FINAL WHITE PAPER

BMP Effectiveness Assessment for Highway Runoff in Western Washington

Prepared for

Washington State Department of Transportation

March 2008

CONTENTS

1 Introduction 1
1.1 Purpose of White Paper 1
1.2 Scope and Limitations of this White Paper 1
1.3 Parameters Evaluated in this White Paper 1
1.4 Scope of the White Paper 2
2 Background and Context (Overview of BMP Treatment, Performance Monitoring, and Performance Measures) 3
2.1 Overview of Stormwater Runoff Treatment Operations or Processes 3
2.1.1 Hydrologic Operations 5
2.1.2 Physical Operations 6
2.1.3 Biological Processes 9
2.1.4 Chemical Processes 11
2.2 Effects of Unit Operation Processes on Contaminants of Potential Concern 11
2.2.1 Particulate Matter (TSS) 12
2.2.2 Trace Metals 12
2.2.3 Phosphorus 13
2.2.4 Nitrogen 13
2.2.5 Organic Compounds 14
2.2.6 Oxygen Demanding Substances 14
2.2.7 Human Pathogens 15
2.2.8 Major Ions 15
2.2.9 Other Conventional Water Quality Parameters 16
2.3 Overview of BMP Performance Monitoring 16
2.4 Overview of BMP Performance Measures 18
2.4.1 Efficiency Ratio and Summation of Loads 18
2.4.2 Plotting Influent Versus Effluent Concentrations 19
2.4.3 Effluent Probability Method 20
2.4.4 Volume Reduction 20
2.4.5 Capture Efficiency 21
3 Methodology 23
4 BMP Treatment Evaluations 28
4.1 Infiltration Facilities 28
4.1.1 Description 28
4.1.2 Unit Operation Processes 28
4.1.3 Applications 29
4.1.4 Evaluation of BMP Performance 29
4.2 Porous/Permeable Pavements 31
4.2.1 Description 31
4.2.2 Unit Operation Processes 31
4.2.3 Applications 31
4.2.4 Performance 32
4.3 Detention Basins 33
4.3.1 Description 33
4.3.2 Unit Operation Processes 33
4.3.3 Applications 33
4.3.4 Performance 33
4.4 Stormwater Treatment Wetlands 36
4.4.1 Description 36
4.4.2 Unit Operation Processes 36
4.4.3 Applications 37

4.4.4 Performance 37
4.5 Wet Ponds 39
4.5.1 Description 39
4.5.2 Unit Operation Processes 39
4.5.3 Applications 39
4.5.4 Performance 40
4.6 Biofiltration Swales 43
4.6.1 Description 43
4.6.2 Unit Operation Processes 43
4.6.3 Applications 43
4.6.4 Performance 44
4.7 Vegetated Filter Strips 47
4.7.1 Definition 47
4.7.2 Unit Operation Processes 47
4.7.3 Applications 47
4.7.4 Performance 48
4.8 Bioretention 50
4.8.1 Definition 50
4.8.2 Unit Operation Processes 50
4.8.3 Applications 50
4.8.4 Performance 50
4.9 Ecology Embankments 52
4.9.1 Description 52
4.9.2 Unit Operation Processes 52
4.9.3 Applications 52
4.9.4 Performance 53
4.10 Dispersion to Landscape (Natural and Engineered) 54
4.10.1 Description 54
4.10.2 Unit Operation Processes 54
4.10.3 Applications 54
4.10.4 Performance 55
4.11 Sand Filters 56
4.11.1 Definition 56
4.11.2 Unit Operation Processes 56
4.11.3 Applications 56
4.11.4 Performance 57
4.12 Multi-Chambered Treatment Trains (MCTT) 59
4.12.1 Description 59
4.12.2 Unit Operation Processes 59
4.12.3 Applications 59
4.12.4 Performance 59
4.13 Highway Sweeping 61
5 Summary and Conclusions 62
5.1 Comparison of International BMP Database and Washington State BMP Data 62
5.2 Areas of Uncertainty and Analysis Considerations 63
5.2.1 General Areas of Uncertainty 63
5.2.2 Capture Efficiency 63
5.2.3 Treatment Trains 64
5.3 BMP Performance for Contaminants of Potential Concern 65
5.3.1 Particulate Matter (TSS) 67

5.3.2 Trace Metals..67
5.3.3 Phosphorus 69
5.3.4 Nitrogen 69
5.3.5 Organic Contaminants...70
5.3.6 Conventional Water Quality Parameters 70
References...71

Appendix 1 Source Control BMPs for Highway Runoff in Washington 73

Appendix 2 Highway Runoff Manual Treatment BMP Selection Process 74

Appendix 3 Highway Sweeping...76
Introduction 76
Street Sweeping Studies...76
Highway Street Sweeping Studies..78
References..79

1 Introduction

1.1 Purpose of White Paper

A series of white papers has been prepared to assist the Washington State Department of Transportation (WSDOT) and a working group of resource agencies in evaluating highway runoff water quality and the ability of Best Management Practices (BMPs) to control runoff quantity and pollutants such that species listed under the Endangered Species Act (ESA) are protected. The purpose of these white papers is to summarize what is known about the issues and potential solutions to help WSDOT and the working group discuss and reach consensus on BMP approaches that would be considered protective of endangered species (i.e., salmonids) in western Washington. This particular white paper is not intended to be a comprehensive review of all facets of BMP selection, design, and performance, nor serve as guidelines or rules for BMPs for WSDOT projects.

The first white paper (*Untreated Highway Runoff in Western Washington*; Herrera 2007a) summarized the current state of knowledge on the characterization of untreated highway runoff in western Washington and the factors that likely influence its characteristics. The purpose of this second white paper is to evaluate the effectiveness of available BMPs in managing highway runoff pollutants and quantity, specifically addressing the potential stressors that may impact ESA-listed species. Data gaps, areas of uncertainty, and limitations of the available BMP effectiveness data are noted and documented. This white paper provides a link between the information presented in the white paper on untreated highway runoff to the third white paper (*Potential Effects off Highway Runoff on Priority Fish Species in Western Washington*; Herrera 2007b).

1.2 Scope and Limitations of this White Paper

At a project kick-off meeting on February 26, 2007, the participants discussed the types of BMPs that should be evaluated in this white paper. The consensus was that BMPs identified in the 2006 Highway Runoff Manual (HRM; WSDOT 2006a) would be included, and that other BMPs would also be evaluated if they are directly applicable for treatment of runoff in the highway environment and would be potentially effective at reducing the concentrations and loads of pollutants of concern for ESA-listed species. At the meeting, it was proposed that the white paper include highway appropriate low impact development (LID) treatment practices, as well as high-efficiency street sweepers. However, BMPs not typically used for treating highway runoff (e.g., green roofs) would not be included. The working group agreed that it would not be practical or possible to quantify treatment efficiencies for all pollutants in highway runoff, and that a suite of representative parameters, referred to as contaminants of potential concern (COPC), would be selected for evaluation in this white paper.

1.3 Parameters Evaluated in this White Paper

As described above, a limited set of parameters were considered and selected for evaluation in this white paper because sufficient data are lacking on highway runoff concentrations as well as BMP performance for many contaminants which could be considered. As noted in the white paper on untreated highway runoff (Herrera 2007a), sufficient data are available for the following key parameters: total suspended solids (TSS); selected heavy metals (total and dissolved); phosphorus (total and dissolved);

and flow (e.g., increases in surface runoff). In addition, the 2006 HRM explicitly requires the control of these parameters.

Although control of petroleum hydrocarbons (oil) is also one of the parameters required under certain circumstances in the HRM, it is rarely measured in BMP performance studies. The HRM has a selection process that specifies certain BMPs for basic treatment (i.e., TSS removal), phosphorus control, oil control, and enhanced treatment for heavy metal control, and/or flow increases. Nitrogen parameters are also addressed in this white paper, as this pollutant has differing unit operation process (UOP) requirements than those for phosphorus control it is an important nutrient (receiving waters are not only phosphorus limited), and there is a reasonable dataset available for nitrogen nutrients.

While TSS itself is considered a contaminant in certain situations, it is also used as a surrogate for other contaminants that bind to particulate matter, such as total petroleum hydrocarbons (TPHs), polycyclic aromatic hydrocarbons (PAHs), legacy organochlorine pesticides and polychlorinated biphenyls (PCBs), and heavy metals. Most studies of these contaminants in stormwater runoff have demonstrated that they are mainly associated with the particulate phase, with a smaller fraction in the dissolved phase. In some situations, the particulate phase is not the dominant phase (e.g., residual herbicides as product on road surfaces or plant leaves, petroleum product spilled on highway through oil leaks). Nevertheless, these organic contaminants are rarely measured in highway runoff and even less so in BMP effluent studies, so evaluation in this white paper is limited to TSS control as a surrogate for these parameters. Where data are lacking, a qualitative evaluation is included to assist the user, focusing on the unit operation processes within a BMP and expected general performance (see Section 2.1 for an explanation of unit operation processes addressed in this paper).

Some information on litter and salts is included, although it is limited and mostly qualitative. Litter, especially plastic, is a serious contaminant for marine animals, and there may be a corresponding issue in fresh waters. Salt is included as a measure of dissolved conservative substances. In addition, common salt is added to highways, and the U.S. Environmental Protection Agency (EPA) has water quality guidelines for chloride.

1.4 Scope of the White Paper

This white paper summarizes and characterizes the current state of knowledge with regard to the following technical issues:

- The processes that operate in BMPs (i.e., unit operation processes, referred to as UOPs)
- UOP effectiveness for removal of contaminants of potential concern (COPC)
- Current and potential BMP methodologies to treat highway runoff in western Washington to address the COPCs
- The effectiveness of these BMP methodologies for key contaminants
- The likely water quality characteristics of BMP effluent (i.e., the water quality of highway runoff after being treated by these different BMPs)
- Data gaps, areas of uncertainty, and limitations with regard to BMP effectiveness, effluent quality, and quantity.

2 Background and Context (Overview of BMP Treatment, Performance Monitoring, and Performance Measures)

To understand the results and conclusions presented in this white paper, a basic understanding of certain concepts related to stormwater runoff treatment BMPs is helpful. This section includes a discussion of stormwater treatment operations or processes that make up the BMPs considered in the paper, as well as an overview of BMP performance measures and performance monitoring. This overall background and context forms the foundation for BMP-related performance information presented throughout the white paper.

2.1 Overview of Stormwater Runoff Treatment Operations or Processes

BMPs possess one or more treatment components or strategies, referred to as unit operation processes (UOPs). Understanding these UOPs is essential to the successful selection and design of BMP treatment systems, as well as system operation and maintenance. BMP UOPs can be divided into four fundamental process categories (Strecker et al. 2005):

1. **Physical operations** including the processes of size separation and exclusion (e.g., screening, filtration); density separation (e.g., sedimentation, flotation); aeration and volatilization; and physical agent disinfection (e.g., ultra-violet light).

2. **Hydrologic operations** are essentially a subset of physical operations and include the principles of flow attenuation (e.g., peak shaving, detention) and runoff volume reduction (e.g., infiltration, evapotranspiration).

3. **Biological processes** include the principles of microbially mediated transformations (e.g., redoximorphic reactions resulting from microbial respiration) and uptake and storage (e.g., bioassimilation).

4. **Chemical processes** include the principles of sorption (e.g., ion exchange, surface complexation); coagulation; and flocculation (e.g., particle agglomeration, precipitation).

The selection of one or more of these UOPs for inclusion in a particular BMP or BMP system should be based on the nature of the target pollutants relative to specific management goals for highway stormwater runoff (i.e., pollutants and their forms).

BMP treatment facilities generally include more than one UOP. For example, dry extended detention basins attenuate peak flows and reduce velocities, which cause particulates to settle out. If unlined and containing porous soils, the basins may significantly reduce total runoff volumes due to infiltration and evapotranspiration (ET) and hence reduce downstream energy from increases in flow. Soil particles within the basin can provide sorption of pollutants.

BMPs can be modified to include unit processes that are not usually incorporated in their design, such as amending soils to promote infiltration in compost-amended vegetated filter strip (CAVFS) or in a dry extended detention basin as discussed above. Individual or combined BMPs can include multiple unit processes; to maximize or assess the synergy between them, the placement or order of BMPs and BMP components within a treatment system should be carefully considered. To do this, it is useful to categorize

BMPs (and their components) according to the unit operation processes that they include. Table 1 provides a guide for linking UOPs and target pollutants to BMPs, while the following text summarizes the details of the UOPs (as presented in Strecker et al. [2005]).[1] Note: as it is not practical to list all of the subcategories of individual UOPs, we have listed the major categories only in Table 1. In descriptions of individual BMPs, more specific UOPs are mentioned (see Strecker et. al. 2005).

Table 1. Unit operation processes provided by common BMPs and BMP components.

Fundamental Process Category	Unit Operation Process (UOP) *Target Pollutants*	BMPs/BMP Components[1]
Hydrologic Operations	Flow and Volume Attenuation	Dry extended detention basins Wet ponds Stormwater treatment wetlands Vegetated filter strips
	Volume Reduction *All pollutant loads*	Infiltration facilities Dry extended detention basins Bioretention Biofiltration (vegetated) swales Filter strips Dispersion to landscaping Ecology embankments Permeable pavements
Physical Treatment Operations	Particle Size Alteration *Fine particulate/TSS*	Naturally occurs in extended detention basins and other BMPs with detention
	Physical Sorption *Nutrients, metals, petroleum compounds*	Bioretention Infiltration facilities Sand filters Engineered media / granular activated carbon* Biofiltration (vegetated) swales Filter strips Dispersion to landscaping Ecology embankment Oil boom
	Size Separation and Exclusion (screening and filtration) *Coarse solids, trash, debris*	Screens/bars/trash racks Bioretention Sand filters Infiltration facilities Permeable pavements Proprietary filters* Hydrodynamic separators* Catch basin inserts (i.e., surficial filters)* Dispersion to landscaping Ecology embankment

[1] The reader is referred to this document for a more complete description, including information source references.

Fundamental Process Category	Unit Operation Process (UOP) *Target Pollutants*	BMPs/BMP Components[1]
	Density, Gravity, Inertial Separation (grit separation, sedimentation, flotation and skimming, and clarification) *suspended solids, trash, debris, oil and grease*	Dry extended detention basins Biofiltration (vegetated) swales Filter strips Wet ponds Stormwater treatment wetlands Settling basins Swales with check dams Oil-water separators Hydrodynamic separators* Oil boom
	Aeration and Volatilization *Oxygen demand, PAHs, VOCs*	Sprinklers* Aerators*
	Physical Disinfection *Pathogens*	Shallow detention ponds Swales Ultra-violet systems*
Biological Processes	Microbially Mediated Transformation (can include oxidation, reduction, or facultative processes) *Metals, nutrients, organic pollutants*	Stormwater treatment wetlands Bioretention Wet ponds Proprietary filters (e.g., compost)
	Uptake and Storage *Metals, nutrients, organic pollutants*	Wetlands basins Bioretention Wet ponds
Chemical Processes	Chemical Sorption Processes *Metals, nutrients, organic pollutants*	Infiltration facilities Sand filters Subsurface wetlands* Proprietary filters (e.g., compost)* Biofiltration (vegetated) swales Filter strips Dispersion to landscaping Ecology embankment Permeable pavements Oil boom*
	Coagulation/Flocculation *Fine sediment, nutrients*	Dry extended detention basins Wet ponds Stormwater treatment wetlands Coagulant/flocculent injection systems*
	Ion Exchange *Metals, nutrients, mineral salts*	Soils, Ecology embankment, engineered media, zeolites, peats, surface complexation media
	Chemical Disinfection *Pathogens*	Custom devices for adding chlorine or ozone*

[1] BMPs not covered in this white paper are noted with an asterisk (*).
Source: Adapted and modified from Strecker et al. (2005).

2.1.1 Hydrologic Operations

Flow alteration is a significant unit operation process for stormwater runoff treatment. Flow alteration includes modifications to components of the hydrologic cycle such as runoff, infiltration, detention, storage, and evaporation. In general, the goals of these hydrologic controls are to reduce runoff volumes, reduce peak flows, and "smooth out" temporal aspects of flow. To varying degrees, these hydrologic controls can have a significant impact on water quality. The following subsections discuss the two fundamental hydrologic unit operation processes: flow attenuation and volume reduction (or minimization of volume increases).

2.1.1.1 Flow Attenuation

Flow attenuation refers to the hydrologic operations responsible for reducing peak event discharges (e.g., "peak shaving"). The primary mechanisms involved in flow attenuation include interception, conveyance, detention, and–to a lesser degree–infiltration (percolation into the ground). Interception is a form of detention storage that occurs when plant leaves, stems, branches, and leaf litter temporarily store rainfall. Conveyance is the transport of surface runoff and includes the entire flow path—from where a raindrop falls to where it enters the receiving body of water. Decentralized controls that provide conveyance also promote infiltration, improve water quality, and increase runoff travel time, or time of concentration. Detention is the temporary storage of stormwater runoff, which is released over a period that can generally range from hours or days after rainfall ceases. Detained stormwater runoff may exist as ponded free water or may be held within moist soil. Flow-duration basins (detention basins designed and built to specifically manage geomorphologically significant flows) can be designed to carefully release runoff to minimize downstream erosion. Infiltration is the downward movement of water into the soil after surficial entry and percolation through pore spaces. It also reduces peak flows along with runoff volumes.

2.1.1.2 Volume Reduction

Volume reduction hydrologic operations are designed to reduce the total volume of runoff via retention, infiltration, and evapotranspiration. Retention captures stormwater runoff to prevent surface release. The volume of retained runoff that may never enter the storm drain system is determined by processes such as vegetative interception, evaporation, transpiration of soil moisture, and reuse. Infiltration is the downward movement of water into the soil after surficial entry and percolation through pore spaces. In an open system (such as a meadow), this movement is unrestricted, and water can infiltrate down to and recharge the groundwater table. Groundwater recharge is a basic component of the natural hydrologic cycle. Stormwater runoff may also be detained, which temporarily reduces the amount of stormwater runoff that would otherwise be in the storm drain system and allows it to enter the system over an extended period of time (see above). The soil moisture content (as well as the pore space) determines the volume of stormwater runoff that is retained and detained. In a given treatment system, the volume of retained water is the volume for which the soil moisture content equals the soil's field capacity. The retained water leaves the soil through evapotranspiration (ET) or deeper infiltration. Evapotranspiration refers to the combined effects of evaporation and transpiration in reducing the volume of water in a soil and/or vegetated area during a specific period of time. The volume of water in the root zone of soils is taken up by roots and then transpired (i.e., diffused through leaves). The amount of surface water "lost" to ET is not well understood within BMPs but is considered an important process, especially during warmer periods.

2.1.2 Physical Operations

A physical operation, in contrast to chemical or biological process, is a form of treatment that is brought about by a physical mechanism such as sedimentation. Physical unit operation processes are the dominant forms of treatment in most stormwater runoff structural BMPs. The following subsections discuss physical unit operation processes used in the BMPs addressed in this white paper.

2.1.2.1 Particle Size Alteration

Particle size alteration processes include the increase in size of smaller colloidal and suspended particles through mixing and flocculation, for subsequent removal via settling or filtration. While engineered chemical and physical flocculation is not addressed in this white paper, flocculation occurs naturally in stormwater runoff. Depending on parameters such as mixing, pH, ionic strength, and particle properties, natural flocculation can begin within several hours to 12 hours of initial runoff. Natural flocculation, while generally not considered by most BMP designers, can have a significant impact on stormwater runoff clarification in sedimentation basins or in detention or retention facilities.

2.1.2.2 Size Separation and Exclusion

Size separation and exclusion include two primary physical operations: filtration and screening. Filtration, a UOP in many of the BMPs described in this white paper, involves a range of physical, chemical, and biological mechanisms, depending on the filter media. These mechanisms include straining, sedimentation, impaction, interception, adhesion, flocculation, chemical adsorption, physical adsorption, biological growth, and micobiologically mediated transformations. The dominant physical processes that typically occur in inert filter media, which include straining, impaction, interception, and adhesion, as described below.

In general, suspended and settleable solids concentrations need to be reduced to less than 50 mg/L for influent to a filter, depending on the media type, filter design, maintenance schedule, and other factors that may affect filter performance. Filters are designed to remove particulate matter either on the surface of the filter through surficial straining, or with depth within the filter. For dedicated filters, where filtration is the main UOP (such as sand and cartridge filters), effective filtration requires that either surficially strained or depth-filtered particles be removed on a regular basis. The buildup of such particles either on the filter surface or within the filter media results in a significant increase in head loss. Filter maintenance is far more challenging in decentralized stormwater runoff treatment systems, as these systems have far less oversight and monitoring, yet require similar or greater maintenance than centralized treatment. In other BMPs that incorporate filtration (such as ecology embankments; see Section 4.9), the filtered particles become incorporated in the media through natural physical, chemical, and biological processes. To avoid overloading these BMPs, the primary UOPs of sedimentation and filtration by vegetation are incorporated as part of the overall treatment train for these devices. The filtration media of improperly operated infiltration devices (e.g., exposure to excess sediment) will need to be partially or completely renewed. In BMPs that include vegetation, the root structures of plants help to reduce the effects of sedimentation by maintaining flow paths.

2.1.2.3 Coarse Solids Removal or Grit Separation

Coarse solids removal or grit separation is generally facilitated by some combination of sedimentation and hydrodynamic separation. Grit is generally classified as sand (generally larger than 200 µm), gravel, and larger inorganic particulate-type materials. In situations where large particles constitute a significant portion of the pollutant mass (e.g., where large quantities of road sand have been applied during winter months), grit removal can be an effective unit operation process for achieving water quality objectives. All of the BMPs considered in this white paper remove grit through sedimentation or filtration, either incidentally or intentionally.

Over the last 10 years, the size or density separation of grit-size material from stormwater runoff has become an important consideration when assessing treatment performance. Many proprietary devices on the market can function as effective design elements for removal of coarse solids, if maintained properly. However, their utility is often dramatically overstated for most common pollutants of concern, which are not largely associated with coarse particles.

2.1.2.4 Sedimentation or Gravity Separation

Sedimentation involves settling of sediment (>75 µm), settleable (25–75 µm), and suspended (<25 µm) particles from aqueous solution, and is the oldest and most widely used particle separation operation in water and wastewater treatment. Gravity separation or settling is a solid-liquid unit operation process that uses gravity and the difference in density of the liquid and particulate components to separate particles. It is enhanced by natural flocculation, which coagulates the smaller (<25 µm) particles. Gravity separation is the most common intentional or unintentional unit operation process in practice, and serves as a treatment that protects downstream operations and processes. Nearly all of the unit operation processes for stormwater runoff use sedimentation either by design for separation of particles, or inadvertently as an inherent function of storage or relatively quiescent conditions.

2.1.2.5 Aeration and Volatilization

Aeration and volatilization are two physical processes that occur simultaneously; the entrainment of air into the water column promotes volatilization of any volatile substances. Aeration is the process of entraining air in the water column to: (1) increase dissolved oxygen (DO), (2) decrease the biochemical oxygen demand (BOD), or (3) decrease dissolved carbon dioxide. Aeration UOPs are not included in any of the BMPs addressed in this white paper, and because BOD, oxygen depletion, or CO_2 buildup are unlikely to be issues in highway runoff, these UOPs are not discussed further.

Volatilization is the process whereby liquids and solids vaporize and escape to the atmosphere. Compounds that readily evaporate at normal pressures and temperatures are volatile compounds. Although volatilization UOPs are not specifically included in the BMPs addressed in this white paper, if such compounds are present, it would be desirable to remove them prior to infiltration. In some circumstances, volatile organic carbons (VOCs) or semi-volatile organic carbons (SVOCs) could be present in highway runoff; these compounds include various petroleum hydrocarbons (e.g., BTEX and low molecular weight PAHs), gasoline oxygenates (MTBE), herbicides, and pesticides. Volatile compounds are usually highly soluble in water and will easily migrate to groundwater.

2.1.2.6 Physical Agent Disinfection

Physical agent disinfection is incidentally included in some of the BMPs described in this white paper. However, contamination of highway runoff with bacteria pathogen indicators is not an ESA issue. This UOP refers to the mitigation of stormwater-borne pathogens through the use of nonchemical agents such as sunlight, ultraviolet light, and heat, and is distinct from chemical disinfection (e.g., with chlorine). Physical disinfection partially destroys pathogens and should not be confused with sterilization, which completely destroys all of the organisms.

Ultraviolet (UV) light disinfection (the main physical disinfection unit operation process) immobilizes stormwater-borne pathogens by penetrating pathogen cell walls and inducing biochemical changes within the pathogens. This prevents replication and/or causes death of the organism. Stormwater runoff applications of deliberate UV disinfection are rare, but they have been used to treat stormwater runoff system discharges (primarily dry weather flows) to California beaches.

The sun is an abundant source of UV light. Die-off of bacteria can occur within shallow ponds, swales, and open conveyance systems and is well documented in swimming pools and large bodies of water (such as lakes and the ocean). However, the efficacy of natural UV disinfection in small water bodies is unknown; regrowth is likely to occur in smaller water bodies such as ponds, wetlands, and streams, where there is a far greater interaction with banks, bottom sediments, and vegetation, and the amount of wildlife per volume of water is high.

2.1.3 Biological Processes

Biological unit operation processes for stormwater runoff treatment involve the use of living organisms (e.g., plants, algae, and microbes) to transform or remove organic and inorganic constituents from water and soil. They include microbially mediated transformations and uptake and storage processes, as described below.

2.1.3.1 Microbially Mediated Transformations

Microbially mediated transformations are chemical transformations promoted by bacteria, algae, and fungi that exist in the water column, soil, root zone of plants, and on wetted surfaces (such as leaves). These processes occur in both aerobic (e.g., well-aerated terrestrial soil) and anaerobic (e.g., wetland sediment) environments. Oxygen is used during aerobic respiration, while other chemicals (e.g., nitrate, sulfate, metal oxides) are used during anaerobic respiration.

Applicability of Microbially Mediated Processes in BMPs

Microbially mediated transformations are used to remove or convert dissolved nitrogen species (e.g., nitrate), metals, and simple and complex organic compounds. Transformations occur relatively slowly and require long residence times, on the order of days; some transformations may require weeks to occur. Because of their moisture and temperature requirements, microbial processes have limited applications in arid climates, regions with long dry seasons (unless supplemental moisture is supplied), and cold climates or seasons.

Most BMP treatment systems have a diverse microbial population. Basic habitat requirements for all microbes include a substrate to colonize (e.g., soil, plant roots, leaf surfaces), appropriate nutrients including carbon sources, absence of toxins, and sufficient moisture. Amending the soil with organic matter can increase populations. Oxygen requirements are another important factor. Depending on the microbe, it may require oxygen (aerobic) or other substances (facultative and anaerobic) for metabolism. Various factors determine available oxygen, including soil characteristics and inundation patterns.

Many of the UOPs that lead to the removal or addition of contaminants of potential concern have been studied. Much of the general knowledge from these studies has been incorporated into BMP designs, such as soil amendments with organic matter, moisture control, creating favorable pH conditions, and incorporating diverse plant communities appropriate to the site and conditions. Most of these are necessary for a healthy and diverse ecosystem. Few of the microbiologically mediated reactions are deliberately developed and controlled in stormwater BMPs, in contrast to bioremediation of sites contaminated by metal and xenobiotic compounds.

Management of denitrification in constructed wetlands is possibly the most advanced microbial UOP, with attention focused on the primary factors that affect denitrification, such as nitrification of ammonia, aeration (or lack of), moisture status, pH, temperature, and the nature and amount of organic matter available as energy sources. Denitrification may be limited by available carbon in mineral soils. The type of vegetation present affects denitrification because decayed vegetation is a carbon source for microbes, and viable systems must provide a sustainable source in the form of litter. To enhance denitrification, anaerobic conditions may be enhanced by adding a deep layer of flooded gravel in wetlands, or by increasing water levels or inundation periods. Recently, these conditions have been carefully manipulated in structural BMPs to remove selenium. Another such BMP is the use of perlite in ecology embankments to provide favorable microbial substrate.

Transformation of nitrogen species occurs relatively easily and is widespread. This can lead to water quality degradation. Nitrification, without significant denitrification, may result in leaching of nitrate from the system, which is of particular concern in areas with water quality impairment due to nutrient enrichment.

2.1.3.2 Uptake and Storage

Uptake and storage processes refer to the assimilation of organic and inorganic constituents by plants and microbes. The organisms may assimilate essential nutrients for metabolism and growth, as well as nonessential constituents. Plants and microbes require essential nutrients to sustain growth, which may be assimilated from the water column or from soil solution. In wetlands, free-floating plants take up nutrients from the water column; emergent plants take up nutrients from soils, and submerged plants may obtain nutrients from both the water column and soils.

Uptake of macronutrients such as phosphorus and nitrogen in vegetated ponds can be significant until storage pools become full. Studies of mature pilot wetlands show that plants account for only about 2–5 percent of phosphorus removal and 2–8 percent of nitrogen removal. Increased performance may require harvesting and replacement of vegetation, which is typically costly. In addition to uptake for nutrition, various algae and wetland and terrestrial plants accumulate organic and inorganic constituents in excess of their immediate needs (bioaccumulation). Bioaccumulation is an evolutionary response to scarcity in the natural environment.
Other plants sequester metals in the root zone and excrete matter that causes metal precipitation.

Uptake and storage can be used to remove dissolved metals, nutrients (phosphorus and nitrogen), and organic compounds from water and soil water. The processes may occur where soil properties and water quality are adequate to support vegetative and microbial growth and residence times are sufficiently long. Ultimately, nutrient storage by plants and microbes is temporary. A portion of nutrients is released through tissue sloughing, plant senescence, and dormancy.

Uptake processes vary by season, latitude, and species, and only occur during the growing season. Establishment and growth of plants and microbes are affected by various soil characteristics including texture, pH, nutrient levels, salinity and toxicity, soil moisture, and drainage (oxygen). Various soil amendments can be used to make the substrate more suitable for plant and microbial growth. Plants should be suitable for the climate and hydrologic regime, be tolerant of concentrations in stormwater runoff, and have appropriate growth characteristics. Increasing the density of vegetation will improve uptake, as will increasing residence times. Symbiotic microbes also enhance nutrient uptake by plants.

2.1.4 Chemical Processes

Chemical characteristics, such as pH, alkalinity, hardness, redox conditions, organic carbon, and ionic concentrations, dictate dissolved solids partitioning and speciation of stormwater runoff pollutants, which in turn control the type of UOPs necessary to treat those pollutants. Three common chemical UOPs used to treat stormwater runoff include sorption, coagulation/flocculation, and chemical agent disinfection. The latter two are not discussed here because they are not part of the UOPs deployed in the BMPs described in this white paper; for details on these UOPs, the reader is referred to Strecker et al. (2005).

Many traditionally utilized filters using natural materials such as sand, gravel, and perlite have relatively minor capacity for sorption of phosphorus or metals. Such materials have relatively small surface areas or hydrodynamic characteristics that are not conducive to flow-through sorption treatment such as sorptive-filtration or ion exchange. Recently, unit operation process designs have started to combine surface reactions (such as sorption) and filtration using materials and systems engineered with hydrodynamic considerations. Examples of such media include the ecology mix for ecology embankments (described in more detail in Section 4.9).

Many filtration systems not engineered for sorption have shown some capacity for metals and phosphorus sorption removals. In many cases, this is due to the filtration or separation of biogenic materials such as leaves or organic debris or particulate matter found in stormwater runoff that then serve as sorption media. However, the biogenic materials are degradable and pollutants may then be released. The overall capacity for removals from biogenic materials and particulate matter is typically significantly less than engineered media. However, this material is added with each storm event, so this sorption media is replenished continually.

Chemical processes are important in many of the BMPs described in this white paper. Sorption can occur on and into plants, as described above, but also by microorganisms (bacteria, algae), dead plant material, soil components (clays, iron and manganese oxides), bacteria, decaying plant matter, and stable soil organic matter (e.g., humic acids).

2.2 Effects of Unit Operation Processes on Contaminants of Potential Concern

This section presents an overview of the effects of the identified unit operation processes on the contaminants of potential concern. In this discussion some of the unit processes discussed below are a sub-class of the more general unit process operations listed in Table 1.

2.2.1 Particulate Matter (TSS)

Removing TSS is one of the most common water quality objectives for treating highway runoff, as well as urban runoff in general, because it is a surrogate for many other contaminants that are associated with particulate matter. In Washington State, the "basic treatment" requirement for TSS is 80 percent removal. The International Stormwater BMP Database (described in more detail in Section 3.2) notes that percent removal of TSS is problematic in that effluent quality of BMPs is relatively uniform and, therefore, percent removal is primarily a function of the influent quality (Strecker et al. 2001, 2005). Well-implemented source controls could result in percent removal requirements being difficult (if not impossible) to meet while still achieving good effluent quality.

Larger suspended solids can be removed effectively by gravitational sedimentation. Sediment (i.e., particles greater than 75 µm) settles readily with slowing flow, either in a pond or other detention basin, or by passing shallow flows through vegetation in bioswales. Settleable solids comprised of inorganic particles in the 25–75 µm range are effectively removed by quiescent gravitational sedimentation. For biofilters (e.g., filter strips, vegetated swales), the primary removal mechanisms for suspended sediments are gravity settling and filtration. Gravity separation is provided by slowing the flow and by the microbackwaters within the vegetation matrix. For media filters (e.g., sand filters), the primary removal mechanism for suspended sediments is filtration, which is usually preceded by gravity settling. Extended detention ponds with longer drawdown times (36 to 72 hours) are also effective at removing settable solids.

The removal of suspended inorganic particles less than 25 µm is more difficult. However, removal of these small particles can be enhanced by natural coagulation/flocculation, followed by sedimentation and/or filtration.

Turbidity, due in part to suspended particles, is often directly related to TSS; however, this relationship is site-specific. For example, depending on particle shape and reflectivity, there can also be an inverse relationship between turbidity and particle size. Therefore, UOPs that reduce TSS concentrations will also reduce turbidity, although the reduction in turbidity may be less than the decrease in TSS because of this particle size effect. While turbidity is a major factor affecting water clarity and appearance, these "observable" qualities can also be affected by "color" from such sources as ligins and tannins.

2.2.2 Trace Metals

Trace metals are recognized as key contaminants of potential concern in highway runoff in Washington State and require specific BMPs above certain traffic densities. Interestingly, WSDOT's monitoring data show that trace metal levels in BMP influents are independent of traffic densities (WSDOT 2006b). Earlier work (Driscoll et al. 1983) found a direct relationship only with zinc and traffic densities ($r^2 = 0.7$). For other metals, however, while there was little or no direct relationship, there was a difference between urban and rural sites.

From a treatability and regulatory perspective, the important forms of trace metals are dissolved, particulate-bound, and total metals. If trace metals are bound to organic or inorganic particulates, viable unit operation processes include sedimentation and filtration, either as separate or combined unit operations. Removal of particulate metals follows suspended solids (SS) removal. If present as a dissolved ionic species such as Cu^{2+}, Pb^{2+}, or Zn^{2+}, sorption (surface complexation, adsorption, and ion exchange) can be effective UOPs in reducing dissolved metals. Effective adsorbing and absorption surfaces include soils, soil organic matter, hydrous iron oxides, clays and other amorphous alumino-silicates, algae (in the water column or on leaves), living and decaying plant tissue, and engineered media. If present as a dissolved organic complex (e.g., dissolved metals bound to dissolved organic matter), then adsorption or ion exchange can be much slower and even inhibited.

Media in sand filters and cartridge filters can be engineered to remove trace metals with relatively rapid flows. Commonly used media include peat, decayed compost, and zeolites. Sorption in soils and wetlands occurs on a variety of materials with varying sorption abilities and relies on longer contact times. Copper is one of the more challenging trace elements to remove sufficiently to meet state water quality standards, likely because it can be strongly bound to dissolved organic matter (which is difficult to remove).

2.2.3 Phosphorus

Phosphorus is also considered a contaminant of potential concern; when highway runoff is discharged to receiving waters that are sensitive to nutrient enrichment, specific UOPs are required for phosphorus treatment.

Treatability for phosphorus is a function of whether it is present in particulate or dissolved form. If phosphorus is bound to organic or inorganic particles, viable UOPs include sedimentation and filtration. In dissolved form, phosphorus may readily undergo surface complexation reactions, sorption, or precipitation. Uptake by vegetation and microbes is another mode by which dissolved phosphorus is effectively removed. Media or soils containing significant quantities of hydrous oxides of iron or aluminum, as well as some types of aluminum silicates (e.g., clays, allophone), can effectively remove dissolved phosphorus species through surface complexation or precipitation.

2.2.4 Nitrogen

Many waters are also sensitive to nitrogen enrichment. As with phosphorus, treatability for nitrogen is a function of whether it is present in particulate or dissolved form. Dissolved forms of nitrogen include nitrate, nitrite, ammonia, and dissolved organic nitrogen, all of which are difficult to remove. Effective removal requires microbiological processes, the most important being denitrification of nitrate and nitrite to nitrogen gas. Secondary microbiological processes include nitrification (conversion of ammonia to nitrate) and mineralization (breakdown of organic matter to ammonia). Uptake by vegetation and microbes can also remove dissolved nitrogen. Media or soils with significant quantities of hydrous oxides of iron or aluminum, as well as some types of aluminum silicates (e.g., clays, allophone), can remove ammonia species through adsorption, but this will likely be a minor process, and the ammonia can be easily remobilized by ion exchange processes at a later stage. If nitrogen is bound to organic or inorganic particles, viable UOPs include sedimentation and filtration.

Mineralization and nitrification in BMPs that incorporate soils and plant material can potentially add significant quantities of dissolved nitrogen to stormwater runoff.

2.2.5 Organic Compounds

Organic compounds addressed in this white paper are those associated with highway runoff that could, in sufficient concentration, exert a deleterious effect on water use. These include fuels (e.g., diesel), oil and grease, PAHs, pesticides and herbicides, plasticizers (phthalates) used in tires, and legacy pesticides and other organochlorines that have accumulated in the environment from past use. In the latter category, the most common and frequently encountered are organochlorine pesticides (such as DDT and its decomposition products in land that has been used for cropping and horticulture in the 1940–1970s) and PCBs in urban areas, especially those associated with industrial land use.

Some of these organic compounds are primarily found in the dissolved phase (e.g., lower molecular weight aliphatics and aromatics in fuels, and low molecular weight PAHs, such as naphthalene from fuels and combustion). These are difficult to remove from highway runoff. Possible removal mechanisms include sorption to other hydrophobic particles, such as oil and grease, limited adsorption onto other organic matter (limited because these compounds are nonpolar, whereas most natural organic matter is polar), and microbiological breakdown. The latter would require relatively long times and be most effective where these compounds have been detained in soils or in wet ponds/constructed wetlands.

Most of the organic compounds of concern are bound to particulate matter, however, either adsorbed to discrete organic particles (usually called particulate organic matter [POM], or inorganic particles coated with organic matter [e.g., soil particles]). Examples of POM in highway runoff are tar, rubber, and vegetable matter. Removal of these from stormwater runoff is achieved through UOPs that remove particulate matter (sedimentation and/or filtration). It is widely expected that achieving low TSS concentrations in effluent from BMPs will also achieve low concentrations of these particulate-associated organic compounds. Once removed, some (such as oil and grease) will undergo slow microbiologically mediated breakdown. Others (such as high molecular weight PAHs, and legacy pesticides such as DDT and PCB) decay slowly and can persist for many years.

Some toxic organic contaminants in petroleum products are soluble and do not adsorb readily onto particulate matter. These include BTEX compounds (benzene, toluene, ethylbenzene, xylene) and low molecular weight PAH (e.g., naphthalene, phenanthrene). Contamination of the aquatic environment by these compounds is usually associated with fuel spills, not with diffuse source pollution from combustion emissions. While these compounds do occur in these emissions and can be deposited on highways, they are easily volatilized under ambient conditions, so concentrations in highway runoff are expected to be low.

2.2.6 Oxygen Demanding Substances

Biologically degradable organic matter and ammonia exert an oxygen demand in receiving waters because they are metabolized by microorganisms. Historically, this was a significant problem with wastewater discharges, and there were concerns in the 1970s about oxygen demand from urban stormwater runoff (i.e., that it would deplete dissolved oxygen in receiving waters and endanger fish and other aquatic life). However, this has been rarely observed and usually only because of other related factors (e.g., high flows disturbing anaerobic sediments and releasing easily oxidized inorganic substances such as sulfides and ferrous iron). Concentrations of readily oxidizable organic matter are relatively low in highway runoff and are discharged under high-flow conditions, which also favor dilution and re-aeration, especially in the time frames for microbiologically mediated oxygen demand (e.g., BOD measured over 5 days). As it is extremely unlikely that highway runoff will cause significant or measurable oxygen depletion through this mechanism, its removal is of little consequence to receiving waters. Most BOD is associated with particulate material; therefore, BOD will be effectively removed with UOPs that target particulate material.

2.2.7 Human Pathogens

The presence of pathogenic microorganisms is an issue for human health, not an ESA issue. Nevertheless, a brief discussion is included here because a number of BMPs addressed in this white paper include UOPs that remove microorganisms. Results of studies on the removal of pathogen-indicator bacteria are highly ambiguous. Bacteria by themselves are difficult to remove because of their small size and low density. A portion of bacteria is frequently associated with particulate matter, which would be more easily removed. In addition, bacterial regrowth is a major confounding influence. Indicator bacteria can grow through filter media and can survive and grow in decaying organic matter, soils, and sediments. Reinoculation is another confounding factor (e.g., by wildlife in ponds and constructed wetlands). Removal processes include die-off (from sunlight inactivation and from predation), sedimentation, physical adsorption, and filtration. Bacteria may be removed in BMPs that incorporate many of these processes, such as biofiltration swales (sedimentation, filtration and adsorption on leaves and root mass, sunlight disinfection on leaves, filtration by soil media, and die-off and predation in soils). However, this removal is counterbalanced by the ability of indicator bacteria to survive in soils and become a source of contamination.

BMPs with prolonged and deep filtration through bioactive media (such as bioretention, infiltration devices, and ecology embankments) are likely to be the most effective in reducing indicator bacteria levels. Wet ponds with shallow open pools area also effective at reducing bacteria levels. BMPs such as swales will also show reductions, primarily due to volume losses from infiltration and soil soaking and drying.

2.2.8 Major Ions

None of the UOPs considered in this white paper remove major ions (e.g., monovalent ions such as Na^+, Cl^- in deicing salt) because they are highly mobile. Some removal from ion exchange can occur, but these adsorbed ions are easily remobilized. Therefore, the total dissolved salts and electrical conductivity will not change materially with passage through most BMPs. “Removal” of salts from stormwater runoff is best accomplished by infiltration, which may not be desirable for groundwater if salt levels are high. Detention in ponds/basins and ion exchange in soils may reduce concentrations when salt levels are high, such as where deicing salts are removed and diluted in the first flush, but these will probably be later mobilized or flushed out by the tail of the storm.

Ions that cause hardness (e.g., Ca^{2+}, Mg^{2+}) are adsorbed more strongly onto surfaces such as clays and organic matter, but their removal is less desirable because their presence in the water reduces the toxicity of many heavy metals (e.g., copper and zinc). In general, removal of these ions is not expected to occur to any significant extent in most BMPs. Other ions that affect speciation of metals (such as H^+, HCO_3^- and CO_3^{2-}) may undergo reversible reactions with soils, and pH, hardness, and carbonate concentrations can be increased by adding limestone to filter media in BMPs.

2.2.9 Other Conventional Water Quality Parameters

Relatively little information is available on other conventional water quality parameters, such as pH and DO (turbidity is discussed above under TSS). However, these parameters may change within runoff as it passes through a BMP. For example, improperly managed vaults and filters can allow water to stagnate and form anoxic conditions, with accompanying lower pH and relatively high ammonia and metal concentrations. A more common example encountered is pH and DO changes in ponds and wetlands. pH and DO can increase during the day because of photosynthesis, and decrease at night from respiration of plants and algae. To some extent, this is a natural cycle and is not expected to be a significant problem unless flushing rates are low and nutrient inputs are high.

2.3 Overview of BMP Performance Monitoring

Monitoring the performance of BMPs is challenging because of factors such as the difficulty in collecting representative samples, measuring flow rates accurately, and other factors. Strecker et al. (2002) developed a detailed guidance document on BMP performance monitoring for meeting the monitoring and reporting protocols identified in the International Stormwater BMP Database. The guidance is extensive and demonstrates the effort needed to conduct BMP performance studies. Jones et al. (2004) summarized the difficulties in collecting BMP performance data. Although this white paper does not provide a detailed discussion of these difficulties, it is important to recognize that: (1) they exist, (2) they are the primary reason that extensive data sets on BMP performance are not available, and (3) there is variability in the available data sets. Therefore, a summary of some of the difficulties is presented below.

An ideal experimental design for measuring BMP performance would include measurements of inflows and outflows, as well as measurements of both influent and effluent quality. This ideal is possible in BMPs with clearly defined inlet(s) and outlet(s) and an unambiguous transition or resident time. Monitoring becomes more challenging for multiple or diffuse inlets (e.g., a continuous inflow along the length of a bioswale), systems with long transition times (e.g., wet pond or constructed wetland with storage), or ill-defined outflows (e.g., bioretention areas). Therefore, before beginning a performance monitoring program, it is critical to clearly identify and understand the specific hydrologic/hydraulic properties at a particular site, which constrain the potential monitoring and analysis methods.

The technical procedures for monitoring BMP performance also present a number of challenges. A fundamental requirement of every successful water quality monitoring program is effective and representative sampling of runoff events at the site. Flow monitoring is an important component, which requires a flow measurement device and a rain gauge. Flow measurement requires a stable flow channel cross section, and instruments may need to be calibrated. Stormwater runoff quality sampling is challenging because it has to be performed during limited time windows, when there is adequate rainfall (or snowmelt). Frequently, it is subject to unforeseen circumstances such as equipment malfunctions, safety issues, discrepancies between the actual event and forecasts, seasonal runoff variations, vandalism of installed field equipment, and impacts of illegal discharges. If sampling is carried out manually, this may require mobilization of sampling teams based on rainfall predictions, but subsequent rainfall intensity, distribution, and/or location can result in insufficient or inadequate samples. Even if sampling and flow measurement are conducted with automatic equipment, its optimum and efficient deployment will require pre-storm set-up, as well as monitoring and adjustments during the storm. If several BMPs are being assessed, for cost reasons there may be limited time when equipment can be deployed at a particular site before it must be shifted to another site. In this case, sufficient and adequate samples may be compromised by the actual weather experienced at each site.

Various methods, all with different cost and time requirements, can be used for sampling. Grab samples at a specific point in time are generally collected manually and can be labor intensive due to the broad time scale of runoff events. If samples need to be collected at different times and over extended time periods, automated samplers could be a more cost-effective option; some constituents, however, require collection by grab sampling. To set up an effective automated monitoring program, initial equipment setup may be costly. To accurately sample a storm event, automated samplers require a flow measurement device, a flow sensor, and a rain gauge. Samples must be collected in appropriate containers (e.g., Teflon or polyethylene for metals, treated glass for other constituents) using clean sampling techniques. Sampler tubing must be an EPA-approved material.

Once sampling equipment has been installed, two types of sampling methods can be employed. The most common and typically most cost-effective method for comprehensive studies is flow-weighted composite sampling. This method uses flow data to collect larger sample amounts during high flows, allowing for a more accurate representation of an entire runoff event. This allows the generation of a flow-weighted mean or event mean concentration[2] (EMC) and is the most commonly used method when assessing BMPs. Compositing results in a considerable cost savings for laboratory analysis. A more costly but more accurate method is discrete (or grab) sampling, which consists of collecting samples from discrete time intervals for individual analyses. Analysis of discrete samples provides a description of the pollution dynamics throughout a storm event. Grab sampling is also required for constituents that transform rapidly, require special preservation, or adhere to bottles, including bacteria and oil and grease sampling.

For a BMP to be considered effective, it must make a significant difference in improving water quality and/or controlling flows. One of the biggest challenges facing BMP monitoring is that stormwater runoff quality is inherently highly variable. Differences observed between inflows and outflows may be significant from a water quality standpoint, but it may be difficult to establish that these differences are significantly different statistically. For smaller differences (e.g., 30 percent change or less), a relatively large number of samples may be required, which can exacerbate the challenges in monitoring described above.

[2] The EMC is the concentration calculated from the total storm load divided by the total storm volume. It can be estimated/measured directly through flow-weighted sampling.
[4] In Washington, detention basins often provide full infiltration for storms from April to October (R. Tveten, pers. comm.).

The number of samples needed can be estimated depending on the study objectives (i.e., how BMP performance is being assessed), as well as knowledge of the variability of highway runoff quality and/or BMP effluent quality. For example, Strecker et al. (2001) estimated the number of samples needed to detect 5, 20, and 50 percent differences in concentrations of parameters between influent and effluent for three catchments in Portland, Oregon. A large number of samples (in some cases, more than 400) is needed to detect relatively small differences of 5–20 percent (Table 2) and may require many years of frequent monitoring. Detecting large differences (e.g., 50 percent) requires relatively few samples (as few as 2).

Table 2. Analysis of sample sizes needed to statistically detect changes in mean pollutant concentrations from two stations in Portland, Oregon.

		Number of Samples Required to Detect Indicated Percent Reduction in Site Mean Concentration		
Monitoring Site	**Parameter**	**5%**	**20%**	**50%**
Residential (R1-Fanno Creek)	TSS	202	14	4
	Cu	442	29	6
	TP	244	16	4
Mixed (M1-NE 122nd)	TSS	61	5	2
	Cu	226	15	4
	TP	105	5	3

Source: Reproduced from Strecker et al. (2001).

2.4 Overview of BMP Performance Measures

Because an objective of this series of white papers is to predict impacts of treated highway runoff on ESA-listed species, it is recommended that estimating the treatment performance of a BMP include an evaluation of the following: (1) runoff volume reductions; (2) long-term, volumetric capture efficiency; (3) expected effluent quality for target constituents; and (4) flow-duration control that limits downstream erosion. Other commonly used methods for assessing the effectiveness of BMPs include the efficiency ratio, summation of loads and plotting effluent data versus influent data and comparing these with water quality objectives, as used in the WSDOT National Pollutant Discharge Elimination System (NPDES) annual progress reports (WSDOT 2007). More details on the various methods including those below are summarized in Strecker et al. (2002).

2.4.1 Efficiency Ratio and Summation of Loads

The efficiency ratio (ER) is defined in terms of the average event mean concentration (EMC) of pollutants over some time period:

$$ER = \frac{\text{average inlet EMC - average outlet EMC}}{\text{average inlet EMC}}$$

EMCs can either be determined from flow-weighted composite samples in the field or calculated from discrete measurements.

The summation of loads (SOL) method defines the efficiency based on the ratio of the summation of all incoming loads to the summation of all outlet loads:

$$SOL = 1 - \frac{\text{sum of outlet loads}}{\text{sum of inlet loads}}$$

This method requires that monitoring data accurately represent the actual entire total loads in and out of the BMP for a period long enough to overshadow any temporary storage or export of pollutants. It assumes that any significant storms that were not monitored had a ratio of inlet-to-outlet loads similar to the storms that were monitored.

These methods should (but often do not) include an appropriate nonparametric (or parametric, if applicable) statistical test indicating if the differences in mean influent and effluent EMCs are statistically significant. Note that it is better to show the actual level of significance found, rather than just noting if the result was significant (assuming a 0.05 level). Parametric tests probably require transformation of the data so that tests are carried out on data with normal distributions. The most commonly observed data distribution is log-normal, so computing the mean and standard deviation of log transformations of the sample EMC data and then converting them to arithmetic estimates often results in a better estimate of the mean of the population due to these more typical distributional characteristics (see Strecker et al. 2002).

The methods above are problematic for a number of reasons, as discussed in Strecker et al. (2002). In particular for this analysis, we are concerned with whether the effluent quality is protective of endangered species and therefore measures of loading or concentration reduction are not that valuable.

2.4.2 Plotting Influent Versus Effluent Concentrations

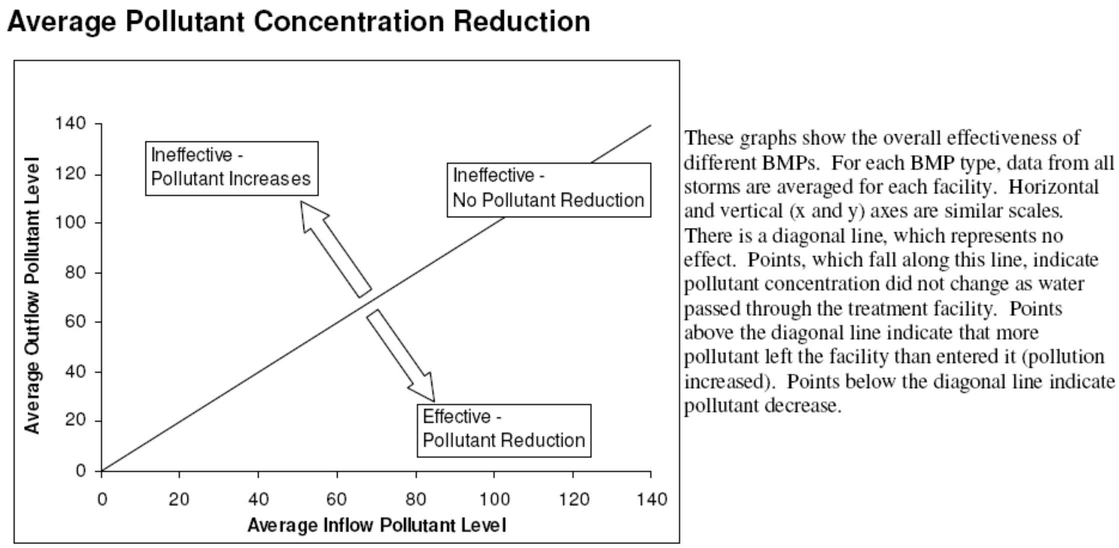
WSDOT has evaluated highway runoff BMP performance using paired sampling of BMP inflow and outflow samples collected during a storm for comparison. The data are plotted in graphs so that readers can quickly compare the quality of treated water to applicable water quality standards, and can view the effectiveness of different BMPs in relation to each other (Figure 1).

Two graphs are presented for each pollutant. One graph presents the average of all data collected per BMP. A second graph shows paired (not averaged) data for each storm to demonstrate variability between storms.

Where feasible, total volumes of water both entering and leaving a BMP are also compared to determine what amounts of pollutants are trapped when water evaporates or soaks into the ground.

While these graphs may be useful for WSDOT purposes, they do not show whether the influent and effluent quality are statistically different from each other. For BMPs with a large permanent wet pool as compared to the storm events volume, pairing data of inlet and outlet can be misleading as the outflow may have come from a previous event. Finally, other data sets used for these analyses are not presented in this fashion and it was beyond the scope of this effort to put these data sets into this format. They are useful for visually comparing the variability of effluent vaules.

Figure 1. WSDOT's method of showing BMP effectiveness.



Source: from WSDOT (2006b).

2.4.3 Effluent Probability Method

The effluent probability method is a technique that provides a statistical view of influent and effluent quality. The approach is to first determine if the BMP is providing treatment (i.e., are the influent and effluent mean of the EMCs statistically different from one another), and then to prepare and examine either a cumulative distribution function of influent and effluent quality or a standard parallel probability plot (see Strecker et al. 2002). Before any efficiency plots are generated, appropriate nonparametric (or parametric, if applicable) statistical tests should be conducted to indicate if any perceived differences in the influent and effluent mean of the EMCs are statistically significant (as noted above; the level of significance should be provided, not just noting if the result was significant; assume a 95 percent confidence level). The effluent probability method is straightforward and provides a clear picture of the ultimate measure of BMP effectiveness (i.e., effluent water quality characteristics).

2.4.4 Volume Reduction

Volume reduction in a BMP is primarily influenced by the infiltration and moisture holding capacity of the soils, through infiltration to the subsurface and (combined with vegetation) evapotranspiration. Soils with a high fraction of clays and/or little vegetion will prevent significant stormwater runoff volume reductions due to their poor infiltration capacity. Higher infiltration rates will result in larger volumes entering the soils for immediate infiltration, as well as after-storm ET losses. The ET rates are also important, as they affect whether soils dry out in time to infiltrate stormwater runoff from the next event as well as provide additional volume losses.

BMPs such as wet ponds and stormwater treatment wetlands (referred to as wetland basins in the International BMP Database and in this document during discussions of these systems) might not significantly decrease the volume of runoff because soils suitable for placement of a wet pond or wetland basin will typically exhibit low infiltration capabilities. Due to the need to maintain a permanent wet pool for optimal pollutant removal in a constructed wetland, little volume reduction can be expected due to infiltration losses, especially during storm events. However, volume reductions would be expected in vegetated BMPs due to drier, more permeable soils and complete vegetative cover.

Based on the limited study data available, dry detention basins and biofilters (such as vegetated filter strips and biofiltration swales) show an average volume reduction of about 30 and 38 percent, respectively, while wet ponds and wetland basins show an average volume reduction of about 7 and 5 percent, respectively (Table 3) (Strecker et al. 2004). Based on this analysis, detention basins (dry ponds) and biofilters (vegetated swales, overland flow, etc.) appear to contribute significantly to volume reductions, even though they are generally not designed specifically for this purpose. Based on the HRM design requirements, infiltration devices should achieve 91 percent reduction (see Section 4.3 in the 2006 HRM).

Table 3. Average volume losses in treatment system components.

BMP Type	Ratio of mean monitored outflow/mean monitored inflow for events where inflow is greater than or equal to 0.2 watershed inches
Detention Basins	0.70
Biofilters	0.62
Media Filters	1.00
Hydrodynamic Devices	1.00
Wetland Basins	0.95
Retention Ponds	0.93[a]

[a] WSDOT wet ponds tend to have greater losses due to low-intensity storms and generous sizing criteria (R. Tveten, pers. comm.).
Source: International Stormwater BMP Database.

2.4.5 Capture Efficiency

The capture efficiency (defined as the percent of stormwater runoff volume treated) of an on-line volume-based BMP (e.g., detention facility) is primarily a function of the size and hydraulic design of the facility. Table 4 (reproduced from the 2006 HRM) identifies the criteria for capture efficiencies for different BMP facility types.

For volume-based BMPs, the bypassed, untreated flows occur most often from the tail end of large storms. These bypasses will frequently have lower pollutant concentrations for total pollutants because the majority of particulate-bound pollutants are expected to be washed off highways and discharged earlier in larger storms. However, in some urban catchments, dissolved pollutants such as copper and zinc have been observed to be more consistent, sometimes increasing in concentration during the tail of events. For on-line systems, when the design volume is exceeded, flows start spilling to an overflow outlet, receiving less treatment than that of the design volume.

For flow-based BMPs, flow bypass occurs whenever the flow rate exceeds the design capacity of the device. This generally occurs near the peak of the runoff hydrograph. If the facility is off-line, a flow splitter typically regulates the bypass. However, if the BMP is an on-line facility (e.g., swale), then flows are not physically bypassed and treatment levels generally decrease as the flow rate exceeds the water quality design flow rate.

Table 4. Criteria for sizing runoff treatment facilities in western Washington.

Facility Type	Criteria	Model
Flow-based: upstream of flow control facility (on- & off-line)	Size treatment facility so that 91% of the annual average runoff will receive treatment at or below the design loading criteria, under postdeveloped conditions for each TDA. If the flow rate is split upstream of the treatment facility, use the off-line flow rates.	Approved continuous simulation model using 15-minute time steps
Flow-based: downstream of flow control facility	Size treatment facility using the full 2-year release rate from the detention facility, under postdeveloped conditions for each TDA.	Approved continuous simulation model using 1-hour time steps
Volume-based (on- & off-line)	*Wetpool*: Size treatment facility using the runoff volume predicted for the 6-month, 24-hour design storm under postdeveloped conditions for each TDA. This design storm is approximated as 72% of the 2-year, 24-hour design storm or 91st percentile, 24-hour runoff volume. AND *Wetpool and other volume-based (infiltration or filtration):* Size the facility to treat 91% of the estimated historic runoff file for the post-developed conditions.	Single event model (SBUH*) OR Approved continuous simulation model with 1-hour time steps

* SBUH method is based on NRCS curve number equations.

Source: Table 4-1 from Section 4.3 of the 2006 HRM (WSDOT 2006a).

It is not possible to provide BMP-specific data on bypass volumes and flows for ESA assessment. This would require hydrological modeling of typical BMP types and designs using long-term precipitation records to determine seasonal and year-to-year variability.

3 Methodology

The methodology in this white paper for evaluating BMP effectiveness in treating highway runoff involved the following: (1) identifying and selecting BMPs for consideration; (2) identifying and selecting existing relevant sources of data that assess the performance of the selected BMPs; (3) evaluating the strengths, weaknesses, and applicability of those data sources; and (4) summarizing the effectiveness of the BMPs in treating highway runoff in western Washington based on the information presented in these relevant data sources.

3.1 Identifying and Selecting BMPs for Consideration in this White Paper

As described in Section 1.1, the intent of this white paper is to document the effectiveness of BMPs that are typically used on highway projects in western Washington; therefore, it focuses primarily on treatment BMP types in the 2006 HRM. As discussed by the working group at the project kick-off meeting, additional treatment BMPs would be considered as well, if they are directly applicable for treatment of runoff in the highway environment and would be potentially effective at reducing the concentrations and loads of pollutants of concern for ESA-listed species. Selection criteria for these other BMPs (i.e., that are not included in the 2006 HRM) included the following: (1) they are commonly used in the highway setting; (2) they incorporate UOPs that would be expected to be effective on the contaminants of potential concern; and (3) performance data exist.

Based on the input from the working group and subsequent screening of potential BMPs for consideration, the following BMPs were selected for evaluation in this white paper:

- Infiltration facilities
- Porous/permeable pavements
- Detention basins
- Stormwater treatment wetlands
- Wet ponds
- Biofiltration swales
- Filter strips
- Bioretention
- Ecology embankments
- Dispersion to landscape
- Sand filters
- Multi-chambered treatment trains

Most of these are considered built BMPs (i.e., structural treatment BMPs). They include processes approved by WSDOT for removal and treatment of dissolved metals, BMPs approved by The Washington State Department of Ecology (Ecology), emerging technologies identified by Ecology, and low impact development (LID) techniques considered applicable for treating highway runoff.

It should be noted that source controls are also very important for protection of ESA species and water quality in general. Appendix 1 provides a listing of source control

BMPs for highway runoff in Washington from the HRM. The HRM also provides guidance on how to select appropriate BMPs, which is summarized in Appendix 2.

In addition, the work group requested that highway sweeping be included in this analysis. However, definitive information on highway sweeping as a BMP was not found in the sources of BMP performance listed above. Therefore, a more detailed review of highway sweeping and its impacts on effluent quality was undertaken. This review is included in Appendix 3, while the conclusions are summarized in the main text along with the other BMPs assessed.

3.2 Identifying and Selecting Existing Data Sources

Numerous studies have been conducted on the performance of stormwater runoff treatment BMPs, and several publications have summarized BMP performance (e.g., ASCE 1998; ASCE 2001; Brown and Schueler 1997; CASQA 2003; Caltrans 2006; NCHRP 2006; Shoemaker et al. 2000; Strecker et al. 2005; Winer 2000). These studies have evaluated BMP effectiveness in both qualitative and quantitative terms.

The most robust source of data on BMP effectiveness is the American Society of Civil Engineers/U.S. Environmental Protection Agency (ASCE/EPA) International Stormwater BMP Database (ASCE and EPA 2007), as summarized in Strecker et al. (2005). The International Stormwater BMP Database (referred to in this white paper as the International Database) includes more than 300 BMP studies, performance analysis results, tools for use in BMP performance studies, monitoring guidance, and other study-related publications. The overall purpose of the database project is to provide scientifically sound information to improve the design, selection, and performance of BMPs. Strecker et al. (2005) conducted a critical assessment of stormwater runoff treatment and control selection issues as presented in the database in 2005; a similar review of the information is currently in process, but results of that review were not available for the analysis presented in this white paper. Therefore, information presented in this white paper synthesizes the results as summarized by Strecker et al. (2005) and more current information contained in the database.

Because the broad scope of the International Database may not account for region-specific conditions, sources of regional data and “gray literature” were also incorporated into this analysis to assess data that are available specifically for western Washington. In particular, data presented in WSDOT National Pollutant Discharge Elimination System reports (WSDOT 2006b and WSDOT 2007) and information collected and analyzed by Herrera Environmental Consultants, Inc. (e.g., Herrera 2007c) were included in the evaluation.

Other sources of BMP evaluation information considered particularly relevant for this analysis include studies conducted by the California Department of Transportation (e.g., Caltrans 2006) and the California Stormwater Quality Association (e.g., CASQA 2003). Although there are some differences in BMP performance in California compared to western Washington, the major difference is likely related to hydrology effects, which would primarily affect the sizing of the facility; the effluent quality would likely be less affected.

In summary, the primary data source of the evaluation was the International Stormwater BMP Database (with results presented in Section 4). Where available, data specific to western Washington were incorporated, analyzed, and compared as well. Other supplemental sources of data were evaluated as available and relevant.

3.3 Evaluation of the Effectiveness of BMPs for Stormwater Runoff Treatment in Western Washington

The purpose of this evaluation was to summarize salient data and expected performance for each of the BMPs, to allow resource managers to evaluate approaches that would be considered protective of endangered species (i.e., salmonids) in western Washington. Available information on each of the BMPs selected for evaluation was synthesized, with results summarized in Section 4. For each BMP, results of the evaluation are organized and presented as follows:

- A general narrative description of the BMP.
- The unit operation processes employed by the BMP.
- The appropriate applications for implementing the BMP (including information on constraints and siting considerations).
- A narrative evaluation of BMP performance.
- A summary table of constituent removal efficiencies (rated as high, medium, or low) for the contaminants of potential concern.

This evaluation is presented in both qualitative and quantitative fashion, depending on available data. While the qualitative presentation format has limitations, it provides the reader with a rapid assessment of expected BMP performance. It also allows comparisons of BMPs, especially between those with quantitative information (e.g., effluent concentrations) and those with little or no quantitative information.

The criteria used to evaluate BMP effectiveness focused on the following:

- The BMP's ability to reduce runoff volumes via infiltration and/or evapotranspiration.
- The amount of runoff that receives treatment or is bypassed.
- The effluent concentrations of the treated runoff (rather than in terms of reductions in concentrations in untreated highway runoff).
- The ability of the BMP to provide flow-duration control that would reduce downstream erosion potential.

Note that an earlier draft of this white paper presented the performance of BMPs pollutant by pollutant, rather then by BMP type. Based on comments received on that earlier draft, the evaluations were revised to be organized by BMP type. Section 5 (*Summary and Conclusions)* includes a summary table prepared specifically to facilitate comparison of performance by BMP type and pollutant.

3.4 Limitations of the Data Sources and Evaluation

When considering the information presented in Section 4 (as well as the summary and conclusions presented in Section 5), it is important to note both the overall intent of the evaluation in this white paper, as well as its limitations, challenges, and related technical issues.

Available data and summaries of BMP effectiveness indicate that there is a wide variation in the performance of each type of BMP, making comparisons of the effectiveness among BMPs problematic. There are several reasons for the observed variations:

- **The variability of stormwater runoff quality:** Stormwater runoff quality is highly variable during a storm, from storm to storm at a site, and between sites even of the same land use.
- **Most field studies monitor too few storms:** High variability of stormwater runoff quality requires that a large number of storms be sampled to discern if there is a significant difference in performance among BMPs.
- **Different design criteria:** Performance of different systems within the same group (e.g., wet ponds) differs significantly, in part because of differing design criteria for each system.
- **Differing influent concentrations and analytical variability**: With most treatment BMPs, percent removal efficiency decreases with decreasing influent concentration. Therefore, percent removal has been questioned as a proper measure of BMP performance (Strecker et al. 2001).
- **Different methods of calculating efficiency:** Researchers: (1) have used different methods to calculate efficiency, (2) do not always indicate which method they have used, and (3) often do not provide sufficient information in their report to allow others to recalculate the efficiency using a common method.
- **Some media used in BMPs can leach or contribute some contaminants to the effluent:** Examples include excessive fertilization of soils (e.g., with compost) in filter strips, vegetated swales, ecology embankments, particulate nutrients from algal biomass in poorly operated wet ponds, and nutrients from leaf compost in cartridge filters.

Consequently, a comprehensive multiple-lines-of-evidence approach is used in this white paper to summarize the potential effectiveness of BMPs in controlling the COPCs. This includes the following:

1. BMP performance based on expected effluent concentrations of treated runoff for various contaminant categories (suspended solids, metals etc), based on the International BMP Database (www.bmpdatabase.org).
2. Summary of findings from the WSDOT BMP evaluation program on the expected effluent concentrations of treated runoff for various contaminant categories (suspended solids, metals etc.).

3. BMP performance based on the unit operating processes (UOP) utilized in the BMP that would be expected to reduce runoff volumes and/or contaminant levels (see Sections 2.1 and 2.2).

Although alluded to as appropriate in this white paper, the following items are not addressed in a comprehensive manner in this analysis:

- **BMP performance in terms of proportional reduction in influent concentrations, or a comparison on influent and effluent concentrations.** This white paper focuses on BMP effluent concentrations so that the reader can assess impacts on the water quality of receiving waters. Describing BMP performance in terms of influent/effluent concentrations and loads would have added an additional layer of complexity, while not advancing ESA assessments. It is therefore considered out of the scope of the analysis of this white paper.

- **Frequency, timing, and duration of events.** Although these considerations may be important for ESA assessments, they require site-specific hydrological modeling as well as time-history data on effluent quality, which are essentially nonexistent. Generalizations were made throughout the white paper where possible.

- **Proportion captured and treated.** This could only be assessed at a design specification level, and requires hydrological modeling at the site-specific level. Some representative sites could be evaluated as a future work item.

4 BMP Treatment Evaluations

The following is a summary of the effectiveness of the BMPs selected for evaluation in this white paper. Information presented for each BMP includes the following: a description of the BMP, the unit operation processes potentially employed, an assessment of appropriate applications for the BMP (including information on constraints and siting considerations), a table of BMP effluent quality (where possible), and a narrative evaluation of its performance including a summary table of constituent removal performance (rated as high, medium, or low for the contaminants of potential concern).

4.1 Infiltration Facilities

4.1.1 Description

Infiltration facilities are stormwater runoff detention systems constructed with a highly permeable base that is specifically designed to infiltrate runoff. Because it is usually impractical to infiltrate runoff at the same rate that it is generated, these facilities generally include both a storage component and a drainage component. Infiltration BMPs include infiltration ponds, trenches, vaults, and tanks.

Infiltration ponds for flow control are earthen impoundments used for the collection, temporary storage, and infiltration of incoming stormwater runoff to groundwater. Infiltration ponds are usually shallow with flat, vegetated bottoms and side slopes; they can be incised by excavating a depression below the existing grade or constructed above grade by constructing a perimeter berm.

Infiltration trenches are long, narrow, rock-filled trenches that receive stormwater runoff from small drainage areas. These facilities may include a shallow depression at the surface, but the majority of runoff is stored in the void space between the stones and infiltrates through the sides and bottom of the trench.

Infiltration vaults are typically bottomless underground structures used for temporary storage and infiltration of stormwater runoff to groundwater. Infiltration tanks are large-diameter cylindrical structures with perforations in the base. These types of underground infiltration facilities can be a useful alternative for sites with constraints that make siting an infiltration pond difficult.

Runoff in excess of the infiltration capacity must be detained and released in compliance with the flow-control requirement described in the 2006 HRM.

4.1.2 Unit Operation Processes

Infiltration facilities are ideal for hydromodification control, where reduction of surface runoff volume is desired. Infiltration facilities can be used to provide complete or nearly complete reduction of pollutant loads to downstream receiving water systems. The primary pollutant removal processes in infiltration facilities are volume and associated pollutant load reduction. Specific UOPs include infiltration, plant and microbiological uptake, evapotranspiration, sedimentation, filtration, and physical and chemical adsorption.

4.1.3 Applications

Infiltration of runoff is the preferred method of flow control for highways (see the 2006 HRM). Ideal sites for infiltration facilities are areas with permeable soils and depth to seasonally high groundwater levels at least 10 feet below the existing ground surface. Soils with high clay content or high water tables limit their application somewhat in western Washington. However, installation in highly permeable substrata, such as gravel, is unsuitable because filtration and adsorption processes are minimal (see the 2006 HRM). Infiltration facilities should not be used for industrial sites or locations where hazardous materials spills may occur.

Sedimentation of coarse particles should be minimized in infiltration facilities through the use of appropriate pretreatment devices to prevent clogging. Pretreatment BMPs (e.g., swales, filter strips, and sediment forebays/basins/manholes) are appropriate to increase longevity and reduce the maintenance burden of infiltration facilities.

General constraints and siting considerations for infiltration facilities include the following:

- Slope stability—Infiltration facilities are not permitted near steep slope hazard areas.
- Setbacks—A minimum setback from structures or leach fields is required for infiltration facilities.
- Native soil infiltration rate—Performance can be limited by the permeability of native soils, either too low (and hence no infiltration) or too high (and hence inadequate filtration before reaching groundwater).
- Depth to groundwater—Vertical separation is required between the infiltration surface and the shallow groundwater table to ensure that the facility will completely drain between storms and that infiltrating water will receive adequate filtration though the soils before it reaches groundwater.
- Depth to bedrock or impervious soil layer—A shallow confining layer may inhibit complete infiltration of the design storm volume.
- Contaminated soils—Infiltration facilities are not permitted at sites with existing soil contamination.
- Surface space availability—A large footprint is required.
- High loading rates—Facility components may clog quickly if flows are not adequately pretreated.

Infiltration trenches can be a useful alternative for sites with constraints that make siting an infiltration pond difficult. Infiltration trenches may be placed beneath parking areas, along the site periphery, or in other suitable linear areas. This BMP is considered a subsurface infiltration facility if it includes the use of a perforated pipe, in which case its use may be subject to Ecology’s rules governing underground injection wells; this type of stormwater runoff facility must be registered through Ecology’s Underground Injection Control (UIC) Program.

4.1.4 Evaluation of BMP Performance

Performance monitoring data are generally lacking for infiltration facilities, presumably due to the difficulty in sampling the infiltrated water and the assumption that stormwater runoff infiltrated equates to loads removed. Properly designed and maintained infiltration facilities sized to infiltrate the water quality design storm will effectively remove all pollutant types (assuming that impacts on groundwater are negligible because good design practices are employed). Due to their reductions or elimination of surface runoff, these BMPs are considered to be one of the most effective at removing pollutant loads from surface waters. However, due to the propensity for clogging and the resulting bypass, the reliability of infiltration facilities may be less than other BMP types. Based on performance of the UOPs employed, the expected efficiencies of infiltration ponds, vaults, and trenches are listed in Table 5.

Table 5. Constituent removal performance ratings for infiltration ponds, vaults, and trenches for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
H	H	H	H	H	H	H	H	H-L[1]	H	H

[1]Removal of dissolved salts may be limited if groundwater below the infiltration basin discharges to the receiving water body.
H=high, M=medium, L=low.

4.2 Porous/Permeable Pavements

4.2.1 Description

Permeable or porous pavements are a special type of material that allows water to drain into the underlying soil, yet is strong enough to structurally support vehicular or pedestrian traffic. Many types of porous pavements and configurations have been developed for a variety of applications. The pavement may be permeable concrete, permeable asphalt, or manufactured systems such as interlocking brick or a combination of sand and brick lattice. Permeable concrete or asphalt pavement surface is an open-graded mix placed in a manner that results in a high degree of interstitial spaces or voids within the cemented aggregate. Most of the systems are supported by a stone base with large pore spaces. This base acts both as pavement support and as a reservoir to store water so that it can be infiltrated, if the soil conditions allow, or detained and slowly released to the storm drain system.

4.2.2 Unit Operation Processes

Permeable surfaces allow stormwater runoff to pass through and infiltrate the soil below, thereby reducing the rate and volume of runoff associated with conventional surfacing, as well as fostering groundwater recharge. The primary pollutant removal processes in infiltration facilities include volume and associated pollutant load reduction, sedimentation, filtration, and adsorption.

4.2.3 Applications

Currently, this BMP is not considered a stand-alone runoff treatment or flow control BMP (see the 2006 HRM). However, when used as part of a project surface, it can reduce the total runoff, thereby providing an overall reduction in the size of other acceptable runoff treatment and flow control BMPs.

Permeable surface systems function as infiltration and temporary retention areas for stormwater runoff that can accommodate pedestrians and light- to medium-load parking areas. They are applicable to both residential and commercial land uses, with the exception of heavy truck traffic. Potential applications of permeable surface materials include the following:

- Sidewalks, bicycle trails, community trail/pedestrian path systems, or any pedestrian-accessible paved areas (such as traffic islands).
- Vehicle access areas, including emergency stopping lanes, maintenance/ enforcement areas on divided highways, and facility maintenance access roads.
- Public and municipal parking lots, including perimeter and overflow parking areas.

Permeable surface installations are not appropriate on roadway lanes because of considerations such as dynamic loading, safety, clogging, and heavy loads.

General application and siting constraints are similar to infiltration facilities; due to these constraints, use of permeable pavement is not appropriate for the following:

- Areas where turbid runoff from adjacent land can introduce sediments onto and clog the permeable surface.
- Traffic areas where sanding or extensive snow removal is carried out in the winter.

- Areas where the risk of groundwater contamination from organic compounds is high (e.g., fueling stations, commercial truck parking areas).
- Close to drinking water wells and within areas designated as sole source aquifers.
- Areas with a high water table or impermeable soil layer.
- Close to building foundations.

4.2.4 Performance

Volume reductions associated with infiltration in porous and permeable pavements are assumed to equate to load reductions. Therefore, assuming that this BMP is appropriately sized and maintained, the relative effectiveness is assumed to be the maximum for all pollutants. Based on performance of the UOPs employed, the overall performance of permeable pavements is listed in Table 6. Note that the expected performance is based on the assumption that all rainfall infiltrates the pavement, and the pavement receives no runoff from adjacent sites.

Table 6. Constituent removal performance ratings for permeable pavements (assuming all rainfall is infiltrated) for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
H	H	H	L	H	H	H	H	H-L[1]	H	H

[1]Removal of dissolved salts may be limited if groundwater below the infiltration basin discharges to the receiving water body.
H=high, M=medium, L=low.

4.3 Detention Basins

4.3.1 Description

Dry extended detention (ED) basins (also referred to as dry ponds, extended detention basins, detention ponds, and extended detention ponds) are basins with outlets that are designed to detain the runoff from a water quality design storm for 36 to 48 hours (or longer) to allow sediment particles and associated pollutants to settle and be removed. Dry ED basins do not have a permanent pool; rather, they are designed to drain completely between storm events. They can also provide flow and/or flood control by modifying the design of the outlet control structure and including additional detention storage. The slopes, bottom, and forebay of ED basins are typically vegetated.

Influent flows enter a sediment forebay where coarse solids are first removed prior to flowing into the main cell of the basin, where finer sediment and associated pollutants settle as stormwater runoff is detained and slowly released through a controlled outlet structure. Dry weather flows and very low storm flows are often infiltrated within the basin[4].

4.3.2 Unit Operation Processes

Extended detention basins provide treatment primarily through sedimentation with some volume loss due to infiltration and soil soaking/drying. Biological, chemical, and physical treatment processes are typically limited due to lack of vegetation or the constant presence of water necessary to support microbes.

4.3.3 Applications

Extended detention basins are commonly used for flow control in locations where space is available for an aboveground stormwater runoff facility but where infiltration of runoff is infeasible (see the 2006 HRM). They can be combined with other BMPs as a way to meter flows into them (e.g., detention upstream of a bioswale, etc.) or a small wet pool can included within the extended detention basin to enhance performance.

General constraints and siting considerations for extended detention basins include the following:

- Surface space availability—Typically, 0.5 to 2.0 percent of the total tributary drainage area is required.
- Depth to groundwater—The bottom of the basin should be higher than the water table.
- Steep slopes—A geotechnical investigation is required for basins placed on slopes greater than 15 percent or within 200 feet from the top of a hazardous slope or landslide area.

4.3.4 Performance

Monitoring results reported in the International Database reflect the limited unit operation processes employed in detention basins, with median effluent EMCs ranging from midlevel treatment for sediment and particulate-bound constituents to low-level treatment for dissolved constituents. Performance of ED basins could likely be improved by designing outlets that maximize detention times for the half-full to empty basin storage volumes and therefore provide more detention for smaller events. Where possible, detention basins are enhanced by allowing direct infiltration into the ground.

Table 7 lists effluent data from the International Database (ASCE and EPA 2007) for two types of detention basins: lined (e.g., with concrete or other impermeable barrier), and grassed and unlined.

Table 7. Performance of detention basins BMPs in terms of effluent concentration: median and 95% confidence interval of storm event mean concentrations.

Constituent	No. of Data Points	No. of BMPs	EMC		
			Median	LCL	UCL
Concrete or Lined Tank					
Cadmium Dissolved (µg/L as Cd)	7	1	0.10	0.10	0.40
Cadmium Total (µg/L as Cd)	16	2	1.30	0.40	1.3
Copper Dissolved (µg/L as Cu)	33	2	7.3	7.0	8.1
Copper Total (µg/L as Cu)	42	3	11	11	13
Lead Dissolved (µg/L as Pb)	13	1	2.20	1.7	3.8
Lead Total (µg/L as Pb)	21	2	17.8	14	18.4
Nitrate + Nitrite (mg/L as N)					
Nitrate (mg/L as N)	21	2	0.42	0.27	0.64
Ammonia (mg/L as N)					
Total Kjeldahl Nitrogen (mg/L as N)	13	1	0.90	0.60	1.72
Phosphorous Dissolved (mg/L as P)	7	1	0.08	0.07	0.18
Phosphorous Total (mg/L as P)	47	4	0.04	0.03	0.06
Total Suspended Solids (mg/L)	42	3	18	12	37.50
Zinc Dissolved (µg/L as Zn)	33	2	41	38	47
Zinc Total (µg/L as Zn)	42	3	60	52	70.50
Surface Grass-Lined Basin					
Cadmium Dissolved (µg/L as Cd)	56	6	0.11	0.08	0.20
Cadmium Total (µg/L as Cd)	69	8	0.52	0.34	0.73
Copper Dissolved (µg/L as Cu)	95	7	10	7.7	12
Copper Total (µg/L as Cu)	118	12	14.4	10.0	18
Lead Dissolved (µg/L as Pb)	83	6	0.69	0.35	1.20
Lead Total (µg/L as Pb)	110	11	10	8.0	13
Nitrate + Nitrite (mg/L as N)	15	2	0.10	0.02	0.14
Nitrate (mg/L as N)	79	6	0.60	0.40	0.64
Ammonia (mg/L as N)	13	1	0.04	0.03	0.11
Total Kjeldahl Nitrogen (mg/L as N)	81	6	1.2	0.96	1.50
Phosphorous Dissolved (mg/L as P)	42	5	0.07	0.05	0.10
Phosphorous Total (mg/L as P)	118	10	0.14	0.11	0.19
Total Suspended Solids (mg/L)	99	8	27	19	34
Zinc Dissolved (µg/L as Zn)	96	7	32	24	44
Zinc Total (µg/L as Zn)	131	13	68	57	80

Source: Adapted from the International Database (ASCE and EPA 2007).
LCL=lower confidence level (5%), UCL=upper confidence level (95%).

Very few local data are available for the performance of detention basins. WSDOT trialed one basin on Interstate 5 (I-5) at milepost (MP) 122, which had no effluent due to complete infiltration (for four storms) (WSDOT 2006b); data from another basin have failed quality assurance/quality control (QA/QC) checks.

Larger suspended solids can be removed effectively by gravitational sedimentation in detention basins. The median effluent TSS concentrations range from about 20 to 40 mg/L (Table 7), provided the concentration and characteristics (e.g., particle size distributions) of influent suspended solids do not significantly deviate from "typical" stormwater runoff. Dry detention basins have been shown to considerably reduce effluent volume (typically up to about 30 percent and even higher with highway runoff in Washington [R. Tveten, pers. comm.]) through infiltration and some evapotranspiration (soil soaking and drying), which may translate to lower total mass loading of TSS downstream. As described earlier, enhancements to outlet configurations could improve the performance of dry basins.

Detention basins should also effectively remove other parameters with a low dissolved component, such as particulate phosphorus, total Kjeldahl nitrogen (TKN), lead, and organic contaminants (herbicides, legacy pesticides, PAHs, phthalates, legacy PCBs).

Detention basins that employ settling as the primary UOP can achieve moderate levels of total and dissolved metals (to compare with other BMPs, see Table 30). Of particular concern is the inability to deal with total and dissolved copper (as discussed in more detail in Section 5.3, *BMP Performance for Contaminants of Potential Concern*).

Based on performance of the UOPs employed and data presented in Table 7, expected efficiencies of detention basins are listed in Table 8.

Table 8. Constituent removal performance ratings for detention basins for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
H	M	L	H	M	L	M	M	L	H	M-L

Efficiency ratings: H=high, M=medium, L=low.

4.4 Stormwater Treatment Wetlands

4.4.1 Description

Stormwater treatment wetlands (also known as constructed wetlands) are shallow, manmade wetlands designed to treat stormwater runoff through settling, filtering, and the biological processes associated with emergent aquatic plants. Stormwater treatment wetlands, like wet ponds (see Section 4.5, *Wet Ponds*), are used to capture and transform pollutants; over time, pollutants concentrate in the sediment.

Stormwater treatment wetlands consist of a sediment forebay and a permanent micropool, with aquatic vegetation covering a significant portion of the basin. Stormwater treatment wetlands typically include components such as an inlet with energy dissipation, a sediment forebay for settling out coarse solids and to facilitate maintenance, a base with shallow sections (1 to 2 feet deep) planted with emergent vegetation, deeper areas or micropools (3 to 5 feet deep), and a water quality outlet structure.

The aquatic vegetation and the associated biological unit processes are a fundamental part of stormwater treatment wetlands. Therefore, it is critical that dry weather base flows exceed losses by evaporation and infiltration to prevent loss of aquatic vegetation and to avoid stagnation and problems related to mosquitoes and other vectors.

It is important to note the difference between stormwater treatment wetlands and wetlands that are constructed as part of a mitigation project. Natural and mitigation wetlands cannot be used to treat stormwater runoff. Constructed mitigation wetlands are designed to provide fully functional habitat similar to (or better than) the habitat they replace. In contrast, stormwater treatment wetlands are a treatment BMP designed to capture and treat pollutants to protect receiving waters, including natural wetlands and other ecologically significant habitat. The accumulation of pollutants in sediment and vegetation of stormwater treatment wetlands may affect the health of aquatic biota. As such, periodic sediment and vegetation removal within stormwater treatment wetlands may be required. These maintenance activities may further limit the use of stormwater treatment wetlands by wildlife.

4.4.2 Unit Operation Processes

Stormwater treatment wetlands include the following UOPs: flow attenuation, volume reduction, and pollutant removal (i.e., sedimentation, filtration, plant uptake and storage, and microbially mediated transformations). Constructed wetlands considerably improve settling processes for smaller storms by the provision of a permanent pool of water, which allows for the introduction of biological, physical, and chemical treatment processes through the ability to sustain vegetation. Constructed wetlands provide multiple biological, physical, and chemical treatment processes associated with aerobic and anaerobic soil zones, submerged and emergent vegetation, and associated microbial activities. The export of nitrogen from constructed wetlands during dormant periods and vegetation die-off has been observed in some studies, and some researchers have recommended plant harvesting to maximize nutrient retention. This observation for nitrogen export is reflected in the California BMP handbook (CASQA 2003), which rates the effectiveness of the BMP for nutrient removal as medium.

4.4.3 Applications

The applications for stormwater treatment wetlands are similar to those of wet ponds (see Section 4.5). As an enhanced treatment BMP, stormwater treatment wetlands can be considered for roadways where removal of metals is an objective. Stormwater treatment wetlands occupy roughly the same surface area as wet ponds but have the potential to be better integrated aesthetically into a site because of the abundance of emergent aquatic vegetation. A critical factor for successful design is an adequate supply of water for most of the year. Careful planning is needed to ensure that sufficient water is retained to sustain the growth of wetland plants. Because water depths in stormwater treatment wetlands are shallower than in wet ponds, water loss by evaporation is an important concern. Stormwater treatment wetlands are a good runoff treatment facility choice in areas where groundwater levels are high in the winter.

Other benefits of stormwater treatment wetlands relative to other BMPs include the enhanced treatment capability for multiple contaminants, aesthetics, and the ability to mitigate large tributary areas, as well as the opportunity for public education. Factors that may limit the use of stormwater treatment wetlands include overly permeable soils and/or nonexistent year-round or seasonal base flows, public acceptance with regards to the potential for vectors (mosquitoes), the large ratio of footprint to treated area (up to 12 percent of the tributary area, depending on its overall imperviousness), and high initial capital cost of implementation.

4.4.4 Performance

The following table summarizes effluent data from the International Database (ASCE and EPA 2007) for constructed wetlands.

Table 9. Performance of constructed wetland BMPs in terms of effluent concentration[1]. median and 95% confidence interval of storm EMCs.

Constituent	No. of Data Points	No. of BMPs	EMC		
			Median	LCL	UCL
Cadmium Dissolved (µg/L as Cd)	7	1	0.12	0.04	0.72
Cadmium Total (µg/L as Cd)	50	2	0.15	0.10	0.33
Copper Dissolved (µg/L as Cu)	7	1	6.5	5.3	7.8
Copper Total (µg/L as Cu)	80	2	3.0	3.0	4.0
Lead Dissolved (µg/L as Pb)	11	2	0.84	0.43	1.0
Lead Total (µg/L as Pb)	91	4	1.0	1.0	1.7
Nitrate + Nitrite (mg/L as N)	144	3	0.04	0.02	0.08
Nitrate (mg/L as N)	91	4	0.20	0.16	0.28
Ammonia (mg/L as N)	188	7	0.04	0.03	0.05
Total Kjeldahl Nitrogen (mg/L as N)	146	5	1.16	1.07	1.2
Phosphorous Dissolved (mg/L as P)	114	4	0.05	0.04	0.08
Phosphorous Total (mg/L as P)	220	10	0.07	0.06	0.08
Total Suspended Solids (mg/L)	211	7	6.5	5.2	8.5
Zinc Dissolved (µg/L as Zn)	7	1	15.2	10.1	21.3
Zinc Total (µg/L as Zn)	96	5	17	15	20

[1]Median and 95 percent confidence interval of storm EMCs.
LCL=lower confidence level (5%), UCL=upper confidence level (95%).
Source: Adapted from the International Database (ASCE and EPA 2007).

No local or WSDOT data are available for the effluent quality of constructed wetlands.

The presence of a permanent wet pool is a key feature of a wetland system. Incorporating even a small permanent wet pool can significantly improve the sediment removal performance by providing long periods of retention during smaller storms. Long retention times during small events allow for appreciable suspended solids removal compared to dry facilities that typically have more limited detention times during small events. Well-designed treatment systems that incorporate wet pools and wetland vegetation typically exhibit even lower concentrations of suspended solids. Based on available data, these BMP facilities can typically achieve effluent TSS concentrations of around 20 mg/L and, in many storms, even lower (~10 mg/L or less; see Table 9).

Because of the use of multiple UOPs and effective particulate removal, constructed wetlands (and wet ponds) generally have the best effluent water quality as compared to other BMPs, with lower effluent quality of contaminants predominantly associated with particulate matter. This includes parameters such as total phosphorus, TKN, lead, and organic contaminants (herbicides, legacy pesticides, PAHs, phthalates, and legacy PCBs).

A number of UOPs also remove dissolved contaminants such as dissolved metals (especially zinc) and dissolved nitrogen (particularly nitrate). For copper, the few results available are ambiguous; total copper data in Table 9 suggest that low levels can be achieved in constructed wetlands, but some limited data for dissolved copper indicate relatively high levels. Because of the sensitivity of ESA-listed species to copper and the potential for low effluent concentrations from constructed wetlands, it is important to investigate this further.

Based on performance of the UOPs employed and data presented in Table 9, expected efficiencies of constructed wetlands are listed in Table 10.

Table 10. Constituent removal performance ratings for stormwater treatment wetlands for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
H	H	M	H	H	H	M	H	L	M-H[1]	L

[1]Can be high when combined with extended-detention basins.
Efficiency ratings: H=high, M=medium, L=low.

4.5 Wet Ponds

4.5.1 Description

Wet ponds (also known as retention ponds) are constructed, naturalistic ponds with a permanent or seasonal pool of water (also called a wet pool or dead storage), at least during the wet season. The effectiveness of the pond in settling particulate pollutants is related to the volume of the wet pool. To provide additional treatment for nutrient removal, a shallow marsh area can be created within the permanent pool volume.

Wet ponds can be designed to detain incoming flows for extended duration, using the volume above the permanent pool surface.

4.5.2 Unit Operation Processes

Sedimentation is the main pollutant removal mechanism in wet ponds; other pollutant reduction processes include biological processes such as microbially mediated transformations and plant uptake and storage. The wet volume also serves to smooth out (average) concentrations in runoff. The permanent pool of water in the wet pond improves treatment of fine particulates and associated pollutants, as well as provides treatment of dry weather flows (i.e., nuisance flows). Permanent pools can also be designed as aesthetically pleasing water features, with additional recreational, wildlife habitat, and educational benefits.

Wet ponds, like constructed wetlands, can also provide multiple biological, physical, and chemical treatment processes associated with aerobic and anaerobic soil zones, submerged and emergent vegetation, and associated microbial activities. However, this may be limited compared to stormwater treatment wetlands if the pond is primarily open water and supports little macrovegetation. Nevertheless, even in this situation, algal growth, die-off and settling, together with pond bottom processes, provide some biological, physical, and chemical processes. Many wet ponds used to treat highway runoff in Washington gradually acquire wetland characteristics (R. Tveten, pers. comm.).

4.5.3 Applications

Wet ponds can be designed in two sizes: basic and large. Basic wet ponds are an approved basic runoff treatment BMP in the 2006 HRM. Large wet ponds are designed for higher levels of pollutant removal and are an appropriate treatment BMP for phosphorus control.

Wet ponds require base flows to exceed or match losses through evaporation and/or infiltration and must be designed with the outlet positioned and/or operated in such a way to maintain a permanent pool. Preferably, base flows exceed evaporation and infiltration so that the pond does not become stagnant.

Wet ponds work best under plug flow conditions during storms, where the water already present in the permanent pool is displaced by incoming storm flows with minimal mixing and no short circuiting. Plug flow refers to the hypothetical condition of stormwater runoff moving through the pond in such a way that older (in terms of residence time in the pond) “slugs” of water are displaced by incoming slugs of water, with little or no mixing in the direction of flow. “Short circuiting” occurs when quiescent areas or dead zones develop in the pond where pockets of water remain relatively stagnant, causing other volumes to bypass via shorter paths through the pond (e.g., incoming stormwater runoff slugs bypass these zones). Water quality benefits are also improved when the permanent wet pool volume is significantly greater than the water quality volume, resulting in longer residence times, including significantly more quiescent time between storms for a larger amount of inflows.

General constraints and siting considerations for wet ponds include the following:

- Availability of base flows—Wet ponds require a regular source of water to maintain the water level and reduce potential mosquito issues.
- Slope stability—Wet ponds are not permitted near steep slope hazard areas.
- Surface space availability—A large footprint is required for this BMP.

Where temperature is an issue, larger wet ponds can significantly increase temperatures in released flows, especially base flows. This needs to be considered in their selection and use.

4.5.4 Performance

The following table summarizes effluent quality for wet ponds from the International Database (ASCE and EPA 2007).

Table 11. Performance of wet pond BMPs in terms of effluent concentration[1]

Constituent	No. of Data Points	No. of BMPs	EMC		
			Median	LCL	UCL
Cadmium Dissolved (µg/L as Cd)	56	2	0.13	0.13	0.13
Cadmium Total (µg/L as Cd)	200	9	0.13	0.10	0.20
Copper Dissolved (µg/L as Cu)	156	6	4.4	4.0	4.8
Copper Total (µg/L as Cu)	301	14	5.0	5.0	5.8
Lead Dissolved (µg/L as Pb)	143	7	3.0	2.0	3.0
Lead Total (µg/L as Pb)	373	17	3.0	2.0	4.0
Nitrate + Nitrite (mg/L as N)	229	8	0.03	0.02	0.04
Nitrate (mg/L as N)	142	6	0.30	0.22	0.45
Ammonia (mg/L as N)	265	9	0.06	0.05	0.07
Total Kjeldahl Nitrogen (mg/L as N)	224	15	1.0	0.94	1.05
Phosphorous Dissolved (mg/L as P)	204	9	0.06	0.05	0.07
Phosphorous Total (mg/L as P)	463	22	0.13	0.12	0.16
Total Suspended Solids (mg/L)	437	21	11.0	9.7	12.4
Zinc Dissolved (µg/L as Zn)	132	6	7.5	5.2	10.0
Zinc Total (µg/L as Zn)	379	18	17.7	15	20

[1]Median and 95% confidence interval of storm EMCs.
LCL=lower confidence level (5%), UCL=upper confidence level (95%).
Source: Adapted from the International Database (ASCE and EPA 2007).

There is a reasonable local database for the performance and effluent quality for wet ponds treating highway runoff in western Washington. The data in Table 12 are summarized from WSDOT's NPDES annual progress reports (WSDOT 2007) (with data failing QA/QC removed), supplemented by additional data from Herrera Environmental Consultants (Herrera 2007c).

Table 12. Average of effluent EMCs for seven wet ponds treating highway runoff in western Washington.

Site	**TSS**	**Total Cu**	**Diss. Cu**	**Total Zn**	**Diss. Zn**	**TP**
	mg/L	µg/L				mg/L
SR18, MP 8	5.7	5.4	2.9	35	28	0.04
SR 522, MP16.06	11.3	3.8	3.1	23.7	14	0.04
SR 525, MP 2.4	11.8	4.8	3	57	41	0.05
SR 525, MP 1.8	5.5	4.2	3.4	32.4	26	0.03
SR 500, MP5	4.4	5	3.4	24	18	0.04
SR 525, MP2 A	5.8	3.7	3.1	27.5	28.8	0.03
SR 525, MP2 B	11	4.5	2.7	47.5	35	0.05
Median	6	4.8	3.1	32	28	0.04
(range of averages)	(4-12)	(3.7-5.4)	(2.7-3.4)	(24-57)	(14-41)	(0.03-0.05)

The presence of a permanent wet pool is a key feature of a wet pond system. Incorporating even a small permanent wet pool can significantly improve the sediment removal performance by providing long periods of retention during smaller storms. Long retention times during small events allow for appreciable removal of suspended solids, compared to dry facilities that typically have more limited detention times during smaller events. Well-designed treatment systems that incorporate vegetation in wet pools typically exhibit even lower suspended solids concentrations. Based on the International Database, these BMP facilities can typically achieve a median effluent TSS concentrations of approximately 11 mg/L and for many storms, concentrations much lower than this. Data from western Washington suggest that even lower concentrations are achievable (Table 12).

Because of the use of multiple UOPs and effective particulate removal, wet ponds generally achieve better effluent water quality than other BMPs. Contaminant removal is primarily associated with particulate matter and includes such parameters as total phosphorus, TKN, lead, and organic contaminants (e.g., herbicides, legacy pesticides, PAHs, phthalates, and legacy PCBs). The effluent of BMP wet ponds in western Washington (Table 12) generally exhibits very low concentrations of total phosphorus as compared with the International Database (Table 11).

A number of UOPs also remove dissolved contaminants such as dissolved metals. Wet ponds show very low total and dissolved copper concentrations (Tables 11 and 12). Data from wet ponds in western Washington demonstrate higher total and dissolved zinc concentrations than found in the International Database; however, the reason for this is not clear. Depending on the sensitivity of ESA-listed species, this may require further investigation.

Based on performance of the UOPs employed and data summarized in Tables 11 and 12, expected efficiencies of wet ponds are listed in Table 13.

Table 13. Constituent removal performance ratings for wet ponds for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
H	H	M	H	H	M	M	H	L	M-H[1]	L

[1]Can be high when combined with extended-detention basin.
Efficiency ratings: H=high, M=medium, L=low.

4.6 Biofiltration Swales

4.6.1 Description

Biofiltration swales (also referred to as vegetated swales, runoff swales, and biofilters) are open, shallow channels with low-lying vegetation covering the side slopes and bottom that collect and slowly convey runoff flow to downstream discharge points. In addition to conveying stormwater runoff, biofiltration swales remove pollutants through settling and filtration in the vegetation (usually grasses) lining the channels, provide the opportunity for volume reduction through infiltration and evapotranspiration, and reduce flow velocities in addition to conveying stormwater runoff. An effective vegetated swale achieves uniform sheet flow over and through a densely vegetated area for a period of several minutes.

A wet biofiltration swale is a variation of a basic biofiltration swale for use where the longitudinal slope is slight, the water table is high, or continuous base flow is likely to result in saturated soil conditions. When saturation exceeds about two continuous weeks, most grasses generally die. Thus, vegetation specifically adapted to saturated soil conditions is needed. This type of vegetation in turn requires modification of several of the design parameters for the basic biofiltration swale to remove low concentrations of pollutants such as TSS, heavy metals, nutrients, and petroleum hydrocarbons.

In situations where storm runoff water enters a biofiltration swale continuously along the side slope rather than discretely at the head, a continuous inflow biofiltration swale may be appropriate. The basic swale design is modified by increasing the length of the swale to achieve an equivalent average hydraulic residence time. A continuous inflow biofiltration swale is used when inflows are not concentrated, such as locations along the shoulder of a road without curbs. This design may also be used where frequent, small-point flows enter a swale, such as through curb inlet ports spaced at intervals along a road or from a parking lot with numerous curb cuts.

The effectiveness of a vegetated swale can be enhanced by adding check dams at approximately 50-foot intervals along its length. These dams maximize the retention time within the swale, decrease flow velocities, and promote particulate settling and are particularly useful for steeper slopes (over 4 percent). The incorporation of vegetated filter strips parallel to the top of the channel banks can also help to treat sheet flow entering the swale.

4.6.2 Unit Operation Processes

The shallow, concentrated flow within these BMP systems allows for the filtration of stormwater runoff by plant stems and leaves, as well as settling in low-turbulence/low flow pockets created by the vegetation. Some volume losses due to infiltration and evapotranspiration also occur. Biological uptake, biotransformation, sorption, and ion exchange are potential secondary pollutant-removal processes, but these are limited as compared to bioretention type BMPs due to the shorter residence times.

4.6.3 Applications

Biofiltration swales provide an effective means of removing conventional pollutants and are considered a relatively low-cost treatment solution. Biofiltration swales can also be integrated into the stormwater runoff conveyance system. Existing roadside ditches are good candidates for upgrading to biofiltration swales.

General constraints and siting considerations for biofiltration swales include the following:

- High flow velocity–Steep terrain and/or large tributary areas may cause erosive flows; however, these can be overcome with the use of check dams.
- Mild relief–A limited site slope may cause ponding.

4.6.4 Performance

The following table summarizes data from the International Database (ASCE and EPA 2007) for biofiltration swales.

Table 14. Performance of biofiltration swale BMPs in terms of effluent concentrations[1].

Constituent	No. of Data Points	No. of BMPs	EMC		
			Median	LCL	UCL
Cadmium Dissolved (µg/L as Cd)	271	26	0.20	0.20	0.20
Cadmium Total (µg/L as Cd)	271	26	0.20	0.20	0.21
Copper Dissolved (µg/L as Cu)	282	26	5.05	4.3	6.2
Copper Total (µg/L as Cu)	282	26	8.0	7.1	9.8
Lead Dissolved (µg/L as Pb)	282	26	1.0	1.0	1.0
Lead Total (µg/L as Pb)	310	28	4.5	3.4	6.1
Nitrate + Nitrite (mg/L as N)			-	-	-
Nitrate (mg/L as N)	331	29	0.44	0.38	0.49
Ammonia (mg/L as N)			-	-	-
Total Kjeldahl Nitrogen (mg/L as N)	317	28	1.33	1.24	1.5
Phosphorous Dissolved (mg/L as P)	17	3	0.22	0.17	0.30
Phosphorous Total (mg/L as P)	329	29	0.26	0.23	0.31
Total Suspended Solids (mg/L)	334	29	20.5	18.0	24.0
Zinc Dissolved (µg/L as Zn)	282	26	15.0	13.0	19.0
Zinc Total (µg/L as Zn)	324	28	30.0	25.0	36.5

[1] Median and 95% confidence interval of storm EMCs.
LCL=lower confidence level (5%), UCL=upper confidence level (95%).
Source: Adapted from the International Database (ASCE and EPA 2007).

Data exist for biofiltration swales treating highway runoff in western Washington; these data are summarized in Table 15, taken from the NPDES Annual Report (WSDOT 2006b) (with data failing QA/QC removed), along with additional recent data from Herrera Environmental Consultants (Herrera 2007c).

Table 15. Average of effluent EMCs for four biofiltration swales treating highway runoff in western Washington.

Site	**TSS**	**Total Cu**	**Diss. Cu**	**Total Zn**	**Diss. Zn**	**TP**
	mg/L	µg/L				mg/L
SR18 at 256th St	43.4	6.9	3	35	31	0.13
SR 18 / Issaquah 522 MP16.06	7.6	2.5	1.7	23.7	20	0.05
SR 14, near SR 192	20.7	9.2	4.6	57	38	0.09
SR18, MP13.3	10.9	6.6	4.9	32.4	27	0.1
Overall average	16	6.8	3.8	32	29	0.09
(range of averages)	(8-43)	(2.5-9.2)	(1.7-4.9)	(24-57)	(20-38)	(0.05-0.13)

For biofiltration swales, the primary removal mechanisms for suspended sediments are gravity settling and, to a limited extent, filtration. Gravity separation is provided by slowing the flow and by the microbackwaters within the vegetation matrix. Well-designed biofiltration swales perform well in achieving low effluent TSS concentrations (on average ~20 mg/L, Table 14; ~16 mg/L, Table 15), but effluent concentrations can be considerably lower in some biofiltration swales. Concentrations of TSS were relatively high at one swale listed in Table 15, but this may have been due to runoff from construction sites.

On the basis of TSS concentrations in effluent, biofiltration swales should effectively remove contaminants associated with particulate matter, including such parameters as TKN, lead, and organic contaminants (e.g., herbicides, legacy pesticides, PAHs, phthalates, and legacy PCBs).

Dissolved copper levels are similar between the International Database and data from western Washington. Dissolved zinc concentrations are higher in the western Washington data, but the reason is unclear. Both dissolved copper and dissolved zinc are relatively high despite a number of UOPs operating in biofiltration swales. The relatively short contact time of runoff in the BMP probably results in insufficient time for the mechanisms (such as adsorption onto plant material, soils, epilithic algae) to affect greater removal. The limited data in the International Database (Table 14) show relatively high dissolved phosphorus concentrations, either because of soils characteristics in other parts of the country or because of inadvertent fertilization of soil media.

Based on the values reported in the database and the California BMP handbook, biofiltration swales provide moderate to good removal of sediment and trace metals, moderate removal of dissolved trace metals, and limited removal of nutrients and bacteria. In the 2006 HRM, biofiltration swales are listed as providing basic treatment only.

Based on performance of the UOPs employed and data summarized in Tables 14 and 15, expected efficiencies of biofiltration swales are listed in Table 16.

Table 16. Constituent removal performance ratings for biofiltration swales for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
H	H	M	H	M	M	M	H	L	M[1]-L	M-L[1]

[1]Can be high in highly permeable soils and small storms
Efficiency ratings: H=high, M=medium, L=low.

4.7 Vegetated Filter Strips

4.7.1 Definition

Filter strips are vegetated areas designed to treat sheet flow runoff. Vegetated filter strips usually consist of gradually sloping areas that run adjacent to the roadway. As highway runoff sheets off the roadway surface, it flows through the grass filter. Vegetated filter strips reduce the velocity of runoff, filter out sediment and other pollutants, and provide infiltration into underlying soils. The flow can then be intercepted by a ditch or other conveyance system and routed to a flow control BMP or outfall.

The 2006 HRM describes three design types for vegetated filter strips: basic vegetated filter strips, compost-amended vegetated filter strips (CAVFS), and narrow area vegetated filter strips. The narrow area vegetated filter strip is the simplest design; however, its use is limited to impervious flow paths less than 30 feet. The basic vegetated filter strip is a compacted roadside embankment that is subsequently hydroseeded. The CAVFS is a variation of the basic vegetated filter strip that adds soil amendments to the roadside embankment; the soil amendments improve infiltration characteristics, increase surface roughness, and improve plant sustainability.

4.7.2 Unit Operation Processes

Filter strips decrease runoff velocity, filter out sediment and associated pollutants, and provide infiltration into underlying soils. While some assimilation of dissolved constituents may occur, filter strips are generally more effective in trapping sediment and particulate-bound metals, nutrients, and pesticides. Nutrients that bind to sediment include phosphorus and ammonium; soluble nutrients include nitrate. Filter strips are more effective when the runoff passes through the vegetation and thatch layer in the form of shallow, uniform flow. Biological and chemical processes may help break down pesticides, uptake metals, and utilize nutrients that are trapped in the filter.

4.7.3 Applications

Vegetated filter strips are an efficient and cost-effective runoff treatment option. Filter strips are well suited to treat runoff from roads and highways, driveways, roof downspouts, small parking lots, and other impervious surfaces. They are also appropriate for use as vegetated buffers between developed areas and natural drainages.

A challenge associated with vegetated filter strips is that sheet flow can sometimes be difficult to maintain. Consequently, vegetated filter strips can be short-circuited by concentrated flows, which create eroded rills or flow channels across the strips. This results in little or no treatment of stormwater runoff. Filter strips rely on dense turf vegetation with a thick thatch growing on a moderately permeable soil. Vegetated filter strips are not recommended for use in arid climates. In semiarid climates, drought-tolerant grasses should be used.

General constraints and siting considerations for vegetated filter strips include the following:

- High flow velocity–Steep terrain and/or large tributary areas may cause concentrated, erosive flows.

- Sheet flow–Shallow, evenly distributed flow across the entire width of the filter strip is required. The flow path from the contributing impervious surface should not exceed 150 feet.
- Mild relief–A limited site slope may cause ponding.

Vegetated filter strips (narrow area and basic) can be used to meet basic runoff treatment objectives, or as part of a treatment train to provide additional removal of phosphorus or dissolved metals. CAVFS can be used to meet both basic runoff treatment and enhanced runoff treatment objectives (for dissolved metals only).

4.7.4 Performance

The following table summarizes data from the International Database (ASCE and EPA 2007) for vegetated filter strips.

Table 17. Performance of vegetated filter strip BMPs in terms of effluent concentration[1].

Constituent	No. of Data Points	No. of BMPs	EMC		
			Median	LCL	UCL
Cadmium Dissolved (µg/L as Cd)	71	12	0.05	0.03	0.07
Cadmium Total (µg/L as Cd)	90	13	0.21	0.17	0.25
Copper Dissolved (µg/L as Cu)	117	15	6.6	6.0	7.79
Copper Total (µg/L as Cu)	186	18	7.8	6.7	9.0
Lead Dissolved (µg/L as Pb)	86	12	1.03	0.65	1.75
Lead Total (µg/L as Pb)	173	16	3.48	2.95	5.8
Nitrate + Nitrite (mg/L as N)	27	2	0.60	0.30	0.80
Nitrate (mg/L as N)	145	14	0.24	0.21	0.30
Ammonia (mg/L as N)	14	3	0.03	0.0	0.06
Total Kjeldahl Nitrogen (mg/L as N)	78	11	1.08	0.97	1.41
Phosphorous Dissolved (mg/L as P)	21	5	0.27	0.22	0.31
Phosphorous Total (mg/L as P)	210	20	0.22	0.18	0.23
Total Suspended Solids (mg/L)	133	15	16.0	13.0	24.0
Zinc Dissolved (µg/L as Zn)	117	15	24.3	22.0	29.0
Zinc Total (µg/L as Zn)	210	20	30.8	25.0	40.0

[1]Median and 95% confidence interval of storm EMCs.
LCL=lower confidence level (5%), UCL=upper confidence level (95%).
Source: Adapted from the International Database (ASCE and EPA 2007).

Limited data exist for filter strips and CAVFS in western Washington (Table 18). These data were summarized from the NPDES Annual Report (WSDOT 2006b) (with data failing QA/QC removed). Data from a second compost shoulder was limited to only one storm out of six that produced effluent (the other five runoff events were completely infiltrated at the site).

TSS concentrations in effluent associated with filter strips are higher than wet ponds or constructed wetlands (see Tables 9 and 11), but lower than BMPs that rely solely on settling (such as detention basins). Consequently, concentrations of particulate-related contaminants, such as organic contaminants, would also be expected to be slightly elevated over what is found in pond or wetland effluent, but similar to biofiltration swales.

Table 18. Average of effluent EMCs for one filter strip and one CAVFS treating highway runoff in western Washington.

Site	**TSS**	**Total Cu**	**Diss. Cu**	**Total Zn**	**Diss. Zn**	**TP**
	mg/L	µg/L				mg/L
Vegetated Filter Strip I-5, MP 185	4.8	5.9	4.5	20	12	0.07
Compost Shoulder I-5, MP 186A	18.3	8.3	4.6	34	12	0.06

Source: WSDOT (2006b).

Concentrations of dissolved contaminants such as dissolved copper and zinc are also relatively high compared with wet ponds and constructed wetlands. Although a number of UOPs are employed in filter strips, the relatively short contact time of runoff in the BMP probably results in insufficient time for these UOPs to affect greater removal. Consequently, concentrations of total and dissolved copper can be high in effluent (Tables 17 and 18).

The few western Washington data indicate that these two different filter strips monitored (reported inTable18) have similar or slightly lower effluent concentrations for TSS, copper, and zinc than the International Database. Total phosphorus concentrations are substantially lower in the data from western Washington; the reason for this might be the higher dissolved phosphorus noted in the International Database, either because of soil characteristics in other parts of the country or because of inadvertent fertilization of soil media. The western Washington data also show that some compost-amended filter strips may have a greater performance because they are able to infiltrate much of the runoff; however, insufficient data are available to estimate what the range of volume reduction might be. Filter strips that have been enhanced through soil amendments with compost allow more vigorous vegetation growth and presumably root mass, as well as more infiltration. Note that in some other parts of the country, filter strips are often required to include compost amendment, and data presented in the International Database likely reflect this design requirement.

Based on performance of the UOPs employed and data summarized in Tables 17 and 18, expected efficiencies of vegetated filter strips are listed in Table 19.

Table 19. Constituent removal performance ratings for vegetated filter strips for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
Vegetated filter strips without compost amendment										
H	M	L	H	M	M	M	M	L	L-M[1]	M[1]
Compost amended vegetated filter strips										
H	H	L	H	M-H	M-H	M	M	L	L-M[1]	M-H[1]

[1]Can be high in highly permeable soils and for small storms.
Efficiency ratings: H=high, M=medium, L=low.

4.8 Bioretention

4.8.1 Definition

Bioretention areas are vegetated (i.e., landscaped), shallow depressions that provide storage, infiltration, filtration, and evapotranspiration. If no underdrain is provided, exfiltration (drainage of the stored water in the engineered soil into the underlying soils) occurs over a period of hours to days, depending on the underlying soils. For areas with low permeability native soils or steep slopes, bioretention areas can be designed with an underdrain system that routes the treated runoff to the storm drain system rather than depending on infiltration. In this situation, treatment is achieved mainly through filtration and adsorption on the vegetation and engineered soils in the bioretention area with some evapotranspiration losses.

4.8.2 Unit Operation Processes

Bioretention areas also remove pollutants by filtering stormwater runoff through plants adapted to the local climate and soil moisture conditions, and an engineered soil mix. In bioretention areas, pore spaces, microbes, and organic material in the engineered soils help to retain water in the form of soil moisture and to promote the adsorption of pollutants (e.g., dissolved metals and petroleum hydrocarbons) into the soil matrix. Plants utilize soil moisture and promote the drying of the soil through transpiration.

4.8.3 Applications

Bioretention areas are an efficient runoff treatment option. They are well suited to treat runoff from roads and highways, driveways, roof downspouts, small parking lots, and other impervious surfaces. They are particularly useful in some constrained space situations where they can be designed as “stormwater planter boxes.” As they typically require underdrains, their design and cost to build are somewhat higher.

General constraints and siting considerations associated with bioretention areas include the following:

- Native soil infiltration rate–An underdrain is required in low permeability soils.
- Vertical relief and proximity to storm drain–The site must have adequate relief between the land surface and storm drain to permit vertical percolation through the soil media and collection and conveyance in the underdrain to storm drain system.
- Depth to groundwater–The shallow groundwater table may not permit complete drawdown between storms.
- Availability of pervious area–Bioretention areas typically require between 2 and 6 percent of the drainage area.

4.8.4 Performance

Performance data are generally lacking for bioretention as a BMP, in part because runoff is often totally infiltrated; therefore, 100 percent treatment can be assumed. There are few other data on bioretention devices with underdrains, apart from proprietary information. The unit operation processes associated with bioretention are a combination of infiltration, evapotranspiration, microbial transformation, and plant uptake. The EPA (1999) has reported high effectiveness for bioretention, but the results are based on only a few studies. The BMP evaluations by Caltrans and CASQA categorize the effectiveness of bioretention as follows (Table 20).

Table 20. Effectiveness of bioretention, based on Caltrans and CASQA data.

	Effectiveness						
	TSS	Nutrients	Litter	Total metals	Dissolved metals	Bacteria	Pesticides
Caltrans	H	L	H	H	M	H	M
CASQA	H	M	H	H	-	H	H

Based upon factsheets in Caltrans (2006) and CASQA (2003).

There is some ambiguity about treatment of pesticides and nutrients in Caltrans (2006) and CASQA (2003), but bioretention is expected to be effective for pesticides and nutrients associated with particulate matter or that are readily adsorbed by surfaces within soil media. Where bioretention results in complete infiltration, its performance is equivalent to other infiltration facilities described above. Where low infiltration rates in native soils require that an underdrain be deployed, then based on the unit operation processes, the actual effectiveness of bioretention is likely somewhere between infiltration facilities and media filtration. In the absence of effluent data, as a preliminary estimate of effectiveness of bioretention with underdrains, it is recommended that the best performance (i.e., lowest concentration range) of either sand filtration (Table 25) or biofiltration swales (Tables 14 or 15) be used.

Based on performance of the UOPs employed, expected efficiencies of bioretention with and without underdrains are listed in Table 21.

Table 21. Constituent removal performance ratings for bioretention for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
Biorentenion without underdrains										
H	H	H	H	H	H	H	H	H	H	H
Biorentenion with underdrains										
H	H	L	H	H	M	H	H	L	M-L	M-L

Efficiency ratings: H=high, M=medium, L=low.

4.9 Ecology Embankments

4.9.1 Description

The ecology embankment is a linear flow-through stormwater runoff treatment device that can be sited along highway side-slopes (conventional design), medians (dual ecology embankment), borrow ditches, or other linear depressions. Ecology embankments have four basic components: a gravel no-vegetation zone, a vegetated filter strip, the ecology mix bed, and a gravel-filled underdrain trench.

Stormwater runoff is conveyed to the ecology embankment via sheet flow over a vegetation-free gravel zone to ensure sheet dispersion, and to trap some pollutants. Next, a vegetated filter strip (which may be amended with compost) is incorporated into the top of the fill slope to provide pretreatment, further enhancing filtration and extending the life of the system. The runoff is then filtered through a bed of porous, alkalinity-generating granular medium—the ecology mix (a fill material composed of crushed rock, dolomite, gypsum, and perlite). Treated water drains from the bed of the ecology mix into the gravel underdrain trench for hydraulic conveyance; an underdrain pipe may be required in the trench.

4.9.2 Unit Operation Processes

The ecology embankment removes suspended solids, phosphorus, and metals from highway runoff through physical straining, settling, adsorption, ion exchange, carbonate precipitation, and biofiltration. The dolomite and gypsum additives in the ecology mix buffer acidic pH conditions and exchange calcium and magnesium for heavy metals. Perlite is incorporated to improve moisture retention, which is critical for the formation of biomass to assist in the biofiltration of solids, metals, and nutrients.

4.9.3 Applications

Ecology embankments are often used where other runoff treatment BMPs are not feasible in many instances due to right-of-way constraints (e.g., adjoining wetlands, geotechnical considerations, etc.). The ecology embankment and the dual ecology embankment are runoff treatment options that can be sited in most confined right-of-way situations. In many cases, an ecology embankment or a dual ecology embankment can be sited without the acquisition of additional land for conventional stormwater runoff facilities or capital-intensive expenditures for underground wet vaults.

The ecology embankment can be used where sheet flow from the highway surface is feasible, lateral gradients are generally less than 25 percent (4H:1V), and longitudinal gradients are less than 5 percent. It is critical to note that water should sheet flow across the ecology embankment. Channelized flows or ditch flows running down the middle of the dual ecology embankment (i.e., continuous off-site inflow) should be minimized.

Areas with a high water table or seasonal groundwater inundations may compromise the hydraulic and runoff treatment performance of ecology embankments due to backwater effects and lack of sufficient hydraulic gradient.

4.9.4 Performance

The only information available for ecology embankments is for highway runoff in western Washington. These data are summarized in Table 22, taken from the NPDES Annual Report (WSDOT 2006b) (data failing QA/QC was removed), along with additional recent unpublished WSDOT data from Herrera Environmental Consultants (Herrera 2007c).

Table 22. Average effluent EMCs for four ecology embankments treating highway runoff in western Washington.

Site	TSS	Total Cu	Diss. Cu	Total Zn	Diss. Zn	TP
	mg/L	µg/L				mg/L
SR18, 244th St Cloverleaf	12.5	6.3	1.9	9.2	6.7	0.10
SR18, 244th St Off-Ramp	61.6	7.5	2.3	21.4	6.6	0.34
SR18, EE Vault [1]	22.4	4.1	2.3	16	7.2	0.19
SR 167, MP16	3.5	10.9	7.7	35	24	0.03
Overall median	17	7	2.3	19	7	0.14
(range of medians)	(4-62)	(4-11)	(1.9-7.7)	(9-35)	(6.6-24)	(0.03-0.34)

[1] Note: this site has very low influent concentrations; EE = ecology embankment.

The data show a wide range of average effluent concentrations, from relatively low concentrations (comparable to or better than wet ponds) to relatively high concentrations (comparable to detention basins).

UOPs employed within ecology embankments include infiltration, physical filtering (by soil and plant stems and root mats), evapotranspiration, microbial transformation, and plant uptake. However, ecology embankments are essentially a flow-through device; therefore, they should not be as effective as bioretention (see Section 4.8) but are probably more effective than biofiltration swales (see Section 4.6). Based on performance of the UOPs employed, the treatment efficiencies are expected to be quite high (Table 23). This relatively new BMP likely requires more development time and experience to realize the expected efficiency.

Table 23. Expected constituent removal performance ratings for ecology embankments for highway runoff[1].

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
H	H	L	H	H	H	M	H	L	L[2]	L-M[2]

[1] Note that these expectations have not yet been realized for all ecology embankments trialed (see Table 22).
[2] Could be medium for small storms and highly permeable underlying soils.
Efficiency ratings: H=high, M=medium, L=low.

4.10 Dispersion to Landscape (Natural and Engineered)

4.10.1 Description

Perhaps the single-most promising and effective approach to mitigating the effects of highway runoff in nonurbanized areas is to use the existing capacity of natural area adjacent to the highway to remove pollutants. Natural dispersion requires that runoff not be concentrated in any way as it flows into a preserved, naturally vegetated area. The preserved, naturally vegetated area must have topographic, soil, and vegetation characteristics that provide for the removal of pollutants. Pollutant removal typically occurs through a combined process of vegetative filtration and shallow surface infiltration.

Notable benefits associated with natural dispersion are that it maintains and preserves the natural functions, reduces the possibility of further impacts on adjacent natural areas associated with the construction of physical treatment facilities, and can be very cost effective. In most cases, this method not only meets the requirements for runoff treatment, but also provides flow attenuation. If channelized drainage features are present and close to the runoff areas requiring treatment, then other types of engineered solutions might be more appropriate.

Engineered dispersion techniques use the same removal processes as natural dispersion. For engineered dispersion, a manmade conveyance system directs concentrated runoff to the dispersion area (via a storm sewer pipe, ditch, or other means). The concentrated flow is dispersed at the end of the conveyance system to mimic sheet flow conditions into the dispersion area. Engineered dispersion techniques enhance the modified area with compost-amended soils and additional vegetation; these upgrades help ensure that the dispersion area has the capacity and ability to infiltrate surface runoff.

4.10.2 Unit Operation Processes

Natural dispersion uses the existing vegetation, soils, and topography to effectively provide flow control and runoff treatment. The ability to disperse to the landscape allows the use of a number of UOPs; the most important are those associated with shallow infiltration into the soils. Other UOPs are similar to biofiltration swales (see Section 4.6) and filter strips (see Section 4.7), where vegetation slows and filters runoff through litter and root mass, and uptake and transpiration by vegetation occurs.

4.10.3 Applications

Natural dispersion is the simplest method of flow control and runoff treatment and requires little or no construction. This BMP can be used for impervious or pervious surfaces that are graded to avoid concentrating flows. Engineered dispersion requires some construction to ensure sheet flow and/or effective dispersion. The key to both dispersion methods is that flows from the impervious area enter the natural or engineered dispersion area as sheet flow. Because stormwater runoff enters the dispersion area as sheet flow, it only needs to traverse a narrow band of contiguous vegetation for effective attenuation and treatment. The goal is to disperse flow into the surrounding landscape such that there is a low probability of any surface runoff reaching a flowing body of water. If sheet flow cannot be maintained, dispersion is not effective.

Natural and engineered dispersion areas meet both basic and enhanced runoff treatment criteria as well as flow control criteria (see the 2006 HRM). Natural areas also contribute to the preservation of native habitat and provide visual buffering of the roadway.

Dispersion areas must be protected from future development. Dispersion areas initially may cost as much as other constructed BMPs if right-of-way or easements need to be purchased, but long-term maintenance costs are lower.

4.10.4 Performance

No performance data are available for dispersion to the landscape. However, in most situations where this BMPs is properly sited and designed, performance similar to full infiltration facilities (Section 4.1) can be assumed.

Table 24. Expected constituent removal performance ratings for dispersion to landscape for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
H	H	H	H	H	H	H	H	H	H	H

Efficiency ratings: H=high, M=medium, L=low.

4.11 Sand Filters

4.11.1 Definition

A sand filter operates much like a bioretention facility; however, instead of filtering stormwater runoff through engineered soils, stormwater runoff is filtered through a constructed sand bed with an underdrain system. Runoff enters the filter and spreads over the surface. As flows increase, water backs up on the surface of the filter, where it is held until it can percolate through the sand. The treatment pathway is usually vertical (downward through the sand), although upflow filters have been developed. High flows in excess of the design volume simply spill out over the top of the pool or over a designed spillway. Water that has percolated through the sand is collected via a perforated underdrain system before being conveyed to the downstream storm drainage system.

4.11.2 Unit Operation Processes

Sand filters have a propensity to clog under high sediment loads or if they are not properly maintained; therefore, pretreatment must be provided in areas with high predicted sediment load so that settling occurs in the pretreatment device (often a vault). As the settled stormwater runoff passes through the sand, pollutants are trapped in the small pore spaces between sand grains or are adsorbed to the sand surface. Over time, bacteria can grow in the sand bed and provide some biological treatment. However, continuous dry weather flows are required to optimally maintain the moisture required by the bacteria. Therefore, physical and chemical adsorption is expected, along with microbiological processes under suitable conditions.

4.11.3 Applications

A sand filter can be used in nearly all developments where site characteristics provide adequate hydraulic head to effectively operate the filter; an elevation difference of approximately 4 feet is recommended between the inlet and outlet of the filter. Landscape uses of sand filters are limited due to the small number of plant species that can survive in sand. Large trees and shrubs that generate leaf litter should not be located near a sand filter, as the leaves tend to clog the surface of the filter and reduce infiltrative capacity.

Sand filters are designed to prevent water backup in the sand layer, as saturated sands can lead to anoxic conditions where metals and phosphorus can be mobilized. The underdrain system must flow freely. In areas with high groundwater tables that could potentially flood the underdrain system, an impermeable liner must be provided.

General constraints and siting considerations associated with sand filters include the following:

- High loading rates–Sand filters may clog quickly if flows are not adequately pretreated.
- Vertical relief and proximity to storm drain–The site must have adequate relief between the land surface and storm drain to permit vertical percolation through the sand filter, collection in the underdrain, and conveyance to the storm drain system.

4.11.4 Performance

Although this BMP is currently not an approved technology for highway runoff in Washington, it is considered here as a possible candidate for situations with limited space and high traffic densities.

The following table summarizes data from the International Database (ASCE and EPA 2007) for media filters including: (1) with sand mixed with peat, and (2) with sand alone.

Table 25. Performance of sand filters in terms of effluent concentration: median and 95% confidence interval of storm EMCs.

Constituent	No. of Data Points	No. of BMPs	EMC		
			Median	LCL	UCL
Filter – Sand Mixed with Peat					
Cadmium Dissolved (µg/L as Cd)	22	3	0.08	0.02	0.26
Cadmium Total (µg/L as Cd)	22	3	0.13	0.05	0.35
Copper Dissolved (µg/L as Cu)	30	3	6.4	3.6	11.1
Copper Total (µg/L as Cu)	30	3	6.8	4.8	11.0
Lead Dissolved (µg/L as Pb)	30	3	0.50	0.50	0.69
Lead Total (µg/L as Pb)	30	3	0.50	0.50	0.64
Nitrate + Nitrite (mg/L as N)	12	1	0.13	0.13	0.13
Nitrate (mg/L as N)	18	2	0.68	0.42	0.78
Ammonia (mg/L as N)	-	-	-	-	-
Total Kjeldahl Nitrogen (mg/L as N)	18	2	1.22	0.42	1.7
Phosphorous Dissolved (mg/L as P)	10	2	0.03	0.02	0.12
Phosphorous Total (mg/L as P)	18	2	0.10	0.09	0.25
Total Suspended Solids (mg/L)	30	3	6.0	4.8	8.0
Zinc Dissolved (µg/L as Zn)	30	3	10.0	3.9	21.5
Zinc Total (µg/L as Zn)	30	3	19.0	12.5	30.5
Filter - Sand					
Cadmium Dissolved (µg/L as Cd)	53	7	0.06	0.04	0.08
Cadmium Total (µg/L as Cd)	73	8	0.06	0.04	0.10
Copper Dissolved (µg/L as Cu)	94	8	5.9	4.6	7.0
Copper Total (µg/L as Cu)	114	9	8.6	7.4	9.9
Lead Dissolved (µg/L as Pb)	91	7	0.10	0.07	0.14
Lead Total (µg/L as Pb)	91	7	2.10	1.54	3.1
Nitrate + Nitrite_Total (mg/L as N)	23	2	1.40	1.16	2.06
Nitrate (mg/L as N)	111	8	0.70	0.62	0.89
Ammonia (mg/L as N)	38	3	0.08	0.04	0.29
Total Kjeldahl Nitrogen (mg/L as N)	114	9	1.20	0.92	1.35
Phosphorous Dissolved (mg/L as P)	44	6	0.08	0.05	0.11
Phosphorous Total (mg/L as P)	114	9	0.15	0.12	0.16
Total Suspended Solids (mg/L)	129	10	11.0	9.0	14.0
Zinc Dissolved (µg/L as Zn)	76	8	18.1	9.8	21.8
Zinc Total (µg/L as Zn)	138	10	23.8	18.2	30.9

LCL=lower confidence level (5%), UCL=upper confidence level (95%).
Source: Adapted from the International Database (ASCE and EPA 2007).

Based on the performance of UOPs employed and data presented in Table 25, expected efficiencies of sand filters are listed in Table 26.

Table 26. Constituent removal performance ratings for sand filters for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
Sand and peat										
H	H	L	H	H	H	M	H	L	L	L
Sand only										
H	H	L	H	H	M	M	H	L	L	L

Efficiency ratings: H=high, M=medium, L=low.

4.12 Multi-Chambered Treatment Trains (MCTT)

4.12.1 Description

The multi-chambered treatment train (MCTT) is an underground device and is typically sized in area between 0.5 to 1.5 percent of the paved drainage area. It is comprised of three main sections: an inlet with a conventional catch basin with litter traps, a main settling chamber with lamella plate separators and oil sorbent pillows, and a final chamber with a mixed sorbent filtering media (usually peat moss and sand).

4.12.2 Unit Operation Processes

UOPs include coarse matter filtration, settling, physical adsorption, and filtration. The settled stormwater runoff is passed through a suitable media material (e.g., sand and peat) so that pollutants are trapped in the small pore spaces between media grains or are adsorbed to the media surface. Therefore, physical and chemical adsorption is expected, along with settling and exclusion (filtering) processes.

4.12.3 Applications

The MCTT was developed to control toxicants in stormwater runoff from critical source areas (Pitt 2002b). The MCTT is most suitable for use in relatively small areas, about 0.1 to 1 ha in size, such as vehicle service facilities, convenience store parking areas, equipment storage and maintenance areas, and salvage yards.

4.12.4 Performance

The effectiveness of MCTT systems has been examined by Caltrans, as well as other studies (e.g., Pitt 2002a, 2002b). Results from these studies have varied. Performance data as measured by Caltrans are summarized in Table 27.

Table 27. Constituent removal performance ratings for MCTT system highway runoff in California.

Effectiveness						
TSS	Nutrients	Litter	Total metals	Dissolved metals	Bacteria	Pesticides
M	L	H	M	M	L	L

Source: from fact sheets listed in Caltrans (2006).
Efficiency ratings: H=high, M=medium, L=low.

On the basis of the above performance expectations from Caltrans, multi-chambered treatment trains may not meet Ecology's basic treatment requirements (80 percent removal of TSS). However, these results are inconsistent with other detailed studies of MCTT described below.

The most comprehensive study of treatment train performance has been Pitt's study of the proprietary MCTT system that he and his coworkers designed (Pitt 2002a, 2002b). Pitt et al. (1999) found that a sand-peat filter was an effective control for many contaminants after stormwater runoff was pretreated by sedimentation. The device was tested in pilot studies using runoff from a university parking area in Birmingham, Alabama (representing 13 runoff events), which showed good treatment performance for most contaminants, including organics; the exception was dissolved copper, where the overall removal rates were only 17 percent, with a median effluent quality of 21 µg/L; no reason was given for this poor performance for copper.

In full-scale tests using industrial yard runoff in Milwaukee, Wisconsin (representing 15 runoff events) and a parking lot in Minocqua, Wisconsin (representing seven runoff events), the following removal and effluent quality data were observed:

Table 28. Performance data for multi-chambered treatment trains.

	Milwaukee		Minocqua	
	Removal	Effluent	Removal	Effluent
TSS	98%	<5 mg/L	85%	10 mg/L
TP	88%	0.02mg/L	>80%	<0.1 mg/L
Dissolved Reactive P	78%	0.002mg/L	-	-
Copper (total)	90%	3µg/L	-	-
Copper (dissolved)	73%	1.4µg/L	-	-
Lead (total)	96%	1.8	nd	<3 µg/L
Lead (dissolved)	78%	<0.4 µg/L	-	-
Zinc (total)	91%	<20 µg/L	90%	15 µg/L
Zinc (dissolved)	68%	<8 µg/L	-	-

nd = non-detect
Source: Pitt (2002b).

In addition, good removal efficiencies were found for a number of PAH congeners. These overall results were much better than found in the Caltrans trials (referenced above) and suggest the potential for designing effective highway runoff treatment in areas with limited space. However, additional trials are needed to confirm or improve effluent quality for dissolved metals.

4.13 Highway Sweeping

As noted in the *Methodology* (Section 3), a separate review was conducted to assess the applicability of highway sweeping as a potential treatment BMP for highway runoff; the results of this review are presented in Appendix 3, with the conclusions summarized here. As described in Appendix 3, stormwater monitoring studies that have evaluated street sweeping effects on roadway runoff have failed to measure benefits to stormwater runoff quality (in the runoff) from roadway sweeping. This is likely due to lower actual effectiveness (e.g., less then 20 to 30 percent) that combined with the high data variability in runoff concentrations means the number of samples required to detect changes are very large (e.g., on the order of 50 or more storm events would need to be sampled to statistically determine an effect at that level). Modeling predictions and studies on contaminants on street surfaces (solids on road surfaces) indicate that highway sweeping yields benefits to street and highway runoff quality (based upon street surface materials sampling), but only if roadways are swept frequently and under rigorously defined operating conditions (e.g., no parked cars, appropriate speeds). Therefore, performance data are not presented here, and the possibility that highway sweeping might have benefits to highway runoff quality in Washington remains to be demonstrated. On the basis of the review, it appears that highway sweeping would not meet the basic requirements for highway runoff treatment, and would not be a suitable candidate at this stage for pollution control for ESA purposes on highways in western Washington.

Potential benefits of highway sweeping that are associated with specific applications include the following:

- Regular sweeping of low-traffic areas, especially those such as maintenance yards which may receive a high pollutant loading from activities in the yard.
- End-of-winter sweeping of highways to remove grit that has been applied on icy roads for traction support.

On the basis of the review, best professional judgment allows the following tentative predictions to be made on expected effluent quality:

Table 29. Constituent removal performance ratings for highway sweeping for highway runoff.

TSS	Particulate nutrients	Dissolved nitrogen	Litter	Total metals	Dissolved metals	Bacteria	Organic contaminants	Dissolved salts	Flow attenuation	Volume reduction
M-L	L	L	H	M-L	L	L	L	L	L	L

Efficiency ratings: H=high, M=medium, L=low.

5 Summary and Conclusions

This section provides a summary and conclusions regarding the ability of BMPs to reduce the contaminants of potential concern in runoff. It includes a discussion of the applicability of data from outside Washington State for this assessment, discusses limitations and data gaps, and then summarizes by pollutant type the ability of BMPs to reduce runoff COPC.

5.1 Comparison of International BMP Database and Washington State BMP Data

The *Untreated Highway Runoff in Western Washington* white paper (Herrera 2007a) indicated that highway runoff in western Washington shares many of the characteristics of urban runoff. Therefore, the findings from urban runoff BMP studies are considered appropriate for assessing their potential effectiveness in treating highway runoff. This is borne out in a general sense from comparing effluent in BMPs from western Washington with the International BMP Database (Section 4), as well as observations regarding findings reported by Caltrans. Some important differences in BMP performance data between the two sets of data include the following:

- Lower TSS (and hence other particulate contaminants) effluent quality for wet ponds in western Washington.
- In general, copper concentrations in effluent are generally lower in western Washington for wet ponds, ecology embankments, and biofiltration swales.
- In general, higher effluent dissolved Zn concentrations for wet ponds, ecology embankments, and biofiltration swales in western Washington.

Another difference amongst the data sets, including the International BMP Database and WSDOT western Washington data, evident from the analysis in this white paper is that highway runoff in western Washington has been frequently observed to be completely infiltrated into the surrounding landscape. In the International Database, infiltration facilities showed large volumes of reductions, along with more minor reductions in runoff for detention basins (30 percent) and biofiltration swales (38 percent). Monitoring by WSDOT has shown a large proportion of storms being infiltrated in a compost shoulder and detention basin (WSDOT 2006b). One potential reason for this difference is that urban runoff is frequently derived from large surface areas, while highway runoff is usually derived from a relatively narrow, linear source area, sometimes conveyed in long, open channels. Other reasons include the low-intensity storms that occur in western Washington, which give the water more time to infiltrate, as well as long, open flow paths, so that much of the water infiltrates before reaching the BMP (R. Tveten, pers. comm.). As these phenomena are highly site specific, it is recommended that volume reductions be assessed for particular sites. This is particularly true for combinations of BMPs (e.g., treatment trains; see below), as well as when the distinction between certain categories of BMPs becomes blurred when dealing with smaller source areas (e.g., detention basins and infiltration ponds). However, the ability of a BMP to reduce runoff volume should be emphasized as this reduces not just the volume of runoff and therefore pollutant loads, but also the frequency of runoff events.

5.2 Areas of Uncertainty and Analysis Considerations

In this discussion of uncertainty and analysis considerations, the general areas of uncertainty are presented. There is also a discussion of capture efficiency analyses and its effects on evaluation, and finally considerations regarding treatment trains are discussed.

5.2.1 General Areas of Uncertainty

Equivalent, rigorously assessed data are not available or have not yet been presented for some of the BMPs considered here. These include some that are already in use to treat highway runoff (e.g., ecology embankments, dispersion to landscaping, compost-amended vegetated filter strips) and other potential candidates (e.g., bioretention, multi-chambered treatment trains). These represent important data gaps that require further study. Until such studies are conducted, where robust information is missing, tentative suggestions have been made in the following section on likely effectiveness and effluent concentrations based on the UOPs that are employed within the BMPs.

Despite the recent advances in our understanding of effectiveness and likely effluent concentrations of some BMPs, significant areas of uncertainty remain. This is illustrated by the relatively large range of reported effluent concentrations that to date cannot be explained by site-specific conditions or BMP designs as presented in Section 4. Although the data in the database have been screened for quality assurance and the studies met most of the database project protocols, the data reflect both well and poorly designed and operated BMPs, as well as a range in the quality of BMP effectiveness studies; Finally there is likely a range in the quality of the sampling programs themselves that could not be assessed based upon submitted reports. The resulting variability and uncertainties will likely be better addressed by future data from well-designed and operated BMPs, which will allow more BMP categories to be separately assessed, help define the effects of site-specific conditions and BMP designs, and “weed out” poorly designed or operating BMPs.

Other uncertainties pertain to the parameters measured. Information on organic COPC remains scarce for both treated and untreated highway runoff. Some of these contaminants have highly distributed sources (e.g., PAHs, phthalates), while others are more site specific (e.g., herbicide spraying regimes, the location of highways in land used for agriculture before 1970).

5.2.2 Capture Efficiency

Although analyzing the effect of capture efficiency (fraction of runoff that is treated; see Section 2.4.5) is beyond the scope of this white paper, its effect on water quality in receiving waters may be a significant factor. However, it can only be analyzed through site-specific or regional long-term storm runoff modeling. There is currently little published information that would guide planners as to the magnitude of the potential impacts of bypassed or less treated flows. The most effective way to examine the effect of less than 100 percent capture efficiency is to apply continuous hydrological modeling with both effluent and untreated water quality information (Strecker et al. 2005). This could be done for a range of locations and site conditions in future efforts.

5.2.3 Treatment Trains

This white paper does not consider in detail the effect of treatment trains—combinations of multiple BMPs, either in series or in parallel. WSDOT specifies and recommends a number of treatment train approaches for enhanced treatment for phosphorus or dissolved metals removal (see the WSDOT website at: http://www.wsdot.wa.gov).

A rapid literature search was performed to determine if any peer-reviewed statistical evidence exists or data analysis performed on treatment trains in comparison to stand-alone BMPs. Apart from the MCTT described in Section 4.12, very few studies were found that have quantitatively compared performance of stand-alone BMPs to those in series. Data were found in the International Database for a study in Lake McCarran, Minnesota, where researchers sampled effluent data from runoff before and after it initially passed through a wet pond and after the same effluent had passed through a stormwater treatment wetland as a secondary BMP. Data analysis showed that no statistical difference was observed between the two BMPs in the effluent value for chemical oxygen demand, total nitrogen, total Kjeldahl nitrogen, total phosphorus, or dissolved phosphorus. There were differences, however, for TSS.

Due to the lack of data, it is not possible to predict the effluent quality of treatment trains, nor their volume reduction. This is a significant information gap and perhaps best dealt with by taking a conservative approach, assuming that the effluent concentration of a treatment train is equivalent to the lowest concentration of the parameter of interest (Table 30) for the BMP types that make up the treatment train. Another option would be to develop an agreed-upon percentile concentration for those BMPs that are part of a “significant” treatment train. For example, it is more likely that concentrations for a given parameter would be below the median effluent quality if there were a BMP upstream that included unit operation processes expected to be effective on the pollutant of concern. In this case, one could choose to subjectively employ a lower 30th or 40th percentile concentration rather then the median.

As a cautionary note, it is incorrect to assume that pollutant removals in BMPs can be additive and hence, for example, can be measured on a percent removal basis regardless of influent concentration. For example, if a swale is assumed to remove 75 percent of a contaminant and a detention basin is assumed to remove 65 percent of the same contaminant, the combination of these two BMPs in series will not remove 92 percent (75 percent and then 65 percent) of the contaminant. Percent removal estimates are derived from studies of stand-alone BMPs, which often have elevated polluted influent concentrations, in contrast to the influent concentration that would be expected in the second BMP in a treatment train. Using percent removal estimations for BMPs in series fails to account for low concentrations in the influent to the subsequent device, changes in particle size distribution of suspended sediments through the treatment train, and minimum effluent quality limitations of BMPs.

5.3 BMP Performance for Contaminants of Potential Concern

As discussed in this white paper, it is best to use ranges when assessing BMP performance data for ESA or other evaluations. The following section presents a discussion of recommended values for predicting BMP performance for ESA evaluations, by contaminant of potential concern. The effluent concentrations summarized in Table 30 are recommended for ESA assessments, with a number of exceptions. These exceptions are wet ponds (Table 12), biofiltration swales (Table 15), and ecology embankments (Table 22), for which a reasonable database for western Washington is available for total suspended solids, total phosphorus, total and dissolved copper, and zinc. These western Washington data can be used to evaluate the effluent quality of those specific BMPs for these parameters, although caution is advised because the data are relatively few compared with the International Database, and some results are considered preliminary. The International Database (Table 30) should be used for other BMPs and other parameters, and as a comparison for the western Washington data.

It is recommended that the median of all individual storm EMCs be used for ESA assessment, rather than the overall average EMC for each BMP. This reduces the bias that may occur from an outlier. As described above, these data represent an average of all BMP facilities in that category, which may include some that are poorly designed or operated. Under the robust design criteria of the 2006 HRM, better-than-average performance is expected in most cases.

The following subsections summarize the effluent quality and volume reduction of BMPs that typically have effluent. BMPs that typically do not have effluent include the following:

- Infiltration facilities (ponds, vaults, and trenches)
- Dispersion to the landscape (engineered and natural)
- Bioretention without underdrains

These BMPs are assumed to have 100 percent volume and contaminant capture and a negligible impact on receiving waters. These are not discussed further in this white paper, but the fact that all storms are not captured and treated by BMPs indicates that these BMPs will discharge to receiving waters on some occasions. This could be evaluated using continuous simulation model.

No performance data are available for bioretention with underdrains (a BMP that has effluent). In this case, recommended effluent concentrations are the lowest median of those reported for biofiltration swales and sand filtration as these systems use similar UOPs. A volume loss could also be assumed (between 30 and 40 percent).

Recommended effluent quality to use for ESA-related evaluations are summarized below, by contaminant of potential concern.

Table 30. Median of individual storm BMP effluent event mean concentrations (EMCs)_

Constituent	Det. basins (lined)	Det. basins (unlined)	Constructed wetlands	Wet ponds	Biofiltration swales	Filter strips	Sand +peat filters	Sand filters
Cadmium Dissolved (µg/L as Cd)	0.1 (0.1-0.4)	0.11 (0.08-0.2)	0.12 (0.04-0.72)	0.13	0.20	0.05 (0.03-0.07)	0.08 (0.02-0.26)	0.06 (0.04-0.08)
Cadmium Total (µg/L as Cd)	1.3 (0.4-1.3)	0.52 (0.34-0.73)	0.15 (0.1-0.33)	0.13 (0.1-0.2)	0.20 (0.2-0.21)	0.21 (0.17-0.25)	0.13 (0.05-0.35)	0.06 (0.04-0.1)
Copper Dissolved (µg/L as Cu)	7.3 (7-8.1)	10 (7.7-12)	6.5 (0.53-7.8)	4.4 (4.0-4.8)	5.05 (4.3-6.2)	6.6 (6.0-7.8)	6.4 (3.6-11)	5.9 (4.6-7)
Copper Total (µg/L as Cu)	11 (11-13)	14.4 (10-18)	3 (3-4)	5.0 (5.0-5.8)	8.0 (7.1-9.8)	7.8 (6.7-9.0)	6.8 (4.8-11)	8.6 (7.4-10)
Lead Dissolved (µg/L as Pb)	2.2 (1.7-3.8)	0.69 (0.35-1.2)	0.84 (0.84-1.0)	3.0 (2.0-3.0)	1.0	1.03 (0.65-1.75)	0.50 (0.5-0.7)	0.10 (0.07-0.14)
Lead Total (µg/L as Pb)	17.8 (14-18.4)	10 (8-13)	1.0 (1.0-1.7)	3.0 (2.0-4.0)	4.5 (3.4-6.1)	3.5 (3.0-5.8)	0.50 (0.5-0.64)	2.1 (1.54-3.1)
Nitrate + Nitrite (mg/L as N)	xx	0.10 (0.02-0.14)	0.04 (0.02-0.08)	0.03 (0.02-0.04)	xx	0.60 (0.3-0.8)	0.13 (0.13-0.13)	1.4 (1.16-2.06)
Nitrate (mg/L as N)	0.42 (0.27-6.4)	0.60 (0.4-0.64)	0.20 (0.16-0.28)	0.30 (0.22-0.45)	0.44 (0.38-0.49)	0.24 (0.21-0.3)	0.68 (0.42-0.78)	0.70 (0.62-0.89)
Ammonia (mg/L as N)	xx	0.04 (0.03-0.11)	0.04 (0.03-0.05)	0.06 (0.05-0.07)	xx	0.03 (0-0.06)	xx	0.08 (0.04-0.29)
Total Kjeldahl Nitrogen (mg/L as N)	0.9 (0.6-1.72)	1.2 (0.96-1.5)	1.16 (1.07-1.2)	1.0 (0.94-1.05)	1.33 (1.24-1.5)	1.08 (0.97-1.41)	1.22 (0.42-1.7)	1.20 (0.92-1.35)
Phosphorous Dissolved (mg/L as P)	0.08 (0.07-0.18)	0.07 (0.05-0.1)	0.05 (0.04-0.08)	0.06 (0.05-0.07)	0.22 (0.17-0.3)	0.27 (0.22-0.31)	0.03 (0.02-0.12)	0.08 (0.05-0.11)
Phosphorous Total (mg/L as P)	0.04 (0.03-0.06)	0.14 (0.11-0.19)	0.07 (0.06-0.08)	0.13 (0.12-0.16)	0.26 (0.23-0.31)	0.22 (0.18-0.23)	0.10 (0.09-0.25)	0.15 (0.12-0.16)
Total Suspended Solids (mg/L)	18 (12-37.5)	27 (19-34)	6.5 (5.2-8.5)	11.0 (9.7-12.4)	20.5 (18-24)	16.0 (13-24)	6.0 (4.8-8)	11 (9-14)
Zinc Dissolved (µg/L as Zn)	41 (38-47)	32 (24-44)	15.2 (10.1-21.3)	7.5 (5.2-10)	15.0 (13-19)	24.3 (22-29)	10.0 (3.9-21.5)	18.1 (9.8-21.8)
Zinc Total (µg/L as Zn)	60 (52-70)	68 (57-80)	17.0 (15-20)	17.7 (15-20)	30 (25-36.5)	30.8 (25-40)	19.0 (12.5-30.5)	23.8 (18-31)

Notes: xx—Lack of sufficient data to report median and confidence interval. Values in parenthesis are the 95% confidence intervals about the median. Data on other BMPs (e.g. Ecology Embankment) are not presented in this table, but when discussed the reader is referred to the appropriate table.
Source: International Stormwater BMP Database, October 15, 2005 (www.bmpdatabase.org). For gray-shaded cells, consider using western Washington values (Tables 12 and 15).

5.3.1 Particulate Matter (TSS)

Larger suspended solids can be removed effectively by gravitational sedimentation. For most well-designed BMPs that incorporate this UOP, the median effluent concentrations range from less than 10 to about 30 mg/L (Table 30), provided the concentration and characteristics (e.g., particle size distributions) of influent suspended solids do not significantly deviate from “typical” stormwater runoff. In general, settleable solids comprised of inorganic particles in the 25–75 µm range are effectively removed by quiescent gravitational sedimentation.

The presence of a permanent wet pool is a key feature of wet pond and constructed wetland systems. Incorporating even a small permanent wet pool into extended detention systems can significantly improve the sediment removal performance by providing long periods of retention during smaller storms and limiting re-entrainment of settled materials. Long retention times during small events allow for appreciable suspended solids removal compared to dry facilities that typically have more limited detention times during small events. Well-designed treatment systems that incorporate wet pools and wetland vegetation typically exhibit even lower suspended solids concentrations. Based on currently available data, these BMPs can typically achieve median effluent concentrations of about 6 to 11 mg/L. For detention basins, performance can likely be improved if the outlet is designed as a “multi-stage” outlet that allows for longer residence times for smaller storms. For example, if the drawdown time of a 36-hour drawdown basin were such that the top half drained over 12 hours and the bottom half drained over 24 hours, smaller storms would receive more detention and therefore more settling time.

For grass filter strips and biofiltration swales, the primary removal mechanisms for suspended sediments are gravity settling and, to a limited extent, filtration. Gravity separation is provided by slowing the flow and by the microbackwaters within the vegetation matrix. For media filters (e.g., sand filters, multi-chambered treatment trains), the primary removal mechanisms for suspended sediment are filtration and to a limited extent gravity settling. Well-designed biofiltration swales and media filters also perform well in achieving low effluent concentrations of suspended solids (on average a median of about 6 to 20 mg/L, Table 30), but effluent concentrations can be considerably lower in many storms (e.g., for western Washington; Table 18). Direct filtration can usually be accomplished effectively at concentrations less than 50 mg/L, and generally requires some level of pretreatment in urban runoff (where solids concentrations are frequently above 100 mg/L and can exceed 1,000 mg/L depending on the site, loading, and hydrology). Consequently, most media filtration BMPs include a pre-settling step.

5.3.2 Trace Metals

From a treatability and regulatory perspective, the important forms of trace metals are total, dissolved, and particulate-bound metals. If trace metals are bound to organic or inorganic particulates, viable unit operation processes include sedimentation and filtration either as separate or combined unit operations. Removal of particulate metals is reflected in the removal of suspended solids. If present as a dissolved ionic species (such as Cu^{2+}, Pb^{2+}, or Zn^{2+}), surface complexation, adsorption, and ion exchange could be effective. Complexation surfaces include soils, soil organic matter, hydrous iron oxides, clays and other amorphous alumino-silicates, algae (in the water column or on leaves), and living plant tissue. If present as a dissolved complex, adsorption or surface complexation can be much slower and even completely inhibited. More detailed information for individual metals is presented below.

Zinc (Zn). The median effluent quality of the BMPs assessed for total zinc ranged from ~17–70 µg/L (Tables 30, 12, 15, 18, and 22). Overall, well-performing wet ponds, constructed wetlands, biofiltration swales, and sand & peat filters should achieve effluent concentrations of the order of a median of 10–20 µg/L. Swales and filter strips have also shown a volume loss on the order of 40 percent from infiltration and/or evapotranspiration. Devices that use gravity alone, such as detention ponds, have the highest median concentrations of total zinc. Ecology embankments (Table 22) and grass filter strips (Table 30) have similar median total zinc concentrations of about 20 to30 µg/L.

Median effluent concentrations for dissolved zinc range from about 8 to 41 µg/L. Based on the limited data available, it appears that detention basins (using settling as the primary UOP) can achieve dissolved zinc concentration of the order 32–41 µg/L. Other BMPs that employ more targeted UOPs can achieve median concentrations in the range of about 7–18 µg/L, including ecology embankments, biofiltration swales, constructed wetlands, and sand filters, while the International Database indicates that wet ponds can achieve very low concentrations(Table 30). However, much higher dissolved zinc concentrations can be found in wet pond effluent in western Washington (14–41 µg/L).

Copper (Cu). Median total copper concentrations in BMP effluent range between about 3 and 15 µg/L (Tables 30, 12, 15, 18, and 22). With concentrations as low as 3-4 µg/L, constructed wetlands appear to have the lowest copper concentrations in their effluent (Table 30), although limited dissolved copper concentrations from one BMP study suggest that this is not always achievable (Table 30). Wet ponds, both from the International BMP Database (Table 30) and western Washington (Table 12) data, can achieve median total copper concentrations of about 4 to 6 µg/L. Detention basins have median EMCs for total copper of about 11 to 14 µg/L, while the other BMPs with more UOPs can achieve “intermediate” levels of 6–10 µg/L (see Tables 30, 15, and 22).

Median dissolved copper effluent concentrations in the International Database range from about 4 to 10 µg/L (Table 30). Overall, BMPs with multiple UOPs (e.g., sand/media filters, biofiltration swales, filter strips, constructed wetlands, and wet ponds) have dissolved copper concentrations of about 4 to 7 µg/L. The western Washington data for wet ponds (Table 12), biofiltration swales (Table 15), and ecology embankments (Table 22) suggest that much lower dissolved copper concentrations can be achieved, on the order of medians of 2 to 7 µg/L. This is a very important distinction, because water quality standards for copper in low hardness waters are about 5 µg/L.

Lead (Pb). Median effluent concentrations for total lead ranged from less than 1 up to18 µg/L (Table 30). Interpretation of results for both total and dissolved lead is hindered by the presence of a large number of non-detects and the wide range of dates of BMP monitoring data. Lead concentrations have been observed to be decreasing from concentrations observed in the late 1970s. This is believed to be the result of the removal of lead from gasoline. Concentrations of total and dissolved lead are typically lower than water quality criteria and standards and therefore in general do not appear to be an issue for ESA-listed species.

Cadmium (Cd). Total cadmium effluent levels ranged from about 0.06 to 1.3 µg/L (Table 30). Dissolved cadmium effluent levels were similar to total concentrations and ranged from about 0.06 to 0.2 µg/L. Data interpretation is somewhat hindered by low sample numbers and high detection limits. However, as these concentrations are lower than water quality standards, BMP effluent quality is thought to be acceptable for this constituent.

5.3.3 Phosphorus

Data for phosphorus are difficult to interpret. Dissolved phosphorus (soluble reactive phosphorus, or SRP) concentrations in the International Database seem to fall within two groups: high SRP for biofiltration swales and grass filter strips (~0.2–0.3 mg/L), and lower concentrations for other BMPs (<0.1 mg/L). The somewhat higher concentrations in biofiltration swales may be due to the release of phosphorus from amended soils in some facilities (or fertilization). In addition, some soils are naturally high in phosphorus, so there is the possibility that the UOPs operating in these biofiltration swales inherently raise SRP levels when soils are relatively high in fertility. The western Washington data for biofiltration swales (Table 15) and ecology embankments (Table 22) do not display as high of total phosphorus (TP) levels as those observed in the International BMP Database.

In the International Database (Table 30), lined detention basins and lined detention basins constructed wetlands have the lowest total phosphorus concentrations in effluent, while wet ponds have much higher concentrations (0.12–0.16 mg/L). While surprising considering the UOPs employed, this observation may reflect an inherent problem with BMPs where nutrients such as total phosphorus can be released during winter die-back of plants or during summer algae bloom. More research is needed of the dynamics and management of nutrients released from wet ponds and constructed wetlands.

Data from western Washington for wet ponds (Table 12) show consistently low levels of total phosphorus.

5.3.4 Nitrogen

Nitrogen nutrients are one of the more difficult contaminant to manage in runoff during storms. UOPs that remove particulate matter should control total Kjeldah nitrogen (TKN) effectively. Examination of the International Database (Table 30) shows reasonably consistent TKN concentrations across all BMPs, but the reason for this is not understood.

Nitrate forms the largest fraction of dissolved nitrogen in stormwater runoff, with ammonia concentrations being relatively low (and relatively unimportant in terms of impacts on receiving waters[5]). Nitrate concentrations reported in Table 30 are difficult to interpret and require additional work. The database reports nitrate and nitrite + nitrate as separate categories; often, nitrite concentrations are a very small fraction of nitrate, and these data groups can be combined. However, there are some significant inconsistencies between these two data groups in Table 30, so the data will need a closer examination before any combining or further assessment can be conducted.

[5] Concentrations are much lower than levels that are toxic to aquatic life.

Overall, on the basis of the UOPs employed, most BMPs would not be expected to reduce nitrate concentrations appreciably, except those with UOPs involving infiltration and evapotranspiration and those with microbiologically mediated reactions and that can provide sustainable and nonpolluting anoxic conditions. BMPs with these reactions include constructed wetlands and, in some situations, wet ponds. Data in Table 30 indeed indicate that the lowest nitrate concentrations are observed in constructed wetlands.

5.3.5 Organic Contaminants

In this white paper, total suspended solids are used as a surrogate indicator for particulate-associated organics; therefore, a lower TSS effluent concentration implies a lower concentration of particulate organic contaminants. In addition, UOPs that are effective for dissolved metals (e.g., chemical and physical adsorption) are also effective for the dissolved fraction of organic COPCs, because many surfaces in BMPs (e.g., soils, media, plant material) are coated with organic material. Therefore, while basic treatment (i.e., removal of TSS) as defined by Ecology is expected to reduce organic COPC by an amount commensurate with the TSS treatment, enhanced treatment is likely to achieve even greater treatments for organic COPC and result in increased safety for receiving waters. The section on TSS should be consulted regarding particulate-associated organics, and the section on dissolved metals should be consulted for the dissolved fraction of organics regarding BMP performance.

5.3.6 Conventional Water Quality Parameters

Little information is available for other conventional parameters, such as pH and dissolved oxygen. The BMP monitoring studies have recorded EMCs for hardness because this parameter is used to derive and evaluate water quality criteria values for copper, zinc, lead, and other heavy metals. The reported concentrations are highly variable (WSDOT 2006b) and probably depend on storm size (and associated dilution effects), as well as local geology (e.g., soil/rock/water interaction). This hardness information will be useful for the white paper on impacts on ESA-listed species (Herrera 2007b). However, further work is recommended to understand the cause of the variability in hardness values so that reasonable expected hardness concentrations can be used to then assess whether BMP effluent concentrations of heavy metals are protective (e.g., effluent data are above or below water quality criteria values computed from hardness values). This is critical because of the similarity of dissolved copper concentrations in BMP effluents and water quality criteria at low hardness, as described earlier.

References

ASCE. 1998. Urban Runoff Quality Management, Manual and Report of Engineering Practice 87. American Society of Civil Engineers. Reston, Virginia.

ASCE. 2001. Guide for Best Management Practice (BMP) Selection in Urban Developed Areas. American Society of Civil Engineers. Reston, Virginia.

ASCE and EPA. 2007. International Stormwater BMP Database. American Society of Civil Engineers and U.S. Environmental Protection Agency, in association with other agencies and organizations. Obtained in 2007 from website. <www.bmpdatabase.org>.

Brown, W., and T.R. Schueler. 1997. National Pollutant Removal Performance Database for Stormwater BMPs. Center for Watershed Protection, Elliott City, Maryland.

Caltrans. 2006. Treatment BMP Technology Report. CTSW-RT-06-167.02.02. California Department of Transportation, Division of Environmental Analysis. April 2006. Obtained from agency website. <http://www.dot.ca.gov/hq/env/stormwater /annual_report/2006/Attachments/CTSW-RT-06-167.02.02.pdf>.

CASQA. 2003. New Development and Redevelopment Handbook. California Stormwater Quality Association. Obtained from agency website. <http://www.cabmphandbooks.com/Development.asp>.

Driscoll E.D., E.W. Strecker,. and P.E. Shelley, "Pollutant Loadings and Impacts from Highway Stormwater Runoff," Volume I, Design Procedures, FHWA-RD-88-006, March 1990; "Users Guide for Interactive Computer Implementation of the Design Procedure," Volume II, FHWA-RD-88-007, March 1990; "Analytical Investigation and Research Report," Volume III, FHWA-RD-88-008, March 1990; "Research Report Data Appendix," Volume IV FHWA-RD-88-009, March 1990.

EPA Office of Water. 1999. Stormwater Technology Fact Sheet: Bioretention. EPA 832-F-99-012.

Herrera. 2007a. Untreated Highway Runoff in Western Washington. Draft. Prepared for Washington State Department of Transportation, Olympia, Washington, by Herrera Environmental Consultants, Inc., Seattle, Washington. September 2007.

Herrera. 2007b. Potential Effects off Highway Runoff on Priority Fish Species in Western Washington. Draft. Prepared for Washington State Department of Transportation, Olympia, Washington, by Herrera Environmental Consultants, Inc., Seattle, Washington. September 2007.

Herrera. 2007c. Unpublished water quality data from WSDOT's NPDES monitoring program, provided to Geosyntec Consultants by Dylan Ahearn, Herrera Environmental Consultants, Seattle, Washington. May 2007.

Jones, Jonathan E., Thomas Langan, Elizabeth A. Fassman, Ben Urbonas, Eric Strecker, and Marcus Quigley. 2004. "Why is it so Difficult to Acquire Reliable BMP Performance Data?" In: Proceedings of the World Water and Environmental Congress 2004, June 27-July 1, 2004, Salt Lake City, UT. Edited by Gerald Sehlke, Donald F. Hayes, and David K. Stevens, ISBN 0-7844-0737-1. American Society of Civil Engineers, Reston, Virginia.

NCHRP. 2006. Evaluation of Best Management Practices for Highway Runoff Control, National Cooperative Highway Research Program, NCHRP Report 565. Obtained from organization website. <http://www.trb.org/crp/nchrp/nchrpprojects.asp>.

Pitt, R. 2002a. Emerging Stormwater Controls for Critical Source Areas. In: Management of Wet-Weather Flows in the watershed (Edited by D Sullivan & R Field). CRC Press, Boca Raton, Florida.

Pitt, R. 2002b. Stormwater treatment at critical source areas using the Multi-Chambered Treatment Train (MCTT). Presented at the 2002 Borchardt Conference, a Seminar on Advancements in Water and Wastewater. University of Michigan, Ann Arbor, Michigan. February 2002.

Pitt, R., B. Robertson, P. Barron, A. Ayyoubi, and S. Clark. 1999. Stormwater Treatment at Critical Areas; the Multi-Chambered Treatment Train (MCTT). EPA Report No. EPA/600/R-99/017. U.S. Environmental Protection Agency, National Risk Management Laboratory, Cincinnati, Ohio. 505pp.

Shoemaker, L., M. Lahlou, A. Doll, and P. Cazenas. 2000. Stormwater Best Management Practices in Ultra-Urban Setting: Selection and Methodology, Federal Highway Administration, FHWA-EP-00-002.

Strecker, E.W., M.M. Quigley, B. Urbonas, J. Jones, and J.K. Clary. 2001. Determining Urban Storm Water BMP Effectiveness, J. Water Resources Planning and Management, 127 (3), 144-149.

Strecker, E., B. Urbonas, M. Quigley, J. Howell, and T. Hesse. 2002. Urban Storm Water BMP Performance Monitoring, A Guidance Manual for Meeting the National Storm Water BMP Database Requirements. U.S. Environmental Protection Agency, USEPA-821-C-02-005, 214pp. April 2002.

Strecker, Eric, W. Huber, J. Heaney, D. Bodine, J. Sansalone, M. Quigley, M. Leisenring, D. Pankani, and A. Thayumanavan. 2005. Critical Assessment of Stormwater Treatment and Control Selection Issues, Water Environment Research Foundation Report 02-SW-1. Accessed online at: https://www.werf.us/products/products.cfm.

Tveten, Richard, WSDOT, pers. comm. 2007

Winer, R. 2000. National Pollutant Removal Performance Database for Stormwater Treatment, 2nd edition, Center for Watershed Protection, Elliott City, Maryland.

WSDOT. 2006a. Highway Runoff Manual. M 31-16. Prepared by the Washington State Department of Transportation Environmental Services Office Stormwater Program. May 2006. Accessed online at: http://www.wsdot.wa.gov/Environment/WaterQuality/Runoff/HighwayRunoffManual.htm

WSDOT. 2006b. Stormwater Report. Washington State Department of Transportation. Obtained from agency website: www.**wsdot**.wa.gov/NR/rdonlyres/09450DED-E0BC-4568-BFF6-341BD96434C9/0/2006StormwaterReport.pdf.

WSDOT. 2007. NPDES Annual Progress Reports. National Pollutant Discharge Elimination System reports. Obtained in 2007 from Washington State Department of Transportation website. www.wsdot.wa.gov/Environment/WaterQuality.

Appendix 1
Source Control BMPs for Highway Runoff in Washington

In addition to the treatment BMPs discussed in the white paper, the 2006 HRM lists the following source control BMPs:

- Deicing and anti-icing for streets/highways
- Dust control at disturbed land areas and unpaved roadways and parking lots
- Fueling at dedicated stations
- Illicit connections to storm drains (i.e., unpermitted sanitary or process water discharged to a storm drain, rather than a sanitary sewer connection)
- Landscaping and lawn/vegetation management
- Maintenance and repair of vehicles and equipment
- Maintenance of roadside ditches
- Maintenance of stormwater drainage and treatment systems
- Painting of buildings and structures (bridges and docks)
- Parking and storage of vehicles and equipment
- Railroad yards
- Spills of oil and hazardous substances
- Storage or transfer (outside) of solid raw materials, byproducts, or finished products
- Urban streets
- Washing and steam cleaning of vehicles, equipment, and building structures.

These should certainly be considered when evaluating and selecting BMPs in all cases, but especially when ESA issues are being addressed.

Appendix 2
Highway Runoff Manual Treatment BMP Selection Process

Summary of selection procedures for treatment BMPs (reproduced from the 2006 HRM)

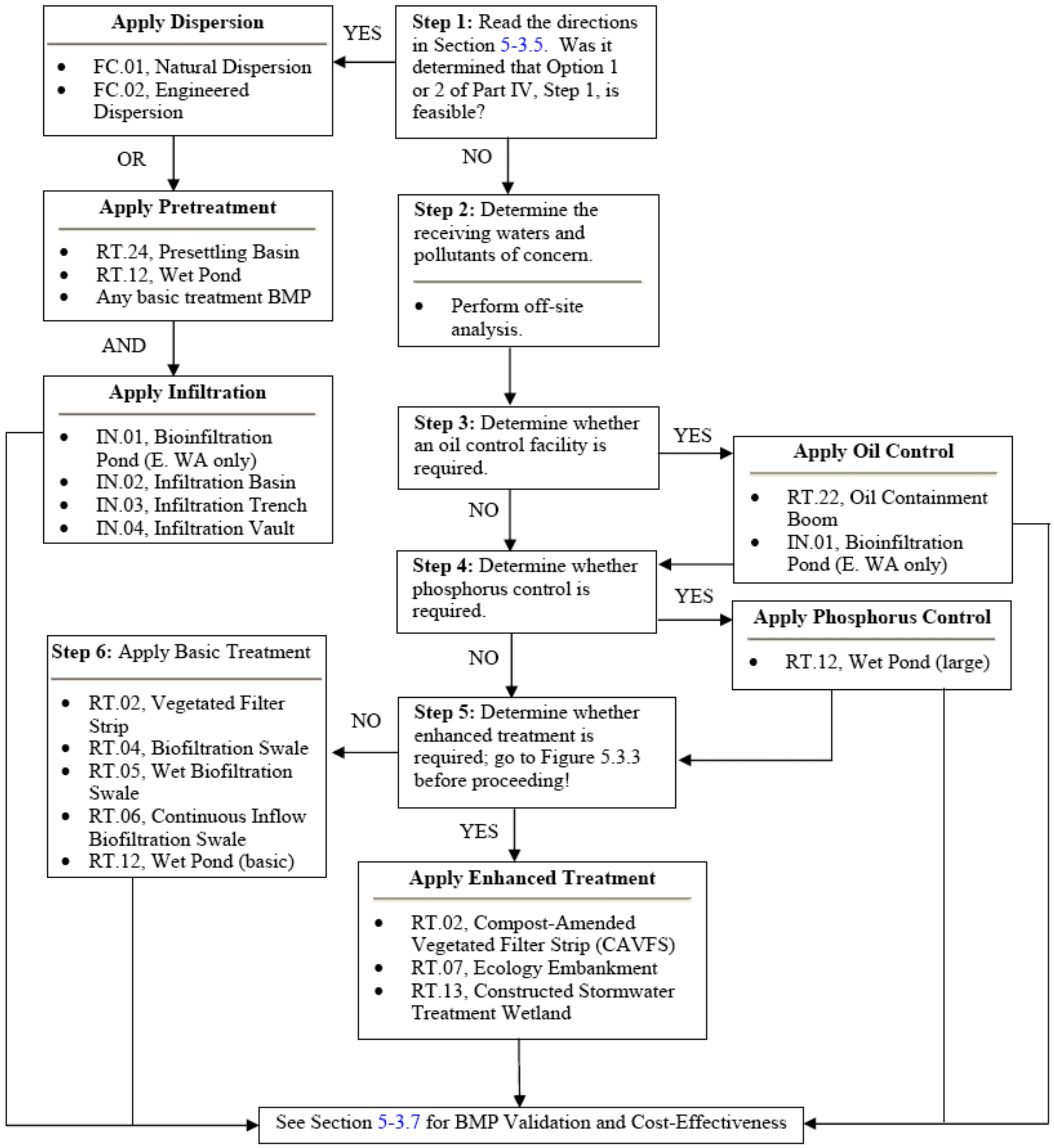


Figure 5.3.2. Runoff treatment BMP selection process.

Table 3-1. Runoff treatment targets and applications for roadway projects.

Treatment Target	Application	Performance Goal
Basic Treatment	All project threshold discharge areas (TDAs) where runoff treatment threshold is met.	80% removal of total suspended solids (TSS)
Enhanced Treatment (dissolved metals)	Same as for Basic Treatment. AND Roadway ADT[1] is ≥ 30,000 or is required by an adopted basin plan or water cleanup plan/TMDL. (See Table 3-2 for receiving water exemptions.)	Provide a higher rate of removal of dissolved metals than Basic Treatment facilities for influent concentrations ranging from 0.003 to 0.02 mg/L for dissolved copper and 0.02-0.3 mg/L for dissolved zinc
Oil Control	Same as for Basic Treatment. AND There is an intersection where either ≥15,000 vehicles (ADT) must stop to cross a roadway with ≥25,000 vehicles (ADT) or vice versa.[2] OR Rest areas with an expected ADT count equal to or greater than 100 vehicles per 1,000 square feet of gross building area. OR Maintenance facilities that park, store, or maintain 25 or more vehicles (trucks or heavy equipment) that exceed 10 tons gross weight each.	No ongoing or recurring visible sheen and 24-hr average total petroleum hydrocarbon concentration of not greater than 10 mg/L with a maximum of 15 mg/L for a discrete (grab) sample
Phosphorus Control	Same as for Basic Treatment. AND The project is located in a designated area requiring phosphorus control as prescribed through an adopted basin plan or water cleanup plan/TMDL.[3]	50% removal of total phosphorus (TP) for influent concentrations ranging from 0.1 to 0.5 mg/L TP

[1] Average daily traffic (ADT) is generally the design year ADT and not the current ADT. A possible exception to this rule is where road ADTs would likely never reach levels that would exceed its design capacity (such as with rural portions of the state). Contact region hydraulics staff for more information.

[2] Treatment is required for these high-use roadway intersections for lanes where vehicles accumulate during the signal cycle, including left- and right-turn lanes from the beginning of the left-turn pocket. If no left-turn pocket exists, the treatable area must begin at a distance equal to three car lengths from the stop line. If runoff from the intersection drains to more than two collection areas that do not combine within the intersection, treatment may be limited to any two of the collection areas where the cars stop.

[3] Contact WSDOT region hydraulics or environmental staff to determine if phosphorus control is required for a project.

Appendix 3
Highway Sweeping

Introduction

A great deal of controversy surrounds the effectiveness of highway sweeping as a BMP. Conflicting claims have been made, and there does not appear to be a definitive assessment in the BMP literature, partly because of the paucity of defensible data. In this appendix, a qualitative assessment using multiple lines of evidence, focusing on the available studies on urban streets (as opposed to highways; most studies on sweeping effectiveness have focused on streets).

Street Sweeping Studies

The effectiveness of street sweeping as a BMP for pollutant removal has been controversial for many years. Given all the materials (including trash, vegetative debris, and sediments) that re removed by street sweepers, many people believe that street sweeping is also effective at removing pollutants. However, in the early 1980s, one of the definitive conclusions of the EPA-sponsored Nationwide Urban Runoff Program (NURP), which collected runoff water quality data from catchments with different sweeping regimes, found that street sweeping was generally an ineffective technique for improving the quality of urban runoff for the pollutants that were analyzed (EPA 1983).

Street sweeping as an effective stormwater runoff quality BMP has undergone some renaissance, with the advent of more sophisticated cleaners (e.g., mechanical/vacuum/ regenerative cleaners), as well as a better understanding of the controlling factors that can influence effectiveness. Recent modeling studies have suggested that street sweeping programs can be optimized to significantly reduce pollutant wash-off from urban streets (Sutherland and Jelen 1997). However as discussed below these estimates are highly questionable.

Numerous factors influence the effectiveness of street sweeping, contributing to the uncertainties and controversies surrounding its use as a BMP. A review by Pitt (1996) lists the following factors:

- Street texture–Dirt pickup is more effective on smooth streets.
- Street loading–Dirt pickup is more efficient at higher street loading.
- Large particle armoring may prevent removal of smaller particles.
- Moisture inhibits pick up.
- Wind/turbulence redistribution–Sweeping should include the whole impervious area and not just the gutter.
- Dust and pollutant buildup rates can be much more rapid than street cleaning frequencies.
- Parking inhibits regular cleaning.
- Driver and device operation abilities are a big factor in efficiencies, especially with respect to speed and clogging.

In addition to the above factors, sweeping of the entire paved area is usually not completed, as well as the fact that there are many other sources not affected by sweeping as described above.

The following describes some of the key factors that affect street sweeping performance.

Particle Size Effects—It is generally accepted that sweepers that remove finer particles will improve runoff water quality. Earlier mechanical street sweepers removed primarily coarse particles (about 70 percent), while rain removed significant amounts of finer particles (about 50 percent) (Pitt 2002). A more recent study (Valiron 1992) confirmed that conventional sweepers achieved only 15 percent removal of those particles less than 40 µm compared to 80 percent removal of particles greater than 2 mm. If most of the mass of contaminants is associated with fine particles, this implies removal efficiencies of 15–80 percent (and likely closer to 15 percent). However, without knowing the size distribution of the sweepings and the concentrations in each size class, it is impossible to predict the efficiency, but less then 15 to 30 percent does not seem unlikely.

Climate Effects—In humid areas, frequent rain minimizes the accumulation of dust and dirt, consequently reducing the apparent effectiveness of sweeping. However, in drier climates where rains are relatively infrequent, streets become quite dirty during the late summer and fall. Street sweeping studies in southern California have shown reductions in concentrations of suspended solids and heavy metal in runoff (Pitt 2002, based on Pitt 1979, Pitt and Shawley 1982) from removal of this dry weather buildup.

Pickup Efficiency—Various reports and studies have claimed or measured different pickup efficiencies. It is impossible to specify a general street sweeping effectiveness because it depends on the many factors described above, as well as particle size measured. Reported efficiencies range from 0 to about 80 percent % for total solids. The higher reported rates are associated with modern efficient sweepers (i.e., sweepers capable of removing small particles) and high frequency of cleaning (Bannerman et al. 2003).

Modeling – Models also have been used to estimate the theoretical effectiveness of street sweeping. “Calibrated” simulation models have taken these factors into account, such as the Simplified Particulate Transport Model (SIMPTM) developed by Sutherland and Jelen (1993, 1996) or the Source Loading and Management Model (SLAMM) developed by Pitt and Voorhees (2000). Some researchers have “calibrated” and applied these models to estimate loads and concentrations from stormwater catchments, as well as to evaluate BMP effectiveness, including street sweeping .

Sutherland and Jelen (2003) (and a number of others) rely on models that use street (and catch basin) buildup/wash-off (BU/WO) functions for introducing all pollutants into runoff. Therefore all other processes for how pollutants are entrained into runoff are assumed to be negligible. However this is certainly not the case as pollutants can be introduced via in the precipitation itself, leaching from highway construction materials, dripping from vehicles during precipitation, run-on from adjacent land uses/covers including roofs and from landscaped and open areas as well as many other sources. Whether these models are “calibrated” to measured BU/WO values (not really a calibration to the parameters of interest) or calibrated to outfall runoff concentration and loading data, when they are used to model street sweeping effectiveness they will significantly over-predict the effectiveness of street sweeping (and catch basin cleaning). This is due to the fact that the sweeping (and catch basin cleaning) are assumed to act on the BU/WU source mechanism(s) in the model. Finally, these models typically model other pollutants based on relationships with TSS, which for many pollutants (especially dissolved ones) is not accurate. In fact, it is likely there is an inverse relationship between TSS and dissolved constituents such as copper for example. Users of the modeling approaches described above predict significant reductions in pollutants in stormwater that have not been able to be observed in actual monitoring studies as described below.

Pollutant Accumulation—Strong seasonal effects exist because of the buildup of pollutants during the drier summer and from leaf fall in autumn months. Note that this buildup is not progressive; after a while, wind and vehicle turbulence limit the accumulation. Street dust buildup rates are highly variable. The maximum loading condition is approached asymptotically with time, and Sartor and Boyd (1972) showed that street loading substantially rebounded within only 1–2 weeks following rain events and sweeping. Pitt (1996) summarized rates for North America, which showed highly variable buildup after sweeping (10–70 days), with the longer times associated with rough streets and dry climates.

In conclusion, there are no definitive studies demonstrating the benefits of street cleaning on contaminant loads in studies that monitored runoff (Selbig and Bannerman 2007). Modeling and studies on contaminant accumulation and removal on street surfaces suggest that effective street sweeping could be achieved if highly efficient sweepers (i.e., sweepers capable of removing small particles) were strategically applied at frequent intervals (i.e., weekly to twice monthly) under proper operating conditions (i.e., no parked cars, correct speeds, and complete street coverage). However, these estimates are likely overestimated due to the problematic modeling assumptions discussed above.

Highway Street Sweeping Studies

High-efficiency street sweepers have been reported to reduce the TSS loads from freeways by about 45 percent (Martinelli et al. 2002), if freeways were swept weekly. A research project to study the effectiveness of a high-efficiency street sweeper used on an urban freeway section to control the quality of stormwater runoff from the pavement surface was conducted by the Wisconsin Department of Transportation, Bureau of Highway Operations (Martinelli et al. 2002). The research process used a paired basin approach using a test section that was swept once per week and a control section that was not swept during the study period. The results of the study indicated with a 90 percent confidence interval that there was a difference of 1 percent and 280 percent in suspended sediment concentrations between the control and test sites, respectively. The researchers concluded that detecting differences due to sweeping is difficult because stormwater quality is so variable and because of the difficulties in measuring particulate matter in freeway runoff. It is likely that the differences are small enough (e.g., 20 percent or so) that detecting the difference would take upwards of 60 to 100 monitoring events given the variability.

Caltrans was concerned that the maximum operating speed of the high-efficiency sweeper precluded it from being used in freeway applications; thus, the agency chose a broom sweeper for its sweeping frequency study. The analysis indicated that litter reduction from monthly sweeping (as compared to weekly) was not statistically significant at the 95 percent confidence level. Analysis of conventional water quality constituents such as metals, nutrients, oil and grease, total suspended solids, and coliform bacteria showed that increasing sweeping from monthly to weekly actually may have increased the concentrations of hardness, total and dissolved copper, dissolved nickel, and total petroleum hydrocarbons (diesel). The cause of this increase is unknown, but could be due to the abrasive action of the sweeper on the road surface, the removal of street litter with pollutant sorption ability, or simply the random variability of the data. In view of the earlier EPA (1983) studies, the Caltrans results are hardly surprising, and broom sweeping of highways is unlikely to significantly reduce contaminant concentrations (except trash and other coarse materials).

In another study, Smith (2002) evaluated the effectiveness of mechanized street sweepers at particulate removal. The first mechanized street sweeping had no observable effect on subsequent storm loads of suspended sediment. Following the second sweeping, a net increase of the suspended-sediment load was observed at one station, and a net decrease of the suspended-sediment load was observed at the second station; however, these effects were only temporary. The highway was swept a third time after continuous monitoring was terminated. The particle-size distribution in sweeper samples for the size fraction less than 4 mm in diameter was similar to the particle-size distribution in bottom sediment in the catch basin. The concentration of particles greater than 0.5 mm in diameter was higher in sweeper samples than in samples from the oil/grit separators, only allowing the conclusion that the sweepers were successful in removing the larger particles.

In conclusion, with respect to highway runoff, monitoring studies have failed to measure benefits to stormwater quality from sweeping, a conclusion reached by one of the principal researchers for this BMP type (Bannerman, pers. comm. 2007). Modeling predictions and studies of contaminants on street surfaces indicate benefits to street and highway runoff quality, but only if the surfaces are swept frequently and under appropriate operating conditions. These conditions are unlikely to be met on highways.

References

Bannerman, R., G. Fries, and J. Horwatich. 2003. “Source Area and Regional Stormwater Treatment Practices: Options for Achieving Phase II Retrofit Requirements in Wisconsin.” Proceedings of the National Conference on Urban Stormwater-Enhancing Programs at the Local Level, Chicago, IL (February 17-20, 2003). pp. 12-19.

Bannerman, Roger. Wisconsin DNR. pers. comm. 2007.

EPA. 1983. Final Report of the Nationwide Urban Runoff Program. U.S. Environmental Protection Agency, Water Planning Division.

Martinelli, T.J., R. Waschbusch, R. Bannerman, and A. Wisner. 2002. Pollutant Loadings to Stormwater Run-Off from Highways: The Impact of a Sweeping Program. Report, Wisconsin Department of Transportation, Division of Transportation Infrastructure Development, Bureau of Highway Operations. 94 pp.

Pitt, R.E. 1979. Demonstration of Nonpoint Pollution Abatement through Improved Street Cleaning Practice. Final Report, U.S. Environmental Protection Agency.

Pitt, R. 1996. Accumulation, washoff, and size distributions of stormwater particulates. In Solids in Sewers: Characteristics, Effects, and Controls of Sewer Solids and Associated Pollutants. Scientific and Technical Report of the International Association of Water Quality (IAWQ). London.

Pitt R. 2002. Emerging Stormwater Controls for Critical Source Areas. In: Management of Wet-Weather Flows in the watershed (Edited by D Sullivan & R Field). CRC Press, Boca Raton, Florida.

Pitt, R.E., and G. Shawley. 1982. A Demonstration of Nonpoint Pollution Management on Castro Valley Creek. Alameda County Flood Control and Water Conservation District, Hayward, California.

Pitt, R.E., and J. and Voorhees. 2000. *The Source Loading and Management Model (SLAMM), A Water Quality Management Planning Model for Urban Stormwater Runoff*. University of Alabama, Department of Civil and Environmental Engineering, Tuscaloosa, Alabama. Obtained from website. <www.winslamm.com>.

Sartor, J., and G. Boyd. 1972. Water Pollution Aspects of Street Surface Contaminants, U.S. Environmental Protection Agency Report, EPA-R2-72-081.

Selbig, W.R., and Bannerman, R.T., 2007, Evaluation of street sweeping as a stormwater-quality-management tool in three residential basins in Madison, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2007–5156, 103 p.

Smith, K.P. 2002. Effectiveness of Three Best Management Practices for Highway Runoff Quality along the Southeast Expressway, Boston, Massachusetts. Water-Resources Investigations Report, U.S. Geological Survey. 170pp.

Sutherland R. C. and S. L. Jelen. 2003. SIMPTM Diagnosis, A technique for accurate urban runoff load estimation WE&T, September. pp. 59-66

Sutherland, R.C., and S.L. Jelen. 1997. Contrary to Conventional Wisdom: Street Sweeping can be an Effective BMP. Advances in Modeling the Management of Stormwater Impact, Vol. 5.

Sutherland, R.C., and S.L. Jelen. 1996. Sophisticated stormwater quality modeling is worth the effort. In: Advances in Modeling the Management of Stormwater Impacts. Edited by W. James. Computational Hydraulics International. Guelph, Ontario.

Sutherland, R.C., and S.L. Jelen. 1993. Simplified Particulate Transport Model-Users Manual, Version 3.1.

Valiron, F. 1992. Usual techniques for stormwater pollutant removal in urban areas. (in French) *Provisory Report for the Seine-Normandie Water Agency*, 61 p.