction loads plus the treatment reduction loads divided by the baseline average runoff loads.

Table 9-10. PFC volume and pollutant load performance.

	Average Annual Volume (f³/year)	Percent of Baseline Runoff Volume	Average Annual Pollutant Loads										
			Pathogens (colonies /year)		Metals (lb/year)			Nutrients (lb/year)					Sediment (lb/year)
			E. Coli	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Baseline average annual runoff	70,257	–	1.200E+15	1.730E+15	0.183	0.193	0.833	4.65	10.18	14.82	1.10	1.94	609.0
Runoff bypassed	0	0.00%	0.000E+00	0.000E+00	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.0
BMP captured	70,257	>99.9%	1.200E+15	1.730E+15	0.183	0.193	0.833	4.65	10.18	14.82	1.10	1.94	609.0
Total volume reduction	0	0.00%	0.000E+00	0.000E+00	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.0
ET reduction	0	0.00%	–	–	–	–	–	–	–	–	–	–	–
Infiltration reduction	0	0.00%	–	–	–	–	–	–	–	–	–	–	–
Treatment reduction	–	–	0.000E+00	0.000E+00	0.126	0.190	0.720	0.00	5.31	5.30	0.00	0.84	548.9
BMP effluent	70,257	>99.9%	1.200E+15	1.730E+15	0.057	0.004	0.113	4.65	4.87	9.52	1.10	1.10	60.1
Total discharge	70,257	>99.9%	1.200E+15	1.730E+15	0.057	0.004	0.113	4.65	4.87	9.52	1.10	1.10	60.1
BMP load reduction	–	–	0.000E+00	0.000E+00	0.126	0.190	0.720	0.00	5.31	5.30	0.00	0.84	548.9
Percent annual BMP load reduction[1]	–	–	0%	0%	69%	98%	86%	0%	52%	36%	0%	43%	90%

[1] Computed as the total volume reduction loads plus the treatment reduction loads divided by the baseline average runoff loads.

not account for hydrologic routing, therefore, tend to be conservative and result in BMPs with larger footprints or storage volumes than needed to provide a cost-effective level of treatment. This section briefly evaluates the effect of routing on the performance and cost of the BMPs. To size based on long-term hydrologic routing, a volumetric percent capture target of 80% was assumed for all BMPs, and a drawdown time of 48 hours was added as an additional requirement for dry detention basins and wet ponds. (Lower retention times would not be expected to provide adequate time for sedimentation-based treatment.) The BMP Evaluation Tool for each of the BMPs was used with the Goal Seek function in Excel to iteratively determine the volume or peak flow capacity needed to meet the volume percent capture target. Goal Seek is part of the what-if analysis tools and is used to seek a desirable value in a formula cell by changing a value of one

Table 9-11. Sand filter volume and pollutant load performance.

	Average Annual Volume (f³/year)	Percent of Baseline Runoff Volume	Average Annual Pollutant Loads										
			Pathogens (colonies /year)		Metals (lb/year)			Nutrients (lb/year)					Sediment (lb/year)
			E. Coli	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Baseline average annual runoff	144,975	–	2.473E+15	3.571E+15	0.3779	0.3989	1.719	9.59	21.00	32.49	2.26	4.00	1256.6
Runoff bypassed	3	0.0%	4.460E+10	6.440E+10	0.0000	0.0000	0.000	0.00	0.00	0.00	0.00	0.00	0.0
BMP captured	144,972	100.0%	2.473E+15	3.571E+15	0.3779	0.3989	1.719	9.59	21.00	32.49	2.26	4.00	1256.5
Total volume reduction	0	0.0%	0.000E+00	0.000E+00	0.0000	0.0000	0.000	0.00	0.00	0.00	0.00	0.00	0.0
ET reduction	0	0.0%	–	–	–	–	–	–	–	–	–	–	–
Infiltration reduction	0	0.0%	–	–	–	–	–	–	–	–	–	–	–
Treatment reduction	–	–	1.732E+15	2.551E+15	0.2099	0.3528	1.481	0.00	11.92	10.79	0.49	2.23	1118.5
BMP effluent	144,972	100.0%	7.410E+14	1.020E+15	0.1680	0.0461	0.238	9.59	9.08	21.70	1.77	1.77	138.0
Total discharge	144,975	100.0%	7.410E+14	1.020E+15	0.1680	0.0461	0.238	9.59	9.08	21.70	1.77	1.77	138.0
BMP load reduction	–	–	1.732E+15	2.551E+15	0.2099	0.3528	1.481	0.00	11.92	10.79	0.49	2.23	1118.5
Percent annual BMP load reduction[1]	–	–	70%	71%	56%	88%	86%	0%	57%	33%	22%	56%	89%

[1] Computed as the total volume reduction loads plus the treatment reduction loads divided by the baseline average runoff loads.

Table 9-12. Percent average annual volume and load reductions.

	Volume		Pathogens Loads		Metals Loads			Nutrients Loads					Sediment Loads
	Captured[1]	Reduced[2]	*E. Coli*	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Swales	98.5%	37.5%	37%	37%	64%	67%	80%	38%	38%	37%	38%	51%	75%
Bioretention	96.9%	96.9%	97%	97%	97%	97%	97%	97%	97%	97%	97%	97%	97%
Wet pond	98.9%	0.0%	88%	58%	69%	91%	74%	51%	43%	48%	49%	54%	83%
Filter strip	>99.9%	72.3%	72%	72%	90%	92%	93%	80%	72%	74%	72%	84%	93%
Dry detention	98.9%	12.3%	87%	55%	52%	67%	63%	25%	28%	27%	12%	42%	74%
PFC	>99.9%	0.0%	0%	0%	69%	98%	86%	0%	52%	36%	0%	43%	90%
Sand filter	>99.9%	0.0%	70%	71%	56%	88%	86%	0%	57%	33%	22%	56%	89%

[1] The captured volume is the percent of the runoff that enters the BMP and either receives treatment and is released or is infiltrated.

[2] The reduced volume is the percent of the runoff that enters the BMP and is infiltrated. Therefore, the percent of the volume treated and discharged can be computed as the difference between captured volume and the reduced volume.

of the reference cells. Bioretention with underdrains was also added since this may be more appropriate and cost-effective for Type C soils.

Volume and load reductions for each of the BMPs sized for 80% capture (except for PFC and filter strips, which are assumed to be 100% self-treating) are shown in Table 9-14. Based on this comparison, bioretention is still a top performer for volume and load reduction for most pollutants, but filter strips show better load reduction for several pollutants. As shown in Table 9-15, routing-based sizing results in huge price differences for most BMPs. Bioretention without underdrain changes from \$0.67 to \$0.11 per cubic foot captured, dry detention changes from \$0.17 to \$0.03 per cubic foot captured, wet ponds change from \$0.29 to \$0.12, and sand filters change from \$0.14 to \$0.05 per cubic foot captured. Unit costs for swales increase slightly for pollutants that are only removed by volume reduction and decrease for the other pollutants. Unit costs for PFC and filter strips

Table 9-13. Annualized cost per unit of performance [whole life-cycle cost per unit, annualized (2013 dollars)].

	Hydrologic Performance		Pathogens (\$/10^{12} colonies)		Metals (\$/lb)			Nutrients (\$/lb)					Sed. (\$/lb)
	Volume Reduction (\$/ft^3 removed)	Volume Capture (\$/ft^3 captured)	*E. Coli*	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Swales	\$0.14	\$0.05	\$8.10	\$5.61	\$31,217	\$27,993	\$5,447	\$2,084	\$952	\$656	\$8,838	\$3,676	\$7.97
Bioretention	\$0.67	\$0.67	\$39.32	\$27.24	\$257,366	\$243,817	\$56,579	\$10,138	\$4,632	\$3,179	\$42,985	\$24,315	\$77.40
Wet pond	N/A	\$0.29	\$19.26	\$20.06	\$158,649	\$115,434	\$32,619	\$8,603	\$4,667	\$2,662	\$37,326	\$19,537	\$40.09
Filter strip	\$0.04	\$0.03	\$2.44	\$1.69	\$12,880	\$11,921	\$2,732	\$566	\$287	\$196	\$2,662	\$1,291	\$3.74
Dry detention	\$1.35	\$0.17	\$11.18	\$12.22	\$122,507	\$89,968	\$22,266	\$10,014	\$4,092	\$2,873	\$86,613	\$14,141	\$25.87
PFC	N/A	\$0.13	N/A	N/A	\$69,966	\$46,558	\$12,264	N/A	\$1,663	\$1,666	N/A	\$10,524	\$16.09
Sand filter	N/A	\$0.14	\$11.30	\$7.68	\$93,282	\$55,503	\$13,224	N/A	\$1,643	\$1,815	\$39,758	\$8,780	\$17.51

Table 9-14. Percent average annual volume and load reductions (sized with routing).

	Volume		Pathogens		Metals			Nutrients					Sediment
	Captured	Reduced	*E. Coli*	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Swales	80.0%	12.9%	13%	13%	42%	46%	70%	13%	13%	13%	13%	28%	54%
Bioretention (without underdrain)	80.0%	80.0%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
Bioretention (with underdrain)	80.0%	25.8%	78%	79%	60%	26%	69%	26%	34%	31%	26%	26%	73%
Wet pond	80.0%	0.0%	71%	46%	53%	70%	58%	36%	31%	36%	34%	41%	65%
Filter strip*	>99.9%	72.3%	72%	72%	90%	92%	93%	80%	72%	74%	72%	84%	93%
Dry detention	80.0%	17.1%	71%	48%	46%	57%	54%	26%	29%	28%	17%	39%	62%
PFC*	>99.9%	0.0%	0%	0%	69%	98%	86%	0%	52%	36%	0%	43%	90%
Sand filter	80.0%	0.0%	56%	57%	44%	71%	69%	0%	45%	27%	18%	45%	71%

*Note that routing has no effect on PFC and filter strips since PFC was applied to the entire available area as an opportunistic BMP and filter strips assume 100% capture.

Table 9-15. Annualized cost per unit of performance [whole life-cycle cost per unit, annualized (2013 dollars)] (sized with routing).

	Hydrologic Performance		Pathogens ($/$10^{12}$ colonies)		Metals ($/lb)			Nutrients ($/lb)					Sed. ($/lb)
	Volume Reduction ($/$ft^3$ removed)	Volume Capture ($/$ft^3$ captured)	*E. Coli*	FC	TCu	TPb	TZn	NO_3	TKN	TN	DP	TP	TSS
Swales	$0.23	$0.04	$13.29	$9.26	$26,883	$23,221	$4,117	$3,408	$1,567	$1,065	$14,574	$3,811	$6.22
Bioretention (no underdrain)	$0.11	$0.11	$6.33	$4.39	$41,451	$39,265	$9,113	$1,633	$746	$512	$6,923	$3,916	$12.47
Bioretention (with underdrain)	$0.21	$0.07	$3.97	$2.73	$33,979	$74,866	$6,490	$3,105	$1,070	$799	$13,173	$7,423	$8.30
Wet pond	N/A	$0.12	$8.00	$8.51	$69,305	$50,134	$13,971	$3,991	$2,119	$1,201	$18,193	$8,563	$16.97
Filter strip*	$0.04	$0.03	$2.44	$1.69	$12,880	$11,921	$2,732	$566	$287	$196	$2,662	$1,291	$3.74
Dry detention	$0.15	$0.03	$2.08	$2.13	$21,234	$16,168	$3,964	$1,450	$610	$427	$9,373	$2,346	$4.72
PFC*	N/A	$0.13	N/A	N/A	$69,966	$46,558	$12,264	N/A	$1,663	$1,666	N/A	$10,524	$16.09
Sand filter	N/A	$0.05	$3.89	$2.64	$32,204	$19,102	$4,549	N/A	$565	$627	$13,431	$3,010	$6.03

*Note that routing has no effect on PFC and filter strips since PFC was applied to the entire available area as an opportunistic BMP and filter strips assume 100% capture.

did not change because they are still based on 100% capture (an underlying assumption for these BMPs). Based on this new comparison of unit annualized costs, which is considered more equitable than the results based on static sizing assumptions, filter strips still have the lowest cost per load removed for all pollutants. However, the PFC and wet pond alternatives are now the highest-cost alternatives rather than bioretention. Bioretention without underdrains is estimated to cost more than bioretention with underdrains for several pollutants (*E. coli*, fecal coliform, total copper, total zinc, and TSS) because the costs associated with a footprint required to infiltrate 80% of the average annual volume in Type C soils (~13% of the drainage area) outweigh the costs associated with the extra infrastructure for a system with an underdrain (~3% of the drainage area).

9.3 Tool Customization

The tool has been designed to be customizable to allow for overwriting of much of the default data so that users can use the best available project information for their sites. It is recognized that customization will allow for each DOT to input information based on localized rainfall statistics and water quality data, as well as BMP construction and maintenance specifications, practices, and costs.

Default data that are editable include precipitation information (85th-percentile storm event depth and annual average rainfall depth), pollutant concentrations, BMP design parameters, and cost inputs. It is suggested that for design purposes, a local precipitation gauge and site-specific information be used to increase the accuracy of volume and pollutant loading results. Editable cost inputs include:

- Location adjustment factor for unit costs;
- Expected level of maintenance;
- Discount rate;
- Inflation rate;
- Percent local sales tax;
- Capital cost quantities and unit costs; and
- Maintenance frequency, hours, labor crew size, labor rates, machinery rates, and incidental costs.

9.4 Tool Intended Uses

The tool treatment performance results together with the whole life cost estimates are intended to provide DOTs with planning-level information useful for evaluating receiving water protection benefits and the magnitude of costs associated with BMP installation efforts. This type of feedback can have a number of potential applications in BMP selection and design for various direct and indirect uses that are described in the following.

9.4.1 Direct Tool Uses

Evaluate Volume and Pollutant Load Reduction in Comparison to Baseline Conditions and/or Performance Targets/Standards. The tool can be used to estimate the volume and pollutant load reduction (i.e., percent reduction of runoff volume and loads compared to the baseline condition without controls) for a wide range of potential BMP configurations. The results from the tool can also be compared directly to project goals or regulatory requirements such as TMDL implementation plans or volume reduction goals. Design parameters can be adjusted in the tool to improve BMP performance and meet project goals.

Quickly Compare Several BMPs for a Given Drainage Area. Once project location and tributary area have been established, the BMP workbooks can be used to evaluate different BMP types, configurations, performance, and costs to provide an understanding of the varying sizing and pollutant removal capabilities of the BMP types and to aid in choosing the most appropriate, cost-effective BMP for a given site.

Evaluate Performance Relationships and Sensitivities of Design Parameters. The tool provides the ability to adjust design parameters and obtain near-immediate estimates of long-term performance (i.e., without requiring delay required to set up and run a continuous simulation model). This functionality can be used to evaluate performance relationships and sensitivities as well as to understand how changing design parameters affect project costs. For example, the water quality benefits of increasing BMP sizing to provide 90% average annual runoff capture instead of 80% can be compared alongside the BMP costs to assess if there is a proportional benefit to increasing the average annual runoff capture. Additionally, BMP sizing can be adjusted to assess the volume and pollutants being captured and treated by the BMP versus the volume and pollutants that bypass or overflow the BMP.

9.4.2 Indirect Tool Uses

Aid in Development of Stormwater Programs. The tool can be used to identify and establish needs and resources as part of DOT stormwater program development, including, for example, BMP land requirements, BMP costs per drainage area to meet local regulatory requirements, and maintenance requirements and costs. The ability to customize input in the tool allows for easy year-to-year changes such as for inflation and tax increases.

Quantify Local Precipitation Statistics. The tool contains the results of an analysis of 343 precipitation gauges across the conterminous United States. Key precipitation statistics include the 85th percentile and 95th percentile, 24-hour precipitation depths, and average annual precipitation depths. These statistics are provided after the user selects the gauge that best represents the project.

Establish Planning-Level Sizing Targets. At the start of the planning process, it may be useful to hold certain parameters fixed and simply vary storage volume or footprint over a representative range to develop general relationships between BMP size and the expected performance. This can help identify how much space may be needed within a site to achieve a certain goal and provide early feedback on what goals are reasonable. The percent capture nomographs can be used to evaluate the BMP sizing impacts of a higher annualized capture volume.

Evaluate Potential Regional Variability in Performance Associated with a Given Design Standard. By holding all other parameters fixed and changing the project location attributes, the user can quickly determine how much variability would be expected in performance as a function of project location if a uniform design standard were to be adopted across an entire jurisdiction (for example, a single design storm depth across a state).

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Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation