NCHRP 25-25/83: Current Practice of Post-Construction Structural Stormwater Control Implementation for Highways

Final White Paper

Requested by:

The American Association of State Highway & Transportation Officials (AASHTO)

Standing Committee on the Environment

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1 Introduction

1.1 Background and Purpose

State highway agencies are installing an increasing number of post-construction structural stormwater treatment facilities to meet the requirements of stricter state and federal National Pollutant Discharge Elimination System (NPDES) regulation of water quality. DOTs also have to comply with other requirements, including Endangered Species Act, 401 certifications, and other state and local requirements. Meanwhile, regulators are asking for more frequent maintenance of existing and new structural controls, more comprehensive controls with new and re-constructed highways, as well as asking DOTs to develop and implement stand-alone stormwater retrofit projects for existing highway infrastructure. Pending U.S. Environmental Protection Agency (EPA) stormwater rulemaking may impose further requirements for implementing best management practices (BMPs) or expanding the scope of NPDES coverage.

Once constructed, stormwater treatment facilities need to be maintained. In order to do that effectively, transportation agencies need to be able to track the location, type, design, condition, and maintenance history of those facilities. This information is as vital for future decision making as for maintenance and operation. Some agencies have NPDES permit conditions that require such an inventory, while others have done it on their own. A number of different methods and systems have been devised to meet the various needs of the agencies.

Meanwhile DOTs are facing tighter budgets than ever before. To ensure effective expenditure of public funds in constrained budget environments, DOT stormwater program managers and hydraulic engineers need to identify effective BMPs that have the lowest whole-life cycle cost and the highest potential for complying with permits and providing other environmental benefits. Additionally, DOTs need to consider operational characteristics of the BMP with respect to the level of service and safety needed from other highway infrastructure and compatibility with local climate, maintenance practices, and physical constraints.

For years, many DOT designers, construction personnel, and contractors installed BMPs with insufficient attention to long-term maintenance costs. Installation of low maintenance designs and overall minimization of long-term maintenance needs was a consideration, but other requirements were typically the determining factor. As stormwater programs evolved and expectations in urban areas increased, regulators have required the implementation of more BMPs, increasing the DOT maintenance burden. Regulators also encouraged or required large numbers of dispersed vegetated controls, e.g., “low impact development” (LID). DOTs complied, but the long-term performance and maintainability of these types of BMPs have been relatively unknown and unreported.

To date, few DOTs have tracked maintenance costs specific to BMPs. Financial and timesheet systems, asset management, and in-vehicle information systems that have been developed do not facilitate isolation and reporting of maintenance costs specific to BMPs. However such maintenance information, including cost, is important to provide DOT managers with adequate budgets to fulfill their NPDES obligations.

Based on a survey of stormwater contacts in which all 50 state DOTs participated (NPDES or Hydraulics Program Managers), this white paper provides an overview of the range of post-construction structural stormwater facility types in use. Also included is an overview of their design, construction, and maintenance requirements, perceived long-term risks in the DOT environment, and lifecycle costs. DOTs can use this baseline information to help formulate an initial framework for a BMP maintenance program. This white paper also provides a brief guide to the stormwater-related research projects in recent years -- what is in process, and what will be available in the next few years, as well as remaining research needs. Finally, the research team identifies additional, remaining research needs that could help DOTs make cost-effective stormwater management decisions, moving forward.

1.2 Document Organization

AASHTO, NCHRP, and practitioners have made significant investments in their stormwater community of practice and in stormwater-related research projects in recent years. Given this background, this white paper provides a brief overview of current activity and near term changes in the arena of storm water-related practices, as well as documenting additional research needs. This report provides an up-to-date (as of the publication date) assessment of the state of the post-construction BMP practice at DOTs, to assist DOTs in complying with and responding to their changing regulatory environment in a cost-effective manner.

This white paper contains:

- A brief overview of regulatory trends.
- An overview of the types of structural stormwater treatment facilities in use, accompanied by fact sheets on existing structural stormwater control implementation practices, with information necessary for the selection of basic types of common BMPs, including:
    - Design criteria
    - Operation
    - Maintenance costs
    - Actual and estimated life cycle costs
- Methodologies or systems agencies have created to inventory, track, and maintain roadside post-construction BMPs, including costs.
- Conclusions on research gaps, from a survey of DOT preferences and team review of an annotated bibliography of research on stormwater control strategies.
- A recommended set of future research needs.

1.3 Regulatory Overview and Trends

The federal Clean Water Act NPDES Municipal Separate Storm Sewer System (MS4) Permit Program is primarily administered by state environmental and health departments under delegation from US EPA. The MS4 permit program is intended to reduce and eliminate municipal storm sewer system pollution from rainfall runoff, which flows through storm drain systems to local streams, ponds, and other waterways. The Clean Water Act outlines the goal of restoring and maintaining the chemical, physical, and biological integrity of the nation's waters, and the MS4 program addresses and tries to minimize previously uncontrolled sources of pollution that are transported by rainfall runoff or stormwater.

In line with national efforts to control nonpoint sources, state DOT NPDES permits for stormwater discharges contain increasingly stringent requirements. New and more prescriptive provisions are showing up in permits requiring permittees to address not only general water quality best management practices but also:

- Hydromodification control
- Retrofitting existing systems
- “Retain on site”
- New lower human health based water quality criteria that would result in additional water bodies being identified as impaired via 303d listings
- Specific receiving water impairments (TMDLs, ESA issues, etc.).

Regulators are increasing requirements with regard to maintenance of existing structural controls, as well as asking DOTs to develop stand-alone stormwater retrofit projects for existing highway infrastructure. The National Research Council’s 2008 report noted that “EPA’s current approach to regulating stormwater is unlikely to produce an accurate or complete picture of the extent of the problem, nor is it likely to adequately control stormwater’s contribution to waterbody impairment.” Furthermore, the report noted that “problems are exacerbated by the fact that the dual responsibilities of land-use planning and stormwater management within local governments are frequently decoupled.” Currently about 90% of urban areas discharge to impaired waters where stormwater runoff has been identified as a contributing to impairments, which requires then results in MS4s Permits that incorporate TMDL requirements (Water Environment Foundation, March 2013).

1.3.1 National Ocean Policy

The Obama Administration’s draft *National Ocean Policy Implementation Plan* (www.whitehouse.gov//sites/default/files/national_ocean_policy_implementation_plan.pdf) describes more than 50 actions the Federal Government will take to improve the health of the ocean, coasts, and Great Lakes, along with key milestones, responsible agencies, and expected timeframes for completion (National Ocean Council, April 2013). The Federal Highway Administration (FHWA) will likely be asked to address stormwater runoff from the Federal-aid highway system, in the context of the existing NPDES permitting program.

1.3.2 Guidance to Clarify Clean Water Act Jurisdiction

Attempting to provide clarity on which waters and wetlands are protected under the Clean Water Act, the USEPA and the U.S. Army Corps of Engineers released proposed guidance on what constitutes “a significant nexus to navigable waters.” The biology of the waterway must be considered, as well as its connection between upstream and downstream navigable waters. The agencies are finalizing guidance and they will work on a rulemaking. The proposed guidance is available at http://water.epa.gov/lawsregs/guidance/wetlands/upload/wous_guidance_4-2011.pdf.

1.3.3 Conclusions Regarding Trends for Post-Construction Stormwater Controls

The research team anticipates that the rulemaking will require the prioritized consideration of practices that reduce runoff volume through the use of infiltration, evaporation, and reuse; expand regulated discharges from urban and highway land uses beyond urbanized areas; and establish a minimum consistent set of requirements for all MS4s, along with potential additional changes to transportation and industrial stormwater requirements. Current trends point to increased requirements to use green infrastructure and to reduce impervious areas and runoff through infiltration and/or reuse. If included, a transportation-specific stormwater permit program would likely acknowledge the practical limitations of siting and maintaining stormwater facilities in linear rights-of-way and the ability of DOTs to regulate pollution-generating land uses and activities near and on the highway. Such a program may allow DOTs to come out from under the MS4 program and into a dedicated Transportation Separate Storm Sewer System ("TS4") program. Environmental advocates have pressed for inclusion of pollutant-specific standards to define impaired waters, stricter oversight of antidegradation implementation plans and more public participation in state regulatory efforts. The CWA requires states to establish a three-tiered system to define waterbody uses and the level of protection they need and to prevent pollutant discharges that unnecessarily degrade those uses. EPA is currently scheduled to finalize the rule before the end of 2014.

2 Post-Construction BMP Selection and Design

This section provides guidance on BMP selection and design and is based upon in part a survey completed for this project. The NCHRP 25-25/83 research team successfully reached all 50 state DOTs, Puerto Rico, and the District of Columbia during a survey on DOTs' existing structural stormwater control practices and frequency of use. Information on BMP performance and cost was developed by the research team from the survey information as well as additional resources available to the project team. The information is intended to provide a description of the state of practice for BMP design, performance and maintenance. The remainder of this section presents a summary of the summary results from the survey and guidance from DOT and other sources on BMP selection and design.

2.1 Existing Structural Stormwater Control Practices and Frequency of Use

State DOTs employ a wide range of post-construction BMPs. The project team developed a comprehensive list of such BMPs, taking into consideration the categorizations used in the International Stormwater Best Management Practices Database and elsewhere in the literature. The project team then surveyed all 50 state DOTs, the District of Columbia, and Puerto Rico to identify which BMPs were used frequently, sometimes, rarely, or never.

In descending order, the five most common BMP types utilized by the DOTs include vegetated swales, rock swales, roadside filter strips, dry detention basins, and wet ponds/retention basins. The top 10 is rounded out by infiltration basins and trenches, compost-amended slopes, wetland swales/channels, and oil/water/grit separator vaults.

DOTs indicated whether they used certain BMPs frequently, sometimes, rarely, or never. Assigning a value of 2 to "frequently", 1 to "sometimes 0 for "rarely" and -1 to "never" was used to helps prioritize the list into those used commonly and those not. These scores were then added for all of the DOT responses to produce the following ordered list of frequency of use of BMPs which is intended to indicate the level of priority of the application of these BMPs. Please note that these numbers do not indicate percentage of DOTs using, but just indicate a level of commonality of use and the relative differences between each.

<u>Frequently and Sometimes Used BMPs included:</u>

86 Vegetated Swale
52 Rock Swale
47 Filter Strip
44 Dry Detention Basin
31 Wet Pond / Retention Basin
16 Infiltration Basin
11 Infiltration Trench
10 Compost-amended slope
10 Wetland Swale / Channel

8 Oil / Water / Grit Separator Vault
5 Bioretention / Rain Garden (Bioretention without Underdrain)
3 Wetland Basin

<u>“Rarely” and “Never” used BMPs are as follows:</u>

-4 Hydrodynamic Device
-4 Other BMPs
-7 Permeable shoulders or parking
-9 Catch Basin Insert
-10 Sand Filter
-13 Permeable (Open-Graded) Friction Course Overlay for Water Quality Purposes
-13 Underground Detention Vault
-19 Bioslope / Ecology Embankment / Filter Strip with Soil Amendment / Media Filter Drain
-26 Underground Infiltration Vault
-26 Dry Well (Class V Injection Well)
-31 MCTT – Multi-Chambered Treatment Train (e.g., with Tube Settlers)
-33 Batch Detention (Real-Time Automated Outlet)
-34 Cartridge Filter

2.2 BMP Selection and Design Guidance

The survey showed that a variety of guidance documents are available to the DOT practitioner for BMP selection and design. Many DOTs have developed stormwater planning and design guidance manuals, which often rely on additional information available from the FHWA and the USEPA. This section provides an overview of the available guidance and a discussion of the scope of the guidance.

2.2.1 DOTs’ Design Guidance

Twenty-nine DOTs (56%) said they have BMP selection criteria or information on how design decisions are made. BMPs must be designed in accordance with stormwater design manuals as specified in regulations or permits. A subset of the 23 links to design guidance provided by DOT practitioners in the course of the initial research for this project were found to be either “broken” or otherwise inaccessible, or linked to unrelated construction specifications, erosion control guidance or other documents that were not focused on post-construction BMPs. Such links were eliminated and the remaining 17 functional links shown in Table 1 were reviewed and categorized based on their content, to facilitate further use by the broad community of DOT water quality and hydraulics managers.

Table 2 shows the BMP types that are included in each of the manuals, while the result of the categorization of topics addressed by each manual is shown in Table 3. A simple categorization scheme was used that consisted of indicating whether state DOT manuals addressed a list of 14 BMP selection and design topics categorized under four main sections, most of which were found to be typical in DOT manuals. The manual topics covered used for the categorization are as follows (yes/no as indicated by x for yes and blank for not for topics covered, unless stated otherwise below):

BMP Objectives and Attributes:

1. **Target Objectives –** The manual provides a list or a discussion of BMP objectives either by BMP type or in a combined section.
2. **Applicability and Constraints** – The manual provides a discussion of applicability and constraints for the various BMP types.
3. **Enhancements and Variations –** The manual provides a discussion of design variations and enhancements, and sometimes the benefits and challenges of the enhancements and when to use them.

Water Quality Performance:

1. **Target Pollutants –** The manual indicates which target pollutants various BMPs are good at addressing.
2. **Unit Processes** – The manual includes a discussion of unit processes and relates BMPs and/or pollutants to unit processes.
3. **Water Quality Performance** – The manual is rated “1” if it provides a qualitative discussion of water quality performance using an ordinal with levels such as high, medium, low, moderate, good, etc. The manual is rated “2” if it provides a quantitative rating, such as dollar amount ranges for cost or percent removal ranges or effluent quality for pollutants.
4. **Key Design Criteria –** The manual highlights important design attributes and sizing considerations.
5. **Sizing Equations –** The manual provides equations, constants, and sizing guidance for various BMPs.

Maintenance:

1. **Inspection Frequency –** The manual provides estimates of recommended inspection frequencies.
2. **Routine Maintenance –** The manual provides guidance and lists of routine maintenance activities associated with the various BMPs. For the purposes of this document, routine maintenance includes vegetation control, minor removal of accumulated pollutants, and minor repair of BMP components.
3. **Major Maintenance –** The manual provides guidance and lists of major maintenance activities associated with the various BMPs. For the purposes of this document, major maintenance is classified as maintenance that requires repair or replacement of major structural components of a BMP.

Lifecycle Costs:

1. **Capital Cost** – The manual is rated “1” or “2” if it provides capital implementation costs for the various BMPs. The manual is assigned “1” if high, medium, low or other ordinal scale is used and “2” if dollar amount ranges are provided.
2. **Retrofit Cost** – The retrofit cost information by BMP type was not found in the manuals reviewed; however, the Fact Sheets that have been included in this document provide this information.

3. **Maintenance Cost** – The manual is rated "1" if high, medium, low or other ordinal scale is used and "2" if dollar amount ranges are provided.

Table 1. Verified Online Stormwater Guidance Available through Various State DOTs

State	Stormwater BMP Manual Link (active as of December 16, 2012)
AZ	www.azdot.gov/Inside_ADOT/OES/Water_Quality/Stormwater/PDF/adot_post_construction_bmp_manual.pdf
CA	www.dot.ca.gov/hq/oppd/stormwtr/ppdg/swdr2012/PPDG-May-2012.pdf
DE	http://www.dnrec.state.de.us/DNREC2000/Divisions/Soil/Stormwater/New/GT_Stds%20%26%20Specs_06-05.pdf
GA	www.georgiastormwater.com/ (facilitated by Atlanta Regional Commission, partly funded by EPA grant)
ID	http://itd.idaho.gov/enviro/Stormwater/BMP/default.htm
MA	http://www.mhd.state.ma.us/downloads/projDev/2009/MHD_Stormwater_Handbook.pdf
MD	http://www.mde.state.md.us/programs/Water/StormwaterManagementProgram/SoilErosionandSedimentControl/Documents/MD%20SWM%20Volume%201.pdf
NJ	nj.gov/dep/stormwater/bmp_manual2.htm
NV	http://www.nevadadot.com/uploadedFiles/NDOT/About_NDOT/NDOT_Divisions/Engineering/Hydraulics/2006_PlanningAndDesignGuide.pdf
NY	www.dec.ny.gov/chemical/29072.html
OH	http://www.dot.state.oh.us/Divisions/Engineering/Hydraulic/LandD/Pages/TableofContents.aspx
OR	ftp://ftp.odot.state.or.us/techserv/Geo-Environmental/Hydraulics/Hydro/Manuals_and_Guidance/HDM%202011/ maintenance is separate document available here: http://www.oregon.gov/ODOT/HWY/OOM/mg/02/act125_waterqualityfacilandtables.pdf
PA	ftp://ftp.dot.state.pa.us/public/bureaus/design/PUB584/
RI	http://www.dem.state.ri.us/programs/benviron/water/permits/ripdes/stwater/t4guide/desman.htm
SD	http://www.sddot.com/business/design/forms/drainage/Default.aspx
TX	http://ftp.dot.state.tx.us/pub/txdot-info/library/pubs/bus/storm_water/5sedimentationcontrol.pdf (see Section 5.2 for permanent post-construction BMPs)
WA	http://www.wsdot.wa.gov/publications/manuals/fulltext/M31-16/HighwayRunoff.pdf

The research team structured the Fact Sheets included in this document based on the 14 topics used to categorize the contents of the state DOT manuals. The list of BMPs for which Fact Sheets were prepared based on the BMPs that DOTs used most widely, as found in the census of DOTs for this project. Table 2 also indicates which of the reviewed state DOT manuals addressed which BMPs and to what extent. To save space and keep the Fact Sheets concise, tables with “High,” “Medium,” and “Low” ratings address some of the topics in summary fashion, while other topics are presented in the form of bulleted text, tables, and paragraphs. At the end of each Fact Sheet, links are provided to online State DOT manuals that contain additional information on each BMP that is the subject of the Fact Sheet. The intent is to provide users access to additional information to supplement the information in the Fact Sheets. The Fact Sheets are attached as Appendices A through I.

Table 2. Online State DOT Manual Coverage of Post-Construction BMPs

STATE	Bioretention	Extended Dry Detention Basins	Filter Strips	Infiltration Facilities (basins /trenches)	Media Bed Filters	Swales	Wet Ponds	Wetland Basins	Wetland Channels
AZ	●		●	●	●	●		○	○
CA	○	●	●	●	●	●	●		
DE	●		●	●		●			
GA*	●	●	●	●	●	●	●	●	
ID	●	●	●	●	●	●	●	●	●
MA		●	●	●	●	●	●	●	●
MD	●			●	●	●	●	●	●
NJ	●	●	●	●	●	○	●	●	○
NV	●	●	●	●		●			
NY	○		●	●	●	●	●	●	
OH	●	●	●	●				●	
OR	●	●	●		●		●		
PA	●	●	●	●		●	●	●	
RI	●	●	●	●	●	●	●		
SD								○	○
TX		●	●		●	●	●	●	
WA	●	●	●	●	●	●	●	●	

Notes:

Blank – implies manual does not address the BMP

○ – implies BMP is mentioned or briefly discussed in manual but may not have been given a dedicated section with content in as many of the various topics as was typical for most Manuals

● – implies BMP is addressed in the manual in sufficient detail on par with other manuals

* The GA manual was not produced by GDOT. It was facilitated by the Atlanta Regional Commission, funded in part by a grant from the EPA.

Table 3. Online DOT Manual Content Summary

State	Objectives & Attributes			Water Quality Performance			Design / Sizing		Maintenance			Life Cycle Costs		
	Target Objectives	Applicability & Constraints	Enhancements & Variations	Target Pollutants	Unit Processes	*Water Quality Performance	Key Design Criteria	Sizing Eq.	Inspection Frequency by BMP Type	Routine Maint.	Major Maint.	*Capital Cost	*Retrofit Cost	*Maint. Cost
AZ	x	x	x	x	x	1	x	x	x	x	x	2		2
CA		x		x	x		x					1		
DE			x	x		1	x		x	x	x			
GA**	x	x		x	x	x	x	x		x		x		
ID	x	x					x			x	x			
MA	x	x		x		1	x	x		x		1		1
MD	x	x						x		x	x	1		
NJ	x	x				1	x			x				
NV	x	x		x		1	x	x		x				
NY	x	x		x		1	x	x	x	x		1		
OH		x					x	x						
OR	x	x	x	x	x	1	x	x		x	x	1		1
PA	x	x		x	x	1	x	x		x				
RI	x	x	x	x		2	x	x	x	x		1		
SD	x					1	x	x		x	x			
TX	x	x	x	x	x	2	x	x		x		2		
WA	x	x		x		1	x	x		x	x	1		1

Notes:

** The GA manual was not produced by GDOT. It was facilitated by the Atlanta Regional Commission, funded in part by a grant from the EPA.

Blank – DOT manual content pertaining to that topic was unavailable or could not be verified

X – DOT manual contains a section for the topic or discusses the topic by BMP

1,2 – numeric scale notes DOT manual provides qualitative or quantitative discussion of the topic with values assigned as follows:

1 – Qualitative description provided including ordinal ratings such are high, medium, low

2 – Quantitative ratings provided including numeric values such as dollar amounts for cost, and percent removals for water quality performance

2.3 Site Conditions and Constraints

Conditions and constraints associated with siting a post-construction stormwater BMP may significantly influence its selection and design. Water quality retrofit of existing infrastructure will in most cases have more constraints than BMPs included as part of a larger highway improvement or construction project. Regardless of the type of project, some of the most common conditions and constraints influencing BMP selection and design are space availability, existing infrastructure, hydraulic gradients, soils and geology, shallow groundwater, and pollutants of concern.

2.3.1 Space Availability

For the highway environment, space availability may vary significantly, but typical open space areas include roadside embankments, medians, cloverleaves, and near on-ramps and off-ramps. In urban and rural areas, highway rights-of-way (ROW) may be limited due to previous development, planning for future expansions, or land conservation that may take precedence over stormwater control projects. When highly constrained, the only option for urbanized or urbanizing areas may be subsurface devices that can be located in-line with the storm drain system, such as media cartridge filters, hydrodynamic separators, underground vaults, and catch basin inserts. Because these devices are underground and out-of-sight, they require frequent inspection and maintenance to ensure continued performance. Also, except for cartridge filters, most of these devices only target coarse particulates, so are more appropriate as pre-treatment devices rather than primary treatment, depending on the pollutants of concern (Geosyntec Consultants and Wright Water Engineers, 2012). However, these types of devices generally provide a lower level of treatment compared to non-proprietary BMPs, and are more difficult to inspect, monitor and maintain.

Detention-based BMPs, such as extended detention basins and wet ponds, usually require a larger footprint than flow through-based BMPs, such as vegetated swales. The amount of space required for a particular BMP is directly dependent upon the amount of runoff the BMP is expected to treat and the desired hydraulic retention time (HRT) for flows through the BMP. The linear, directly connected impervious nature of the highway environment often restricts the size of the catchment that can be treated with a single BMP. Therefore, rather than large regional facilities, typically small, distributed BMPs along the right-of-way are often more feasible. With the establishment of stormwater banks or fee in-lieu programs, it may be possible to treat highway runoff or otherwise mitigate them in regional, offsite BMPs at a lower life-cycle cost. Off-site mitigation may also provide relief as water quality agencies continue to incorporate a watershed approach to mitigation.

2.3.2 Existing Infrastructure

One of the primary constraints when selecting and sizing a BMP for a site is the existing infrastructure, particularly in the urban environment. Urban highway water quality retrofits of a BMP to an existing drainage system are almost always more expensive than construction of new BMPs associated with rural and suburban new highway construction projects. The Caltrans retrofit study (2004) found that unsuitable subsurface materials and buried utilities was a reoccurring issue. Encounters with buried objects and utility conflicts accounted for 4.3% of the total adjusted retrofit construction costs in the Caltrans study (Caltrans, 2001). Schueler et al. (2007) indicate that contingency factors for BMP retrofits could be as high as 40%, particularly when existing infrastructure is complex or subsurface conditions are unknown. In addition, the configuration of roadways and bridges and the presence of utilities may inhibit BMP selection and placement. Concern over the structural integrity of roadways, shoulders, footings, bridge abutments, and retaining walls may also discourage certain roadside infiltration/exfiltration practices.

2.3.3 Hydraulic Gradient and Slope

The available hydraulic gradient at a site is another factor that must be considered when selecting and designing a post-construction BMP. A slope that is too mild may cause ponding and backwater effects, which in turn may cause premature sedimentation and clogging of inlet pipes or not have sufficient head for filters, etc.

A slope that is too large may cause scour at the inlets and outlets of a facility or could be a hazard when detaining water near the top of the slope. Some designs may be modified to accommodate steeper slopes, such as using check dams and energy dissipaters to minimize erosion or liners to limit infiltration, but a slope stability and/or scour analysis should be is recommended for any potential BMP location where slopes are greater than about 15%. In addition to slope, many types of BMPs require sufficient hydraulic head for proper operation. For example, underground vaults and inlet devices typically require a minimum amount of relief between the inlet and storm drain invert. In addition, the ability to design a BMP treatment train is also extremely dependent on the available hydraulic gradient between the inlet and final discharge point.

2.3.4 Soil Properties

The type of soils and geologic formations at a site may influence the type and design of stormwater BMPs. Soils that are highly erosive or cut slopes that contain a slip plane that is prone to failure should be avoided. BMPs that rely on infiltration must have well-drained underlying soils, and the depth to bedrock must be sufficient so as not to cause excessive ponding or wetting of roadway or other infrastructure. For BMPs designed to have a permanent pool, low permeability is needed, so if native soils are in soil groups A or B, a clay or geotextile liner would likely be needed to maintain the permanent pool. Soil is an integral part of the hydrologic cycle, as it regulates the processes of surface runoff, infiltration, and percolation, and is a major controlling factor in evapotranspiration through the capacity of the soil to store and release water.

Soil characteristics are extremely variable, even for locations just a few meters apart. Moreover, in urban areas, disturbed (often compacted) soils bear little resemblance in their physical properties to their natural state (Pitt et al., 2001). Site-specific measurements of infiltration should be made whenever infiltration-based BMPs are being considered. Contaminated soils, particularly in urban areas, may be another challenge.

2.3.5 Groundwater

A physical driver that may influence BMP selection and design is groundwater quality and aquifer configuration. If the quality of the groundwater is limited and the depth to the aquifer is shallow, facilities that rely on infiltration should be avoided unless significant pretreatment is provided. In addition, a basic understanding of the connectivity of groundwater resources may help determine the overall threat that a particular BMP may have to receiving waters and drinking water supplies. Another consideration is contaminated groundwater conditions where additional infiltration needs should be avoided to reduce the potential for exacerbating the problem.

Several northern states and provinces use pavement deicers for snow and ice control in winter. Several types of deicers are commonly used, such as sodium chloride, calcium chloride, calcium chloride acetate (CMA), ethylene glycol, and urea. Runoff with high salt content concentrations of any of these deicer chemicals can be a problem for both surface and groundwater and the environmental impact associated with road salt is well known (Field et al., 1973). BMP devices discussed in this project are not suitable for control of salt pavement deicer contamination. Source control is the only practical solution and salt pile coverage has been determined to be an economical and effective approach. See NCHRP 25-25/04 and AASHTO's Compendium of Environmental Stewardship Practices, Policies, and Procedures (Venner, 2004, 2005). AASHTO now maintains this guide online: http://environment.transportation.org/environmental_issues/construct_maint_prac/compendium/manual/detailed_toc.aspx. For Winter Maintenance BMPs see Chapter 8. For BMPs at maintenance facilities see Chapter 6.

2.3.6 Constituents of Concern

In addition to the physical surroundings and infrastructure considerations, BMP selection should also consider the water quality that runs off the highway and the receiving water impairments. Constituents of concern generated from traffic-related activities include sediment, metals, organic and inorganic compounds, nutrients, bacteria, oil and grease, and trash and debris (Smith and Granato, 2010; Sansalone et al., 1997). Deposition and accumulation of these pollutants generally results from traffic activities such as vehicular component wear, fluid leakage, and vehicular transport of material but may also derive from the roadway itself, such as pavement degradation and roadway maintenance activities.

2.4 Performance Factors

Performance is a significant consideration when selecting and designing BMPs. The overall performance of a treatment BMP is a combination of the following:

1. How much of the runoff is bypassed, captured, and treated (volumetric percent capture)
2. How much of the captured runoff is lost via infiltration and evapotranspiration (volume loss)
3. What the effluent quality is of the volume discharged (effluent concentrations)
4. How the BMP affects overall discharge rates (peak shaving and flow-duration control)

Thus, performance metrics can be divided up into how well a BMP reduces runoff constituent of concern concentrations, decreases runoff volumes, and controls discharge rates. The first two can be combined to determine load reductions.

Figure 1 highlights the main fate and transport pathways of runoff through a BMP. The relative magnitude of each mechanism varies by BMP type, soil conditions, groundwater conditions, connectivity to receiving water, and climate. For flow based BMPs, exceedance of the water quality design flow rate is the mechanism that causes untreated bypass or overflow. For volume based BMPs, water quality storage volume exceedance is the mechanism that causes bypass or overflow.

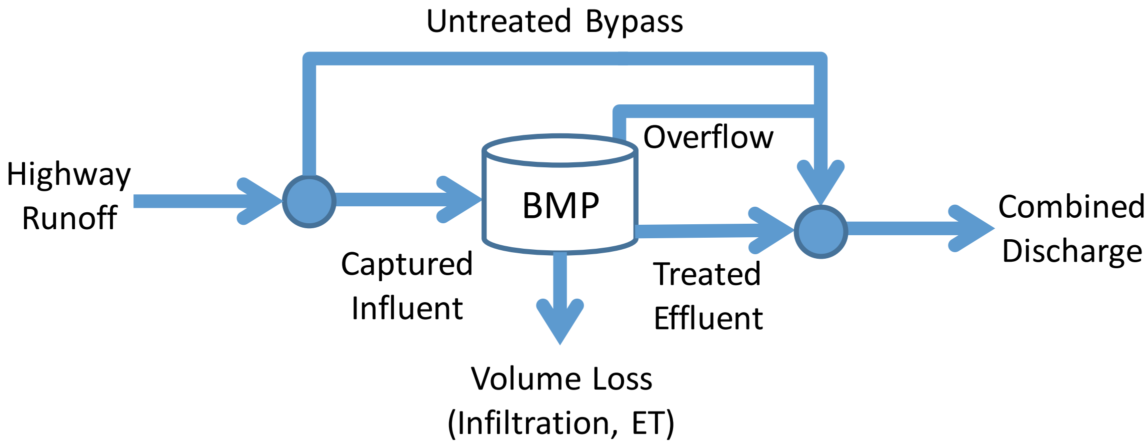

Figure 1. Stormwater Runoff Pathways through a BMP

The following sections will discuss each of these performance metrics with respect to specific BMP design components.

2.4.1 Volume Control

The hydrologic performance of stormwater BMPs is an important factor in the overall effectiveness of BMPs in reducing potential adverse impacts of road and highway development on receiving waters. Volume control is increasingly recognized as a "constituent of concern" in the realm of water quality regulations. Increased runoff volumes resulting from urbanization incorporate increased pollutant loads. In addition, increased volumes and peak flow rates carry more energy to receiving channels and can result in channel erosion.

Volume reduction in the context of BMP effectiveness refers to the volume that enters a BMP that does not discharge to the surface water. This water is considered "lost" or "retained." The key volume reduction mechanisms can be categorized as follows:

- Evaporation of ponded water
- Evapotranspiration (ET) of water temporarily stored in the root zone
- Infiltration of water below the BMP

The infiltration capacity of the soil within or beneath a BMP primarily influences the volume reduction through infiltration to subsurface and, combined with vegetation, ET. Soils below BMPs with a high fraction of clays will prevent significant stormwater volume reductions due to their poor infiltration capacity. If stormwater volume reductions are a goal, soils can be amended to improve the capacity for infiltration in cases where the layer of clay is relatively shallow.

Normally dry-vegetated BMPs, such as filter strips, vegetated swales, and bioretention facilities, exhibit relatively high volume reductions (e.g., 30-50%) over a long-term basis. Based on an analysis of flow data contained in the International Stormwater BMP Database, these BMPs are typically most effective at reducing significant (>30%) runoff volumes from discrete storm events less than approximately 2 inches (WERF, 2011). However, volume losses achieved for any given storm event will highly depend on design features (e.g., slope, width, storage volume, underdrain, etc.), site soil conditions (e.g., hydrologic soil group, level of compaction, antecedent moisture content), and storm characteristics (e.g., intensity distribution and duration). Other BMP types specifically designed for volume control, such as infiltration trenches and basins can also achieve significant reductions in runoff volumes. Wet ponds and wetland basins/channels typically do not show distinct volume reduction performance trends based on data contained in the BMP Database and would not be recommended for implementation for volume control purposes (WERF, 2011).

2.4.2 Flow Control

In addition to controlling stormwater volume, controlling post-construction stormwater flow rate can be important to protect downstream landscapes and channels from erosion and the potential contaminants associated with increased sediment transport. This can be accomplished through flow attenuation (detention) and outlet control. However, due to increases in imperviousness, flow control without volume reduction can cause an increase in the duration of elevated flows compared to what would have occurred naturally. In other words, the duration of low flows is increased because of the redistribution of the hydrograph shape (higher flows converted to lower flows through storage) and because of the increase in low flows necessary to account for the higher volume of runoff. Flow-duration control methods aim to minimize the difference in both the peak flow rate and the time period that flows persist between the pre- and post-development conditions. This can be accomplished by designing BMP storage basins to capture the desired storm volume and installing precisely designed outlet structures to control effluent flow rates for a range of storm events (typically between the 2-year and 10-year, 24-hour storms).

2.4.3 Effluent Quality

Another major component of BMP performance is the quality of discharge achieved by a BMP. In fact, the combination of effluent quality and quantity will determine the total load discharged to downstream water bodies, which is particularly important with respect to long-term water quality impacts and the ability of BMPs to meet Total Maximum Daily Loads (TMDLs).

Stormwater BMP effluent quality has been estimated using individual BMP statistical analysis from the International Stormwater BMP Database (WERF, 2012). The Database contains summaries of solid, metal, and nutrient effluent concentrations for a wide range of BMPs. Tables 4 through 6 contain the median effluent concentration as well as the 95^{th} percent confidence interval for each constituent by BMP. Values in each table are footnoted to indicate the statistical difference of the influent median and effluent median. The following subsections describe the summary of results from the BMP database; however, it is worth noting that the treatment efficiency for many of these constituents can be significantly influenced by environmental and chemical factors such as pH, electrical conductivity, and temperature.

Table 4. Median Effluent Concentrations (95th Percent Conf. Int.) for Suspended Solids and Nutrients by BMP

Constituent BMP Type	TSS (mg/L)	NO3/NO3 (mg/L)	TN (mg/L)	DP (mg/L)	TP (mg/L)
Grass Strip	19.14 ↓ (16.00, 22.00)	0.27 ↓ (0.23, 0.31)	1.13 ≈ (1.00, 1.23)	0.25 ≈ (0.16, 0.26)	0.18 ↑ (0.15, 0.20)
Bioretention	8.29 ↓ (5.60, 9.00)	0.22 ↓ (0.19, 0.25)	0.90 ↓ (0.74, 1.00)	0.13 ≈ (0.05, 0.18)	0.09 ≈ (0.07, 0.10)
Bioswale	13.54 ↓ (11.85, 15.50)	0.25 ≈ (0.20, 0.28)	0.71 ≈ (0.62, 0.83)	0.07 ↑ (0.05, 0.11)	0.19 ↑ (0.17, 0.20)
Detention Basin	24.18 ↓ (19.00, 26.00)	0.36 ↓ (0.24, 0.44)	2.37 ↑ (1.77, 2.73)	0.11 ↓ (0.08, 0.12)	0.22 ↓ (0.19, 0.24)
Media Filter	8.69 ↓ (7.40, 10.00)	0.51 ↑ (0.46, 0.57)	0.82 ≈ (0.68, 0.99)	0.08 ↓ (0.06, 0.09)	0.09 ↓ (0.08, 0.10)
Retention Pond	13.48 ↓ (12.00, 15.00)	0.18 ↓ (0.15, 0.20)	1.28 ↓ (1.20, 1.36)	0.06 ↓ (0.06, 0.07)	0.13 ↓ (0.12, 0.14)
Wetland Basin	9.05 ↓ (7.00, 11.00)	0.08 ↓ (0.05, 0.11)	1.19 ≈ (1.00, 1.21)	0.05 ↓ (0.03, 0.06)	0.08 ↓ (0.07, 0.09)
Wetland Channel	14.35 ↓ (10.00, 16.00)	0.19 ↓ (0.15, 0.22)	1.33 ≈ (1.05, 1.55)	0.09 ↓ (0.07, 0.10)	0.14 ≈ (0.12, 0.15)

- ≈ indicates influent and effluent concentrations are not statistically significantly different
- ↓ indicates a statically significant *decrease* in concentration from influent to effluent
- ↑ indicates a statistically significant *increase* in concentration from influent to effluent

Table 5. Median Effluent Concentrations (95th percent conf. int.) for Metals by BMP.

Constituent BMP Type	TCd (ug/L)	TCu (ug/L)	TPb (ug/L)	TNi (ug/L)	TZn (ug/L)
Grass Strip	0.18 ↓ (0.10, 0.20)	7.30 ↓ (6.40, 7.90)	1.95 ↓ (1.30, 2.20)	2.92 ↓ (2.40, 3.10)	24.29 ↓ (15.61, 26.00)
Bioretention	0.94 ↓ (0.50, 1.00)	7.66 ↓ (4.85, 9.85)	2.53 ≈ (2.50, 2.50)	NA	18.30 ↓ (7.71, 25.00)
Bioswale	0.31 ↓ (0.27, 0.34)	6.55 ↓ (5.70, 7.70)	2.02 ↓ (1.80, 2.29)	3.16 ↓ (2.30, 4.20)	22.84 ↓ (20.00, 26.60)
Detention Basin	0.31 ≈ (0.25, 0.35)	5.65 ↓ (4.00, 6.80)	3.10 ≈ (2.17, 4.30)	3.35 ↓ (2.20, 3.70)	29.70 ↓ (16.93, 37.75)
Media Filter	0.16 ↓ (0.10, 0.20)	6.01 ↓ (5.00, 6.60)	1.69 ↓ (1.30, 2.00)	2.20 ↓ (2.00, 2.60)	17.92 ↓ (15.00, 20.00)
Retention Pond	0.23 ↓ (0.20, 0.29)	5.00 ↓ (4.30, 5.00)	2.76 ↓ (2.00, 3.00)	2.19 ↓ (2.00, 2.61)	21.24 ↓ (20.00, 23.00)
Wetland Basin	0.18 ↓ (0.10, 0.20)	3.57 ↓ (3.00, 4.00)	1.22 ↓ (1.00, 1.55)	NA	21.96 ↓ (16.60, 24.30)
Wetland Channel	0.49 ≈ (0.18, 0.50)	4.81 ≈ (3.68, 5.20)	2.49 ≈ (1.36, 3.11)	2.18 ≈ (2.00, 2.40)	15.61 ≈ (10.50, 20.00)

- NA not available
- ≈ indicates influent and effluent concentrations are not statistically significantly different
- ↓ indicates a statically significant decrease in concentration from influent to effluent

Table 6. Median Effluent Concentration (95th Percent Conf. Int.) for Bacteria by BMP

Constituent BMP Type	Enterococcus (#/100 mL)	E. coli (#/100 mL)	Fecal Coliform (#/100 mL)
Grass Strip	NA	NA	23200 ≈ (300, 39600)
Bioretention	234 ↓ (58, 437)	44 ≈ (6,137)	NA
Bioswale	NA	4190 ≈ (1200, 5900)	5000 ≈ (2600, 6200)
Detention Basin	NA	429 ↓ (82, 720)	1030 ≈ (500,1900)
Media Filter	NA	NA	542 ↓ (200, 625)
Retention Pond	NA	150 ↓ (31, 387)	707 ↓ (200,1160)
Wetland Basin	153 ↓ (56,300)	632 ≈ (199, 1160)	6140 ≈ (230,11800)
Wetland Channel	NA	NA	NA

- ≈ indicates influent and effluent concentrations are not statistically significantly different
- ↓ indicates a statically significant decrease in concentration from influent to effluent

Solids

Dominant removal mechanisms for sediment (TSS) include sedimentation and filtration. Both processes are effectively achieved by the BMPs recommended in this report, as illustrated by the statistically significant reductions in median effluent concentrations by all BMPs (Table 4). Bioretention facilities, media filters, and wetland basins showed particularly good performance, with median effluent concentrations below 10 mg/L. Swales, filter strips, and wetland channels, while providing good overall removal, are susceptible to re-suspension of sediment during high flow events.

Nutrients

Phosphorus in stormwater runoff is generally highly particulate-bound. As a result, BMPs with unit processes for removing particulates (i.e., sedimentation and filtration) will generally provide good removal for total phosphorus, as seen in most results in Table 4. In particular, BMPs with permanent pools appear to be effective at reducing the major forms of phosphorus. Leaching of phosphorus from soils/planting media and re-suspension of captured particulate phosphorus may be a cause of phosphorus increases observed in vegetated BMPs such as bioswales and filter strips. Vegetated BMPs should be designed with adequate inlet protection, dense vegetation, and drop structures or check dams to minimize re-suspension of particulates. The use of virgin compost or chemical fertilizers should be avoided, and planting media within BMPs should be tested for phosphorus content if phosphorus is a constituent of concern.

BMPs with permanent pools (i.e., retention ponds and wetlands) appear to be the most effective at reducing nitrate concentrations, but these may increase organic nitrogen. The opposite appears to be true for media filters. Total nitrogen appears to be most effectively removed by retention facilities. Based on the theory of unit processes and knowledge of the nitrogen cycle, retention ponds and wetlands may sequester nitrate in wetland sediments and vegetation during the growing season and then release nitrogenous solids during vegetation die-off periods. Therefore, a BMP designed for permanently reducing nitrogen may include a permanent wet pool followed by a vegetated swale or media filter. However, permanent pools may not be acceptable in some locations due to mosquito breeding concerns. Alternatively, a bioretention cell with pore storage above and below the underdrain may provide aerobic and anaerobic zones for nitrification/denitrification processes. Harvesting of vegetation and removal of captured sediment may also be key maintenance practices for reliable removal of nitrogen.

Metals

Generally, particulate-bound metals are effectively removed by BMPs through sedimentation and filtration. Overall, most BMP categories provided good pollutant removal for total metals. Statistically significant reductions in median effluent concentration were observed for all metals in most BMP types. Media filters, wetland basins, and retention ponds provided the lowest median effluent concentrations while wetland channels, which are vulnerable to sediment re-suspension, did not provide statistically significant reductions for any metals, though general reductions were observed in the data set.

Metals in stormwater may occur in particulate, dissolved or colloidal forms, depending on other water quality parameters such as pH, redox potential and the presence of dissolved organic carbon and other species such as sulfide or carbonate (WERF, 2005). Dissolved metals are of particular concern with respect to aquatic toxicity. While the data in the BMP Database is limited for dissolved metals, the BMPs expected to be able to reduce dissolved metals based on their fundamental unit processes and dependent on their design features include media filters containing adsorptive media, bioretention cells, wet ponds, and wetlands. Vegetated swales and filter strips would also be expected to provide some removal of dissolved metals. Data in the BMP Database indicate statistically significant reductions in dissolved copper for filter strips and retention ponds and for dissolved zinc for filter strips, media filters, porous pavement, and retention ponds (Table 5; WERF, 2012).

Indicator Bacteria

Due to limited performance data available to date, only general inferences regarding BMP selection are appropriate at this time. Data provided in the BMP database suggest that most BMPs recommended in this report provide at least some reduction in indicator bacteria concentrations in stormwater effluent. Based on the unit treatment processes provided in retention ponds, media filters, and bioretention, bacteria reductions are expected, so the data, for the most part, support the theory. Grass strips and swales, however, do not appear to be as effective as other BMPs. It is possible that some BMPs introduce indicator bacteria via the animals that inhabit them BMP.

2.5 Cost Considerations

Whole life cost or life-cycle cost of a BMP represents the estimated present value of the capital cost, maintenance cost, and cost to reconstruct or rehabilitate the BMP, if necessary, over the assumed life of the underlying capital facility. The annual series of payments for maintenance are computed as a present value using a discount rate, or cost of funds. The appropriate discount rate is the cost of funds the Federal Reserve charges banks to borrow money, or, the average rate of inflation over the period of study.

2.5.1 Discussion of Capital Costs

Capital costs can be highly variable and will depend on the size of the system being considered, the state of the economy and bidding climate, additional land acquisition (if required), geographic location, and whether the BMP is constructed with other improvements (‘new’ construction) or as a stand-alone project (‘retrofit’ construction). Economies of scale can be realized as project size increases, due to the existence of significant fixed initial costs such as mobilization of staff and equipment and travel.

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., 25%). 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. Many suburban jurisdictions require open space allocations within the developed site, reducing the effective cost of land for the control to zero for some types of facilities. DOTs may have surplus right-of-way that can be used to locate a BMP. On the other hand, the cost of land may far outweigh construction and design costs in dense urban settings. Cost for land acquisition is excluded from the estimates herein due to the extreme variability across the U.S. as well as specific locations.

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. Consequently, locally derived cost estimates are more useful than generic estimates made using national data, but generalized costs are useful for comparison between BMPs for planning purposes. The following is a brief description of some major factors affecting capital costs (Lampe et al., 2005):

1. **Retrofits vs. new construction.** Stormwater controls can typically be built at much lower costs as part of a larger project rather than as stand-alone projects, which require their own mobilization and project initiation. These two scenarios exhibit very different costs, with retrofit costs being much higher in most cases. 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. Retrofits also bear their own utility relocation and road realignment costs. Many sites are not in optimal hydraulic locations due to constraints imposed by prior development. In general, the construction cost for highway BMP retrofits can be quite high, as much as ten times more expensive than new construction (Caltrans, 2001). An exception to the rule of higher costs for retrofits can be the retrofit of the outlet of an existing flood control basin to change its operation to enhance water quality.
2. **Regulatory requirements.** Jurisdictions have varying requirements for treatment water quantity and quality volume, especially where TMDLs are involved. NPDES and associated state reporting requirements along with the additional stringency imposed by pollution reduction targets and TMDLs are driving increases in BMP inspection and maintenance. NCHRP 25-40 found that regulatory requirements in permits and consent decrees drive DOT standards and costs.
3. **Flexibility in site selection, site suitability.** Stormwater control cost can vary considerably due to local conditions (i.e., the need for traffic control on all but new alignments, shoring, and availability of work area).
4. **Level of experience of both agency and contractors.** Some regions in the U.S. have required and constructed stormwater controls for over twenty years. In these areas, local contractors adapt to the market and learn the skills needed to build the controls.

5. **State of the economy at the time of construction.** Another consideration is the strength of a local economy when a control is bid and built. If work is plentiful, the work may be less desirable and the cost may rise.
6. **Region.** Region may influence the design rainfall and rainfall runoff characteristics of a site, which will in turn affect drainage system component sizing.
7. **Soil type/groundwater vulnerability.** These will dictate whether infiltration methods can be used to dispose of excess runoff volumes on site, or whether additional storage and attenuation will be required.
8. **Planting.** The availability of suitable plants and required level of planting planned for a particular control component will have a significant influence on costs, including whether irrigation is required for plant establishment.
9. **An important consideration when assessing cost is what would be constructed in lieu of the selected practice.** For instance, engineered swales are a much less expensive option for storm water conveyance than the curb and gutter systems they replace, which leads to the conclusion that these water quality benefit facilities are effectively “free”, since some type of system is required for drainage purposes. Consequently, one should consider the net cost attributable to the water quality BMP (including the necessary appurtenances, such as retaining walls, fencing, etc.) rather than the cost of the BMP when assessing cost impacts to a project . However, in retrofit situations the removal of existing curb and gutter to accommodate a more natural drainage system such as a swale such costs then should be considered.

2.5.2 Discussion of Maintenance Costs

Maintenance is needed to preserve the intended water quality benefit and stormwater conveyance capacity of stormwater controls. Maintenance costs are site specific but can be relatively stable from year to year. Maintenance costs can generally be categorized as “minor,” such as vegetation trimming or trash removal, or “major,” such as sediment removal from a detention basin.

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, visual concerns from highway users or by regulatory requirements. 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 (mostly aesthetic) of the nearby community. Again as in construction costs, it is important to consider the net difference in cost. If areas would have required vegetation maintenance and/or trash removal anyway, the net cost may be minor for minor maintenance activities.

Two general maintenance categories have been established in the whole life cost models: 1) **minor**, and 2) **major**. Minor maintenance consists of basic tasks performed on a frequent and predictable schedule. These include inspections, vegetation management, and litter and minor debris removal. Three levels of minor 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 required 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 and site conditions.

Major 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 major maintenance 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.).

2.5.3 Capital Costs

Capital costs have been estimated for the most frequently used DOT BMPs for both new construction and retrofit. Facility base costs were developed using unit costs (2012 dollars) and estimated quantities based on common design assumptions for each BMP type. The unit costs and assumptions are summarized in Appendix B. Table 7 summarizes BMP costs per acre served for both small and large drainage areas. Due to economies of scale, larger drainage areas have lower capital costs on a per area basis. However, the relationship between cost and drainage area is non-linear, so precaution should be taken before applying these unit estimates to areas much smaller or much larger than 3 acres. These capital costs per BMP are also included in Appendix B.

Table 7. Summary of Estimated New Construction and Retrofit Cost (2012 $) per area served by BMP Type.

	2012 $/acre (Area Served < 3 acres)		2012 $/acre (Area Served > 3 acres)	
BMP Type (variation for which cost is based upon, if applicable)	New Construction	Retrofit	New Construction	Retrofit
Bioretention (no underdrain)	$24,500	$35,400	$14,000	$20,200
Extended Dry Detention Basins	$29,200	$58,800	$9,700	$19,500
Filter Strips	$11,100	$30,900	$1,900	$5,200
Infiltration Facilities (basins)	$27,300	$92,700	$9,700	$32,800
Media Bed Filters (sand)	$88,000	$113,800	$48,100	$62,300
Swales (vegetated)	$19,500	$37,500	$2,300	$4,400
Wet Ponds	$32,600	$52,100	$13,100	$20,900
Wetland Basins	$32,800	$52,300	$13,700	$21,900

Note: The costs provided in the table above will not scale linearly with changes in area served and will vary significantly with changes in design assumptions and site specific conditions.

2.5.4 Operations and Maintenance

The recommended frequency of both inspection and maintenance depends on how much and how often the BMP manages stormwater runoff and the quality characteristics of the runoff. Runoff frequency is one of the foundations upon which stormwater management systems are designed and constructed. 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 frequency. Finally, the amount of solids and debree contained in runoff from a site impacts the inspection and maintenance frequency..

Detailed maintenance activities for each type of BMP were developed along with their average annual frequency based on records of prototype installations. Maintenance functions can be divided into two categories: functional and aesthetic. These two categories can overlap. Functional maintenance is important for performance and safety reasons, while aesthetic maintenance is important for public acceptance of stormwater facilities but not necessary for performance.

Functional maintenance is necessary to keep a stormwater management system operational. Functional maintenance has two components: preventive maintenance and corrective maintenance. Preventive maintenance is performed on a regular basis and includes vegetative cover maintenance to prevent erosion and provide treatment, minor sediment removal and disposal, mechanical component maintenance, and vector control. Preventative maintenance is generally characterized as ‘minor’ since it is routine. Corrective maintenance is required on an as-needed basis because of unforeseen operational problems that may be encountered, such as structural repairs or erosion repair; it is generally characterized as ‘major’ since its magnitude and frequency are not easily predicted. Large sediment removals in ponds, for example, would also be considered major.

Aesthetic maintenance enhances the visual appearance and appeal of a stormwater facility. Aboveground, open-air facilities may need more aesthetic maintenance than underground stormwater systems. Aesthetic maintenance includes the removal of trash and debris and vegetation management, such as trimming grass and removal of weeds and undesirable plants and is characterized as ‘minor’. Some trash and debris removal may also be functional maintenance if it could contribute to clogging or other function disruption.

A summary of estimated minor and major maintenance costs for several BMP types is provided in Table 8. The summary was developed using information from a literature review and the California Department of Transportation BMP Retrofit Pilot Program (Caltrans, 2004) final recommendations for inspection and maintenance protocols and then comparing them to the inspection and maintenance intervals occurring over the past 10 years. These costs are also provided in the individual BMP Fact Sheets in Appendix A. Additional support information and assumptions for these maintenance costs, such as the actual maintenance needs and frequencies, are provided in Appendix C.

Table 8. Summary of Estimated Minor and Major Maintenance Cost (2012$) by BMP Type.

	2012 $/acre (Area Served < 3 acres)		2012 $/acre (Area Served > 3 acres)	
BMP Type (variation for which cost based upon, if applicable)	**Annual Minor Maintenance**	**Annual Major Maintenance (M)**	**Annual Minor Maintenance**	**Annual Major Maintenance**
Bioretention (no underdrain)	$950	$150	$480	$50
Extended Dry Detention Basins	$580	$510	$270	$210
Filter Strips	$490	$140	$250	$90
Infiltration Facilities (basins)	$570	$90	$250	$50
Media Bed Filters (sand filters)	$360	$240	$130	$80
Swales (vegetated)	$490	$260	$250	$180
Wet Ponds	$520	$4,840	$170	$2,360
Wetland Basins	$360	$4,360	$130	$2,120

	2012 $/acre (Area Served < 3 acres)		2012 $/acre (Area Served > 3 acres)	
BMP Type (variation for which cost based upon, if applicable)	**Annual Minor Maintenance**	**Annual Major Maintenance (M)**	**Annual Minor Maintenance**	**Annual Major Maintenance**
Wetland Channels	$360	$2,990	$130	$1,340

Note: The costs provided in the table above will not scale linearly with changes in area served and will vary significantly with changes in design assumptions and site specific conditions. To determine the maintenance costs a drainage area of 2 acres was used as the basis of the <3 acre tributary area, and for the >3 acre tributary area, a drainage area of 7 acres was used.

2.5.5 Whole Life Costs

Whole life costs were estimated for each of the BMPs using an estimated project life span of 50 years and an average discount rate (5.5%) consistent with the average Federal Reserve discount rates since 1972 (Table 9). The life-cycle costs are a useful metric for comparing BMPs on a consistent basis. The life-cycle cost represents the estimated present value of the capital cost, annual minor maintenance cost, and major rehabilitation maintenance cost for the BMP, if necessary over the assumed 50-year life of the facility. The annual series of payments for maintenance are computed as a present value using a discount rate of 5.5%.

Table 9. Summary of Estimated Whole Life Cost (2012 $) by BMP Type.

	2012 $/acre (Area Served < 3 acres)		2012 $/acre (Area Served > 3 acres)	
BMP Type (variation for which cost is based upon, if applicable)	**New Construction**	**Retrofit**	**New Construction**	**Retrofit**
Bioretention (no underdrain)	$41,000	$52,000	$22,000	$28,000
Extended Dry Detention Basins	$39,000	$69,000	$14,000	$24,000
Filter Strips	$22,000	$41,000	$8,000	$11,000
Infiltration Facilities (basins)	$37,000	$102,000	$14,000	$37,000
Media Bed Filters (sand)	$97,000	$123,000	$51,000	$65,000
Swales (vegetated)	$29,000	$47,000	$7,000	$10,000
Wet Ponds	$118,000	$137,000	$53,000	$61,000
Wetland Basins	$106,000	$125,000	$49,000	$57,000

*The costs provided in the table are total life-cycle costs based on a 50-year life span assumption for all BMPs. These costs will not scale linearly with changes in drainage area. Economies of scale are expected for capital costs as the BMPs get larger and maintenance effort will minimally increase with the addition of drainage area. An upper limit for the drainage area serve would be 10 acres for filter strips and swales, and 25 acres for the remaining BMPs. See the BMP Face Sheets in Appendix A.

2.6 Summary of BMP Selection and Design Process

DOT stormwater program managers and engineers (practitioners) face the challenge of identifying which stormwater controls have the lowest whole-life cycle costs, highest environmental and permit compliance benefits and are easiest to operate and maintain. Most of the state DOT manuals evaluated include guidance for selecting stormwater BMPs based on pollutants of concern, relative costs, and site constraints. Several also provide BMP design criteria and sizing guidance. As a general process, BMP selection and design can be summarized a series of six steps as identified in Figure 2.

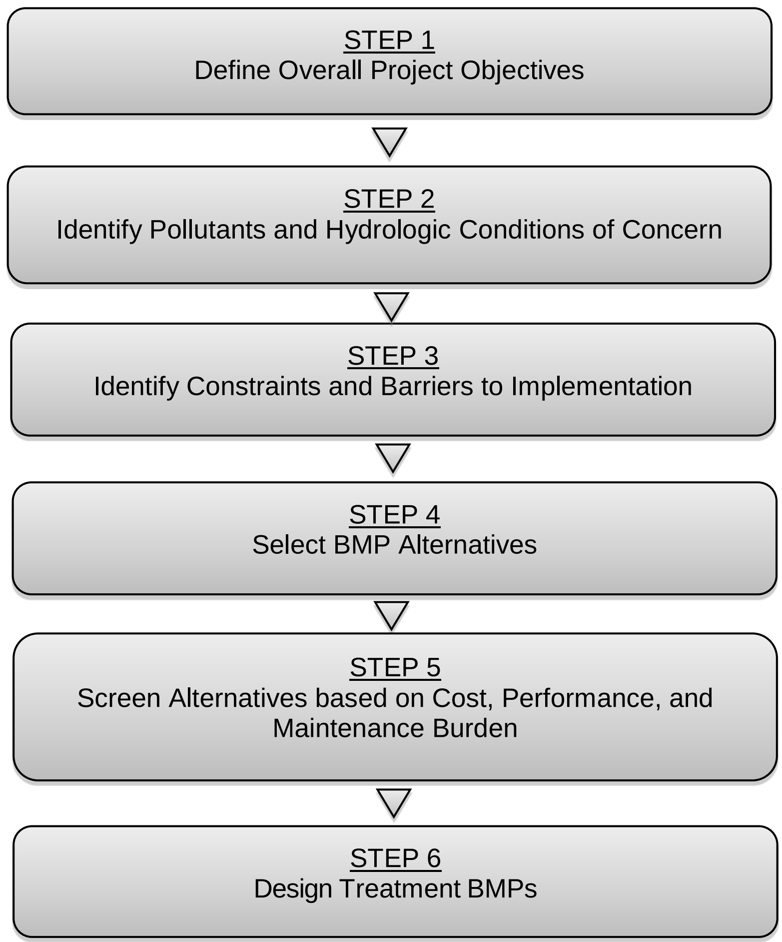

Figure 2. General Process for BMP Selection and Design

The Fact Sheets provided in Appendix A can be used to assist DOTs with this BMP selection process. Each Fact Sheet also includes links to BMP design manuals to provide more specific guidance on sizing and design. The six steps above are briefly discussed in the following subsections.

2.6.1 Step 1: Define Overall Project Objectives for Stormwater Treatment

The design of any engineered system requires a clear definition of the problem. Without clear descriptions of the storm water issues that need to be addressed, including the desired results, it is difficult (if not impossible) to evaluate the steps needed to select and design a practicable and cost-effective post-construction BMP. The following key concepts should be considered when defining the overall objectives of DOT projects:

- What is the purpose of the DOT's BMP design standards and what are the regulatory drivers of stormwater management?
- What are the objectives beyond stormwater management?
- How do these objectives relate to or conflict with other project objectives?
- What site conditions (e.g., roadway configuration, topography, soil types, receiving waters) should be evaluated to properly define the problem?

2.6.2 Step 2: Identify Pollutants of Concern and Hydrologic Conditions of Concern

Primary pollutants of concern are identified based on consideration of traffic densities, adjacent land uses, and known water quality issues identified on the Section 303(d) list of impaired receiving waters or established TMDLs. The primary pollutants of concern for highways are generally trash and debris, metals, hydrocarbons, and sediment. However, other pollutants may also be a concern depending on the sensitivity of the receiving water and adjacent land uses. For example, nutrients may be a concern if a receiving water body is already impacted by over-enrichment and/or there is mixing of highway runoff from agricultural lands and intensively landscaped areas. Pathogens may also be a concern in areas with frequent animal crossings or if there is comingling of water from leaking septic systems or combined sewer overflows. Finally, in locations where deicing materials are applied, chlorides and oxygen demanding substances may be a concern.

In addition to pollutants, receiving waters may be sensitive to hydrologic changes. Hydromodification may occur when a stream receives larger and more frequent discharge volumes or when the natural sediment budget is disrupted. While energy dissipation can be used to reduce localized erosion and scour, a combination of detention and volume reduction is also often needed to limit long-term hydromodification impacts (see Section 2.4.2 for an overview of flow control).

2.6.3 Step 3: Identify Constraints and Barriers for Implementation

Factors other than pollutants and hydrologic conditions of concern may influence BMP selection, such as regulatory requirements, site-specific constraints, regional constraints, aesthetics, cost, reliability, safety, and maintenance considerations. Watershed planning considerations and the desire to integrate low impact development techniques may also influence which stormwater treatment BMPs are chosen for a given project. Refer to Section 2.3 for a discussion of some of the other factors and constraints that may influence BMP selection and design.

2.6.4 Step 4: Select BMP Alternatives

Once the issues and constraints have been identified, appropriate BMP alternatives are selected based on their ability to address the issues, overcome the constraints and meet cost goals. As opposed to other design approaches that recommend the selection of typical BMPs based solely on documented performance factors, such as percent removal, effluent quality and/or percent capture, the recommended approach is to select BMPs through consideration of several factors. The ultimate selection of appropriate stormwater treatment BMPs includes consideration of the methods of pollutant removal that address the primary pollutants and hydrologic conditions of concern, consideration of other factors/constraints, and consideration of performance factors (provided in Section 2.4). Table 10 summarizes the major constraints and the pollutants and hydrologic conditions addressed by various commonly implemented BMP types. The high (H), medium (M), and low (L) rankings are relative to all of the BMPs listed in this table (H = BMP is very effective; L = BMP is not very effective). This table can be used to identify potential BMP alternatives for initial screening.

Table 10. BMP Alternatives Selection Matrix.

BMP Type	Major Constraints	Typical Pollutants Removed and Hydrologic Conditions Addressed									
		Sediment	Metals	Organics	Nutrients	Bacteria	Trash and Debris	Chlorides	Oil and Grease	Volume	Peak Flow
Dry Extended Detention Basin	Surface space availability, hydraulic head, water table, soil permeability, steep slopes/ stability, vegetation maintenance	H	L	L	L	L	H	L	M	M	H
Retention Basin (Wet Pond)	Surface space availability, compatibility with flood control, vector control, steep slopes/ stability, lack of base flow to maintain wet pool, vegetation maintenance	H	H	M	M	M	H	L	M	L	H
Stormwater Wetland	Surface space availability, steep slopes/stability, soil type, system hydraulics, vector control, lack of base flow, vegetation maintenance	H	H	M	M	M	H	L	H	L	M
Wetland Channels	Surface space availability, steep slopes/ stability, hydraulic head, vector control, lack of base flow, vegetation maintenance	H	H	M	M	L	M	L	H	L	L
Vegetated Swale	Steep slopes/ stability, availability of pervious area, hydraulic head, vegetation maintenance	M	M	L	L	L	M	L	M	M	L
Filter Strip	Steep slopes/ stability, surface space, ability to maintain sheet flow, size of tributary area, vegetation maintenance	H	M	L	L	M	M	L	H	L	M
Media Filter	Vertical relief and proximity to storm drain, subsurface space, high sediment loadings, aesthetics, hydraulic head	H	H	L	M	M	H	L	M	L	L
Bioretention / Rain Gardens	Soil permeability, hydraulic head, water table, contaminated soils, vertical relief and proximity to storm drain, surface space availability, subsurface requirements, steep slopes/ stability, vegetation maintenance	H	H	M	M	M	M	L	M	H	M

BMP Type	Major Constraints	Typical Pollutants Removed and Hydrologic Conditions Addressed									
		Sediment	Metals	Organics	Nutrients	Bacteria	Trash and Debris	Chlorides	Oil and Grease	Volume	Peak Flow
Infiltration Facilities	Water table, soil permeability, contaminated soils, surface space, subsurface space, steep slopes/ stability	H	H	H	H	H	H	H	H	H	M

2.6.5 Step 5: Screen Alternatives based on Cost, Performance, and Maintenance Burden

After an initial list of BMP alternatives has been selected, order-of-magnitude costs should be estimated given the tributary area. Planning-level capital and operations and maintenance costs per acre treated were provided in Section 2.5. These costs, along with performance information provided in Section 2.4, can be used to estimate the relative cost benefit of the candidate BMP alternatives. The final selection should also consider the logistics and staffing requirements for maintaining the BMP.

2.6.6 Step 6: Design Treatment BMPs

Stormwater treatment system design involves both the *mechanism* for hydrologic and hydraulic controls as well as the *design criteria* for determining the runoff volume and/or flow rate for which to design. Hydrologic and hydraulic design guidelines can be found in the DOT design guidance manuals summarized in Section 0. Design criteria are agency specific and may be based on regulatory or jurisdictional requirements, so they are not covered here. General water quality design concepts are presented below with recommendations on where to find additional information. Table 11 summarizes some of the critical design parameters that may impact performance and operation for commonly implemented BMP types.

Table 11. Critical BMP Design Parameters.

BMP Type	Critical Design Parameters
Dry Extended Detention Basin (Dry Pond)	Stage-discharge relationship and drain time (outlet design), storage capacity, length-to-width ratio, location of inlets and outlets, flow rate diversion for off-line facilities
Retention Basin (Wet Pond)	Length-to-width ratio, stage-discharge relationship, permanent pool and surcharge capacity, maximum depth, base flow, plant selection, flow rate diversion for off-line facilities
Stormwater Wetland	Volume of design storm, length-to-width ratio, depth distribution, base flow, plant selection, flow rate diversion for off-line facilities
Wetland Channels	Base flow, plant selection, longitudinal slope, width, range of depths
Vegetated Swale	Retention time, minimum length, maximum width, flow rate, velocity, depth, number and size of check dams, grass/vegetation selection

BMP Type	Critical Design Parameters
Filter Strip	Retention time, minimum length, longitudinal slope, flow spreaders, flow rate, velocity, depth, grass selection
Media Filter	Maximum emptying time, media type and depth, particle size gradation, depth to groundwater
Bioretention / Rain Gardens	Soil characteristics and amendments, depth to groundwater, area and ponding depth, storage capacity, plant selection
Infiltration Facilities	Storage capacity, soil characteristics and amendments, sediment reduction pre-treatment

Typically sizing is conducted by selecting a design storm and then computing the water quality design volume or the water quality design flow rate for the BMP. Design storms for water quality are typically specified as part of minimum design criteria in permits and BMP manuals, such as capturing and treating the 85^{th} percentile, 24-hour storm event. A common goal for selecting a water quality design storm is to achieve 80 to 90 percent capture of the average annual runoff volume from the site. Design storm nomographs that relate design storms to percent capture at 30 different locations across the United States were developed by Huber et al. (2006). These nomographs can be used for selecting a water quality design storm if one is not available from local guidance.

Most treatment facilities include more than one method of pollutant removal. For example, dry extended detention basins may reduce the total runoff volume due to infiltration and evapotranspiration (ET), as well as attenuate peak flows, which help particulates to settle out. Furthermore, some BMPs can be modified to include unit processes that are typically not incorporated in their design, such as including amended soils to promote retention and infiltration/evapotranspiration in a vegetated swale. Consequently, several BMPs may include multiple unit processes. In order to exploit the synergy amongst BMPs, the placement or order of BMPs and BMP components within a treatment system should be carefully considered. The recommended design approach is to use the concept of the treatment train based on the following general progression (Huber et al., 2006):

- Minimize flow rates and/or volume of runoff (site design practices and hydrological source controls, including within the BMP system).
- Remove bulk solids (> 5 mm) (primary treatment)
- Remove settleable solids (>75 µm) and liquid floatables (primary treatment)
- Remove suspended (25-75 µm) and colloidal solids (> 0.1-25 µm) (secondary treatment)
- Remove colloidal, dissolved, volatile, and pathogenic constituents (tertiary treatment)

The BMP Fact Sheets in Appendix A summarize the target constituents and unit treatment processes for the most commonly used BMPs and provide general design guidance and cost information. If snowmelt is expected to be a significant contributor to annual runoff at a site, the designer can review Novotny et al. (1999) for additional information on snowmelt characteristics and treatment options. In addition, see Caraco and Claytor (1997) and Metropolitan Council (2001) for guidance on the selection and design of stormwater treatment systems in cold climates.

3 Systems and Methodologies for Inventory and Tracking of Post-Construction BMPs

3.1 Historical Tracking of Drainage Infrastructure

Prior to the last decade, only a couple state DOTs had implemented tracking systems for their drainage infrastructure. Florida DOT was one of the first state DOTs to start to inventory outfalls, and the state's first inventory that included BMPs was in 1975. Maryland SHA developed one of the first comprehensive drainage infrastructure management systems.

Approximately 20 states have instituted a data management system for drainage infrastructure since 2000, with a quarter of those in the last three years. Prior to this recent push, maintenance of post-construction BMPs was primarily reactive or locally initiated. Historically, DOTs maintained stormwater BMPs when problems were observed. Maintenance activities included removal of excess sediment from ditches and re-vegetating ditches and embankments when necessary. BMPs were 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 in one study reported that BMP maintenance guidelines in various stormwater BMP guidance documents were based "mostly on regulatory judgment or back-of-envelope calculations of sediment accumulation, rather than empirical data" (WSDOT, 2005).

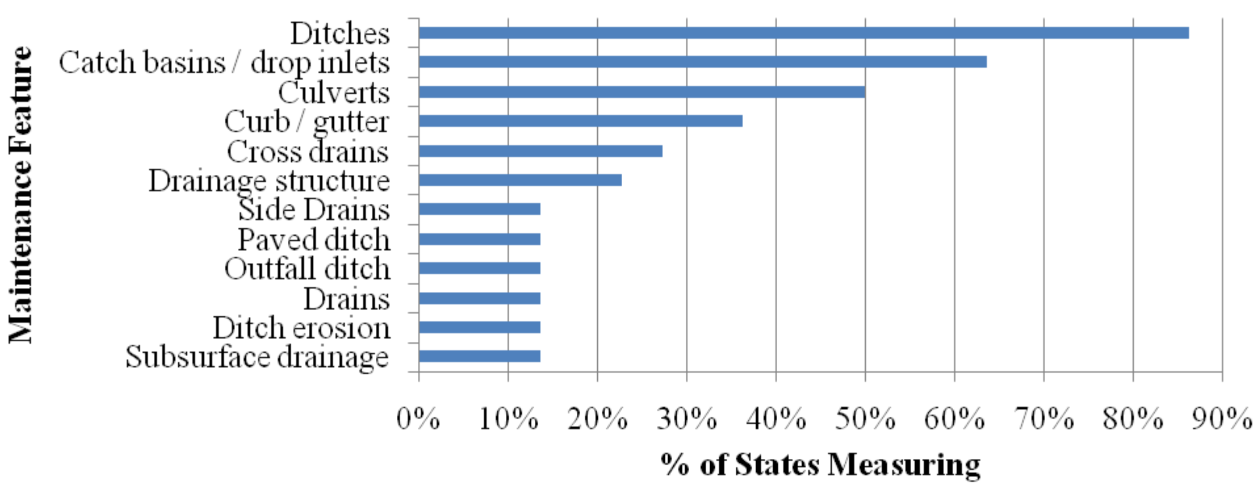

Figure 3. Drainage Infrastructure Features Captured in 23 DOT Maintenance Quality Assurance Systems (Adams and Bittner, 2009)

Drainage infrastructure asset management focused on where work was most often performed; i.e., on ditches. Teresa Adams' 2009 survey of 23 state and provincial transportation agencies in the US and Canada found that 93% were inventorying ditches, 48% had begun inventorying culverts, but **as of 2008 only 22% were inventorying "drainage structures,"** beyond curbs and gutters (35%) and cross drains (26%), which had their own categories.(Adams, 2009). Sixty-one percent of the 23 respondents were inventorying catch basins or drop inlets.

It is reasonable to assume that many of the states that did not respond to the Maintenance Quality Assurance Asset Management survey were doing less asset management, as a group, than those that responded or felt they had something to contribute to the study. A study by the Water Environment Research Foundation (Lampe et al., 2005) sheds light on reasons why tracking and maintenance may not be occurring, in some places. WERF identified reasons why maintenance of stormwater controls has been historically difficult to implement, many of which have to do with insufficient funding and the lack of a long-term maintenance plan: (Lampe et. al., 2005).

- Proliferation of BMPs that require intensive maintenance
- Designs not conducive to easy maintenance
- Inability to physically locate BMP
- Inability to track responsible parties
- Need to hire staff and maintain a database of the physical location of stormwater controls and provide for routine inspections
- Dedicated staff not assigned to inspection
- Lack of enforcement authority and access
- Owners of BMPs are unaware of their responsibilities
- Need to establish a legal framework (and persistence) to have enforcement authority, ensure access, and track responsible parties
- Need to educate about the responsibilities and proper practices needed to maintain stormwater control function

3.2 Post-Construction BMP Tracking Systems

Based on the survey for this research project (completed in fall 2012), 27% of all state DOTs said they had mapped post-construction stormwater BMPs statewide (and 69% indicated they had not). Twenty percent had mapped stormwater BMPs in MS4 areas only. Seven other states (14%) had inventoried and mapped outfalls statewide, but not BMPs. Just under half of DOTs (48% of total) had inventoried outfalls in MS4 areas only. Three more state DOTs had mapped outfalls only in MS4 areas outside of that which municipalities controlled.

Many states did not know or were not able to project the year in which they would have 100% of their roadside BMPs in their database or tracking system. Just six (6) states indicated they had achieved 100% coverage as of 2012. Five more DOTs either thought they would attain 100% coverage in 2013 or were already very close (i.e., at a 90% level), raising the percentage of DOTs with complete or nearly complete BMP inventories to over 20% by May 2013, when the NCHRP 25-25/83 final white paper will be released. Two more state DOTs anticipate completion in 2014 and 2015.

Fifteen percent of state DOTs (8 of 52) said they are currently utilizing an asset management system, environmental management system, or other database to track performance of permanent stormwater BMPs. For state DOTs' reference and mutual assistance, these eight states include: Delaware, Florida, Hawaii, Maryland, Minnesota, New Jersey, North Carolina, and Utah DOTs. Half of these are web accessible systems, i.e., Florida, Hawaii, and North

Carolina DOTs as well as DelDOT, MDSHA, and MnDOT are performing tracking in enterprise GIS databases. All eight states with tracking systems include individual BMPs and types, but not low impact development (LID) practices. DelDOT and NCDOT include as-built drawings or maintenance specifications for each BMP, viewable in the field. NCDOT and NJDOT include stormwater computations/design report; e.g., drainage area, land use, sizing, design criteria – if able to meet volumes, any exemptions, agreements with local entities. New Jersey DOT is tracking "a couple BMP types, in a limited way (hydraulic function only)," in the state DOT's asset management system, a non-geospatial database. Florida DOT is using their asset management system to record some water quality and quantity attributes as well. Hawaii DOT indicated that they conduct tracking in a proprietary system. Utah DOT is unique in the sense that tracking is linked to a formal Environmental Management System (EMS). This occurs in the context of general tracking of environmental commitments at Utah DOT.

With the exception of Utah, DOTs tend not to track roadside post-construction BMPs in the context of an Environmental Management System (EMS), a formal environmental continuous improvement process. For example, Illinois DOT has an EMS in place, but it is not currently tracking permanent BMPs. Rather, DOT EMSs more often track maintenance facilities, yards, or depots and a few DOTs track construction sites in an EMS context. Hawaii and Texas DOTs may be the most notable examples of the latter. In EPA audits, construction implementation has received considerably more attention than maintenance of installed permanent stormwater controls. (Taylor, 2012) In fact, Washington State DOT staff commented that, "Auditors did not focus on post-construction best management practices (BMPs) that WSDOT had constructed as a part of CIP projects." (Taylor, 2012)

According to survey research conducted for NCHRP 25-40 on BMP effectiveness and life cycle cost, only DelDOT includes BMP effectiveness (percent removal, percent volume reduced, pounds of pollution removed) in their BMP tracking system. At this point, no DOT has implemented metrics for long-term performance of BMPs. Nor has any DOT calculated extent of statewide application. MDSHA does track issues with different BMPs and aspects of performance.

The development of systems for tracking post-construction BMPs is a time-consuming process. It took Maryland almost 10 years to fully populate their system. MDSHA started by scanning as-built drawings and has invested continuously in GPS locating and field evaluating each BMP. Even with a high level of effort, MDSHA did not complete its inventory of existing stormwater BMPs until 2011. (Pujara, NCHRP 25-40, 2012). Colorado DOT, building on the knowledge of the wider community of practice, developed a fully populated system (tracking for all post-construction BMPs) on a relatively rapid timeline of 2-3 years. Maine DOT is currently developing a system wide inspection/maintenance system for their Maintenance and Operations Division. DOT definitions of "tracking" can vary. The survey response from West Virginia DOT said that existing plans are being used to help the agency map the stormwater system; currently BMPs there are considered "tracked" to some extent because they occur on the DOT's plan sheets. While results of inspections used to be stored on paper, DOTs increasingly capture and record data electronically for instant uploading to databases. Such databases are described further in the upcoming section. Below is a brief summary of selected states post-construction BMP tracking systems.

3.2.1 District of Columbia DOT (DDOT) BMP Inventory & Geodatabase

The District of Columbia DOT (DDOT) created their BMP inventory in 2011. DDOT's system is GIS-based; staff used GIS-enabled field tablets to record all vegetated BMPs, their location, size, plants, and basic structure information. Maintenance staff members also record the date of maintenance that occurred. As DDOT expands the system, the agency is starting to use Microstation files imported into GIS to map newly built structures.

3.2.2 Colorado DOT's System for Recording Post-Construction BMP Assessments

Colorado DOT developed their own software and data entry system for stormwater BMPs. CDOT water quality staff conducted the inspection and inventory of the state's 900+ post-construction BMPs in 2010, in consultation with maintenance. Headquarters staff consulted maintenance staff and as-built plans and located and reviewed all BMPs in the field, recording results in the state's Stormwater Inspection Tool (SWIT). They developed "Maintenance manuals" for each BMP from as-built drawings, to guide staff maintenance activities. Now CDOT is developing a custom software application to record inspection results and reviews, tailored to BMP types, in C sharp programming language and SQL2005. (Survey response from Rik Gay, NCHRP 25-40, 2012) That system will move to CDOT's Virtual Server as soon as it is ready. (Survey response from Rik Gay, NCHRP 25-40, 2012a)

Inspectors send results sent to Maintenance to help identify labor/maintenance action needed to address identified issues. CDOT maintenance staff record maintenance performed and costs/labor hours in CDOT's accounting database, SAP ERP. CDOT annually reports to the state regulatory authority on the number of post-construction water quality structures (PWQS) inspected, the total maintenance expenditures on those, and the results of limited, automated stormwater runoff monitoring.

Colorado DOT reports to the Colorado Department of Public Health and Environment on how much CDOT is spending on DOT inspection and maintenance of BMPs, on an annual basis; CDOT is required to inspect all 900+ BMPs annually. CDOT plans to start collecting discrete maintenance costs on each BMP by 2013. CDOT has established maintenance timesheet codes for:

- Environmental Permanent BMP- Installation & Maintenance of any permanent BMP.
- Environmental 30 day Inspection- use for completing 30 day inspection in conjunction in with MS4 and Stormwater management Plans.
- Drainage Structures- Clean, repair or replace.

With this coded information available for each post-construction BMP, CDOT will be able to make better estimates of maintenance costs.

3.2.3 Maryland SHA's Drainage Infrastructure Assessment System

Maryland SHA's Drainage Infrastructure Assessment System was the first comprehensive DOT system for recording and storing inspection results of post-construction stormwater treatment BMPs. MDSHA's system assesses conditions in a duplicable way, subject to rigorous quality control and quality assurance. MDSHA uses the system to manage the approximately 1,500 stormwater management facilities owned by MDSHA. MDSHA has also mapped the entire state for opportunities for BMP retrofits and begun to develop a plan for systematic implementation of those improvements.

MDSHA tracks maintenance for each post-construction BMP, which has an identification number and geolocation in the state's drainage infrastructure geodatabase. Maintenance activities are described in detail in the maintenance work order for each facility and stored for the record under the facility/BMP identification number, available in GIS. Newly constructed BMPs are added during county-wide inspections on a cyclical basis, every 3-5 years. As-built plans are provided to the field inspection teams to perform the inspection ratings using

MDSHA's Standard Procedures protocol. Inspectors update the spatial and inventory information and upload it to the geodatabase. Inspection teams of trained staff identify further environmental improvements that can be made.

The grade-based rating system for stormwater management facilities includes an inventory, database, and photo record of all facilities statewide and their maintenance status. Under the rating system, those graded A or B are considered functionally adequate. By 2009, MDSHA had reached their long-term goal of 95 percent functional adequacy for their system, with that percentage being rated A = everything fine, working fine, no maintenance required or B = minor maintenance, need mowing or trash removal), leaving only 5 percent needing maintenance or retrofitting to achieve functional adequacy. New regulatory standards are changing the retrofit picture though, as may be seen in the graphic from MDSHA's NPDES report on the following page.

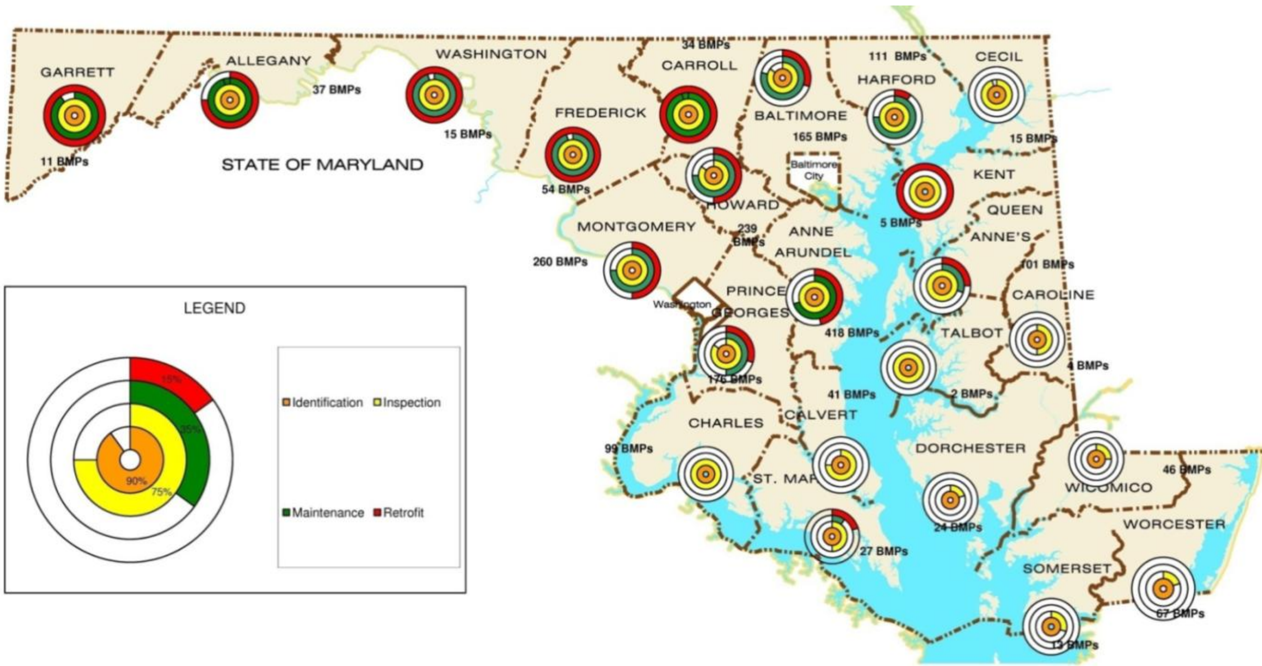

Figure 4. MDSHA's BMP Geodatabase Shows All BMPs Have Been Geolocated (Orange) and Inspected (Yellow). Some Require Maintenance (Green) or Retrofit (Red).

MDSHA's drainage system GIS is designed to be used for planning level computations and operations level activities, rather than for design or simulation modeling, though such capabilities are in the works. The database is used to determine the general location of systems and drainage areas, to track maintenance activities, and address public complaints.

Information in the drainage infrastructure asset management 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 MS4permit. It supports GIS queries based on:

- Individual structure or system and Best Management Practices (BMPs) e.g. pipes, inlets, manholes, endwalls, etc. and their associated data attributes.
- By outfall (size, type, etc.)
- Within a drainage area

- Within a watershed
- Within a jurisdiction
- Statewide
- 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 storm water runoff from the SHA right-of-way and the effects of changes in stormwater management (SWM) practices.

Maryland SHA's inventory and inspection system for all post-construction BMPs and drainage elements rates each individual element of a facility; for example, whether inflow is working well (1-5 rating), outflow (1-5), storage (1-5), and the degree to which the riser structure is in good shape. All the elements combine to produce one rating for the entire facility.

At MDSHA, every is BMP rated during inspections, and the agency then has a year to provide a rating or assessment for maintenance needs. MDSHA allows "a little longer" to do major maintenance. (Pujara NCHRP 25-40, 2012) For major reconstruction, a timeline is not specified in regulation. 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 MDSHA's drainage infrastructure improvement program.

3.2.4 DelDOT BMP Inspection/Maintenance Program & Rating System

In 2007, DelDOT developed a statewide stormwater BMP inspection/maintenance program with a consistent protocol for inventorying, inspecting and maintaining BMPs. DelDOT documented this protocol in their comprehensive BMP Field Inspection Manual and inspected over 300 BMPs, evaluating Site Conditions, Water Quality, Embankment, and Outlet Structure, each with their own set of parameters, differing among BMP types. (DelDOT, 2007)

DelDOT's scoring schema parallels Maryland's. Parameters are evaluated on a scale of 1 to 5 to reflect their relative condition, and are rated from good to poor. A "0" is used in cases where the parameter cannot be evaluated, or is not part of a BMP. The grade-based inspection rating schema provides an overall assessment of the BMP performance and provides an indication of the level of needed maintenance, again like Maryland's. DelDOT is currently in the process of mapping the drainage area to all of their BMPs so that the agency can determine statewide coverage of stormwater treatment.

3.2.5 North Carolina LOS Rating and Performance Reporting for Post-Construction BMPs and Stormwater Control Management System

In North Carolina, each BMP type has specific maintenance requirements which are defined in the DOT's *Stormwater Control Inspection and Maintenance Manual.* NCDOT does not use their Maintenance Management System to track which device type of maintenance is being performed or work performed on an individual employee's timesheet; however, upon completion of new projects, NCDOT staff members enter stormwater controls into the Department's Stormwater Control Management System. Subsequently, field staff members perform visual inspections of devices. If a device is intended to infiltrate runoff through a media or into the ground water and standing water is noted for extended period of time, then NCDOT initiates field and lab infiltration testing to evaluate the need for possible major maintenance.

NCDOT has a system for evaluating the Level of Service (LOS) for post-construction BMPs that both scores asset condition and gauges the maintenance needed for individual devices. Their A to F scale gives an “A” 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 and/or the lack of adequate maintenance. A related percentage rating was also developed. Individual LOS ratings are taken at least once a year for all stormwater control measures. NCDOT averages these ratings for division, counties, and road types. Every other year, NCDOT’s Asset Management Group evaluates the ratings. In addition, in each Division, Roadside Environmental Engineers (DREEs) receive ratings (e.g., “does not meet,” “meets,” or “exceeds) on their individual Performance Dashboard Appraisals (PDA), taking BMP condition assessments into account. Any rating below “C” indicates to the DREE that maintenance is needed on that particular device.

North Carolina DOT’s December 2012 Maintenance Condition Assessment Report showed over 95% of facilities functioning as designed, exceeding the 90% target the agency set for itself. With over 22,000 1/10th of a mile sample points, NCDOT has enough points to directly manage from its sample and confidently set maintenance budgets.

	Roadway		Interstate		Primary		Secondary	
			2012	State Average	2012	State Average	2012	State Average
	ELEMENT	PERFORMANCE MEASURE	Target	Score	Target	Score	Target	Score
DRAINAGE	Unpaved Shoulders	No dropoffs greater than 3 inches and no shoulders higher than 2 inches	95	92	90	92	85	93
	Ditches (Lateral Ditches)	No blocked, eroded, or nonfunctioning ditches	95	99	90	97	85	96
	Crossline Pipe (Blocked)	Greater than 50% diameter open	95	87	90	81	85	82
	Crossline Pipe (Damaged)	No damage or structural deficiency effecting functionality	95	91	90	97	85	96
	Curb & Gutter (Blocked)	No obstruction greater than 2 inches for 2 feet	95	96	90	97	85	97
	Boxes (Blocked or Damaged)	Grates and outlet pipes of boxes blocked <50%. Inlets and outlets of boxes are not damaged, and grates are present and not broken.	95	84	90	90	85	92

Figure 5. North Carolina DOT December 2010 Maintenance Condition Assessment Report Shows Over 90% of Stormwater Devices Functioning as Designed.

3.2.6 Minnesota DOT’s (MnDOT) System for Inventorying Hydraulic Conveyance Structures

MnDOT’s system for inventorying hydraulic conveyance structures is called “HYDRINFRA.” HydInfra employs consultant services for three levels of inspection, location, and repair of hydraulic structures. (Venner, 2004)

- MS4/HydInfra Inspection may include inspection, GPS location of hydraulic structures, and/or development of an electronic map (“stick map”) showing all hydraulic structures located during either the inspection and/or cleaning. The map will also show flow connection and direction for all structures as listed above and rating/evaluation of hydraulic structure condition. Any indicators of illicit discharges to the system are noted on reports.
- Video Inspection is completed in digital (MPEG-1) format for hydraulic structures (pipes, culverts, manholes, catch basins, drop inlets, etc.) and is conducted using remote controlled, self-propelled, explosion-proof video cameras. Video inspection includes providing video of the entire damaged structure. Defects along the pipe are identified, indexed, and stamped on the screen to allow for easier processing by MnDOT personnel.
- Hydraulic Structure Cleaning includes removal and proper disposal (including certification) of material from all types of hydraulic structures.

3.2.7 Washington State DOT Maintenance Accountability Process and LOS Rating

WSDOT has a Maintenance Accountability Process (MAP) that utilizes outcome based performance measures with a rating scale of A (best) to F (worst) for reporting the level of service provided and tasks/results accomplished by maintenance personnel. This can be a percentage of proactive or preventive maintenance performed. WSDOT is at the top of its class in assessing maintenance needs of its various physical assets outside of bridges and pavements and understanding and communicating the costs of maintaining these “ancillary” assets. Now WSDOT personnel are implementing a comprehensive, rigorous inspection and maintenance schedule for these highway assets and providing maintenance staff training in this regard. WSDOT is expecting to see improved overall condition of BMP assets that will translate into higher MAP LOS ratings.

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 the picture in telling the agency what has and hasn’t been done and whether budgets are sufficient. Operational Assessment deals with the operational side, such as how many repairs per signal were needed in a given period.” (Baroga NCHRP 25-40, 2012) Condition Assessment data is collected using statistically valid, randomly chosen sites for Field Surveys. Task Completion data is 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 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 2011-13 biennium expanded 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 (WSDOT, 2012).

WSDOT’s performance measures for stormwater BMPs and other assets are comprised of a condition indicator, (deficiency or condition to be measured), outcome measure, (unit of measure), and thresholds for the five service levels for each maintenance activity described in MAP. A threshold is the range of allowable deficiencies or conditions for each service level. Along with performance measures, WSDOT provides information on timing (when the information is gathered and reported), what level the reporting is at (region, area, section). At the “C” maintenance service level, “very few deficiencies are present in safety related activities, but moderate deficiencies exist for investment protection activities and significant aesthetic related deficiencies. Preventive maintenance is deferred for most activities except safety-critical work. More emphasis is placed on routine maintenance activities, and corrective maintenance occurs as necessary. A backlog of deficiencies begins to build up that will have to be dealt with eventually, at a higher cost. Some roadway structural problems begin to appear due to the long-term deterioration of the system. There is a noticeable decrease in appearance” (WSDOT, 2012). Service Level B, in contrast, is considered a “high” maintenance service level in which the feature is in good condition. All systems are operational…very few deficiencies are present in safety and investment protection activities, but moderate deficiencies exist in all other areas. Preventive maintenance is practiced for safety-related work, is deferred in other areas, resulting in additional routine and corrective maintenance measures. Corrective maintenance of all elements is handled in a timely manner. Life-cycle costs for maintenance activities are generally low” (WSDOT, 2012).

While WSDOT provides a pictorial overview of what these service levels mean for many maintenance categories, the agency did not do this for catch basins or retention/detention basins, prior to its new NPDES permit and effort to describe these conditions and costs.

In balancing the investment decisions among the assets the agency maintains, WSDOT draws on a Service Level Effectiveness Model, as depicted in Figure 6, which tries to balance preventive and corrective maintenance, keeping overall life cycle costs from getting too high by letting facilities deteriorate until they must be totally replaced, minimizing overall risk for the agency, and maximizing reliability, to the extent possible, for the agency's customers, including the public and resource agencies.

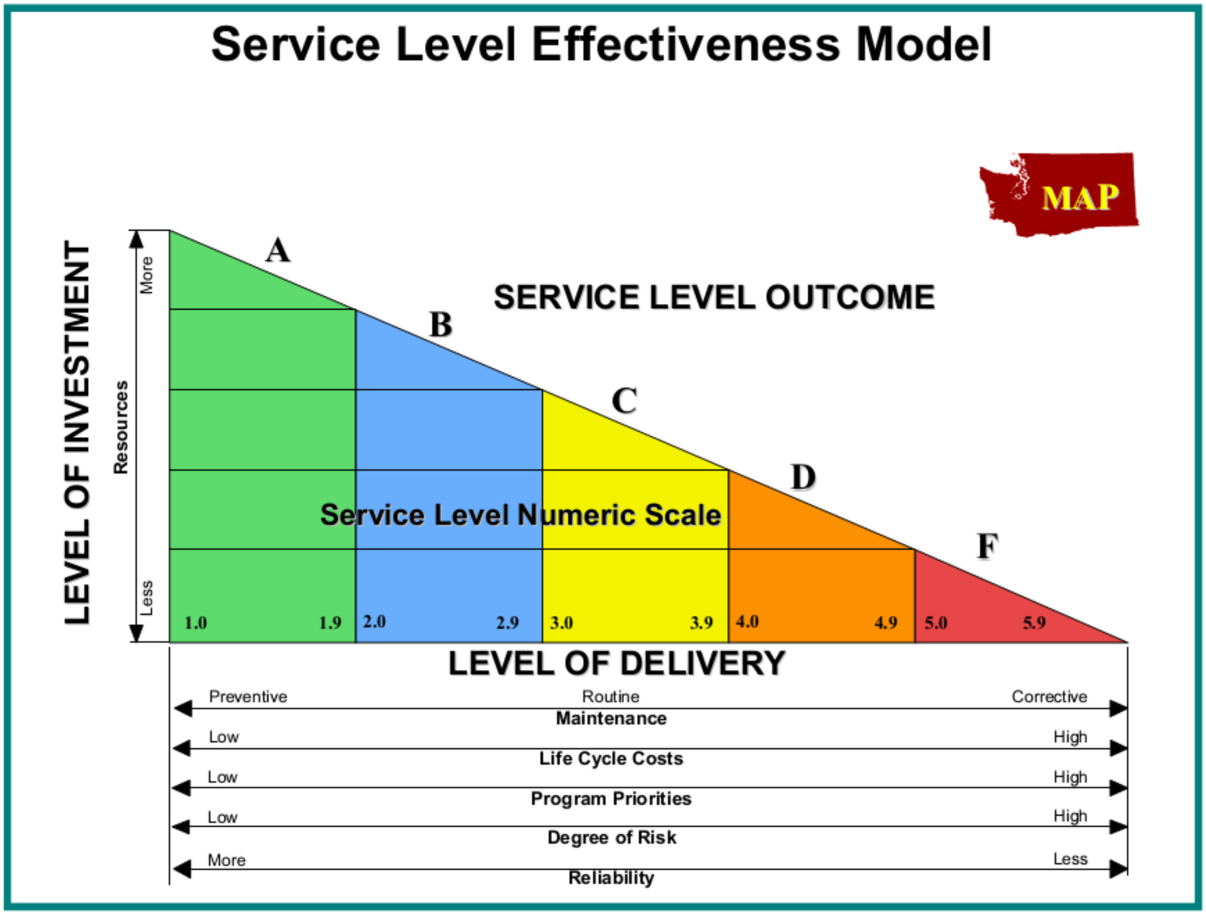

Figure 6. WSDOT MAP Level of Service Effectiveness Model

Regular inspection is a regulatory expectation that is being required in some states as NPDES permits are renewed. WSDOT established an inspection schedule and made estimates for associated effort/labor and materials as part of the WSDOT Maintenance and Operations budgeting process and part of the state's Joint Legislative Audit and Review Committee's (JLARC) review. The JLARC review noted "new and expanded requirements from WSDOT's previous permit," which "primarily fall into three major activities: maintenance of stormwater control devices, such as detention ponds; water quality monitoring; and inventory of stormwater systems.

Maintenance is the single largest activity in WSDOT's budget request. (Washington State JLARC, 2011) The audit noted, "A large portion of the maintenance cost estimate is for an activity that has not been routinely performed in the past" and "timing considerations and lack of comparable cost information I don't think a box repeating the text that is right next to it is helpful. I would remove.

complicate choosing among options." (Washington State JLARC, 2011) WSDOT is providing initial training and orientation to maintenance forces on the new expectations and the regularity of the inspections to be required, in PowerPoint presentations and in field outreach.

In the early stages of MAP, targets were established based on initial levels of service achieved. Decisions to adjust targets up or down were made at the discretion of the Regional Maintenance Engineers and the State Maintenance Engineer, again based on history and level of service achieved. This was changed during the 2007 Legislative Session. Legislators' fine-tuned the targets and wrote the targets for the 07-09 biennium into "legislation." In the 09-11 biennium the Secretary of WSDOT lowered some MAP targets in response to budget constraints. WSDOT's inspection/sampling schedule and procedure for producing these ratings is available online at 2012 MAP Manual and 2012 Field Data Collection Manual.

3.2.8 Other DOT Processes for Tracking/Adding Newly Constructed BMPs to Existing Databases

Some states without comprehensive or complete tracking systems for all BMPs are nevertheless recording and tracking new post-construction BMPs when they are installed, so that such information is readily available if and when more comprehensive statewide systems are developed.

Connecticut DOT requires addition of newly constructed BMPs to the state's database during the final design planning process. WSDOT includes such entry as a component of the construction project close-out process. MnDOT also uses plan sheets, and CDOT too is working on a process for tracking/adding newly constructed BMPs to existing databases. Michigan DOT acknowledges this transitional process is a challenge; currently MDOT is sending out letters annual requesting updates from their regional offices, but MDOT is "looking for a better way to track BMPs, through the clearance process." PennDOT also relies on letters and manual entry of newly constructed post-construction BMPs into Excel.

In some states, such as Mississippi, the DOT GIS section has a long range plan to map post-construction BMPs. In other states, such as New Hampshire, it is up to an individual to monitor construction projects as they leave project development, to track newly constructed BMPs. New York State DOT expects to issue an Engineering Instruction outlining the process by which newly installed BMPs should be recorded and tracked, within the next year. Vermont also expects to start doing this within the next year.

3.3 Labor Tracking Systems

Historically DOTs have managed labor more than they have managed assets. Though that is changing, DOTs still do little tracking of BMP maintenance work in their Maintenance Management Systems (MMSs), though some are adding an activity or function code to plan and capture work activities associated the BMP maintenance.

DOTs have not generally tracked maintenance of individual BMPs (or sometimes even the entire class of activity) in their MMS, though MDSHA is beginning to do so and Colorado and Washington State have plans to generate such information. Some DOTs know what they are spending on BMP maintenance monthly or annually, on a District/Region/Division basis but not by individual BMP or stormwater facility. Nor do DOTs generally characterize BMP maintenance by larger facility types or groups, like dry ponds or street sweeping, though Maryland and other states beginning to track maintenance by individual BMP will be able to create "roll up" characterizations by categories. This information should be able to inform future BMP design and selection choices as well as enable more accurate budget creation and regulatory reporting.

ODOT staff commented in response to the project survey that they don't currently "break out maintenance by type of facility" and the agency "has not done an analysis of what it costs to maintain the different types of facilities nor a thorough analysis of overall maintenance costs for water quality" (Fletcher NCHRP 25-40, 2012). ODOT does track the cost of water quality facility maintenance, but some activities may not be recorded as BMP maintenance. For example, if a water quality swale needs to be mowed, mowing is tracked as mowing and recorded as acres mowed; it is not tracked as water quality facility maintenance.

Currently many DOTs do not track even a general category of (all) BMP maintenance as a separate item in their MMS. If a DOT does, it is often just one code and not broken out by whether the activity is mowing, excavating, or replacing a BMP or which BMP is receiving the improvement, though several DOTs are moving in the direction of implementing this capacity. Most commonly, DOTs track daily maintenance work by type of work performed and person-hours spent, which can sometimes be traced to "accomplishments." For instance, some DOTs reported they have a separate maintenance activity for planning and repairing inlets and can probably estimate how much was expended over months or annually and what was accomplished. CDOT uses two activity codes related to maintenance of permanent BMPs (treated as a group): permanent BMP maintenance and permanent BMP inspection (Wieder interview, NCHRP 25-40, 2012).

Contract maintenance work also tends not to be "broken out" by individual BMPs or even types of BMPs; they are "time and material," including equipment, without any tracking of facility type. Contracts may be for pumping, an excavator, a certain quantity of stone placement, similar to DOT paving contracts.

The following summaries contain overviews of DOT codes and systems for tracking maintenance to post-construction BMPs.

- **DelDOT MMS Tracking of BMPs**: Street Sweeping, Mowing of BMPs, and Sediment Removal in Sand Filters are the recurring activities in DelDOT's Maintenance Management System. All work orders are submitted on an as-needed basis. DelDOT plans to add fields for routine basic maintenance of stormwater BMPs; e.g., Forebay Cleanout, Inspection of slopes.
- **Florida DOT Tracking of Routine Maintenance Costs for Stormwater.** The survey response from Florida DOT indicated that they track routine maintenance cost and production for drainage, inlet, catch basin, and other stormwater/drainage activities. The project survey response noted that "the inventory, and maintenance activities reporting production, and cost systems the FDOT has in place are not always specific to individual locations of stormwater functions."
- **Rhode Island DOT BMP Inventory and Maintenance Tracking in VueWorks.** Rhode Island DOT is developing a BMP inventory and maintenance tracking system in VueWorks, which will be online in 2013. Currently RIDOT has no tracking of maintenance work in the agency's timesheet system; any tracking occurs in Maintenance Daily Logs, in Excel. BMP and drainage work tracked includes: catch basin (not a detention or stormwater treatment) cleaning, repair, waterway cleaning, and pipe cleaning. RIDOT's stormwater program is in the process of developing a compliance-oriented Environmental Management System.

- **Texas DOT MMS Codes Related to BMP Maintenance**. Texas DOT has a relatively large number of codes related to maintenance of post-construction BMPs, in their Maintenance Management System, including: Mowing, Spot Mowing, Street Sweeping, Debris Removal, Spot Litter, Maintenance of Specialty Facilities, Riprap Installation and Maintenance, Ditch Maintenance, Culvert and Storm Drain Maintenance, Storm Water Pump Maintenance, and Slope Repair and Stabilization.
- **Washington State DOT maintenance tracking system (HATS)** is incorporating a number of maintenance activity codes for post-construction BMPs, when maintenance is undertaken to restore design capacity and allow for proper function of structure.
    - Detention/Infiltration/Wet Pond Maintenance
    - Underground Retention Detention Facility Maintenance
    - Stormwater Facility Inspection
    - Stormwater Facility Inspection In Response to Weather Event
    - Stormwater Facility Marking
    - Bioinfiltration Swale Maintenance
    - Media Filter Drain/Ecology Ditch Maintenance
    - Dry Well Maintenance
    - Filter Strip Maintenance
    - Sand Filter Maintenance
    - Miscellaneous Stormwater Facility Maintenance

  When activities are conducted within an NPDES area, they are charged to a certain maintenance series, to facilitate tracking of regulatory compliance costs.

3.4 DOT Plans to Improve the Specificity of BMP Maintenance Related Codes in their Maintenance Management Systems

Fifteen DOTs (almost 30% of the total 52) have plans to improve the specificity of BMP maintenance activities in their MMSs, in the next year.

- Caltrans has a system for tracking workload and is working toward a more comprehensive asset management database. Caltrans commented that “Maintenance tracks their activities, which has led to some confusion about treatment BMPs. A traction sand trap needs to be vactored to be cleaned; so does a drop inlet. Any drop inlet that is vactored (i.e., not designed with a self-cleaning velocity or slope) ends up being classified as a traction sand trap, which is a treatment BMP).”
- MassDOT is working on a geodatabase of stormwater BMPs.
- New Jersey DOT is in the process of inventorying stormwater features and will eventually add to Maintenance Management System by code. The first stage was to list all known MTDs and this is being followed by identifying and cataloguing the other BMPs. This effort has been delayed as project funding was lost in 2011.
- Ohio DOT is in the process of planning for separating BMP maintenance activities and connecting those to individual BMPs.
- Oregon DOT commented that some Maintenance Districts do their own tracking, but the DOT has no agency or system wide process or expectation.
- Washington State DOT (WSDOT) is in the process of conducting a stormwater features inventory (which includes stormwater BMPs and outfalls), a NPDES municipal permit requirement.

3.5 DOT Comments and Lessons Learned on Inventory/Tracking of Post-Construction BMPs

As part of the survey research on the state of the practice with regard to post-construction stormwater BMPs, some DOTs shared comments or lessons learned on inventory and tracking. For example, Caltrans pointed out that having a tracking system or not is not a simple “have it or not” question. DOTs are tracking and have systems for tracking some elements (hours/timesheets, limited asset management systems) but not others, and to various degrees (e.g., extent of coding of maintenance activities, coverage of maintenance actions for some BMPs but not others). Utah DOT utilizes an environmental commitment tracking system to ensure that BMPs and other commitments are carried through design, construction and into maintenance.

Other highlights included the following:

- MDSHA has developed extensive Standard Procedures for inspection and maintenance requirements.
- MDSHA said the key to successful programmatic efforts within an asset management program is a comprehensive and well maintained inventory database along with tracking system with friendly interface to track maintenance and remedial activities and associated costs.
- At Mississippi DOT, a third-party consultant tracks and manages their environmental maintenance program. Individuals assigned to each district track compliance and upkeep. Mississippi DOT has inspection forms and utilizes a SharePoint website to track progress.
- Rhode Island DOT located, inventoried, and assessed the condition of post-construction BMPs in 2006 and 2007 for the agency’s annual report; however, RIDOT has not been able to keep that up to date or ensure that information is used outside of the water quality section. RIDOT is implementing a GIS-based asset management system in the next year and hopes to implement what they feel will be more viable management processes for post-construction BMPs.
- Washington State DOT has used both field and office methods for inventory, including digitizing as-built plan sheets, to spatially locate outfalls and BMPs.
- Wisconsin DOT reported that “difficulties arise when the conditions do not fit our standard BMPs.”
- MD SHA noted that a list of standard maintenance activities by BMP type is very useful for creating maintenance work orders, so well worth the time investment to create.

3.6 DOTs’ Open Questions and Points Noted for Future Research Regarding Inventory and Tracking of Post-Construction BMPs

Topics and open areas noted by the DOTs could be considered for future research:

Local Knowledge. DOTs also described how knowledge of the surrounding landscape can be critical in understanding why certain BMPs fail. This “prior knowledge of the surrounding landscape, other things occurring in the county such as pumping or ceasing of pumping, data on the external environment or the BMP performance, and then analysis of all this aren’t easily available,” according to interviewed DOTs.

DOTs often do not have good systems for recording and transferring historical knowledge about surrounding landscapes and BMPs. Sometimes that information is acquired somewhat accidentally, as a local resident or over many years of service in a given geographic area. Certain DOTs, such as Virginia, are becoming very systematic about capturing information, and

DOT asset management systems assist with transfer of knowledge and the DOT's ability to cope with staff turnover as well.

Inspecting & Rating BMPs Transitioning from One Type to Another. When a BMP fails, it often undergoes a transition to another type of BMP. For example, when MDSHA rates an infiltration BMP, "agency specialists do a functional rating and assess whether the BMP is infiltrating. When an infiltration structure fails though, it turns into a wet pond or other wet facility." (Pujara NCHRP 25-40, 2012) MDSHA has documented the functioning of a number of failed infiltration BMPs as wet ponds; however, according to the existing assessment criteria assigned to the facility, based on its (former) infiltration function, "the facility is completely failing as an infiltration facility. MDSHA is trying to figure out how to reassign ratings." (Pujara NCHRP 25-40, 2012)

Using AVL to Reduce Data Collection Burdens. Though DOTs generally characterize BMP maintenance by larger facility types or groups, a few DOTs are integrating GPS and Automatic Vehicle Location (AVL) technologies to automatically download location information (and thereby individual BMP) and connect that to maintenance work performed, by adding codes to their Maintenance Management Systems. This will enable such DOTs to begin to track maintenance by individual BMP and to create "roll up" characterizations by categories. This information should be able to inform future BMP design and selection choices as well as enable more accurate budget creation and regulatory reporting.

Analytical Capacity – Really Using the Databases DOTs are Investing in Creating. Analytical capacity is an issue for DOTs as well. While some DOTs have data analysis staff in maintenance, such as staff consulted in Colorado, Utah, and Washington, many other DOTs do not. Some DOTs allocate the resources for analysis and optimization, as essential functions of public decision making. Analyses are performed in maintenance policy offices, by maintenance environmental support staff, by statewide BMP or drainage infrastructure database support staff, or to evaluate and report on performance for NPDES permits. Such staff support and analysis may even be considered a high-leverage, non-structural BMP, as analysis is designed to improve program effectiveness.

4 Research Gaps and Needs

AASHTO, NCHRP, and DOT practitioners have made significant investments in their stormwater community of practice and in stormwater-related research projects in recent years. DOTs are in particular need of a brief guide to what exists, what is in process, and what will be available in the next few years, as well as remaining research needs.

At the panel's request, the research team developed annotated bibliographies of research in the preceding 24 months related to post-construction stormwater discharge control, relevant to DOTs. The team used the annotated bibliography (Appendix D), as well as professional knowledge and DOT preferences recorded in the survey, to identify gaps in the literature and research priorities. The team also considered and incorporated research statements developed by state DOTs in AASHTO's Stormwater Management Community of Practice (CoP) as well as needs based on likely regulatory requirements associated with EPA's impending stormwater rule.

4.1 DOT Water Quality Research Priorities from September 2012 Survey of all 50 States

4.1.1 Generation of the List of Prospective Research Needs for DOT Survey

Before surveying state DOTs, prospective research needs were first reviewed and combined from several sources, including the project panel, support staff for recent DOT Stormwater Community of Practice meetings and discussions, and experts on the research team, practitioners on the field and academics. The research team consulted with the TRB Committee on Hydrology, Hydraulics and Water Quality (AFB60) via the DOT Chair of that group. The research team also consulted select DOT water quality practitioners, including the panelists for this project, to identify any potential gaps in the list of topics circulated to DOTs.

The research team also revisited the research needs identified in NCHRP 20-25(02). Completed in 2003, NCHRP 25-20(02), Identification of Research Needs Related to Highway Runoff Management, identified and described research projects addressing priority needs in the area of highway runoff management. The project reviewed work by FHWA, EPA, and state DOTs and summarized significant stormwater management practices and research efforts. It identified the most pressing gaps and needs in the current state of knowledge that were hindering DOTs' abilities to implement effective stormwater runoff management programs. DOTs were asked about a number of these again in 2012, but many were lower priorities by this time; many DOTs felt many of the former issues had been dealt with adequately or examined somewhere by now.

The consultant supporting the meetings of AASHTO's Stormwater Community of Practice reviewed research and data needs and topic focus areas suggested by that group as well as additional topics and research ideas related to construction stormwater issues based on DOT feedback during the June 2008 AASHTO Stormwater Conference and the AASHTO Transportation and Environment Research Ideas (TERI) database list.

4.1.2 State Ranking of DOT Research Needs

The complete list of research needs that survey respondents ranked are shown below numbered 1 through 29. This data can be examined as two different ways. The following list is in order based solely on the number of states, which indicated that the research topic is a "high" priority to them. This list is ordered such that #1 is the one with the greatest number of "high" rankings; the "top 10" were:

1. **BMP Maintenance Requirements and Cost Information** to maintain performance for a variety of highway settings.
2. **Structural and Non-Structural Practices Generating the Greatest Benefits**: Research/ recommendations/guidance on which structural and especially non-structural practices (e.g., of all the many potential practices within EPA's 6 minimum measures categories) generate the greatest benefits.
3. **Measuring DOTs' Contribution to Watershed Impairments from Roads or Sites and Potential Improvement of Watershed Constituents/Issues through Off-Site Investments –** Guidance on watershed approaches to stormwater mitigation and TMDL compliance whereby DOTs may invest in conservation or restoration of off-site areas or off-site BMPs to address some portion of on-site stormwater runoff needs.
4. **Garnering Regulatory Support/Credit for newly quantified BMPs including Vegetated Filter Strips** and unlined conveyance stormwater quality/quantity management, when not originally designed for this purpose. **Permeable friction course** produces water quality benefits, for which some DOTs would like to get credit.
5. **Data on BMP Performance vs. Age and Level of Maintenance.** Some DOTs are beginning to collect data on the actual maintenance costs of individual BMPs. Washington State DOT is linking in-vehicle GPS (and others are linking smart phone/tablet systems and automatic data-downloading) with increasingly fine coding in Maintenance Management Systems to begin to compile data on BMP maintenance. This data may be associated with condition assessments for greater insight on BMP performance vs. age and level of maintenance.
6. **Critical BMP Design Variables –** Understanding of critical BMP design variables that influence performance for different water quality constituents.
7. **How to Adequately Resource Stormwater Maintenance and Operations** from the standpoint of labor (skills and level of effort) and equipment to meet basic current requirements, especially as regulatory demands are rising and overall staff numbers continue to fall.
8. **Guidance on Watershed Approaches to Stormwater Mitigation and TMDL Compliance;** e.g., Watershed-Based Stormwater Mitigation Approaches, off-site In Lieu Fees, Offsite Mitigation, Pollutant Trading, Mitigation Banking.
9. **Standardized Data Management Systems and Performance Measurement for BMP Inspection, Maintenance, and Corrective Action –** Evaluating quality assurance and control (QA/QC) and systems/standards DOTs have developed for performance measurement, inspection, maintenance, and corrective action.
10. **Self-Auditing and Continuous Process Improvement** – Collecting and sharing procedures for stormwater program auditing and continuous process improvement.

The next five priorities are shown below:

11. **Highway Runoff Quality Characterization and Compliance Assessment**. In retrospect, this question should have been split into two, to better understand the respondents' preferences.
12. **Methods for Retrofitting** existing detention basins to improve water quality.
13. **TMDL Coordination and Participation** – DOT best practices for coordinating with stakeholders and mutual education on what is practical, feasible, and a good use of public funds.
14. **Tools for Modeling BMP Performance and Receiving Water Impacts**, including both water quality and hydro-modification.
15. **System Performance Estimating for Treatment/Coverage** – Methods for DOTs to estimate of stormwater BMP coverage/treatment across the DOT system.

Research topics with fewer "high" priority rankings include the following, in descending order:

16. **Maintenance Water Quality Practice Update**. Update of latest knowledge and best practice compendium relating to water quality in Maintenance (e.g., Vegetation, Inlet Cleaning, Inventories, BMP Maintenance, Waste Management, Illicit Discharge, Managing Run-on to DOT Facilities).
17. **Low Impact Development – Performance and Maintenance Information** for distributed/LID BMPs and how DOTs are managing the maintenance demands.
18. **Connecting BMP Condition with Percent of Maintenance Tasks Completed**: integrating and using the main types of performance measures (measured condition of stormwater infrastructure and percentage of maintenance tasks completed) in a basic maintenance program, developing an "owner's manual" for stormwater infrastructure that can be estimated for potential full funding.
19. **Construction Compliance**: Construction Program-CGP Compliance, Construction BMPs, Violations, Inspections, Contractor Compliance – Use of specifications and contracts.
20. **Post-Construction BMP Selection – Decision Support.** Development of a Nationally-applicable decision support system for selecting and sizing effective post-construction BMPs.
21. **Different Expectations for Rural versus Urban Performance**. Assess differences in stormwater performance measurement in an urban vs. rural setting.
22. **Maintenance Training Resources**. Identify and share generalized templates of training resources for ongoing maintenance of structural BMPs. DOTs have identified needs for training resources for engineers, contractors, and inspectors.
23. **Construction BMP Selection – Decision Support**. Develop a nationally-applicable decision support system for selecting and sizing effective BMPs at construction sites.
24. **DOT Cold Climate Water Quality Issues and Best Practices** – a synthesis of the practice.
25. **Construction BMP Selection – Decision Support**. Nationally-applicable decision
26. **Outreach and Collaboration with Environmental Groups and Regulators**.
27. **DOT Slope Management Practices** – Synthesis of Inspections, Tracking, Maintenance, Slides, Water Quality.

28. **Bridge / Crossing Stream Stability and Water Quality**.
29. **Understanding of pollutant partitioning to different particle sizes**.
30. **Information on potential impacts to biota utilizing stormwater BMPs as habitat**.

Other suggested topics included the following.

- Methods to deal with DOT responsibility for “run-on” from adjacent lands, particularly agriculture, including DOT best practices, legislated relief, or monitoring inflow and outflow to document the inflow ‘baseline.’
- Turbidity compliance practices and the benefits of vs. the drawbacks from polyacrylamide for erosion control.
- Tradeoffs and parity for money being spent on design vs. compliance in the field?
- Interface with regulators: Lessons learned.
- Construction/Erosion and Sedimentation Control Best Management Practice related.
- Should the contractor or the DOT prepare the erosion control plan?
- How are specifications and contracts for enforcement being used?
- Short-and long-term effects of highway construction on water quality.
- Testing of construction site BMPs
- Managing environmental impacts of erosion and sedimentation from low-volume roads.
- Framework for new multi-state collaborative program to appraise effectiveness of highway stormwater runoff treatment options – f methods for data collection, sampling, and characterizing stormwater properties, and for assessing the performance of a full range of construction and post-construction BMPs.
- Is there potential for compost filters/berms to become hazardous waste?

4.2 Suggested Research and Relation to Pending Research

To complement the list of research priorities developed above, the following section provides a list of research suggested by the research team, selected and expanded from the DOT surveys, assessments of needs from the research team, and the AASHTO Stormwater Community of Practice. Relations to pending research and gaps are also discussed.

4.2.1 Highway Runoff Characterization and Assessment

Runoff characterization is a fundamental component of assessing potential impacts of a highway project and evaluating BMPs necessary and/or capable of minimizing those impacts. While this research category is vast and has been an area of interest for decades, highway runoff characterization and assessment will continue to be important for DOTs’ stormwater programs. The following topics are some of the many informational needs under this broad category of research.

Highway Runoff Database

FHWA and the USGS have developed the Highway Runoff Database (Granato et. al, 2002), which was expanded by MassDOT in 2010 (Smith and Granato, 2010). However, the database includes limited information on some pollutants and does not have complete national coverage. Additional research is needed to expand the database to cover broader ranges of ecological and climatic regions and a wider variety of average daily traffic counts and other highway characteristics.

Development of a Model Monitoring Program for a DOT

Many NPDES Permits require DOTs to monitor receiving waters to characterize runoff from DOT facilities, to assess the effectiveness of BMPs, and for compliance with TMDLs. Monitoring programs require considerable time and resources to implement. The objectives of DOT monitoring programs may not be well defined, and the data may not be used to the fullest extent to provide feedback to improve the performance of the stormwater program.

A primary purpose of this suggested research is to develop a list of common highway runoff quality study questions and prepare a model monitoring program for state DOTs. The study questions should be used to define the most important data gaps and data needs to improve the performance of the DOTs stormwater program in demonstrating compliance and evaluating different management strategies. There is also a need to examine sampling protocols to determine the most appropriate approach for DOTs, as well as to establish a consistent recommendation nationally to ensure that data across the U.S. is comparable.

Parameters for Hydromodification Control

Permits and regulations are beginning to require management of stormwater to minimize adverse hydromodification, but there are no consistent standards for determining when a water body needs hydrologic protection or setting a range of flows that should be managed.

DOTs need consistent and scientifically supportable criteria for determining when hydrologic mitigation is appropriate and necessary for a site, as well as guidance for designing hydromodification controls. This research could include critically reviewing existing criteria and their rationales, recommending appropriate criteria by climatic region and geomorphologic conditions, and preparing hydromodification control design guidance.

Contribution of Zinc from Highways

Concentrations of zinc in highway runoff often exceed water quality objectives (CH2MHILL, 1998; Nelson, Huber, & Eldin, 2000), and galvanized metal surfaces, motor oil, tires, and hydraulic fluids are known sources (Golding, 2006). A number of receiving waters in the United States are listed as impaired for zinc and TMDLs have been adopted or are being developed. These TMDLs currently require DOTs to construct and operate structural BMPs at substantial costs to treat the storm water at the end-of-pipe. A potentially more cost-effective approach for managing zinc in stormwater would be to remove the sources from the highway environment. Unfortunately, little is known about the relative magnitude of the various sources. This research would be designed to address that knowledge gap. The work would include an analysis of the potential reduction in lifespan of highway infrastructure and the associated costs if zinc use is curtailed and the costs and benefits (longer life) associated with coating exposed galvanized metals such as guardrails.

Contribution of Tire Weights to Lead in Runoff

Lead tire weights used to balance wheels may be a substantial source of lead in the highway environment today. These weights can be released from wheels and then abraded by traffic, releasing lead into the environment. The purpose of this research would be to provide the following information:

- Whether abrasion of lead wheel balancing weights occurs on the road, and, if so, the extent of the abrasion and the mass of lead lost from the abrasion;

- The contribution of lead from wheel balancing weights to the overall levels of lead near roadways;
- The quantity of lead from lead wheel balancing weights deposited on highways that subsequently enters various environmental pathways; and
- The percentage of deposited lead that enters each pathway (to determine which pathways are of concern).

The work would include collection and evaluation of the amount of lead contributed to highway runoff by lead tire weights. This evaluation includes the contribution of both in-place weights and weights lost during use.

Salt/Deicing Practices Source Control

The purpose of this study would be to determine the optimal practices for roadway winter maintenance operations or snow and ice control. Some receiving waters in areas of the United States are impaired for road salts (mainly chlorides and additives), either 303(d) listed or enforced through Total Maximum Daily Loads. In such cases, DOTs are frequently named stakeholders for TMDLs focusing on road salts.

This research is intended to provide a common ground between the highway and regulatory communities targeting environmentally responsible deicing practices and that seek to employ feasible and economically prudent strategies for the safe operation of the roadway. To highway agencies, deicing operations are an essential element to maintaining the safety of the traveling public. Given the expectations of the public and the scarcity of public highway funding, it is essential to optimize deicing practices with a balance of fiscal, environmental and safety concerns.

This study would determine the optimum timing and application rates of various anti-icing and deicing materials under typical road weather scenarios (snow intensity, pavement temperature, relative humidity etc.) and provide guidance when traction sand should be considered as a supplementary tool. The effectiveness of various chemicals can be determined by a variety of standard tests, including but not limited to:

- Ice Melting
- Ice Undercutting
- Ice Penetration
- Controlled Site Testing

The following five chemicals have been used extensively for anti-icing or deicing treatments: sodium chloride (NaCl), magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), calcium magnesium acetate (CMA), and potassium acetate ($KC_2H_3O_2$). Each has its own set of pros and cons, dependent upon application location and cost sensitivity. Other chemicals are becoming more common, as are a number of additives (such as agro-based byproducts) to minimize the negative impacts of the deicers.

Study is needed to determine comparative costs and environmental concerns of each deicer based on the optimal application processes. BMPs to mitigate possible environmental concerns associated with road salts could be incorporated into the analysis, considering current BMPs are often designed to treat stormwater runoff instead of targeting the contaminants from salting practices. As it is difficult to truly treat chlorides or remove chlorides from the environment, additional research is needed to address such needs.

As suggested by Fay et al. (2013), "there is an apparent need for further research in the design options, performance and cost-effectiveness of reactive strategies for managing the footprint of chloride roadway deicers. There is also a lack of knowledge regarding the fate and transport of relevant pollutants (e.g., deicers, anti-icers, and their additives) in soil, vegetation, or water bodies, whereas such knowledge is much needed to guide the design, monitoring and evaluation of reactive strategies in treating chloride-laden roadway runoff and minimizing their potential damage to the receiving environment. Existing studies generally either focused on dynamics in a laboratory setting or an actual field setting, with the former lacking the field variables and the latter producing site-specific results with limited transferability. It is desirable to conduct such research in a controlled field environment where a comprehensive test program can be formulated to examine selected processes or to test significant hypotheses". (Fay et al., 2013)

Characterization of Nutrients and Pathogens in Highway Runoff

Stormwater runoff from transportation rights-of-way may contain nutrients (particularly phosphorus and nitrogen) and may contain pathogens, which can have adverse environmental impacts on receiving waterbodies. Accordingly, DOTs are being named or have been named in TMDLs for nutrients and pathogens across the country. There is a need to determine if roadways and roadside areas are a significant source of receiving water impacts as a result of discharging these constituents/indicators. Research should evaluate the significance of the contributions of these pollutants from road surfaces and roadside areas relative to other land uses and provide a cost/benefit analysis of implementation of BMPs vs. the environmental benefit, determining if the discharge of these constituents/indicators is significant and if treatment BMPs are necessary to meet the MEP standard.

This research would involve:

- Synthesis of prior studies done to characterize the stormwater runoff from the ROW (with special focus on nutrients and pathogens), and
- Synthesis of prior studies that have findings about the effectiveness of BMPs to treat nutrients and pathogens. The research would result in a) a determination of whether DOTs need to remove nutrients and pathogens from runoff to meet the MEP standard, b) if it is appropriate to include DOTs as a stakeholder in TMDLs for these constituents/indicators, and c) a list of BMPs that are appropriate for use within a transportation ROW. Recommendations would be made as to the most effective and least costly options for DOTs to control these constituents/indicators.

4.2.2 BMP Selection and Design

The selection and design of appropriate and cost-effective BMPs to meet evolving environmental goals and regulatory requirements continues to be a challenge for many DOTs. While most BMP manuals provide guidance for selection, such manuals rarely provide quantitative information on BMP performance and costs. In addition, the benefits of design alternatives are not easy to assess.

DOTs need simple tools that can be used to identify, select, and design BMPs that can meet increasingly challenging regulatory requirements. NCHRP 25-31 (Report 728) provides BMP selection guidance and a simple tool for evaluating BMPs for ultra-urban environments (Geosyntec Consultants et al., 2012). NCHRP 20-05 will provide general guidance on BMP implementation costs and performance. NCHRP 25-42 will provide guidance on BMP selection for bridge runoff analysis. The BMP performance and life-cycle cost analysis tool being developed for NCHRP 25-40 will allow DOTs to quickly evaluate load reductions and costs associated with different BMP designs.

The guidance and tools developed or being developed as part of these efforts could be improved with additional information on design variables that influence treatment, particularly those associated with the biological and physiochemical treatment mechanisms, such as pollutant uptake and adsorption. This research gap should be partially filled with NCHRP 25-32 where dissolved metals removal is being evaluated. Additional potential research gaps and needs related to BMP selection and design are summarized below.

Structural and Non-Structural Practices Generating the Greatest Benefits

Research/recommendations/guidance is suggested on which structural and especially non-structural practices (e.g., potential practices within EPA's 6 minimum measures categories) generate the greatest benefits and return on investment. NCHRP 25-40 will summarize the performance of eight commonly implemented structural BMPs (swales, filter strips, dry detention basins, bioretention, wet ponds, sand filters, and porous pavement) and will evaluate 11 non-structural control measures/programs. These measures/programs will be evaluated based on the following criteria: 1) pollution avoidance or pollutant removal effectiveness; 2) cost of implementation; and 3) social/institutional impacts of implementation. This evaluation is intended to facilitate sustainable stormwater management decision-making using a "triple-bottom line" analysis to allow the DOT stormwater manager to prioritize non-structural BMPs relative to other structural and non-structural measures identified in this study. Non-structural and source control measures/programs that will be included in the analysis are:

1. Municipal separate storm sewer system (MS4) system cleaning
2. Sweeping
3. Irrigation runoff reduction practices
4. Fertilizer/pesticide usage and integrated pest management (IPM)
5. Trash pickup programs
6. Elimination of groundwater inflow to the MS4
7. Slope and channel stabilization
8. Public education/outreach
9. Enforcement
10. Inspection and elimination of illicit connection and illegal dumping (ICID)
11. Training for DOT employees

The performance of these measures and programs at reducing pollutant loads is extremely difficult to quantify and, as such, there is limited empirical data available (information that is available is primarily anecdotal). Consequently, this research is focused on providing DOT practitioners with a qualitative process for evaluating the cost-effectiveness of non-structural controls for the highway environment. Further research on establishing actual costs and benefits could be conducted, but would require carefully controlled studies of actual applications of these measures and in some cases comparisons to areas where they are not implemented.

Guidance for Targeted BMP Needs

DOTs are struggling with BMP selection and the benefits that may be attained with different design alternatives. NCHRP 25-31 provides BMP selection guidance and a simple tool for evaluating BMPs in ultra-urban environments. NCHRP 20-05 will provide general guidance on

BMP implementation costs and performance. NCHRP 25-42 will provide guidance on BMP selection for bridge runoff analysis. NCHRP 25-41 will provide guidance on volume reduction approaches. The BMP performance and life-cycle cost analysis tool being developed for NCHRP 25-40 will allow DOTs to quickly evaluate load reductions and costs associated with different BMP designs. BMP selection guidance is available, but gaps exist with regard to controlling nutrients and meeting increasingly stringent limits on contaminants such as heavy metals, phthalates, PCBs and polycyclic aromatic hydrocarbons (PAHs). For example, in the Pacific Northwest the National Marine Fisheries Service has been issuing Biological Opinions with not-to-exceed dissolved copper limits of less than 5 µg/l and under CERCLA, PCBs and PAHs are increasing pollutants of concern at very low levels as well. Guidance is particularly needed for BMP designs that address low pollutant limits and provide DOTs with strategies for obtaining technology-based BMP approvals. The latter is particularly needed when proposed discharge limitations are so low that they would require the use of active treatment technologies to meet.

Permeable Friction Course Related Topics

Permeable friction course (PFC) is an approximately 2-inch thick layer of porous asphalt placed on a conventional asphalt concrete or Portland cement concrete structural section to improve driver safety in wet weather. Water quality improvements and reduction in noise levels have also been observed. Implementation has been widespread in the southern and western portions of the US as well as in many countries in Europe and Asia though the overlay is still not accounted as a BMP and credit given by environmental agencies, due to the newness of the technology as a water quality application.

Nevertheless, research conducted for TxDOT and NCDOT indicates that there is a substantial water quality benefit from PFC. Runoff water quality discharged from PFC pavements has been shown to be roughly equivalent to that achieved by treating highway runoff with a sand filter system. Importantly, Eck et al. (2012) indicated that performance was sustained without maintenance. This level of treatment is sufficient to meet stormwater requirements in many jurisdictions and for many receiving water conditions and has substantial implications for DOTs, stormwater treatment, and maintenance thereof in the future.

A variety of research questions could be addressed to increase the applicability of PFC and to document the water quality improvement.

Use of PFC in curbed sections. Does accumulation of pollutants adjacent to a curb negate the water quality benefits of PFC? What is the best standard configuration (e.g., pave all the way to the curb, end the pavement at the edge of the gutter, etc.) and what are the impacts on flooded width of the roadway and spacing of inlets?

PFC mix design: Many DOTs still use older mix designs known as Open Graded Friction Course (OGFC). These pavements may not have sufficient permeability and porosity to provide an initial or long term water quality benefit. In addition, many pavements include recycled materials such as crumb rubber. Investigation is needed to better understand how these materials affect permeability and porosity and to ensure that there is no leaching of pollutants from these materials. Finally, research on potential additional materials to include to enhance performance would be helpful.

Cold weather use: DOTs in locations with multiple freeze/thaw cycles per year have been reluctant to use or evaluate PFC because of concerns related to service life of the overlay, deicing, and damage from snow plows. Some research has been conducted in northern states recently (e.g. Indiana DOT) but additional research to address these concerns is warranted.

Full-depth porous asphalt: DOTs have traditionally shied away from full-depth infiltration/permeable pavement in the highway environment because of concerns about the durability of the pavement section; however, recent EPA stormwater requirements have included volume reduction requirements and there is every indication that EPA will adopt similar requirements nationwide. Consequently, DOTs may need to revisit this configuration in an attempt to infiltrate more runoff.

Establishing equivalency to other BMPs and Coordination and Crediting for PFC Use*:* Following a better understanding of the water quality performance of PFC, there is a need to gain acceptance by regulatory agencies of its equivalency to other water quality BMPs.

Media Filter Drains (Linear Filtration Devices)

The media filter drain (previously known as the Ecology Embankment or Bioslopes) is a technology developed by Washington State DOT (WSDOT) to improve runoff quality in a linear, small footprint facility that is appropriate for the constrained ROWs associated with highways. It consists of a trench excavated parallel to the roadway that is backfilled with engineered media and an underdrain. Research by WSDOT has demonstrated improved water quality and a reduction in stormwater runoff volume. Similar systems have also been used internationally. For instance, in Scotland most roadways are bordered by a “filter drain,” an excavated trench filled with gravel and an underdrain. Improvement in water quality has been demonstrated by this configuration, and it is also used to limit moisture accumulation in the roadway base material.

The benefit of media filter drains to DOTs is the ability to provide stormwater treatment in a footprint that is suited to the linear constraints of transportation systems. Relatively high levels of treatment are possible. It should also be feasible to develop specialized filter media to meet more restrictive requirements associated with TMDLs or other site-specific needs.

A variety of research questions could be addressed to increase the applicability of media filter drains and to document the water quality improvement.

Media formulation: There is a need to identify materials that will effectively reduce the concentrations of dissolved constituents, particularly metals and nutrients. These constituents are often addressed in TMDLs and conventional stormwater treatment controls; consequently, their control is a priority. NCHRP 25-32 is currently underway to identify materials that exhibit substantial removal of dissolved metals. In addition, Oregon DOT has a project under construction that will evaluate media filter drains with different materials, such as pulverized fish bone. Additional research in this area may not be a priority until the results of these ongoing studies are available and gaps may be better discerned.

Design guidelines: A number of questions remain related to the design of filter drains. The first question is what impact drain location (relative to the pavement) might have on moisture levels in the highway base material (pavement life) and slope stability. The second question is what safety issues exist related to the choice of backfill materials. Since filter drains are installed within the clear recovery zone, the trench backfill needs to be sufficiently strong to support the weight of vehicles where no guardrail is present. Since volume control of highway runoff may be required in the future, configurations should be developed that maximize infiltration. The tool being developed by NCHRP 25-41, *Guidance for Achieving Volume Reduction of Highway Runoff in Urban Areas*, will be helpful for evaluating such configurations. Media filter drain technology shows promise in helping to address runoff water quality and quantity mitigation that could otherwise be a substantial challenge on highways with significant longitudinal slopes.

Maintenance requirements: Most roadside media filter drains have been in operation for a relatively brief period of time; consequently, little is known about the long-term maintenance requirements. If replacement of the media is required or if the trench must be excavated to re-establish infiltration into the surrounding soils, the cost could be prohibitive. Research on filter drains in Washington State may be appropriate as these systems have been in place for some time. ODOT is also in the process of evaluating media filter drain maintenance requirements.

Batch Release and Enhanced Detention

The concept behind batch detention is that the outlet for an extended detention or flood control basin is fitted with an automated valve system to control the timing and rate of runoff release rather than the conventional method of using a passive orifice or weir. An automated system is easily operated using a solar panel, deep cycle battery and motor operator to facilitate installations in remote locations. The use of batch detention has a number of advantages in that it can substantially improve the water quality performance of the basin, it allows the basin to be better used as a hazardous material trap for spills, it is well suited for retrofitting existing flood control facilities to provide a water quality benefit (drain before large storms arrive), and it can be used to meet hydromodification requirements. TxDOT has retrofit two facilities for batch detention in the Austin, TX area and documented the water quality improvements. In addition, the Water Environment Research Foundation (WERF) is currently sponsoring a project called *Transforming Our Cities: High Performance Green Infrastructure* (INFR1R11) to demonstrate distributed real-time control technologies, including retrofitting existing detention basins with logic-controlled actuated outlets. The data to make decisions on when to open or close a valve can come from the web (quantitative precipitation forecasts for example) or any local sensor.

The University of Texas and NCSU have provided initial investigations into how to retrofit detention basins for water quality, yet practical applications are still needed and the science is evolving. For example, some of the potential retrofits besides active control may include increasing the capacity, vegetating and benching, incorporating a wet pool, installing berms and baffles, adding a sedimentation forebay or a bottom grid structure, modifying the outlet, as well as installing a real-time controlled actuated valve. Research is needed to identify which of these types or combinations of retrofits are the most cost-effective and then guidance is needed on implementing them.

TxDOT has already demonstrated the proof of concept for this treatment technology and the WERF project will be providing additional data on the benefits of more controlled detention. Future research would be helpful related to the following:

Development of linked systems: Flood control systems in a watershed are conventionally designed and operated independently, without regard to their location in the watershed. This can actually lead to greater flood depths in downstream receiving channels than if no detention basins had been constructed. By linking the automated valves to a central controller/decision support system (by cell phone, WiMAX, or other technology) the discharge of the basins can be optimized to comply with water quality, hydromodification requirements or flood control requirements on an event-specific basis and address the interaction of multiple-basin discharge. The WERF project is specifically evaluating the use of real-time monitoring of these systems using centralized, web-based controllers.

Soil Amendments

A number of DOTs have investigated and found promising results with soil amendments such as compost to retain runoff, promote vegetation growth and remove particulates. Investigating DOTs include Caltrans, WSDOT and TxDOT. The reduction in runoff volume is a particularly important element, considering the new nationwide rules on volume control currently being evaluated by EPA. TxDOT research indicates that areas where vegetation coverage is near 100% in the existing condition showed little benefit from the addition of compost into the soil. Other research in Texas and other locations have documented a substantial improvement in the rate of vegetation establishment in disturbed areas.

A potential issue is that many compost formulations contain a substantial amount of phosphorus (and some have copper in municipal sources) that will leach into the discharge during storm events. Some amendments such as zeolite and rhyolite can improve metals retention and hydrologic characteristics of the existing soils.

Additional research would be helpful in the areas of pollutant removal documentation, soil amendment specification, configurations of placement, and volume reduction.

Quality improvement: The improvement in runoff quality resulting from the application of soil amendments has been investigated as permanent post-construction BMPs in only a few locations. More research nationwide would be helpful in demonstrating the performance to regulatory agencies. One focus should be establishing the benefits in areas with sandy soils that do not support full vegetated coverage under natural conditions.

Amendment specification: A second area of research is the improvement in specifications for soil amendments. For instance, compost has many potential sources including dairy waste, feedlots, chicken litter, biosolids, and yard trimmings. The chemistry of these composts differs substantially and care should be taken to develop specifications that limit the leaching of nutrients as well as heavy metals, while still providing the benefits of vegetation establishment and runoff volume reduction. In addition, field studies that utilize amendments to improve the rate of infiltration and increase pollutant retention are needed. Finally, there is concern that imported soils and compost may contain seeds of invasive plants. Specifications often state that soil amendments should be free of weeds, roots, rocks, and other foreign material, but additional guidance on testing of such specifications and when to require sterilization environments sensitive to invasive species is needed.

Configurations of placement: Research could also evaluate the relative impact of soil amendments on water quality resulting from variations in placement. Options for placement include a) placing compost on the surface of steep embankments (including on the top of stone covered slopes); b) soil amendment mixed with the native shoulder soils along the width of the shoulder; and c) linear application of amended soil along the highway adjacent to pavement. This research could evaluate configurations that could look at stability, safety and soil amendment quantity, width, and depth.

Volume reduction: Outside of Washington State, little work has been done on documenting the runoff volume reduction achieved with soil amendments. Given the EPA focus on this issue much more work is required in areas with different rainfall characteristics to document the degree of runoff reduction.

4.2.3 Volume Reduction Approaches for Highways

Volume reduction is an area of tremendous interest by the regulatory community and a pressing area of research gaps and needs. Several topics are described in detail below and yet more topics, such as these bulleted below, could be expanded and added:

- What is meant by “predevelopment hydrology”? Does it need to be matched to protect water resources?
- Development of baseflow mimicking discharge concepts
- Investigating maintenance requirements of volume reduction approaches

- Whole life cycle costs and longevity of volume reduction approaches
- Post mortem analysis of infiltration failures – conduct analysis of failed facilities to determine what went wrong – document research
- Guidance for evaluating infiltration rates – which methods are appropriate in which cases

General Guidelines for Achieving Volume Reduction and Evaluating Feasibility

State and local MS4 permits, including some that apply to highways, are increasingly emphasizing volume reduction as the highest priority for stormwater BMP selection. The proposed USEPA rulemaking will most likely require volume reduction from highways. The intent of these regulations is to reduce runoff volume from urbanized areas, including highways. However, the reduction in runoff volume from highways in urban areas is problematic. There is limited space in the right-of-way to accomplish infiltration, evapotranspiration, or re-use. Additionally, safety considerations limit the types of stormwater control measures that can be constructed in the right-of-way. Research is needed to develop methods to reduce runoff volumes from existing and new highways to comply with current and potential future NPDES regulations. NCHRP Project 25-41 is currently developing *Guidelines for Achieving Volume Reduction of Urban Highway Runoff*.

Infiltration-related Groundwater Risks

Reducing runoff volumes using infiltration of stormwater has drawn increasing interest in recent years, given its ability to reduce stormwater volume, increase groundwater recharge, reduce peak flows, and lessen the transport of non-point source pollutants. Generally, volume reduction efforts are focused on infiltration and therefore have the potential for environmental impacts in the areas of water balance (e.g. groundwater mounding; unseasonal seeps and springs) and the introduction or mobilization of contaminants into groundwater. NCHRP Project 25-41 is currently investigating volume reduction strategies in the highway environment and the potential implications of such efforts.

Literature has shown that heavy metals are generally captured by the upper layers of soil, but that breakthrough can occur due to sorption limitations of the soil. Hydrocarbons (including PAHs) tend to sorb to soil particles and are generally trapped within the first few centimeters of soil in infiltration basins. More research is needed, however, on the fate and biodegradation of hydrocarbons captured in infiltration facilities.

Given the solubility and poor sorption characteristics of salts, groundwater impacts are difficult to mitigate where infiltration BMPs are used. NCHRP 20-05/Topic 43-12 is currently investigating the use of chloride deicers in the highway environment and potential strategies for managing these risks. Following this work, there will likely be the need to develop more detailed guidance for managing these risks as well as additional identified research needs. The issue of hydrocarbon accumulation is just one of a vast number of issues that could be studied in more depth for the highway environment:

- Bacteria and viruses
- Nutrients
- Accumulation of pollutants to hazardous waste criteria
- Shallow groundwater is an important risk factor for contamination, but how shallow? Guidance ranges from 2 ft to 10+ ft

- Risk of contaminant spills relative to groundwater impacts as well as remediation of soils below BMPs after a spill occurs – should this be a controlling design factor?
- Guidelines for evaluating risk of water balance impacts – function of regional climate factors as well as watershed factors.
- Guidelines for interagency coordination (i.e., stormwater permitting agency, groundwater quality protection agency, water supply agency)

DOTs have also highlighted the need to begin to account for feasibility, life cycle/durability, and maintenance costs in implementation of stormwater BMPs, as well as regulatory credit as infiltration BMPs fail and become or can be transformed into wet ponds, if funds can be found for re-design and retrofit. Research is needed on these pressing questions and issues.

Permeable Shoulders and Potentially Permeable Travel Lanes

Permeable pavements in shoulder areas would be one way for DOTs to reduce the volume of runoff from highways; these BMPs represent a unique opportunity to potentially achieve volume reduction even when there is very limited space within the right of way. NCHRP 25-25/82 is currently evaluating the feasibility and potential benefits of using permeable pavement with stone reservoirs on shoulders to function as a flow spreader and interceptor to prevent concentrated runoff flow and to provide a stormwater treatment. The project includes a review of literature and development of design and maintenance guidance and identification of construction issues.

Additional research will likely be needed to understand longevity of permeable shoulders and `the treatment benefits with respect to managing highway stormwater runoff. The benefits that could result from additional research include:

- Revealing the challenges of constructing permeable pavements in a highway setting;
- Identifying the maintenance necessary to keep permeable shoulders functioning properly;
- Determining life expectancy of pervious pavement in typical highway shoulder applications;
- Developing/refining design criteria for pervious pavement shoulder applications; and
- Identifying in-situ flow spreading, energy dissipation, and treatment performance in Washington State and how that could be applicable to other DOTs.

Need for much more research and pilot regarding the durability, design implications, maintenance needs, clogging potential, etc. of permeable shoulders. There has been very limited application of permeable shoulders, relative to other BMPs. Additionally, opportunity for consideration of full depth permeable pavement in travel lanes.

Stormwater Storage

New construction and replaced impervious surfaces is triggering calls for LID in some cases. In implementing the new LID standard, DOTs need a factual basis to assess the feasibility of applying these standards to the states' transportation networks. The proposed research is to conduct a literature search to determine to what extent, if any, highway runoff can be redistributed below impervious pavement, allowing the subgrade to be used for stormwater storage and infiltration, without presenting significant risk to the integrity of the highway infrastructure.

This project would benefit the DOTs by defining feasibility and establishing guidelines for redistributing highway runoff below impervious pavement (i.e., subgrades) in preparation of impending stormwater-related LID regulatory requirements. NCHRP 25-41, which will include a white paper on the geotechnical concerns and considerations associated with infiltration near and within pavement subgrades, will provide some initial information toward these research gaps.

The proposed USEPA rulemaking will most likely require volume reduction from highways. Storage of runoff under pavements would be one way for DOTs to reduce the volume of runoff from highways. The research should be started as soon as possible to support DOTs as the final EPA rule is released in 2013.

4.2.4 BMP Performance Monitoring and Modeling

Performance of structural stormwater controls has been well documented in numerous sources, and data has been collected in databases such as the International Stormwater BMP Database. Certain newer BMPs, such as permeable friction course (PFC) overlay have been studied, but much remains to be learned with regard to its applicability, and water quality and hydrologic performance. Also, there is a need for detailed monitoring data to support both statistical and physically-based BMP performance modeling approaches. Potential research needed with respect to performance monitoring and modeling is summarized below.

Targeted Within-Storm Monitoring of BMPs

Most BMP monitoring focuses on either limited grab sampling or the use of flow-weighted composite samples. In some cases it would be useful to have extensive within-storm monitoring to evaluate the performance of a BMP throughout the storm events. This can be very important in some cases when evaluating potential first flush or end-of-storm concentrations for dissolved parameters, for example. Within-storm data could also be used to help develop parameters for first order decay models of BMP performance that are utilized in some models, but for which almost no data is available.

Treatment of Emerging Contaminants

There are a number of emerging contaminants of concern in urban and highway runoff, including pollutants associated with contaminated sediments and those that are bioaccumulative. The parameters include PCBs, PAHs, Dioxins, and others that traditionally have been less of an issue. There is a need to research the fate, transport, and BMP performance for these constituents.

Monitoring Guidance Improvements

DOTs experience time and financial losses as well as frustrating exchanges with resource agencies when monitoring programs are poorly designed and inadequate data are collected. A BMP performance monitoring guidance document was developed for the International Stormwater BMP Database in 2009 that provides very useful information for developing a robust performance monitoring program. However, evolving data collection and management technology, regulatory requirements/expectations, and desire to better understand BMP treatment processes have created a need for regular updates to this guide in both methodology and instrumentation. One approach may be to develop and release “monitoring technology circulars” that could be used to keep DOTs informed of this rapidly evolving science. Another approach may include conducting a review of recent literature of innovative data collection approaches used by researchers to better understand the performance of stormwater BMPs.

Tools for Modeling BMP Performance and Receiving Water Impacts

The Water Environment Research Foundation (WERF) funded a project entitled Linking BMP Systems Performance to Receiving Water Protection to Improve BMP Selection and Design. The project is resulting in a modeling tool called the BMP Selection/Receiving Water Protection Toolbox (Toolbox). The Toolbox will allow users to link a watershed model to a receiving water model while evaluating the effects of stormwater BMPs. BMPs are being modeled using a combination of empirical and physically based approaches that are described in the BMP performance algorithms report (Leisenring et al. 20013). The beta version of the Toolbox is expected for release in late 2013 and will be capable of linking a limited number of watershed models (e.g., QUALHYMO and EPA SWMM) and limited number of receiving water models (e.g., QUAL2K). Future development will be needed to support other watershed and receiving water models. In addition, research is needed to develop and refine default parameters for the supported BMP algorithms. Finally, improvements to existing receiving water models are needed to better estimate the acute effects of stormwater runoff. One option for enhancing the system would be to incorporate highway-specific BMPs more explicitly.

The USGS and FHWA recently released a tool called the Stochastic Empirical Loading and Dilution Model (SELDM) that utilizes the Highway Runoff Database and other national data sets to estimate project impacts on receiving water quality (Granato, 2013). SELDM is a stochastic model that allows users to estimate the risk of exceeding water quality criteria due to highway runoff with and without BMPs.

4.2.5 Economics of Stormwater BMPs

NCHRP Project 25-40 will provide performance, whole life cost, and maintenance protocols for treatment BMPs used by DOTs and a Maintenance Indicator Document, describing the recommended maintenance indicator, maintenance activity, and suggested inspection frequencies will be provided. The whole life costs will be provided in the form of a spreadsheet model. The model will be based on unit prices and will be available with a range of values for maintenance frequency that the user can select. While this ongoing research is expected to partially fill the gap in BMP cost information and provide a valuable assessment tool for DOTs, research gaps will likely remain. Below are a few of those anticipated gaps related to the economics of BMPs.

BMP Maintenance Requirements and Life-Cycle Cost Information

BMP maintenance requirements and knowledge of the costs thereof necessary to maintain function and performance is currently lacking. Washington State DOT has developed estimates of costs to maintain stormwater BMPs, to comply with the state’s new NPDES permit (Washington State DOT, 2012). However, additional information is needed to develop life-cycle costs. Existing life-cycle cost studies are generally based upon a relatively small amount of historical data, and a need exists to increase the number of longitudinal studies in which actual costs are recorded. Further complicating the data available is the fact that many of the extant studies use differing bases for comparison (e.g. cost per acre treated, cost per water quality volume, etc.)

Going forward, it might be beneficial to develop suggested standardized life-cycle cost metrics that could be more uniformly used by DOTs as well as research efforts. Costs associated with public education, catch-basin maintenance, and roadside vegetation control activities would aid in the optimization and adequate allocation of stormwater management funds. More cost information on these non-structural BMPs would be beneficial.

For a number of BMP types, capital cost regression equations have been developed that are primarily based on imperviousness, land use, and/or flow rates and volumes; however, life-cycle costs, opportunity costs, and externalities are often neglected in cost estimation. Typically, land costs and opportunity costs are often neglected in studies because these tend to vary considerably from application to application. Quantification of benefits from receiving waters protection requires the use of existing water quality, habitat, and bioassessment monitoring data for both the runoff and receiving waters. More research and guidance is needed on standardizing the benefits of stormwater controls.

How to Adequately Resource Stormwater Maintenance and Operations

DOTs are struggling to find maintenance resources in response to increasing regulatory pressure to implement and operate BMPs and report a higher level of inspection and maintenance of stormwater control structures. In many cases, this regulatory pressure is being formalized in NPDES permits. Some DOTs, such as WSDOT, have tracked maintenance tasks and costs and developed owner's guides of sorts for some ancillary assets such as guardrails. This may need to be done for structural water quality BMPs as well. Producing estimates for the costs of meeting the regulatory maintenance requirements can be an effective method to garner funding at the legislative level. NCHRP 25-40 is developing maintenance and inspection guidance and protocols for treatment BMPs from maintenance requirements for proprietary and non-proprietary BMPs at DOTs around the country that DOTs may use as a guide to project effort and cost for stormwater maintenance and operation and negotiate for funding.

Caltrans' BMP Retrofit Pilot Program developed a Maintenance Indicator Document (MID) that establishes the inspection and maintenance requirements for each BMP. Labor estimates, based on the recommendations in the Maintenance Indicator Document, were provided and this information is being used by NCHRP 25-40 to estimate maintenance costs by BMP type.

As DOTs increasingly document maintenance effort and costs, more data will be available to accurately portray costs to regulators, executives, and legislators. Effort is needed to compile information on DOT labor and equipment used for BMP inspection and maintenance and also to explore how DOTs are successfully acquiring the necessary funding to adequately resource stormwater maintenance and operations.

Best Practices for Operations and Maintenance of Water Quality Facilities

Potential research topics could include topics such as investigation and repair of energy dissipation structures, vegetation management and inventory, inlet and outlet cleaning, trash and debris management, solids removal, media replacement/regeneration and illicit discharge identification. Research is needed to compile best practice information from across the DOTs and potentially to update the AASHTO Compendium of Environmental Stewardship Practices, Policies, and Procedures in relation to these topics.

4.2.6 Watershed Planning and Mitigation Approaches

State DOTs are sometimes unable to meet stormwater management requirements on site or in close proximity to the impacted area; therefore, additional approaches to accomplishing mitigation requirements are needed, including off-site mitigation and non-traditional techniques and strategies that would allow greater environmental benefits to be achieved. DOTs may invest in conservation or restoration of off-site areas or off-site BMPs to address some portion of on-site stormwater runoff requirements. NCHRP 25-37 is examining the watershed approach to stormwater mitigation, as the current legislative and regulatory climate has placed a spotlight on watershed protection, stormwater pollutant reduction, and hydrologic impairment. State DOTs are exploring a variety of approaches and regulatory mechanisms to achieve compliance with water quality permits that are based on watershed-based Total Maximum Daily Load limitations and receiving water quality standards. NCHRP 25-37 is in the process of producing (1) a practical watershed-based decision-making framework that will enable DOTs to identify and implement cost-effective and environmentally beneficial water quality solutions for stormwater impacts and (2) a toolbox of feasible water quality solutions for stormwater impacts.

Additional research could include more detailed studies for specific parameters and data to support the toolbox as well as case studies that implement the recommended approaches. Below are some additional watershed-related stormwater management research topics not likely to be addressed by NCHRP 25-37.

Characterizing DOTs' Contribution to Watershed Impairments

DOTs typically occupy a small portion of the watershed and have a proportionately small portion of the pollutant load to a receiving water, but they may carry a disproportionate share of the technical, monitoring, and investigative burdens, since they can be perceived as 'deep pocket' entities with superior technical resources compared to other MS4 stakeholders. These perceptions may lead to DOTs being assigned WLAs for pollutants of which they are a *de minimis* contributor or assigned WLAs that exceed their proportionate share. It is difficult to separate load from off-site flows, and the DOT may be responsible for pollutant load in upstream runoff tributary to their systems. DOTs have no authority to require upstream landholders to reduce pollutant loads that run-on to the state ROW. Investigation is needed at the national level to assess options for managing off-site run-on. Research is also needed to assess methods for estimating appropriate load allocations for DOTs for constituents that originate within the ROW.

Effect of Pollutant Source Controls on Watershed Impairments

DOTs have very limited authority to regulate activities within their ROW, limiting their options for meeting waste load allocations. Investigation is needed to assess other administrative options for controlling sources of potential pollutants in the DOT right-of-way. For metals, TMDLs should include discussions with the auto industry and investigation of such potential items as brake pad legislation for copper source reduction as well as zinc levels in tires. Legislation has been passed in California and Washington to limit copper in auto brake pads. True source control will be an important tool for future TMDL compliance. DOTs will need to focus on constituents they can remove at concentration levels that do not have a high marginal cost, with the objective of spending their resources to achieve the greatest overall environmental benefit. Investigation into true source control options is needed. NCHRP Report 448 (Nelson et al., 2001), under project 25-09 provides an assessment of the potential environmental impacts of highway construction and repair materials themselves as sources to surface and ground waters. This research and the tool developed can be used to evaluate potential improvements that materials-based source controls may have on runoff quality. DOTs need guidance on how to evaluate the potential improvements source controls may have on watershed impairments.

Watershed Approach for Hydromodification Control

As watersheds become highly urbanized it gets much more difficult if not impossible when sediment supply is taken into account to manage all of the impacts outside of the channel. One area that could use more research is the appropriate distribution of controls, both on-site and off-site, for addressing hydromodification impacts between volume controls, flow-duration controls, and channel grade controls.

4.2.7 Stormwater Information Management Systems

According to original research and a 50-state survey of DOTs performed for this white paper, approximately 20 states have instituted a data management system for drainage infrastructure since 2000, with a quarter of those in the last three years. By May 2013, over 20% of the 50 state DOTs said they would have completed or nearly completed BMP inventories. Two more state DOTs anticipate completion in 2014 and 2015. Some state DOTs are also moving toward collecting actual time, costs, equipment, and materials for maintaining certain BMPs. Other state DOTs have been beginning to assess level of treatment across the roadway system. These developments will facilitate filling the following gaps and key research questions for state DOTs and regulatory agencies.

Standardized Data Management Systems and Performance Measurement for BMP Inspections, Maintenance, and Corrective Actions

Research into the effectiveness of erosion and sediment control quality assurance and control (QA/QC) and the systems/standards DOTs have developed for performance measurement, inspection, maintenance, and corrective action is needed. This research would examine the different program and institutional mechanisms DOTs have employed to raise performance and assess their relative effectiveness, to provide guidance to other DOTs in how such efficiencies can be attained.

Self-Auditing and Continuous Process Improvement

A number of leading DOT stormwater management programs have developed internal procedures for checking performance and improving processes. This research would collect and share procedures and the results for stormwater program auditing and continuous process improvement from across the country.

System Performance Estimating for Treatment/Coverage

Regulatory agencies currently discuss the percentage of the stormwater system that is effectively treated versus untreated. DOTs need efficient methods for estimating and tracking this for large areas while also accounting for the percent of the runoff that is treated and the disconnected impervious areas that may not need additional structural controls. Spatial databases can be used to track this information, but DOTs need guidance on developing such databases and keeping them updated. Research is needed on evaluating the accuracy of different methods of estimating effectively treated areas. Guidance can then be developed that will help DOTs provide an estimate of stormwater BMP coverage/treatment across the entire DOT system.

5 Summary and Conclusions

DOT stormwater quality programs continue to evolve in response to changes in NPDES Permits, TMDLs, receiving water quality information, and BMP research. This White Paper provides a synopsis of current information relative to treatment BMP selection, design, performance and cost, DOT implementation of BMPs and research needed to improve BMP application, performance and implementation. There are a variety research projects and guidance manuals developed specifically for BMP applications in the highway environment. DOTs could leverage these resources in refining their stormwater programs to improve effectiveness and reduce costs.

Future changes in the stormwater program are likely to come as a result of the EPA National Rulemaking for post-construction stormwater control. The Rulemaking will propose changes to stormwater NPDES permits that will become the new ‘floor’ for permitting authorities. Changes are likely to impact how post-construction BMPs are designed and potentially the geographic extent to which they must be employed for some DOTs, including retrofitting of existing highways. The National Ocean Policy may also require performance measures that would impact DOT stormwater programs for those jurisdictions draining to the ocean or the Great Lakes.

5.15 Post Construction BMP Selection and Design

Some of the best references for post-construction BMP selection and design are the guidance manuals prepared by DOTs. This paper provides summary analysis of and links to 17 DOT manuals, most providing siting, design, construction, performance and cost information for BMPs. Performance information, based on data reduced from the International BMP database is also provided. Fact sheets, summarizing key design and performance attributes for selected BMPs that DOTs use most commonly are included in Appendix A. This information is supplemented with average whole life cost information to facilitate BMP benefit cost comparisons by the practitioner. The data available for most non-proprietary BMPs is sufficient to allow the DOT to make informed decisions regarding BMP selection and operation and maintenance. Finally, there are a number of NCHRP reports that provide detailed guidance on BMP selection and design, including Report 565 (Huber et al., 2006) (highly detailed guidance suitable for manual prepares or for complex projects) and Report 728 (Geosyntec Consultants et al., 2012), which provides more applicable for the road designer guidance.

5.16 BMP Retrofit Programs

The interstate highway system is largely complete, and generally did not include provisions to improve runoff water quality. Consequently, DOT programs are increasingly being asked to consider retrofit of stormwater facilities as a part of their program. When constructed as stand-alone projects, stormwater BMP retrofits are typically significantly more costly as compared to BMPs constructed with other highway improvements. Accordingly, many DOTs are developing ‘retrofit’ programs that are aligned with capital improvement programs and maintenance projects through their asset management programs. Stand-alone stormwater retrofits are most often considered in association with a TMDL. DOTs should address BMP retrofits within their stormwater program on a level that is consistent with watershed objectives of their state to complement the efforts of municipal NPDES programs. There are several emerging technologies and approaches that may result in less-expensive retrofits of some types of drainage features, including PFC and multi-media filter strips.

5.17 BMP Research

There has been a significant level of research supporting the implementation of DOT stormwater programs over the last several decades. The research has focused on the development of BMPs the meet the unique requirements of highway infrastructure and for the constituents of concern from highways. Much of the research is applicable to DOTs nationally, and DOT programs can benefit greatly from technology transfer. Unfortunately, some research is not easily accessible, and there is no universal agreement on the potential issues with translating BMP effectiveness and maintenance and operation experience from geographic location to another. Clearly a central clearinghouse for DOT stormwater program research would be of value.

5.18 Research Gaps and Needs

This paper has assembled a long list of research gaps for DOT stormwater programs. A suggested list of research has also been reduced from the assembled needs list. Research needs are primarily being driven by regulatory changes and information from monitoring programs. A variety of BMP, constituent specific, and programmatic topics are provided in Section 4. Common themes include broader, watershed approaches to program implementation and consideration of effectiveness, reducing whole life cost of measures, and improving constituent removal performance. From a broader perspective, DOTs will also need to work with other agencies, such as the USEPA and FHWA to implement source controls from sources outside of DOT control (i.e. vehicles, etc.). Cross media contamination, such as airborne sources, are an important but difficult problem to address within the right-of-way. The use of lead tire weights, zinc in tires, mercury from diesel combustion, copper from brake lining wear and platinum and palladium from catalytic converters are all potential source reduction opportunities, in keeping with the theme of identifying where pollutants can be reduced most efficiently and cost-effectively. The geographic extent of the interstate highway system demonstrates that end of pipe solutions cannot be the singular solution for DOT stormwater programs from either a performance or cost perspective.

6 References

Adams T., Janowiak, Sierzchula W., Bittner, J. (2009) Maintenance Quality Assurance 2 - Synthesis of Measures, MRUTC Report 08-15. University of Wisconsin-Madison http://www.wistrans.org/mrutc/files/08-15_MQA_Synthesis_Final_Report.pdf

Adams, T. and Jason Bittner (2011). Maintenance Quality Assurance surveys, (2004) and (2008), University of Wisconsin, Maintenance Quality Assurance reports, provided for Venner, AASHTO Subcommittee on Maintenance Annual Meeting, presentation, Kentucky, July 2011.

American Association of State Highway and Transportation Officials (AASHTO, State of the Practice Reports, (2012) http://www.environment.transportation.org/center/products_programs/communities_of_practice.aspx#StormwaterManagement

Baroga, R. (2012) NCHRP 25-40: Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices Project interview on May 21.

Barrett, M., et al. (2012) Design of Urban Stormwater Controls, Water Environment Federation Manual of Practice No. 23 and ASCE Manual and Report on Engineering Practice No. 87, June 2012, McGraw Hill, New York.

Caltrans (2001). BMP Retrofit Pilot Program, Construction Cost Data Summary Districts 7 and 11, California Department of Transportation, CTSW-RT-01-003, May 2001.

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

Caraco, D. and Claytor, R. (1997). "Stormwater BMP Design Supplement for Cold Climates." Prepared by the Center for Watershed Protection for the U.S. EPA Office of Wetlands, Oceans and Watersheds and U.S. EPA Region 5.

CH2MHILL. (1998). Highway Stormwater Runoff Study. Prepared for the Michigan Department of Transportation.

DelDOT statewide stormwater BMP inspection/maintenance program, (2007), http://www.deldot.gov/stormwater/pdfs/P23_DelDOT-BMP-Inspection.pdf.

Eck, B. et al. (2012), Water Quality of Drainage from Permeable Friction Course. J of Env Engineering, DOI: 10.1061/(ASCE)EE.1943-7870.0000476. pp. 174-181.

Fay, L., Akin, M. and Shi. X. (2012) Cost-Effective and Sustainable Road Slope Stabilization and Erosion Control, A Synthesis of Highway Practice. Final Report for NCHRP 20-

05/42-09. Prepared for the National Cooperative Highway Research Program (NCHRP), Washington D.C.

Fay, L., Shi, X., et al. (2013) Exploring the performance and corrosivity of chloride deicer solutions: Laboratory investigation and quantitative modeling. Cold Regions Science and Technology, 86, 36-44.

Federal Highway Administration (FHWA), (1990). Pollutant Loadings and Impacts from Stormwater Runoff, Volume III: Analytical Investigations and Research Report. Prepared by Woodward-Clyde Consultants: E.D. Driscoll, P.E. Shelley, and E.W. Strecker. FHWA-R..

Field, R., Struzeski, E.J. Jr., Masters, H.E. and Tafuri, A.N. (1973). Water Pollution and Associate Effects from Street Salting. EPA-R2-73-257 (NTIS PB-222795), Environmental Protection Agency, Cincinnati, OH, May.

Fletcher, W., Water Quality/Resources Program Coordinator, Oregon DOT. (2012) NCHRP 25-40: Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices Project interview on June 1.

Gay, R. Deputy Hydrology Program Manager, Colorado DOT, (2012a), NCHRP 25-40: Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices, project interview on June 5.

Gay, R. Deputy Hydrology Program Manager, Colorado DOT, (2012b), NCHRP 25-40: Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices, project interview on June 28.

Geosyntec Consultants and Wright Water Engineers (2012). International Stormwater BMP Database – Manufactured Devices Performance Summary. Prepared for the Water Environment Research Foundation. http://www.bmpdatabase.org/Docs/2012%20Manufactured%20Device%20Analysis/BMP%20Database%20Manufactured_Devices_PerformanceSummary_Final.pdf

Geosyntec Consultants, Oregon State University, Venner Consulting, Low Impact Development Center, and Wright Water Engineers (2012). NCHRP Report 728: Guidelines for Evaluating and Selecting Modifications to Existing Roadway Drainage Infrastructure to Improve Water Quality in Ultra-Urban Areas. Project 25-31. Transportation Research Board: Washington, DC.

Golding, S. (2006). A Survey of Zinc Concentrations in Industrial Stormwater Runoff. Washington Department of Ecology.

Granato, G. (2013). Stochastic empirical loading and dilution model (SELDM) version 1.0.0. Washington D.C.: U.S. Geological Survey Techniques and Methods.

Granato, G.E., Zenone, C., and Cazenas, P.A. eds. (2002). National Highway Runoff WaterQuality Data and Methodology Synthesis, Volume I --Technical issues for monitoring highway runoff and urban stormwater. U.S. Department of Transportation, Federal Highway Administration. FHWA-EP- 03-054. 479 p.

Huber, W.C., J.P. Heaney, E.W. Strecker, N. Weinstein. (2006). NCHRP Report 565: Evaluation of Best Management Practices for Highway Runoff Control. Project 25-20(01). Transportation Research Board, Washington, DC.

Lampe, L., H. Andrews, M.E. Barrett, P. Martin, C. Jefferies, B. Woods-Ballard, and M. Hollon. (2005). Performance and Whole Life Costs of Best Management Practices and Sustainable Urban Drainage Systems. (WERF No. 01-CTS-21T). Water Environment Research Foundation.

Leisenring, M., M. Barrett, C. Pomeroy, A. Poresky, L. Roesner, A.C. Rowney, E. Strecker (2013). Linking BMP Systems Performance to Receiving Water Protection: BMP Performance Algorithms. (WERF No. SWC1R06bmp). Water Environment Research Foundation. http://www.werf.org/a/ka/Search/ResearchProfile.aspx?ReportId=SWC1R06bmp

Metropolitan Council (2001). Minnesota Urban Small Sites BMP Manual – Stormwater Best Management Practices for Cold Climates. Prepared by Barr Engineering Company. [Online] http://www.metrocouncil.org/environment/water/BMP/manual.htm Accessed 10/16/08.

National Ocean Council (2013), National Ocean Policy Implementation Plan www.whitehouse.gov//sites/default/files/national_ocean_policy_implementation_plan.pdf

National Research Council (2008). Urban Stormwater Management in the United States. Water Science and Technology Board Division on Earth and Life Studies. http://www.epa.gov/npdes/pubs/nrc_stormwaterreport.pdf.

Nelson, P.O., Huber, W.C., Eldin, N.N., Williamson, K.J., Azizian, M.F., Thayumanavan, P., Quigley, M.M., Hesse, E.T., Lundy, J.R., Frey, K.M., and Leahy, R.B. (2001). Environmental Impact of Construction and Repair Materials on Surface and Ground Waters-Summary of Methodology, Laboratory Results, and Model Development. NCHRP Report 448, prepared for National Cooperative Highway Research Program, Transportation Research Board, National Research Council, National Academy Press, Washington, DC.

Novotny, V., Smith, D.W., Kuemmel, D.A., Mastriano, J., and Bartosova, A. (1999). Urban and Highway Snowmelt: Minimizing the Impact of Receiving Waters. Water Environment Research Foundation Project 94-IRM-2, Water Environment Research Foundation, Alexand.

Pitt, R.E., Chen, S-E., Ong, C-K., and Clark, S. (2001). “Measurements of Infiltration Rates in Compacted Urban Soils,” in Linking Stormwater BMP designs and Performance to Receiving Water Impact Mitigation, R.R. Urbonas, ed., Proceedings Engineering Foun.

Public Sector Consultants. (1993). The Use of Selected Deicing Materials on Michigan Roads: Environmental and Economic Impacts. Michigan Department of Transportation.

Pujara, Karuna. (2012). MDSHA Hydraulics, Chief, NCHRP 25-40: Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices project interview.

Sansalone, J.J., Koran, J.M., Buchberger, S.G. and Smithson, J.A. (1997). "Partitioning and First Flush of Metals and Solids in Urban Highway Runoff." J. of Environmental Engineering, ASCE, Vol. 123, No.2, pp. 134-143.

Schueler, T., D. Hirschman, M. Novotney and J Zielinkski (2007). Urban Subwatershed Restoration Manual No. 3. Urban Stormwater Retrofit Practices Version 1.0, Center for Watershed Protection, Ellicott City, MD.

Smith, K.P. and Granato, G. E. (2010). "Quality of Stormwater Runoff Discharged from Massachusetts Highways, 2005-07." U. S. Geological Survey, Reston, Virginia.

Taylor, S. (2012) AASHTO Stormwater Community of Practice, State of the Practice Report: Program Effectiveness Assessment and Stormwater Program Audits for Stormwater Compliance, June 2012. p. 16.

United States Environmental Protection Agency (2013) Proposed National Rulemaking to Strengthen the Stormwater Program. http://cfpub.epa.gov/npdes/stormwater/rulemaking.cfm..

Venner, M. (2004, 2005) AASHTO's Compendium of Environmental Stewardship Practices, Policies, and Procedures. National Academy of Sciences Transportation Research Board. Volumes 6 and 8. http://environment.transportation.org/environmental_issues/construct_maint_prac/compendium/manual/8_0.aspx (2005). For BMPs at maintenance facilities, see http://environment.transportation.org/environmental_issues/construct_maint_prac/compendium/manual/6_1.aspx

Venner, M., (2004). AASHTO Compendium of Environmental Stewardship Practices in Construction and Maintenance, NCHRP 25-25/04, Volume 10: Roadside Environmental Maintenance, Section 6.

Venner, M., Taylor, S. et al.,(2012). NCHRP 25-40: Long-Term Performance and Life-Cycle Costs of Stormwater Best Management Practices, Initial Literature Review and Interview Results. National Academies' Transportation Research Board.

Venner, M., Weinstein N., et al., (anticipated completion 2014) developed for NCHRP 25-37: A Watershed Approach to Mitigating Stormwater Impacts, National Academies' Transportation Research Board.

Washington State, Joint Legislative Audit and Review Committee, (2011) Stormwater Permit Requirements at the Department of Transportation, Report Summary, January, 5, 2011, http://www.leg.wa.gov/JLARC/AuditAndStudyReports/2011/Documents/11-2ReportSummary.pdf..

Washington State, Joint Legislative Audit and Review Committee, Stormwater Permit Requirements at the Department of Transportation, Report Summary, January, 5, 2011 http://www.leg.wa.gov/JLARC/AuditAndStudyReports/2011/Documents/11-2ReportSummary.pdf..

Water Environment Federation (WEF) and American Society of Civil Engineers (ASCE) (1998). Urban Runoff Quality Management, WEF Manual of Practice No. 23, ASCE Manual and Report on Engineering Practice No. 87. Water Environment Federation, Arlington, VA..

Water Environment Research Foundation (WERF) (2005). Critical Assessment of Stormwater Treatment Controls and Control Selection Issues. Prepared by E.W. Strecker, W.C Huber, J.P. Heaney, D. Bodine, J.J. Sansalone, M.M. Quigley, D. Pankani, M. Leisenring, and P. Thayumanavan. 02-SW-01. Water Environment Federation (publisher), Alexandria, VA; IWA Publishing, London.

Water Environment Research Foundation (WERF) (2011). Technical Summary: Volume Reduction. January. Available at http://www.bmpdatabase.org/BMPPerformance.htm.

Water Environment Research Foundation (WERF) (2012). International Stormwater Best Management Practices (BMP) Database Pollutant Category Summary Statistical Addendum: TSS, Bacteria, Nutrients, and Metals Available. July. Available at http://www.bmpdatabase.org/BMPPerformance.htm.

Weider, D., (2012) interview performed for NCHRP 25-40. May 7, 2012

WSDOT (2005). Research proposal on BMP maintenance schedules, http://www.wsdot.wa.gov/NR/rdonlyres/85610D43-2181-45C4-8ED2-4E1E8A269B49/0/researchproposal19.pdf.

WSDOT (2011). Maintenance Accountability Process Manual, Chapter 5: Service Levels, http://www.wsdot.wa.gov/NR/rdonlyres/05705143-4581-4AD1-8ADD-DEE22763DCED/0/Chpt5MAP.pdf, July 2011, p. 5-1.

WSDOT Maintenance Accountability Process Results, (2011), http://www.wsdot.wa.gov/NR/rdonlyres/01E8BDD0-734B-432E-AEDE-F1C0A9DBD5E0/0/Statewide2011LOS.pdf..

WSDOT MAP Manual, Chapter 1, Introduction,(n.d.) http://www.wsdot.wa.gov/NR/rdonlyres/6B63BDD3-6454-4AF4-B75A-DE1B0810AA92/0/Chpt1MAP.pdf, p. 1-2 and p. 1-3.

WSDOT, Maintenance Accountability Process Performance Targets, (n.d.). http://www.wsdot.wa.gov/NR/rdonlyres/072D7A39-1AD5-48C8-AA73-94177D5D417C/0/0911TargetBarchart.pdf.

WSDOT, MAP Manual, (2012), http://www.wsdot.wa.gov/NR/rdonlyres/7C5CE6BD-1E82-46A8-AD7D-33726D52DC0A/0/Chpt6MAP.pdf, p. 6-5.