NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

# NCHRP REPORT 565

# Evaluation of Best Management Practices for Highway Runoff Control

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# NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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# CHAPTER 1

# Introduction and Objectives

## 1.1 Motivation and Objectives

Many forms of stormwater-related nonpoint source pollution from highways are associated with detrimental water-quality characteristics of surface waters. Highways are the vital arteries of the nation, but prevention or mitigation of the discharge of pollutants from highways has become a primary goal for many jurisdictions, including state departments of transportation (DOTs). As vehicular traffic on highways has increased, vehicular-related pollution (oil and grease, heavy metals, nutrients, and sediment) has become an even greater problem. Furthermore, highways serve as a streamlined means of transport for other sources of pollution such as irrigation run-on, pesticides and fertilizers from landscaped areas, and particulates from pavement breakdown. Finally, because of limited infiltration and expedited transport of runoff, paved surfaces promote a variety of indirect water-quality problems such as higher temperature of discharge and increased flooding hazards.

In recognition of the urgent need by highway engineers and related environmental professionals for guidance, the National Cooperative Research Program (NCHRP) initiated NCHRP Project 25-20(1) with a goal of providing a means for evaluating best management practices (BMPs) and low-impact development (LID) for stormwater quantity and quality. An evaluation scheme for implementation of BMP and LID facilities in the highway environment has been prepared. To the extent possible, fundamental principles of environmental engineering unit processes are applied to the analysis of the many BMP/LID options. In addition to considering hydrologic and water-quality issues, management practices are considered in the evaluation scheme, including issues of safety, operation and maintenance, practicability constraints, regional issues, costs, and other concerns. The evaluation methods developed during this project include methods applicable to both BMP and LID facilities. This report presents findings related to the research that are moderately peripheral to the main goal of presenting screening guidance to highway engineers for selection and preliminary design of facilities for control of stormwater quality and quantity. That guidance is presented in *CRP-CD-63* (affixed to the back cover of this book), which contains the *User Guide for BMP/LID Selection*, designated henceforth in this document by the briefer *Guidelines Manual*. While there are several reports and web sites with design guidance for BMPs, less guidance is available for LID, especially in the highway context. Hence, an additional project report, the *Low-Impact Development Design Manual for Highway Runoff Control* (designated henceforth as the *LID Design Manual* and also available on *CRP-CD-63*), presents detailed design guidelines for LID facilities in the highway environment.

Two rainfall-runoff models were used extensively in the project to simulate regional hydrologic impacts on BMP performance. One model, the USEPA Storm Water Management Model (SWMM), may be obtained directly from that agency at http://www.epa.gov/ednnrmrl/models/swmm/index.htm. The second model is a spreadsheet model developed at the University of Florida, primarily for this project. That model and its documentation are also included in *CRP-CD-63*. Modeling results are presented in detail in the *Guidelines Manual* and its appendices.

## 1.2 Background

The Clean Water Act was revised in 1987 in an attempt to address nonpoint source pollution via the National Pollutant Discharge Elimination System (NPDES). As a result, state agencies—such as DOTs—as well as cities, counties, and municipalities were required to meet discharge requirements for runoff originating within their jurisdictions. "Best management practice" (BMP) became probably the three most common words in the stormwater management vocabulary and were used to describe everything from street sweeping to constructed wetlands, regardless of whether a particular management measure was the “best” management practice for the site conditions and constraints. In the late 1990s, decentralized hydrologic source control was formalized as low-impact development (LID) by the Prince George’s County Department of Environmental Regulation (Prince George’s County 1997, 2000) in Maryland as a viable alternative to watershed outlet (“end-of-pipe”) treatment. Analogous to the indiscriminate use of BMPs whether or not they are in fact the “best” management practices for a particular site is the broad interpretation of the term “LID,” especially with regard to what constitutes “low” impact. Nonetheless, the principle of decentralized, on-site retention of stormwater is of great value.

## 1.3 What’s in a Name (Typology of Wet-Weather Control)?

Wet-weather controls have various names around the world. BMPs are best known in North America (and perhaps worldwide). However, “sustainable urban drainage systems” (SUDS) is the terminology used in the United Kingdom, and “stormwater quality improvement devices” (SQIDs) is used in Australia. The name SUDS suggests that these systems rank higher on the sustainability scale (CIRIA 2000a, 2000b, 2000c). However, the term “sustainability” is not very well defined in the science of stormwater management. One general definition is that sustainability requires a balance among community development, economic development, and ecological protection (ICLEI 1996). The concept of sustainability can also mean calculating the cost of a wet-weather control based on compliance or resource protection over the life cycle of the project rather than just on the expenditures necessary to complete the project.

LID has a more restricted meaning (decentralized hydrologic source control) than does BMP, but it is also widely used in the United States. The LID approach is based on selecting “integrated management practices” (IMPs), which are distributed small-scale controls that can closely maintain or replicate the hydrology of predevelopment conditions or achieve another identified regulatory requirement or other resource protection goals. Rather than working from a small range, or list, of BMPs, the goal is to achieve the highest efficiency in or effectiveness at approximating the predevelopment condition or other requirements.

BMP and LID are most often associated with control of stormwater only, whereas runoff from urban areas can occur during dry weather as well (e.g., baseflow in channels from irrigation and other common urban sources can cause runoff), and many of the same control principles (discussed below) apply to control of wet-weather phenomena such as combined sewer overflows (CSOs) and to dry-weather, sanitary sewer overflows (SSOs) (due to infiltration into the sewer system).

With the exception of some baseflow in arid areas, most discharges do originate as a result of current or recent rainfall. However, there appears to be no universally accepted terminology for control of such discharges. If a practice is shown to be the most cost-effective control, then it would be the “best” wet-weather control. This term combines and synthesizes all of the key characteristics of BMPs, IMPs, and SUDS. Wright and Heaney (2001) presented an overview of how distributed BMPs (wet-weather controls) can be an integral and cost-effective component of stormwater management in urban areas. They argue that sustainability principles such as decentralized or distributed systems may provide better long-term solutions because the stormwater is managed close to its source in a distributed manner.

The consensus within the highway engineering community is that whether or not BMP is the best terminology for a wet-weather control, almost every drainage engineer has a good idea of what is meant by BMP. BMP is generally an inclusive term, one that includes LID-like devices that emphasize infiltration and evapotranspiration (ET) for retention of stormwater, but it often connotes an end-of-pipe treatment facility, such as a detention pond or wetland. Nonetheless, BMP is used throughout this report and the *Guidelines Manual* to mean control of discharges from highway and urban areas that typically originate from rainfall. BMP in this document will often, but not always, include LID within its meaning. BMP/LID will be used, despite its awkwardness, when it is necessary to emphasize application to both.

## 1.4 Environmental Engineering Principles

Many organizations have developed their own stormwater BMP design manuals, and a large number are currently in existence. While many of these manuals are quite good and provide helpful recommendations on choosing and sizing structural stormwater BMPs, a number of them lack a conceptual framework for addressing specific stormwater-quality and -quantity issues occurring at a particular site. The general approach in most manuals that are currently available is to choose a BMP that has been shown to address the pollutants of concern and then apply “rules-of-thumb” sizing and design methods. While this is often an appropriate and valid approach, it does not adequately build upon more than a century of accumulated experience in the fields of environmental process and wastewater engineering (e.g., Metcalf and Eddy 2003) and indeed the full suite of technical skills and experience available to professional civil and environmental engineers. Use of treatment trains (BMPs in series) and integration of fundamental unit operations and processes (UOPs) are some of the most basic and profound concepts of environmental engineering. Unfortunately, these concepts have only recently been advocated as design approaches for stormwater treatment. As stormwater regulations continue to become more stringent, the need for more advanced treatment technologies will grow. However, in order to meet this need, the collective knowledge and understanding of stormwater treatment must be reduced to a more fundamental level, which may require drainage engineers to be open to new ideas, as well as the tried-and-true treatment technologies of the wastewater industry. Because of the complexity of the fundamental unit processes for treating many stormwater constituents, available information on field-verified treatability is currently limited. Thus, until the knowledge base of UOPs for stormwater treatment is expanded, reliance on theoretical principles and laboratory analyses will be needed.

The *Guidelines Manual* of this project provides a framework for applying fundamental principles of UOPs, such as those commonly applied in water and wastewater engineering, to aid in the evaluation and selection of runoff management and treatment control systems for highway and urban areas. As opposed to other design approaches that recommend the selection of BMPs based solely on documented performance factors such as percent removal and effluent quality and/or percent capture, the design approach presented in this project is to first select the UOPs that address the pollutants of concern and then to individually select treatment system components (TSCs) based on those UOPs. However, in accordance with the earlier discussion of terminology, BMP is used generically instead of TSC. Within this research report, UOPs are discussed in the context of their incorporation into common BMPs. This information serves as a technical background for the BMP/LID evaluation strategy presented in the *Guidelines Manual*. LID facilities treat stormwater according to exactly the same UOP principles, and this research report also provides background on the design principles described in the *LID Design Manual*.

Available stormwater treatability options as a function of complexity and scope are presented schematically in Figure 1-1. Within this project, the *Guidelines Manual* and the *LID Design Manual* refer to the material presented in the lower part of the figure, whereas this research report deals more with the principles embodied in the middle and top parts of the figure.

## 1.5 Taxonomy of Road and Drainage Systems

It is useful to place stormwater issues for highways in context. FHWA statistics classify urban and rural roads according to population density rather than design capacity or other functional characteristics. The FHWA provides statistical data concerning highway planning, development, financing, construction, operation, modernization, maintenance, safety, and traffic conditions (http://www.fhwa.dot.gov/policy/ohim/hs04/index.htm). These data are needed to meet DOT responsibilities to Congress and the general public. The data are not used for roadway design purposes and/or BMP design, but rather as an accounting and planning tool. Nonetheless, the data are useful in conveying the enormous magnitude of highways in the United States.

Nearly four million miles of road exist in the United States, as shown in Table 1-1. Over 77% of these roads are in rural areas. In keeping with this report's focus on the handling and treatment of stormwater, "urban" and "rural" are defined here according to the type of runoff conveyance system used. The 2006 Florida DOT *Drainage Manual* (State of Florida DOT 2006) differentiates between urban and rural as follows, with respect to major culvert installations: "Urban facilities include any typical section with a fixed roadside traffic barrier such as curb or barrier wall. Additionally, rural typical sections with greater than 1,600 ADT are also included in this [major culvert installation] category." The implication is that rural roads generally have open drainage, such as ditches, whereas urban roads may have piped systems to accommodate curbs and gutters.

The focus of this project is on how BMP and LID facilities can be incorporated into both types of DOT road systems. Typically, public transportation agencies own and manage about 20% of these roads. (Some states, such as Virginia, maintain almost all of the highway and local roadway systems.) In this project, attention has been restricted to the typical DOT highways, to focus efforts on the 20% of the transportation network that carries the bulk of the traffic. The remaining 80% of the roads are used less intensively, and many of them are primarily access roads; however, many stormwater control practices can be applied to these situations as well. DOT highways are those that are considered to be "large-scale" facilities with extensive infrastructure designed either to convey water generated from the roadway system and/or to convey off-site stormwater through the system.

The mix of roads owned by state DOTs is shown in Table 1-2. Nearly 86% of these roads are rural. Interstate and other expressways account for about 19.4% of the total mileage. Minor arterial roads comprise 28.5% of the mileage, other principal arterials comprise 21.5%, and local roads comprise 20.4%. Interstates, other expressways, and other principal arterial roads typically have four or more lanes and carry a disproportionate amount of the traffic flow. Thus, their relative importance would increase substantially if lane-miles and/or traffic flow were used as the measure of activity.

Heaney (2000) reviewed opportunities for using decentralized or distributed wet-weather controls associated with transportation activities and concluded that the most promising stormwater control opportunities are associated with smaller

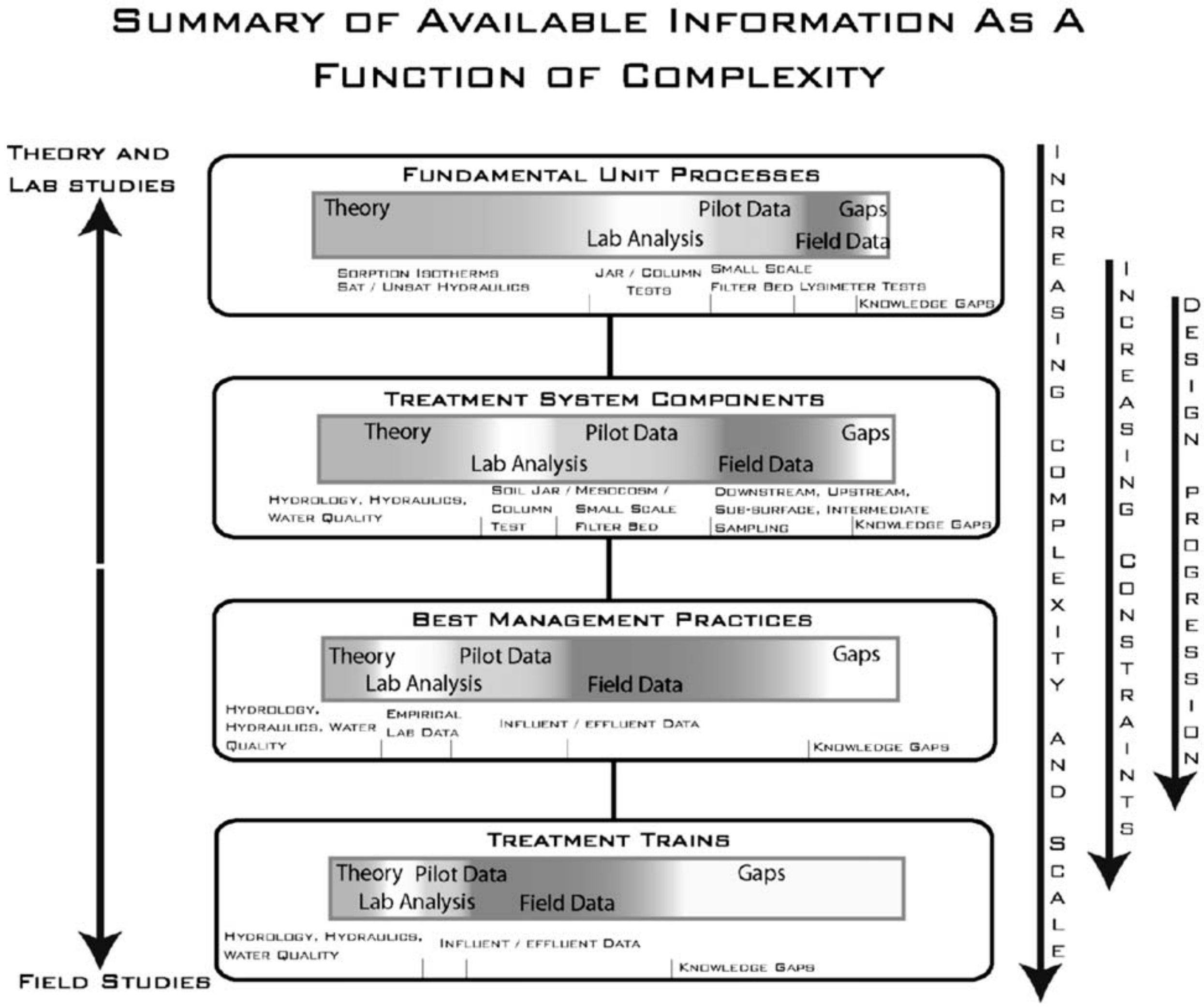


*Figure 1-1. Available stormwater treatment options as a function of complexity.*

access roads and parking facilities that are infrequently used. The key factor in reducing the impact of transportation-related wet-weather flows was the ability to avoid curbs and gutters, which result in closed drainage systems.

Much of the general literature about LID has been devoted to promoting distributed open drainage systems in lower-activity areas. However, the objective of this research project is to identify opportunities and develop strategies for using BMP/LID on high-volume roads with open and closed drainage systems. Much of the work is based on the success of, and lessons learned from, the use of stormwater controls in less-intense roadway systems and in land development projects.

To summarize: the focus of this project is on large, linear highways as opposed to the vehicular transportation system of a typical urban area. That is, the focus is away from

**Table 1-1. Ownership of U.S. highways, 2002.**

| | Miles | | | |
|---|---|---|---|---|
| **Organization** | **Rural** | **Urban** | **Total** | **% of Total** |
| State Highway Agency | 662,855 | 110,434 | 773,289 | 19.5 |
| County | 1,628,510 | 144,615 | 1,773,125 | 44.7 |
| Town or City | 606,389 | 624,163 | 1,230,552 | 31.0 |
| Other Jurisdictions | 56,254 | 12,695 | 68,949 | 1.7 |
| Federal Agency | 117,751 | 2,819 | 120,570 | 3.0 |
| Total | 3,071,759 | 894,726 | 3,966,485 | 100.0 |
| Percent of Total | 77.4 | 22.6 | 100.0 | |

Source: Office of Highway Policy Information 2002.

**Table 1-2. Roads owned by state highway agencies, 2002.**

| | Miles | | | |
|---|---|---|---|---|
| **Type of Road** | **Rural** | **Urban** | **Total** | **% of Total** |
| Interstate | 31,445 | 12,528 | 43,973 | 5.7 |
| Other Expressways | 97,784 | 8,447 | 106,231 | 13.7 |
| Other Principal Arterials | 130,362 | 35,787 | 166,149 | 21.5 |
| Minor Arterials | 195,939 | 24,535 | 220,474 | 28.5 |
| Collector | 67,092 | 11,726 | 78,818 | 10.2 |
| Local | 140,233 | 17,386 | 157,619 | 20.4 |
| Total | 662,855 | 110,409 | 773,264 | 100.0 |
| Percent of Total | 85.7 | 14.3 | 100.0 | |

Source: Office of Highway Policy Information 2002.

neighborhoods and arterials, even though virtually the same guidance methodology could be applied in those settings as well. A parallel research effort for the Water Environment Research Federation (WERF) (Strecker et al. 2005) extends the BMP selection methodology to the more general urban situation.

## 1.6 This Document

This research report mainly presents information in support of the BMP selection methodology provided in the *Guidelines Manual* and of the design methods presented in the *LID Design Manual*. This approach allows the other two documents to have a more practice-oriented focus. This research report also presents other general background information as well as recommendations applicable to the technology presented in this project.

The performance and effectiveness of a BMP for treating and/or controlling stormwater runoff depend upon numerous variables, related not only to the design and operation of the system, but also to the conditions of the site, techniques related to sampling, and constituents found in the water (Strecker et al. 2001). These variables, when combined with the discrepancies and inconsistencies regarding analysis and reporting of data, prevent many performance assessments from being used on a widespread basis (Strecker et al. 2001). Thus, the selection, design, and in some instances, approval status, of a particular system for use on a site may not be consistent from jurisdiction to jurisdiction. Background on typical stormwater BMPs and on application of LID in the highway environment is presented in Chapters 2 and 3, respectively. Stormwater and fundamental processes for its treatment are characterized in Chapter 4. The influence of highway and hydrologic characteristics is described in Chapters 5 and 6, while institutional and many other regional influences are described in Chapter 7.

Chapter 8 treats the topic of performance evaluation. In order to ensure that BMP/LID facility performance data may be transferable and comparable between locations and types of BMP systems and thus ensure that the evaluation and selection of a facility is consistent, the overall evaluation methodology allows for both performance- and practicability-based assessment by evaluating BMP performance data from the International BMP Database (see Section 8.3) (Strecker 1994). Principles of environmental engineering unit operations as well as BMP/LID performance data have been integrated into an overall evaluation strategy that is outlined in Chapter 9 and presented in detail in the *Guidelines Manual*. A major modeling effort has been conducted to evaluate regional hydrologic influences on BMP/LID performance. Extensive results, based on continuous simulation of highway runoff quantity and quality, are presented for both flow-limited (meaning minimal storage, such as filters and some proprietary devices) BMPs and off-line and on-line volume-limited BMPs (e.g., ponds and extended detention basins). The basis for these results is presented in Chapter 10. A summary, conclusions, and recommendations are presented in Chapter 11.

# CHAPTER 2

# BMP/LID Characterization

## 2.1 Introduction

Performance evaluation and selection of a stormwater management system from among the many available options can be characterized in different ways. Control of water quantity, that is, control of the flow and volume of the runoff is always an aspect of stormwater management, if for no other reason than that flood control and management of drainage volumes and peak flows will always be a part of the drainage engineer's job. Because a pollutant load is the product of flow and concentration, hydrologic (and sometimes, hydraulic) controls offer fundamental mechanisms by which to reduce pollutant loadings to off-site locations. Hence, hydrologic controls are discussed in the first part of this chapter.

Unit processes for removal of pollutants from waste streams are the building blocks of environmental engineering. Pollutant removal within BMP and LID facilities follows the same principles of physics, chemistry, and biology as pollutant removal within municipal or industrial wastewater treatment systems. Hence, the second part of this chapter discusses the performance of stormwater management facilities in the context of unit treatment processes.

Finally, it is often convenient to group BMPs with similar characteristics, such as storage, filtration, biological removal, etc., as well as to consider nonstructural options for stormwater management. This kind of characterization is discussed in the third part of this chapter.

Throughout, this chapter emphasizes *principles* and background information for control of stormwater runoff. These principles as well as the *application* of these principles are included in the *Guidelines Manual* of this project. The sections of this chapter that follow discuss the fundamental principles and characteristics of stormwater management facilities with regard to hydrologic controls, unit treatment processes, and BMP types. These topics are also discussed in Chapters 4 and 5 of the *Guidelines Manual*.

## 2.2 Characterization by Hydrologic Control

### 2.2.1 Hydrologic Basis

Flow alteration is a significant unit operation for stormwater treatment and has been the single major unit operation for stormwater management for decades in the United States and many parts of the world. Water quality and quantity cannot be separated; alterations to the hydrograph affect water quality. In large part, flow alteration is implemented as a hydrologic control. Flow alteration includes modifications to components of the hydrologic cycle such as runoff, infiltration, detention, storage, and evaporation. In general, the goals of these physical operations (recognized as hydrologic controls) have been to reduce volume, reduce peak flows, generate more uniform flow rates, and attenuate temporal aspects of flow. To varying degrees, these hydrologic controls can have a significant impact on water quality. Applications of hydrologic modification are ubiquitous in the built environment and are intentional or inadvertent, as well as beneficial or detrimental. Examples of intentional applications that have potential water-quality and -quantity benefits include infiltration, detention, and flow equalization; detrimental applications include impervious paving or loss of vegetation.

The sections that follow discuss the two fundamental hydrologic unit operations: flow attenuation and volume reduction (or minimization of volume increases). Flow attenuation refers to the hydrologic operations responsible for reducing peak-event discharges (e.g., "peak shaving," see 10.2.1). The primary mechanisms involved in flow attenuation include interception, conveyance, and detention, and, to a lesser degree, infiltration. Volume reduction hydrologic operations are responsible for reducing the total volume of runoff via retention, infiltration, and ET. Runoff can also be detained in storage vessels such as underground tanks and vaults and reused (e.g., irrigation water). If pollutant loads are a primary concern, then volume reduction should be a major unit operation in any selected treatment system design. Volume reduction is the essence of most LID approaches to stormwater management. Finally, downstream hydrologic impacts often depend upon the similarity of hydrographs between predrainage and postdrainage conditions. One method for this type of analysis is to evaluate flow-duration curves, discussed more extensively in Section 10.2.3.

## 2.2.2 Flow Attenuation

### *2.2.2.1 Interception*

Interception is a form of detention storage that occurs when leaves, stems, branches, and leaf litter temporarily store rainfall. Interception is considered to be detention storage if raindrops drain off vegetation by "throughfall" (dripping off a leaf onto the ground) or by stemflow (flowing down stems or trunks). Throughfall accounts for the majority of the movement of intercepted rainfall. Intercepted rainfall that is retained is lost to the atmosphere by evaporation from the surface of leaves. The retained and evaporated fraction of rainfall is considered a volume-reduction operation and is discussed in more detail in Section 2.2.3.

The percentage of rainfall that is intercepted increases with the density of vegetation, including all vertical layers from canopy to leaf litter. At maximum density, both trees and grasses may intercept 10 to 20% of precipitation from an individual storm. Per unit of ground area, some grass species have the same leaf area as many trees (Dunne and Leopold 1978).

### *2.2.2.2 Conveyance*

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. In conventional stormwater designs, conveyance is synonymous with the efficient drainage of runoff. By contrast, decentralized controls, like LID, which provide conveyance, also promote infiltration, improve water quality, and increase runoff travel time, or time of concentration ($T_c$). These controls are often critical components of the treatment train approach. In this guidance, "conveyance" refers to the act of transporting runoff, rather than the carrying capacity of a treatment system or other structure.

### *2.2.2.3 Detention*

Detention is the temporary storage of stormwater, which is then released over a period that can generally range from hours to days after rainfall ceases. (This is as opposed to retention, in which stormwater is captured and not released downstream.) Detained stormwater may exist as ponded free water or can be held within moist soil. In highly urbanized environments, detained runoff ultimately enters the storm drain system. In a vegetated system, ponded water and any soil moisture above the field capacity are detained, rather than retained, because that portion of the stormwater slowly percolates by gravity through the soil column into the underdrain. For small, frequently occurring storms, the release of detained water will not usually cause flooding because the stormwater will enter the system over a much longer period of time and at a lower rate than it would if detention storage controls were not in place.

## 2.2.3 Volume Reduction/Minimization of Volume Increases

### *2.2.3.1 Retention*

Retention captures stormwater permanently. The volume of retained runoff that may never enter the storm drain system can include vegetative interception, evaporation, transpiration of soil moisture, and reuse. The combination of evaporation and transpiration is called "evapotranspiration" (ET), and may occur at differing rates and extents from soil, vegetation, or hard surfaces such as pavement. Transpiration reduces the water volume within the root zone of soil. As stormwater enters a treatment system, infiltrating water will be retained up to the point that the soil moisture content equals the field capacity. If the rainfall is sufficiently light that the soil moisture content in a vegetated system never reaches field capacity, ET alone will eliminate the volume of stormwater in the soil.

### *2.2.3.2 Infiltration*

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. In urban areas and areas near highways, the soil is always disturbed and, when compacted, may inhibit easy movement of water into the ground, even in sandy soils. Groundwater recharge is a basic component of the natural hydrologic cycle. In urban areas, unrestricted infiltration may exacerbate infiltration and inflow (I/I) problems in both separate and combined sewer systems; the likelihood of this scenario must be evaluated before constructing unlined infiltration systems.

Some of the infiltrated stormwater will be retained and its volume permanently taken "out of the system" through ET, deep percolation, or both. Another component of the infiltrated stormwater may simply be detained, which temporarily reduces the amount of stormwater that would otherwise be in the storm drain system and allows it to enter the system over an extended period of time.

The soil moisture content determines the volume of stormwater 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 ET. The field capacity is the point at which free drainage by gravity ceases and the remaining water is held in the soil pores by capillary and osmotic forces. At this moisture content, the soil is unsaturated. The volume of additional stormwater that causes the soil moisture content to exceed the field capacity will be detained and will drain by gravity into underdrains over a period of several hours or days.

Infiltration is influenced by factors such as soil type, vegetative cover, and groundwater conditions at the site (Urbonas and Stahre 1993). Some common BMP systems that rely on infiltration include infiltration trenches and basins and a number of LID installations, such as porous pavement, lawns, green roofs, and swales. Other BMP systems using some aspect of infiltration within their removal processes include wet ponds, wetlands, and bioswales.

#### *2.2.3.3 Evapotranspiration*

Evapotranspiration (ET) refers to the combined effects of evaporation and transpiration in reducing the volume of water in a 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 by being diffused through leaves. (Uptake by roots may also remove a variety of pollutants from stormwater.)

For the first 2 to 3 days after a rainfall, ponding and infiltration control (i.e., detain) a large proportion of the stormwater volume, even when ET is occurring. After this time, gravitational drainage into the underdrains effectively ceases, and the field capacity is reached. ET becomes the dominant process because the volume of water present in the soil at field capacity will be lost to the atmosphere through ET alone. The following equation gives the maximum volume of water that ET can potentially remove once the soil moisture content equals the field capacity.

$$V_{\text{trans}} = D_r \cdot A \cdot (FC - WP) \qquad (2\text{-}1)$$

where

$V_{\text{trans}}$ = Transpired volume;
$D_r$ = Rooting depth;
$A$ = Soil surface area;
$FC$ = Field capacity, dimensionless; and
$WP$ = Wilting point, dimensionless.

The wilting point is the soil moisture content (volume of water per volume of soil plus voids) beyond which plants cannot exert enough suction to draw more water out of the soil. The difference between the field capacity and the wilting point is the moisture content available for transpiration.

The field capacity of urban stormwater treatment systems can be designed to meet desired drainage characteristics. The connectivity to underlying soils, including the presence of underdrains and gravel bedding, also affects the field capacity. Many vegetated systems, such as rain gardens, have a low field capacity in order to maximize free drainage and filter pollutants.

### 2.2.4 Flow Duration

Flow duration control is an extension of volume control, but is more accurate for sizing controls because matching flow duration maintains runoff volume for the full distribution of flows, as opposed to a single storm event. The concept is illustrated in detail in Section 10.2.3. When one matches the pre-urban flow duration curve, the total number of hours that flows persist at any given magnitude is maintained, and thus the total work on downstream channel boundaries is maintained. Flow duration control can be used on-site or for mixed regional solution strategies. Flow duration control may also be effective at maintaining the erosion potential of receiving streams.

## 2.3 Characterization by Unit Processes

### 2.3.1 Fundamental Process Categories

Fundamental process categories (FPCs) are often used as one method of classifying BMP technology, and these processes influence a respective system's pollutant-removal mechanisms and efficiency. FPCs incorporate both *unit operations* (treatment in which the application of physical forces predominates) and *unit processes* (treatment in which chemical or biological processes predominate) (Metcalf and Eddy 2003). A thorough evaluation, analysis, and categorization of FPCs, originating from principles associated with water and wastewater treatment engineering, may provide a structure and outline for the numerous pollutant-removal mechanisms and systems currently used for stormwater treatment (Minton 2005). In association with unit operations generally found in wastewater treatment technologies, BMPs may be generally classified by single or multiple FPCs (Metcalf and Eddy 2003) as outlined in Table 2-1. In many cases, the primary FPC utilized is not well determined, and thus the efficiency of any of the unit processes may depend upon static and state variables (Quigley et al. 2002). Some static variables

### Table 2-1. Structural BMPs listed by fundamental process category and unit operation.

| **Fundamental Process Category (FPC)** | **Unit Operation or Process (UOP)** *Target Pollutants* | **BMPs** |
|---|---|---|
| Hydrologic Operations | Flow and Volume Attenuation | Extended detention basins<br>Retention/detention ponds<br>Wetlands<br>Tanks/vaults<br>Equalization basins |
| | Volume Reduction | Infiltration/exfiltration trenches and basins<br>Permeable or porous pavement<br>Bioretention cells<br>Dry swales<br>Dry well<br>Extended detention basins |
| Physical Treatment Operations | Particle Size Alteration<br>*Coarse sediment* | Comminutors (not common for stormwater)<br>Mixers (not common for stormwater) |
| | Physical Sorption<br>*Nutrients, metals, petroleum compounds* | Engineered media, granular activated carbon, and sand/gravel (at a lower capacity) |
| | Size Separation and Exclusion (screening and filtration)<br>*Coarse sediment, trash, debris* | Screens/bars/trash racks<br>Biofilters<br>Permeable or porous pavement<br>Infiltration/exfiltration trenches and basins<br>Manufactured bioretention systems<br>Engineered media/granular/sand/compost filters<br>Hydrodynamic separators<br>Catch basin inserts (i.e., surficial filters) |
| | Density, Gravity, Inertial Separation (grit separation, sedimentation, flotation and skimming, and clarification)<br>*Sediment, trash, debris, oil and grease* | Extended detention basins<br>Retention/detention ponds<br>Wetlands<br>Settling basins<br>Tanks/vaults<br>Swales with check dams<br>Oil-water separators<br>Hydrodynamic separators |
| | Aeration and Volatilization<br>*Oxygen demand, polycyclic aromatic hydrocarbons (PAHs), volatile organic carbons (VOCs)* | Sprinklers<br>Aerators<br>Mixers (not common for stormwater) |
| | Physical Agent Disinfection<br>*Pathogens* | Shallow detention ponds<br>Ultraviolet systems |
| Biological Processes | Microbiotically Mediated Transformation (can include oxidation, reduction, or facultative processes)<br>*Metals, nutrients, organic pollutants* | Wetlands<br>Bioretention systems<br>Biofilters (and engineered biomedia filters)<br>Retention ponds<br>Media/sand/compost filters |
| | Uptake and Storage<br>*Metals, nutrients, organic pollutants* | Wetlands/wetland channels<br>Bioretention systems<br>Biofilters<br>Retention ponds |
| Chemical Processes | Chemical Sorption Processes<br>*Metals, nutrients, organic pollutants* | Subsurface wetlands<br>Engineered media/sand/compost filters<br>Infiltration/exfiltration trenches and basins |
| | Coagulation/Flocculation<br>*Fine sediment, nutrients* | Detention/retention ponds<br>Coagulant/flocculent injection systems |
| | Ion Exchange<br>*Metals, nutrients* | Engineered media, zeolites, peats, surface complexation media |
| | Chemical Disinfection<br>*Pathogens* | Custom devices for mixing chlorine or aerating with ozone<br>Advanced treatment systems |

include the system design parameters (e.g., volumes, dimensions, and bypass systems), watershed location, size, slope, imperviousness, vegetative canopy, and soil type and compaction (Huber et al. 2006). State variables include rainfall volume and intensity, detention time, season, vegetation, and maintenance.

As implied within Table 2-1, some means of hydrologic control is commonly included in LID installations, such as swales and infiltration facilities. Also, some of the advanced treatment processes listed are unlikely to be routinely encountered as stormwater BMPs and are more likely to be encountered in the context of CSO control, for example. Additional information on all methods, including those not discussed herein, such as volatilization, aeration, and natural disinfection, is included in Chapter 4 of the *Guidelines Manual*.

### 2.3.2 Settling/Sedimentation

Settling/sedimentation is a physical process associated with the separation of particles downward because of a difference in density between water and solids (Minton 2005). Generally, sedimentation is a two-phase process in which settling occurs during storm runoff under turbulent conditions, followed by intermittent settling between storm periods under quiescent conditions (Urbonas 1995). Total suspended solids (TSS) and larger sediments, as well as adsorbed constituents such as heavy metals, are the primary pollutants associated with this removal mechanism. The relative efficiency of BMPs utilizing sedimentation as an FPC depends upon numerous outside influences. Dynamic removal (under turbulent conditions) is generally dependent upon surface hydraulic loading, TSS particle-settling velocities, and shear stress, while removal under quiescent conditions is generally a function of particle density, particle size, and fluid viscosity (which is affected by temperature) (Urbonas 1995). Typically, sedimentation is a highly effective removal mechanism when higher pollutant concentrations (>400 mg/L) and larger particle sizes (>50 μ) are encountered (Urbonas 1995, Minton 2005). Sedimentation of adsorbed or complexed constituents is often the most effective means for removal of these pollutants in their particulate form.

Generally all BMP systems use sedimentation as one of the fundamental unit processes prompting removal, especially retention/detention facilities such as ponds and wetlands, but also others, such as swales, hydrodynamic devices, and filters. Efficiency of any settling system is generally a function of residence time, which in turn is dependent upon the design of the sedimentation system itself (Huber et al. 2006). The influent water characteristics (stormwater characterization or "treatability") are also highly influential when determining the projected removal efficiency.

### 2.3.3 Filtration/Sorption

Filtration is a process identified by the physical straining of particles through a porous medium, whereas sorption refers to the individual unit processes of both absorption and adsorption. Absorption is a physical process whereby a substance of one state is incorporated into another substance of a different state (e.g., liquids being absorbed by a solid or gases being absorbed by water). Adsorption is the physiochemical adherence or bonding of ions and molecules (ion exchange) onto the surface of another molecule. In stormwater treatment applications, particularly for highway runoff, the primary pollutant types targeted with absorption unit processes are petroleum hydrocarbons, while adsorption processes typically target dissolved metals, nutrients, and organic toxicants such as pesticides and polycyclic aromatic hydrocarbons (PAHs). Adsorption of pollutants to a particular media is based upon the characteristics of the sorption media and constituents present (Minton 2005). While filtration and sorption are two distinct treatment processes, they are typically inseparable in media filter systems because both processes are a function of the water-media interface.

Filtration and sorption media for BMPs vary greatly, ranging from vegetation, sand, perlite, and other inert medias to compost, zeolite, activated carbon (used in drinking water treatment facilities), and numerous other organic and manufactured materials. The physical straining process observed with filtration systems, used specifically with inert filtration media, provides removal for particulate pollutants by lodging the solids between gaps in the media. This straining process is thus influenced by factors such as media size, type, and porosity and influent characteristics such as pollutant particle sizes (Minton 2005).

The chemical removal process, observed when a sorptive medium is used, generally involves the processes of ion exchange, adsorption, and absorption between the water and the medium at a molecular level to remove dissolved constituents such as metals, hydrocarbons, nitrogen, and phosphorus (Minton 2005). These processes are highly influenced by a number of factors, including medium surface area (for sorption), medium size and porosity, ionic conductivity (preference for specific ions of constituents in the water), and the operating capacity of the medium (determines how frequently the medium should be replaced) (Minton 2005).

Filtration and sorption are common unit processes observed in a number of BMP systems, especially in swales, sand filters, and wet ponds, and within wetlands. Generally, the residence time of stormwater flowing through a system, in combination with the overall media contact area over which the filtration and/or sorption process(es) may occur, is the primary factor influencing the efficiency of the system. Influent characteristics such as constituent particle sizes and water chemistry are also important when attempting to achieve a projected effluent quality or removal fraction.

In order to function well, devices (such as some proprietary BMPs) that rely upon both filtration and sorption must remain in an aerobic state. If anaerobic conditions occur, the oxidation-reduction (redox) state will change, and sorbed metals will be released (J. Sansalone, personal communication, 2003). In addition, higher-particulate metals concentrations (e.g., a higher proportion of metals sorbed to sediment) will occur when solids concentrations are greater. Because particulate-bound constituents are easier to remove than dissolved constituents, it is possible that removal of total (dissolved plus particulate) metals will be higher when runoff has more solids (and organic) content, than when suspended sediment concentrations are relatively low.

### 2.3.4 Flotation

Flotation is a physical treatment process, essentially the reverse of sedimentation, in which particles are separated upwardly because of a density differential between the water and the pollutant. Flotation is generally encountered in the removal of petroleum hydrocarbons and trash and debris (bottles, papers, etc.)—pollutants that are of specific concern in highway environments. When the specific gravity of a pollutant is less then 1.0, as in the case of petroleum products and some plastics and paper, a negative settling velocity exists. Similar to removal via sedimentation, the negative settling velocity, or rise rate, of a substance indicates the rate at which pollutants may be removed from the water (Minton 2005). Oil/water separators are the primary BMP systems that utilize flotation (and subsequent skimming) as the fundamental unit operation. However, a number of hydrodynamic devices that incorporate centrifugal forces created by circular motion also rely on flotation (in addition to sedimentation) for removing pollutants.

### 2.3.5 Biological Treatment

Biological processes use living organisms (plants, algae, and microbes) to transform or remove organic and inorganic pollutants. Relevant processes for stormwater treatment have been divided into two broad categories: microbially mediated transformations and uptake and storage.

#### *2.3.5.1 Microbially Mediated Transformations*

**Definitions.** Microbially mediated transformations are the unit processes of microbial activity that promote or catalyze redox reactions and transformations. These processes include the degradation of organic pollutants as well as the oxidation or reduction of inorganic pollutants. Microbially mediated transformations are chemical transformations performed primarily by bacteria, algae, and fungi that exist in the water column, soil, root zone of plants, and on wetted surfaces, such as leaves (Kadlec and Knight 1996; Karthikeyan and Kulakow 2003; Minton 2005). Most microbes are concentrated in the upper layers (0.3 m) of soil and in the plant root zone. Of all transformation processes, conversion of nitrogen species (e.g., ammonia and nitrate) is probably the most significant in stormwater treatment systems.

**Metabolism.** Microbially mediated transformations occur as a result of respiration, which is a redox reaction. Redox reactions are chemical transformations involving the transfer of protons and electrons. Terminal electron acceptors are oxidizers, and electron donors are reducers. Respiration is the process that releases the energy and nutrients from food sources so that they can be assimilated by organisms. The process occurs in both aerobic (e.g., well-aerated terrestrial soil) and anaerobic (e.g., wetlands) environments. Oxygen is used as the electron acceptor during aerobic respiration, while other chemicals (e.g., nitrate or sulfate) function as electron acceptors during anaerobic respiration. Facultative microbes undergo both aerobic and anaerobic respiration. Therefore, microbial transformations that occur in stormwater treatment systems are largely influenced by the oxidation-reduction (redox) potential of the system.

**Organic material decomposition and mineralization.** When microbes aerobically oxidize simple organic compounds, the process releases, or mineralizes, organically bound elements. Mineralization refers to the release of elements from organic matter to produce inorganic (mineral) forms. Most of the inorganic elements released by mineralization are in forms more available as nutrients to higher plants and microbes. Once released through mineralization, the elements can be further transformed by specific microbes. Alternatively, they can be sequestered by binding to other inorganic constituents or by sorbing to nondegradable organic matter (humus). Less-desirable products, such as methane and hydrogen sulfide, may form in anaerobic decomposition. Mineralization is an important source of nitrogen, sulfur, phosphorus, and other nutrients for plants and microbes. Rates of decomposition and mineralization depend on various chemical factors such as pH (near neutral is best), moisture, temperature (25°C to 35°C is best), oxygen, and quality of food sources for microbes.

**Inorganic transformations and the nitrogen cycle.** Some microbes can enzymatically oxidize or reduce metals during respiration, affecting metal solubility and reactivity. Such inorganic transformations are used to treat metals in the practice of bioremediation. Example reactions include the following:

- Oxidation of ferrous to ferric ions precipitates ferric hydroxides or phosphates.
- Reduction of sulfate to sulfide causes formation of insoluble metal sulfides, for instance, pyrite and mercuric sulfide. Hydrogen sulfide may form when concentrations are significantly greater than metals concentrations.
- Reduction of hexavalent ($Cr^{6+}$) to trivalent ($Cr^{3+}$) chromium precipitates chromium oxides, sulfides, or phosphates.
- Reduction of manganese from $Mn^{4+}$ to $Mn^{2+}$ releases soluble cations.

The nitrogen cycle includes nitrogen transformations facilitated by microbes (primarily bacteria) in addition to uptake and release of nitrogen from multicellular organisms and abiological processes. The microbial transformations of ammonification, nitrification, denitrification, and fixation are of interest for improvements in runoff water quality.

Ammonification is the mineralization of organic nitrogen to ammonium by chemoheterotrophic bacteria and may occur aerobically or anaerobically. This is the main process supplying nitrogen to wetland plants, with about 1.5 to 3.5% of the organic nitrogen in soil mineralizing annually (Brady and Weil 2000). The rate of ammonification is typically highest in the aerobic zone of wetland soils and decreases with depth because of the reduced efficiency of decomposition in anaerobic environments. However, because wetland soils have mostly anaerobic microbes, the overall mass of ammonium generated is greater in anaerobic conditions. Therefore, ammonification is significantly reduced under nonflooded conditions (Minton 2005; Kadlec and Knight 1996). Warm seasons, good moisture, or high organic matter content will increase the mineralization rate.

Nitrification is the oxidation of ammonium to nitrate by chemoautotrophic bacteria in aerobic conditions (e.g., the water column, well-drained soils or the aerobic layer of flooded soils, and the plant root zone). It is a two-stage reaction, in which ammonium is oxidized to nitrite in the first stage (by *Nitrosomonas* primarily), and nitrite is oxidized to nitrate in the second stage (by *Nitrobacter* primarily). Typically the second stage occurs quickly enough to prevent accumulation of nitrite. Denitrification is the reduction of nitrate to gaseous forms of nitrogen (nitric oxide, nitrous oxide, and dinitrogen gas) under anaerobic conditions, such as flooded soils. It may occur in wetland soils and in anaerobic pockets in terrestrial soils. Mechanisms for denitrification vary depending on the conditions and organisms involved. Nitric oxide and nitrous oxide are often formed under fluctuating oxygen levels, and, generally, when oxygen levels are very low, the end product is dinitrogen gas. The amount formed of each gas depends on pH, temperature, degree of oxygen depletion, and concentration of nitrate and nitrite.

Nitrogen fixation is the process by which nitrogen gas in the atmosphere (or nitrogen gas generated during denitrification) is reduced to ammonia by bacteria, algae, and higher plants. Nitrogen-fixing bacteria form symbiotic relationships with certain plants, forming nodules in the roots. The plants provide the bacteria with carbohydrates for energy and a stable environment for growth, while the bacteria give the plants usable nitrogen and other essential nutrients. Non-symbiotic fixation can also occur. Nitrogen can also be lost to the system as it volatilizes as ammonia gas at alkaline pH. This chemical process occurs frequently in wetlands.

**Degradation of xenobiotic compounds.** In addition to simple organics, various microbes (primarily heterotrophic bacteria) are able to use more complex organics (such as xenobiotic compounds, that is, compounds foreign to the biological system) as energy sources during metabolism, which often results in microbial decomposition to less-toxic compounds. In some cases, xenobiotic compounds undergo incomplete degradation, and the products may be as toxic, or more toxic, than the parent compound. For example, trichloroethene (TCE) is degraded to vinyl chloride rather easily. However, subsequent degradation of vinyl chloride, a carcinogen, usually occurs slowly.

Degradation can occur aerobically or anaerobically, although both processes occur relatively slowly (thus requiring long residence times). Significant degradation is possible for phenols, phthalate esters, naphthalenes, chlorinated benzenes, and nitroaromatics in aerobic conditions. Some compounds degrade more rapidly in anaerobic conditions, including carbon tetrachloride, chloroform, lindane, phenol, and methylene chloride (Minton 2005). Complete degradation of some constituents may require alternating aerobic and anaerobic conditions (Knapp and Bromley-Challenor 2002). Under the right conditions, some microbes can transform xenobiotic compounds even when the chemical is not the primary energy source (cometabolism). Cometabolism is important for the breakdown of chlorinated solvents, polychlorinated biphenyls, and many PAHs, and, therefore, cometabolism is the basis for bioremediation of many organic pollutants.

**Applicability to stormwater treatment.** Stormwater treatment that incorporates vegetation and/or permanent water bodies usually has a diverse microbial population. While it is not possible to optimize conditions for all beneficial species, basic habitat requirements for all microbes include a substrate to colonize (e.g., soil, plant roots, or leaf surfaces), appropriate nutrients (including carbon sources), absence of toxics, and sufficient moisture. The pH also affects microbe populations because different species have different limits of pH tolerance. Many microbes form symbiotic relations with plants and plant roots; therefore, increasing vegetation density (and using the right plants) may increase microbial populations. Degradation that occurs in the plant root zone is referred to as rhizodegradation and occurs, for example, in the presence of deep-rooted turf grasses (e.g., swales). Adding organic amendments can also increase populations. Oxygen requirements are another important factor. Depending on the microbe, it may require the presence of oxygen (aerobic) or other electron-donating substances (facultative and anaerobic) for metabolism. Various factors determine available oxygen, including soil characteristics and inundation patterns.

Microbially mediated transformations can remove dissolved nitrogen species (e.g., nitrate), metals, and simple and complex organic compounds. Many transformations only occur in the presence of specific microbes. Soils may be inoculated with desirable microbes to promote specific reactions or to boost a low initial microbial population. Transformations occur relatively slowly and require long residence times. Temperature affects microbial growth and transformation rates. Generally, increasing the temperature increases transformation kinetics. The optimum temperature range for much microbial activity is between 15°C and 45°C (Tate 1995).

Stormwater BMPs (wetlands, swales, and retention ponds) that facilitate these processes can require relevantly large land areas and therefore may not be suitable in highly urbanized areas. They may also have limited applications in arid climates, areas with long dry seasons, and cold climates. Some microbially mediated processes have the potential for stream warming and should not be used where effluents discharge to temperature-sensitive water bodies, such as cold-water habitats. Nitrification may result in leaching of nitrate from the system, which is of particular concern in areas with water-quality impairment that is due to nutrient enrichment.

### *2.3.5.2 Uptake and Storage*

**Definitions.** Uptake and storage refer to the removal of organic and inorganic constituents by plants and microbes through nutrient uptake and bioaccumulation. Nutrient uptake converts required micronutrients and macronutrients (summarized at the end of this section) into living tissue, whereas bioaccumulation incorporates compounds (e.g., pollutants) into an organism, regardless of, or in excess of, what is immediately needed. Uptake and storage processes are generally not major pollutant-removal processes in stormwater treatment systems because of the extended retention times required for such processes.

Plants and microbes require essential nutrients to sustain growth (see Table 2-2), which may be assimilated from the water column or from soil solution through metabolic processes. In wetlands, free-floating plants take up nutrients from the water column; emergent plants take up nutrients from soil pore water; submerged plants may obtain nutrients from both the water column and soil pore water. The specific forms in which nutrients exist are determined largely by pH and redox potential. Micronutrient cations are most available for uptake under acidic conditions. The presence of constituents such as silicate clays and organic matter also affects nutrient speciation. Organic matter, along with organic residues excreted by plant roots and microbes, may react with cationic micronutrients to form organometallic complexes (chelates), which are generally more available for uptake than nonchelated metal species in the aqueous phase. The strength of metal chelate formation is approximately of the order (Miller and Gardiner 1998):

$$Fe^{3+} > Al^{3+} > Cu^{2+} > Co^{2+} > Zn^{2+} > Fe^{2+} > Mn^{2+} > Ca^{2+} = Mg^{2+}$$

Removal of phosphorus is the most significant uptake mechanism in stormwater treatment systems. Phosphorus uptake by plants and microbes may improve the capacity of the soil to sorb other constituents. However, phosphorus assimilated for metabolism is released back into the system upon death (or dormancy) of the microbe or plant. In addition to nutrients, 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 and is the basis of phytoremediation. The organic compounds can remain in the water column or be metabolized in the root tissue, become assimilated into the cell wall, or become translocated to plant leaves and volatilized. These processes contribute to the effectiveness of constructed wetlands for wastewater treatment. The ability to remove chlorinated solvents, petroleum hydrocarbons, herbicides, insecticides, and phenolic compounds has been investigated for wetland and terrestrial plants. Mechanisms of organic compound degradation by plants are not well understood (Scragg 1999). Degradation by plants is probably assisted by microbes, particularly in the root zone.

The term hyperaccumulator applies to plants that can accumulate metals at concentrations 100-fold greater than concentrations found in the tissue of nonhyperaccumulators. Thus, hyperaccumulators can accumulate more than 10 ppm mercury, 100 ppm cadmium, 1,000 ppm cobalt, chromium, copper, and lead, and 10,000 ppm nickel and zinc. Metal tolerance is the primary characteristic of these plants. These plants are also capable of translocating the metal from the root to plant stems and leaves. There are about 400 plants from 45 plant families capable of hyperaccumulation (USEPA

## Table 2-2. Characteristics of essential nutrients for plants and microbes.

| Nutrient Category | Chemical Species Assimilated | Function |
|---|---|---|
| *Primary Nutrients* | | |
| Nitrogen | $NO_3^-$, $NH_4^+$ | Constituent of amino acids, proteins, enzymes, and chlorophyll. Important in photosynthesis, metabolism, and protoplasm reactions. Component of DNA. Important for many growth and development processes. Stimulates uptake of other nutrients. Ammonium uptake is favored over nitrate. |
| Phosphorus | $H_2PO_4^-$, $HPO_4^{2-}$, $PO_4^3$, organic phosphorus | Constituent of proteins, phospholipids, enzyme systems, and nucleic acids. Essential component of Adenosine Triphosphate (ATP), which drives most energy-requiring biochemical processes, including nutrient uptake. Stimulates early growth and root formation. Important in photosynthesis.<br>*Comments:*<br>Organic phosphorus is a major nutrient source. Phosphorus concentrations in soil water are typically low because phosphorus tends to form insoluble compounds in soil. |
| Potassium | $K^+$ | Principal inorganic cation in cells. Cofactor of some enzymes. Affects cell division, formation of carbohydrates, translocation of sugars, various enzyme actions, disease resistance, stomata opening/closing, cell membrane permeability, and $H^+$ relationships.<br>*Comments:*<br>Abundant in soils, but often bound to soil minerals, making it unavailable for assimilation. |
| *Secondary Nutrients* | | |
| Calcium | $Ca^{2+}$ | Cofactor of enzymes. Regulates membrane permeability, cell integrity, and acidity. Essential component of plant cell walls and membranes. |
| Magnesium | $Mg^{2+}$ | Cofactor of many enzymes (for reactions such as denitrification and sulfate reduction). Present in cell walls, membranes, and phosphate esters. Constituent of chlorophyll. Aids mobility and efficiency of phosphorus. |
| Sulfur | $SO_4^{2-}$, $HS^-$, $S^0$, $S_2O_2^{2-}$<br>Sulfur oxidizing bacteria use FeS and $FeS_2$ | Essential for production of protein, constituent in amino acids. Promotes activity and development of enzymes and vitamins. Helps in chlorophyll formation. Improves root growth.<br>*Comments:*<br>Organic sulfur is a major nutrient source. |
| *Micronutrients* | | |
| Boron | $BO_3^{3-}$, $B_4O_7^{2-}$ | Required by higher plants and some microbes for growth of new cells. |
| Chlorine | Most likely $Cl^-$ | Coenzyme for photosynthesis. Influences cell membrane permeability. Prevents desiccation. Required by halophilic bacteria (which also need sodium). |
| Copper | $Cu^+$, $Cu^{2+}$ | Important in photosynthesis and vitamin A synthesis, protein and carbohydrate metabolism, and probably nitrogen fixation (cofactor for several enzymes). |
| Iron | $Fe^{2+}$, $Fe^{3+}$ | Essential for chlorophyll synthesis. Catalyst in respiration. Important in cell division. Important for nitrogen fixation. |
| Manganese | $Mn^{2+}$ | Enzyme cofactor in many metabolic reactions. Catalyst with iron in chlorophyll synthesis. Role in chloroplast structure. Promotes pigment and vitamin C synthesis. |
| Molybdenum | $MoO_4^{2-}$ | Required for nitrogen use. Needed for conversion of nitrate into amino acids and for nitrogen fixation. Role in plant hormones. |
| Nickel | Most likely $Ni^{2+}$ | Enzyme component. Important in nitrogen metabolism. Required for growth of some bacteria. |
| Selenium | $SeO_3^{2-}$ | Present in some proteins. May be more important for microbes than plants. |
| Zinc | $Zn^{2+}$ | Enzyme component, including enzymes involved in zinc synthesis of hormones that regulate growth and development. Role in chlorophyll synthesis. |

Sources: Pittenger 2002; Miller and Gardiner 1998; Portier and Palmer 1989.

2000a). Various constructed wetland plants, such as duckweed (*Lemna minor*) and water hyacinth (*Eichhornia crassipes*) can hyperaccumulate metals (Zhu et al. 1999; Zayed et al. 1998; Qian et al. 1999).

Other plants keep metals sorbed in the root zone and excrete matter that causes metal precipitation. This is a defensive strategy to prevent toxicity by inhibiting translocation from the roots to other parts of the plant and is referred to as phytostabilization in phytoremediation. Phytostabilizing plants exhibit low levels of metal accumulation in their shoots. Plants with this characteristic are also effective for erosion control because of their extensive and deep root systems.

**Uptake of organics.** Plant uptake of organics is a function of the organic compound's solubility, hydrophobicity (octanol-water distribution coefficient, $K_{ow}$), and polarity. Generally, moderately hydrophobic compounds with log $K_{ow}$ between 0.5 and 3.0 are most readily taken up by and translocated within plants. More hydrophobic compounds may be sorbed by roots, but not translocated (USEPA 2000a). Nonpolar molecules with molecular weights less than 500 will sorb to root surfaces, while polar molecules will enter the root and be translocated. Soil conditions (e.g., pH, acid ionization constant [$pK_a$], organic and moisture content, and texture) affect the solubility of the organic compound. Plant physiology also influences uptake of organics (Salt et al. 1998). Plant ET rates are important because of the movement of organics through the plant. Seasonal and diurnal shifts in transpiration rates are relevant. In order for uptake mechanisms to occur, plants with appropriate characteristics must be selected. Differences in uptake of organics among plant species are well recognized (Salt et al. 1998).

**Uptake of metals.** Hyperaccumulating plants have affinities for specific metals, and metal affinity may vary within different species within the same genus. Consequently, significant metal uptake by plants will not occur unless the appropriate species are selected. The number of plant species that hyperaccumulate specific metals is shown in Table 2-3.

**Table 2-3. Number of hyperaccumulating plant families.**

| Metal | Number of Hyperaccumulating Plant Species |
|---|---|
| Nickel | > 300 |
| Cobalt | 26 |
| Copper | 24 |
| Zinc | 18 |
| Manganese | 8 |
| Lead | 5 |
| Cadmium | 1 |

Source: U.S.EPA 2000a.

Uptake of metals depends on metal bioavailability. Low bioavailability may explain why there are so few hyperaccumulators of lead, as lead tends to form insoluble precipitates. Organic matter excreted by roots can increase metal bioavailability by lowering the pH or by forming metal chelates.

Uptake and storage can be used to remove dissolved metals, nutrients (phosphorus and nitrogen), and organic compounds. The process is suitable where soil properties and water quality are adequate to support organism growth. As a general rule, readily bioavailable metals for plant uptake include cadmium, nickel, zinc, arsenic, selenium, and copper. Moderately bioavailable metals are cobalt, manganese, and iron. Lead, chromium, and uranium are not very bioavailable. Lead can be made much more bioavailable by the addition of chelating agents to soils. The efficiency of uptake processes may be reduced in cold or arid climates. Many systems require a large area of land. Some uptake and storage processes have the potential for stream warming and should not be used where effluents discharge to temperature-sensitive water bodies, such as cold-water habitats. Concentrations in stormwater treatment systems may not be high enough for processes such as metal hyperaccumulation or organic compound reduction to occur.

Uptake varies by season, latitude, and plant species. Uptake only occurs during the growing season. Establishment and growth of plants and microbes is 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, and have appropriate growth characteristics. Uptake processes are enhanced in warm climates because of the extended growing season. Symbiotic microbes also enhance nutrient uptake by plants. Soils can be inoculated with the desired beneficial microbe (such as nitrogen-fixing bacteria).

## 2.3.6 Chemical Processes

The chemical characteristics of stormwater (e.g., pH, alkalinity, hardness, redox conditions, organic carbon, and ionic concentrations) affect the partitioning and speciation of stormwater pollutants, which in turn dictate the type of UOPs necessary to treat those pollutants. Three common chemical UOPs applied in the field of stormwater treatment include sorption, coagulation/flocculation, and chemical agent disinfection.

### *2.3.6.1 Sorption*

While often inseparable from filtration unit operations, sorption refers to the individual unit processes of absorption and adsorption. Absorption is a physical process whereby a substance in one state is incorporated into another substance in a different state (e.g., liquids being absorbed by a solid or gases being absorbed by water). Adsorption is the physiochemical adherence or bonding of ions and molecules (ion exchange) onto the surface of another molecule. In stormwater treatment application, particularly for highway runoff, the primary pollutant types targeted with absorption unit processes are petroleum hydrocarbons, while adsorption processes typically target dissolved metals, nutrients, and organic toxicants such as pesticides and PAHs. Different types of filter media may provide either or both of these unit processes: these filter media include the use of activated carbon to improve adsorption and synthetic polymers to improve absorption. Media can be engineered so that the chemistry of the media promotes chemical processes that result in more permanent chemical bonds between media and adsorbed solute (Liu et al. 2005b).

Sorptive unit processes are specific mechanisms that range from surface complexation to precipitation, and such processes are generally designed for solute mass transfer onto materials with high surface area, generally engineered media. In stormwater, solutes of interest include phosphorus and metals. In combination with sorptive processes, unit operations such as filtration can be an effective treatment control for dissolved and particulate-bound metal and phosphorus species. Mass transfer of dissolved species can occur to either engineered media or to stormwater runoff particles (partitioning), and then the dissolved species can be separated as particulate-bound constituents through filtration. Mass transfer for solutes occurs through different mechanisms and at different rates in stormwater. For example, phosphorus mass transfer to particles is generally through a combination of sorption and precipitation, depending on pH, and the rate of reaction can be very rapid, on the order of minutes to several hours. In contrast, mass transfer for different metals occurs differently and also has differing kinetics. For example, mechanisms of lead mass transfer to particles (depending on the solid phase and pH) generally range from precipitation to surface complexation, with relatively rapid kinetics, while zinc mass-transfer mechanisms generally range from surface complexation to hydrolysis, with relatively slow kinetics. However, it must be recognized that the sorption phenomena rates are dependent on the sorbent, hydrodynamics, and water chemistry, and such phenomena are reversible (desorption). Thus, leaching of metals or phosphorus from filter media is possible. Designs that allow drawdown of stormwater from a filter medium within several hours can help prevent leaching and other issues, such as biological growth, and therefore reduce hydraulic conductivity (Liu et al. 2005b).

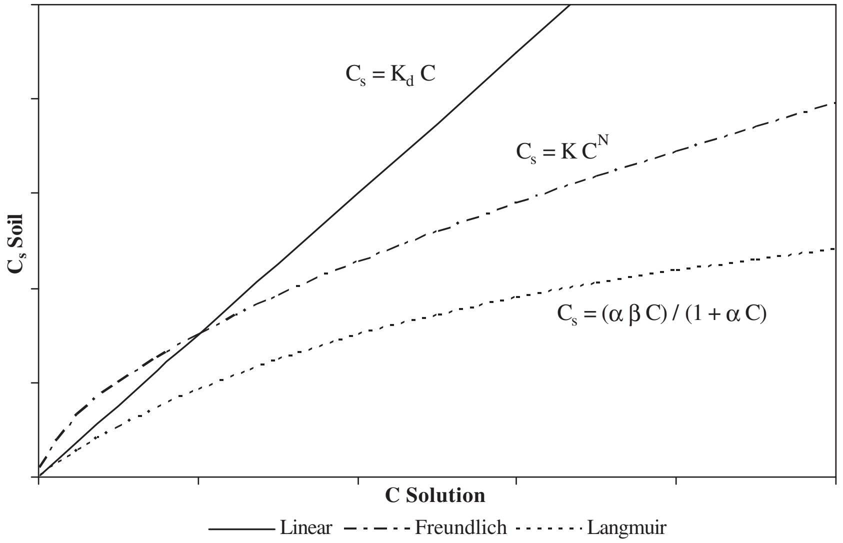
Engineered media such as oxide-coated filter media with high surface area and amphoteric (pH-dependent) surface charge can be utilized to carry out the combined unit operations of filtration and processes of surface complexation for a range of treatment configurations for in situ, decentralized treatment or centralized stormwater runoff treatment. Such treatment can be designed as a passive and integral part of existing urban infrastructure (e.g., urban and transportation infrastructure), or it can be designed as a centralized stormwater treatment component. For process design, control, and optimization, it is important to know the quantitative metal species adsorption properties of the engineered media. Experimental studies and modeling of media metal species adsorption properties are required for a quantitative evaluation of stormwater media. One particular combined UOP providing in situ treatment for metal and phosphorus species removal in stormwater is an upflow sorptive buoyant media clarifier (SBMC). SBMCs are particularly well suited for stormwater discharges from elevated urban infrastructure such as an elevated roadway over water, where both solutes and particles in stormwater runoff are a concern. There are many examples of in situ treatments that combine sorptive processes and filtration operations either intentionally (by design) or inadvertently.

Equilibrium isotherms are an important tool for describing the equilibrium between aqueous and solid (media) phases for a known combination and concentration of solute(s), media, water chemistry, media/solution ratio, experimental geometry, and hydrodynamics. Isotherms indicate the adsorption capacity of a media or particulate solid under a prescribed or given set of conditions.

Sorption isotherms are used to relate the concentration of solute adsorbed and/or absorbed to the soil or medium as a function of the solute concentration in solution. Three commonly used isotherms are the linear, Freundlich, and Langmuir isotherms widely discussed in contaminant hydrogeology literature (e.g., see Fetter 1999). Their general shapes and equations are shown in Figure 2-1, where

$C_s$ = mass of solute sorbed per dry weight of soil (mg/kg),
$C$ = solute concentration in solution at equilibrium with sorbed mass of solute (mg/L),
$K_d$ = distribution coefficient (L/kg),
$K$ & $N$ = constants found by regression,
$\alpha$ = sorption constant (L/mg), and
$\beta$ = maximum sorbed concentration (mg/kg).

Isotherm analysis can provide engineering parameters as well as a qualitative indication of more fundamental mechanisms. Isotherms generated for a given set of conditions can provide a quantitative indication of media capacity for individual solutes (i.e., mass of solute adsorbed per dry mass of media) even under the competitive conditions (multiple



Source: Adapted from Fetter 1999.

*Figure 2-1. Sorption isotherms.*

competing solutes) of stormwater. For a basic analysis of media parameters required for design and analysis, the engineering behavior of any media or substrate utilized for sorption requires knowledge of the equilibrium capacity of the media (how much pollutant will the media retain at equilibrium) and the pace at which the pollutant can be transferred and retained by the media. The equilibrium capacity is simply how much pollutant the media will hold when the rate of adsorption equals the rate of desorption.

Sorption isotherms are derived experimentally by placing a known mass of soil (or media) in a known volume and concentration of solute or solutes in solution (i.e., water), allowing the solute(s) to reach equilibrium, and then measuring the remaining solute(s) concentration in solution. The reduction in solute concentration in solution is assumed to be the result of sorption, and the sorbed concentration can be calculated. This is repeated for a range of soil masses and solute volumes (and possibly concentrations) and to derive experimental data that can then be fit to the preferred or most representative sorption isotherm. The development of sorption isotherms can be used in part to evaluate the potential impacts from highway construction and repair materials (Nelson et al. 2001).

Isotherms are an effective tool for describing solute species (e.g., aqueous metals and aqueous phosphorus) interaction and media capacity as a function of equilibrium conditions and concentration of solid and aqueous phases; however, isotherms will yield only indirect information on the role of water chemistry and adsorbent characteristics. There are additional tools to model complex and variable natural or engineered systems. In contrast to isotherm models, surface complexation (SC) models, based on double-layer theory, belong to a group of models that take a mechanistic and molecular-scale approach to surface interaction. As a result, SC models are versatile and have a fundamental physical-chemical basis for predicting metal species surface interaction phenomena over a wide range of experimental and natural conditions. SC models are particularly important when the species of interest are minor or trace ionic species and the solid phase substrate exhibits a pH-dependent (amphoteric) surface charge. It is important to recognize that most stormwater particles exhibit amphoteric behavior, and engineered media are generally amphoteric, in many cases by design.

It cannot be overemphasized that an isotherm is a specific relationship for adsorption capacity under a specific set of conditions. Isotherms should be generated for the specific conditions of the media application and range that are consistent with the variability anticipated. Often the media manufacturer will be able to assist with the development or predication of potential removal of pollutants of interest by the media. This information is central to sorptive filter designs. A review of media, isotherms, and kinetics can be found elsewhere (Liu et al. 2005a; Sansalone and Teng 2004; Teng and Sansalone 2004a, 2004b; Liu et al. 2001a, 2001b; Sansalone 1999; Masel 1996; Bar-Tal et al. 1990). SC models represent an additional tool to examine the complexity of sorption interactions. Such models are becoming more common in routine environmental chemistry applications and are emerging as stormwater tools (Dean et al. 2005).

Small pore spaces and large surface areas are desirable properties for media used to remove stormwater pollutants with sorption processes. Because of the propensity of small pore spaces to clog, pretreatment for particulates is essential for continued functionality of sorptive media.

### *2.3.6.2 Precipitation/Coagulation/Flocculation*

Precipitation, coagulation, and flocculation are three processes that occur simultaneously or in quick succession. Precipitation is the process by which a pollutant is transformed from a primarily dissolved state to a solid state. Coagulation is the process by which colloidal particles are destabilized so that particle growth can occur. Flocculation is the process by which fine particles collide to form larger particles that can be readily removed through filtration and settling. While these three processes will occur naturally, the addition of chemicals is usually necessary to accelerate the process.

Engineered chemical and physical flocculation is beginning to be applied in specific applications for 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 accounted for, can have a significant impact on stormwater runoff clarification in unit operations such as sedimentation basins or detention/retention facilities.

When existing treatment technologies do not provide enough treatment to achieve water-quality goals, the use of chemicals may be necessary. The types of pollutants typically targeted with precipitation/coagulation/flocculation processes include fine and colloidal particulates, dissolved metals, and phosphorus. The disadvantage of using these processes in stormwater treatment applications is the generation of potentially significant quantities of sludge that must be properly handled and disposed. Depending on the particular chemicals used, the effluent may not be suitable for discharge because of reduced or elevated pH, high dissolved-aluminum or iron concentrations, or the presence of other undesirable by-products.

The conditions and factors that enhance precipitation and flocculation processes are highly dependent on the chemicals being used; the primary factors include pH, temperature, and hardness. Other factors such as the particle-size distribution, free-ion concentration, and electronegativity of colloidal particles will also influence these processes.

### *2.3.6.3 Chemical Disinfection*

Chemical disinfection refers to the mitigation of stormwater-borne pathogens through the use of chemical agents such as chlorine and its compounds and ozone. The California Department of Transportation (Caltrans) has recently examined chemical disinfection as a potential new technology for application to highway runoff (Caltrans 2004). Chemical disinfection is used more extensively in wastewater applications with a wider range of chemical agents, including chlorine and its compounds, bromine, iodine, ozone, phenol and phenolic compounds, alcohol and heavy metals and related compounds, dyes, soaps and synthetic detergents, quaternary ammonium compounds, hydrogen peroxide, paracetic acid, various alkalis, and various acids (Metcalf and Eddy 2003). Because wastewater technologies are often adopted for stormwater applications, the list of agents currently used for stormwater disinfection could expand in the future.

Chemical disinfection immobilizes pathogens through a variety of mechanisms, including damage to pathogen cell walls, alteration of pathogen cell-wall permeability, alteration of the colloidal nature of the protoplasm of the pathogen, alteration of the DNA or the RNA of the pathogen, and the inhibition of pathogen enzyme activity (Metcalf and Eddy 2003). The factors that affect the chlorine disinfection process include initial mixing, chemical characteristics of the influent, impact of particles in the influent, particles with coliform organisms, and the characteristics of the target organisms (Metcalf and Eddy 2003). The effectiveness of ozone disinfection systems depends on the dose, mixing, and contact time. Tables 2-4 and 2-5 present the impact of stormwater constituents on chlorine disinfection and ozone disinfection, respectively.

Projects that have identified pathogens as constituents of concern must select either chemical or natural disinfection. These are the only two unit processes discussed in this document that specifically target pathogens.

Chemical-agent disinfection may be cheaper than natural disinfection and hence may be a more suitable choice for a tight budget. Chlorine disinfection leaves a residual in the effluent that may provide added benefits by preventing the regrowth of pathogens and improving downstream water quality. Projects that use upstream BMPs that significantly reduce organic content and suspended solid content will increase the efficiency of any downstream chemical facilities.

## 2.3.7 Targeted Pollutants

As implied in the previous discussion, different FPCs are applied for removal or reduction of different pollutants. Targeted pollutants for each FPC are included in Table 2-1. The interrelationship of pollutants, FPCs, and structural BMPs is summarized in another way in Table 2-6. As indicated in both Table 2-1 and Table 2-6, the choice of a BMP should be based on the water-quality characteristics of the stormwater relative to the treatment goals. Chapter 4 provides a thorough discussion of pollutant sources and the water-quality characteristics of stormwater runoff from various land uses, including highways.

**Table 2-4. Potential effects of selected constituents on the use of chlorine.**

| Constituent | Effect |
|---|---|
| BOD, COD, TOC etc. | Organic compounds that comprise the BOD and COD can exert a chlorine demand. The degree of interference depends on their functional groups and their chemical structure. |
| Humic Materials | Reduce effectiveness of chlorine by forming chlorinated organic compounds that are measured as chlorine residual but are not effective for disinfection. |
| Oil and Grease | Can exert a chlorine demand. |
| TSS | Shield embedded bacteria. |
| Alkalinity | No effect or minor effect. |
| Hardness | No effect or minor effect. |
| Ammonia | Combines with chlorine to form chloramines. |
| Nitrite | Oxidized by chlorine, formation of NDMA. |
| Nitrate | Chlorine dose is reduced because chloramines are not formed. Complete nitrification may lead to the formation of NDMA because of the presence of free chlorine. Partial nitrification may lead to difficulties in establishing the proper chlorine dose. |
| Iron | Oxidized by chlorine. |
| Manganese | Oxidized by chlorine. |
| pH | Affects distribution between hypochlorous acid and hypochlorite ion. |

Note: BOD =biochemical oxygen demand, COD = chemical oxygen demand, TOC =total organic carbon, NDMA = N-nitrosodimethylamine.
Source: Metcalf and Eddy 2003.

**Table 2-5. Potential effects of selected constituents on the use of ozone.**

| Constituent | Effect |
|---|---|
| BOD, COD, TOC etc. | Organic compounds that comprise BOD and COD can exert an ozone demand. The degree of interference depends on their functional groups and their chemical structure. |
| Humic Materials | Affects the rate of ozone decomposition and the ozone demand. |
| Oil and Grease | Can exert an ozone demand. |
| TSS | Increase ozone demand and shielding of embedded bacteria. |
| Alkalinity | No effect or minor effect. |
| Hardness | No effect or minor effect. |
| Ammonia | No effect or minor effect, can react at high pH. |
| Nitrite | Oxidized by ozone. |
| Nitrate | Can reduce effectiveness of ozone. |
| Iron | Oxidized by ozone. |
| Manganese | Oxidized by ozone. |
| pH | Affects the rate of ozone decomposition. |

Note: BOD = biochemical oxygen demand, COD = chemical oxygen demand, TOC = total organic carbon.
Source: Metcalf and Eddy 2003.

## 2.4 Characterization by BMP Type

### 2.4.1 Introduction

Another common initial categorization measure for BMP systems is based upon system design, whether structural (constructed on site), proprietary (pre-engineered), or nonstructural (source control). Structural BMPs are generally above-ground systems that are constructed on site and are intended to provide passive treatment or flow control of the stormwater using a variety of FPCs, as described above. Nonstructural BMPs are generally associated with source control measures aimed at reducing the volume of runoff and the amount of pollutants directly at the source (Urbonas and Stahre 1993). Finally, proprietary BMPs are pre-engineered and typically premanufactured devices that use one or more treatment mechanisms and unit processes. They are often installed underground to minimize the required land area and are often used in conjunction with other BMPs in a treatment train.

### 2.4.2 Structural BMP Systems

Structural systems generally rely on more than one unit process to achieve removal, and they may be configured and installed above or below ground, in a series (treatment train), or stand alone, depending upon the BMP(s) chosen, site

**Table 2-6. Summary of groups of pollutants and relevant BMPs listed based on FPCs.**

| Pollutants | | BMPs | | | | | |
|---|---|---|---|---|---|---|---|
| | | Gravity Settling/Flotation | Filtration/ Sorption | Infiltration (Inf.) | Biological | Chemical | Others/ Proprietary BMPs |
| Particulates | Sediments<br>Solids<br>Heavy metals<br>Organics<br>Nutrients | Retention ponds<br>Detention basins<br>Wetlands<br>Tanks/Vaults | Biofilters<br>Media filters<br>Compost filters<br>Wetlands | Inf. trenches<br>Inf. basins<br>Porous pavement<br>Swales<br>Biofilters/ Bioretention | Biofilters/Compost filters<br>Wetlands/Wetland channels | Coagulation/ Flocculation | Wet vaults<br>Vortex separators<br>Modular wetland systems<br>Inert media filters |
| Solubles | Heavy metals<br>Organics/ BOD<br>Nutrients | | Media filters<br>Compost filters<br>Wetlands/Wetland channels<br>Retention ponds | Inf. trenches<br>Inf. basins<br>Porous pavement | Biofilters/Compost filters<br>Wetlands/Wetland channels | Precipitation/ Flocculation<br>Activated carbon | Media filters (StormFilter) |
| Trash/ Debris | Trash/ Debris | N/A Screening | | N/A* | N/A | N/A | Vortex separators<br>Skimmers |
| Floatables | Oil and Grease | Retention ponds<br>Wetlands<br>Hooded catch basins | Catch basin inserts<br>Vault filters<br>Compost filters | N/A | Biofilters/Compost filters<br>Wetlands | N/A | Oil/Water separators<br>Absorptive media filters |

* N/A = not applicable.

constraints, and removal desired. A fair amount of research, both publicly (e.g., USEPA 1983) and privately funded, has been conducted regarding common structural systems, focusing upon their design and projected efficiency. A variety of standard BMP systems has been identified, and extensive literature exists for a number of these systems:

- Wet ponds—(MacDonald et al. 1999; Schueler et al. 1992; Urbonas and Stahre 1993; Yonge et al. 2002)
- Dry ponds and retention ponds—(Schueler et al. 1992)
- Infiltration trenches—(ASCE 2001; Hathhorn and Yonge 1996; Schueler et al. 1992)
- Wetlands—(Kadlec and Knight 1996; Rushton et al. 2002; Schueler et al. 1992)
- Bioswales and filter strips—(Barrett et al. 1995a, 1995b; Fletcher et al. 2002; Schueler et al. 1992; Walsh et al. 1997; Yu et al. 2001)
- Oil/grit separators—(ASCE 2001; Schueler et al. 1992)
- Sand filters—(Barrett 2003; Keblin et al. 1997; Schueler et al. 1992; Tenney et al. 1995)
- LID facilities—(Prince George's County 2000; Puget Sound Action Team 2003)

There are also a number of web sites pertaining to standard BMP evaluations (e.g., the International BMP Database site [www.bmpdatabase.org] discussed in Section 8.3). One example of a useful compendium of web sites and BMP documents is available from the California State Water Resources Control Board (www.swrcb.ca.gov/rwqcb2/news_items/Tobi%20Reference%20Attachment%20sept%206.doc). In addition, a number of references are available that describe the design and performance of standard BMP systems along with descriptions of the surrounding land and hydrologic characteristics. These references include Sutherland 1991; Schueler et al. 1992; Christensen et al. 1995; Barrett et al. 1995a,1995b, 1998; WEF and ASCE 1998; ASCE 2001; Strecker et al. 2001; and Minton 2005.

## 2.4.3 Proprietary BMP Systems

Like structural systems, proprietary BMPs also may rely on more than one unit process for removal. Generally, proprietary systems are more compact than many standard systems and are installed underground; thus, in many urban and ultra-urban settings, proprietary systems are preferred and used. Ranging from filtration to hydrodynamic devices, these proprietary systems are unique in both their design and operation. A variety of proprietary BMPs has been identified during the course of this project. A selection of these devices judged to be currently in use is given in Table 2-7. Information on most of these devices may be found on the Internet.

Whereas much analysis has been conducted on the effectiveness of standard BMPs, there is limited independent, third-party literature regarding the proprietary BMP technology and its pollutant-removal effectiveness. Independent evaluations are available for at least four of the devices listed: Stormcepter (Winkler 1997b), CDS (Herrera Environmental Consultants 2002), StormTreat (Winkler 1997a), and Vortechs

**Table 2-7. Example proprietary BMPs in current use by treatment type.**

| Proprietary BMP | Trade Names |
|---|---|
| Wet Vaults | StormCeptor |
| | BaySaver |
| | StormVault |
| | ADS Retention/Detention System |
| | |
| Constructed Wetlands | StormTreat |
| | |
| Hydrodynamic/Vortex Separators | Vortechs |
| | Aquafilter |
| | V2B1 |
| | Downstream Defender |
| | Continuous Deflective Separation (CDS) Unit |
| | |
| Inert/Sorptive Media Filters | StormFilter |
| | |
| High-flow Bypass (Flow Splitter) | StormGate |
| | |
| Modular Pavement | Various |

(Taylor Associates 2002; Winkler and Guswa 2002). Each proprietary system web site contains valuable information regarding constructability, system operation, system performance, and cost. Public agencies are also becoming involved in identifying and assessing proprietary BMP systems, e.g., USEPA Technology Verification program (www.epa.gov/etv/verifications/vcenter9-9.html), Washington State Department of Ecology (2002), City of Portland Bureau of Environmental Services (BES 2001a). In addition, a number of individuals have analyzed or assessed proprietary BMP systems within the realm of their individual fields of research (e.g., Minton 2005; ICBIC 1995; Lau et al. 2001; Alsaigh et al. 1999).

### 2.4.4 Nonstructural BMP Systems

Nonstructural BMPs, listed in Table 2-8, are generally source controls undertaken by communities to promote good housekeeping measures and activities aimed at reducing and preventing pollution on a community or neighborhood basis. These range from BMP maintenance and source control efforts such as reducing vehicle use, sweeping streets, cleaning catch basins, controlling and picking up litter, and controlling vegetation, to publishing informational brochures, making presentations at schools, stenciling storm drains, and regulating land use. Nonstructural BMPs are generally most effective with the full support and participation of the community (WEF and ASCE 1998). However, the emphasis of this report is on structural and proprietary systems suitable for highways; thus, nonstructural systems will not be discussed any further.

**Table 2-8. Nonstructural BMPs.**

| Nonstructural BMP | Type |
|---|---|
| Source Control/Maintenance | Street sweeping |
| | Catch basin cleaning |
| | Good housekeeping practices, e.g., covering of stockpiled materials, washing of construction vehicles before leaving construction sites |
| | Safer alternative products, e.g., highway construction materials, herbicides, road salts |
| | Material storage control |
| | Reduction in vehicle use |
| | *Household hazardous waste collection** |
| | Used oil recycling |
| | Vehicle spill control |
| | Above-ground tank spill control |
| | Illegal dumping control |
| | Vegetation control |
| | Storm drain flushing |
| | Roadway and bridge maintenance |
| | Detention and infiltration device maintenance |
| | Litter control |
| | Litter pickup |
| Public Education and Participation | Education, e.g., newspapers, brochures, K–12 |
| | Land use planning and management |
| | Adopt-A-Highway |
| | Integrated pest management |
| | Storm drain system signs (stenciling) |
| Other | Curb elimination |
| | Reduction of runoff velocity |

*Entries in italics are unlikely to be applicable to highways.

## CHAPTER 3

# LID in the Highway Environment

## 3.1 Introduction

Most information about LID facilities and their design is contained in the *LID Design Manual* developed for this project and available on *CRP-CD-63*. This chapter only summarizes the status of LID and highway systems. State DOTs continue to demonstrate a significant amount of interest and effort in using individual LID techniques. Specific LID technologies such as bioretention and soil amendments are already being incorporated into the roadway design and construction programs of several states, including Washington, Texas, Ohio, North Carolina, and Maryland. Much of the basis for the planning, design, and maintenance of these techniques for linear projects has been adapted from planning and land-development standards and specifications in state and local government programs or manuals. In addition, many state DOTs' designs for rural roads include LID aspects, including use of swales and overland flow for drainage.

## 3.2 General LID Definitions

LID is a *decentralized* source and treatment control strategy for stormwater management. The LID site design approach can be used to address planning as well as overall watershed regulatory requirements and resource protection goals. This approach uses an optimal combination of the following design and management elements:

- **Conservation Design.** Overall conservation goals—such as wetlands protection, habitat preservation, or aesthetic requirements—are integrated into the design.
- **Minimizing Development Impacts.** Sensitive environmental areas, such as soils with high infiltration rates or potential for erosion and stands of mature vegetation, are preserved by using highly detailed, site-specific design and engineering strategies and techniques. In the highway environment, this may include additional emphasis placed on alignment and realignment of roads.
- **Maintaining Watershed Hydrologic Timing.** Designs goals include preserving runoff patterns and timing peak-runoff rates to approximate existing or predeveloped conditions.
- **Integrated Management Practices (IMPs).** IMPs are multifunctional, small-scale, source and treatment control stormwater management practices that can be integrated directly into the infrastructure and landscape. IMPs are an integral component of the highway design process; selection of specific IMPs depends on the alignment and profile conditions.
- **Pollution Prevention (P2).** P2 is the use of management techniques and materials that reduce or eliminate pollution at its source. P2s work in the same way as the non-structural BMP systems discussed in Section 2.4.4.

An LID design integrates natural hydrologic functions into the design to replicate the processes of storage, detention, infiltration, evaporation and transpiration, or uptake by plants in order to reduce runoff volumes, attenuate peak-runoff rates, and filter and remove pollutants from runoff. By incorporating controls specifically into upland areas, impacts to wetlands, streams, rivers, lakes, estuaries, and other sensitive areas can be reduced or eliminated.

## 3.3 LID Expands Stormwater Responsibilities

The design and management elements listed above allow for LID to meet objectives in addition to replicating predevelopment conditions and to help expand stormwater management science into community development issues and programs. Some of the new concepts and areas opened to the stormwater planning community by the LID approach include the following:

- An emphasis on bringing overall watershed conservation concepts into roadway design, including maintaining

runoff and recharge patterns that preserve the overall watershed resource protection goals. This encourages designers to consider impacts on habitats and sensitive environmental areas rather than just trying to meet a standard discharge rate.
- Consideration of the entire range of frequencies and durations of storm events during the course of any given time period. Many conventional approaches target control for only a few specific storm events (e.g., 2-yr 24-hr or 1 in. over 24 hrs). By using natural processes of storage, ET, and infiltration, the runoff from smaller but much more frequent *microscale* storms can be controlled or completely eliminated. These microstorms typically constitute 70 to 90% of the total annual precipitation (Wright and Heaney 2001). Larger storms can be controlled by adding sufficient storage volume distributed throughout the site or in more centralized detention facilities.
- Use of minimization techniques. For instance, reducing lane and paved shoulder widths can reduce the volume of stormwater and required area for treatment. This reduction in infrastructure could potentially save capital and increase the area of developable land (Thurston et al. 2003).
- Designing stormwater controls for targeted pollutant issues and using a treatment train approach when multiple opportunities exist for treatment by a variety of techniques along the flow path. A high-efficiency filter path may now be possible.
- Use of P2 to reduce pollutant loads by the selection of road and associated infrastructure materials and operational procedures that minimize sources of pollution. Pollutants can be treated more closely to their source rather than conveyed and allowed to potentially escape into the environment.
- Integration of stormwater controls into the roadway, landscaping, and/or infrastructure, including adjacent systems. This creates opportunities to share costs for construction, construct facilities incrementally, and create aesthetically pleasing landscapes and building components that can manage stormwater (NAHBRC 2003).

Historically, the approach to managing stormwater quality on highways has been to collect and convey stormwater through swales or pipes to a centralized end-of-pipe discharge point or treatment system. However, the rolling topography in piedmont areas and the flat slopes in coastal zones limit the length and extent of any centralized system. The existing highway runoff infrastructure in the United States is inherently "distributed" and may provide unintentional, but likely significant, water-quality and -quantity benefits. Therefore, a key difference between conventional and LID designs for roads is the scale of the distribution of runoff and the integration of water-quality controls into and throughout the drainage network. Any application of LID in the highway environment must recognize opportunities for runoff control resulting from the inherent characteristic of many small catchments distributed over long, linear roadways. Note that the LID approach is not a significant departure from current rural road design practices, in which curb-and-gutter systems are not typically used. The difference is that, in the LID approach, flows are specifically designed not to be concentrated or transported for long distances. The LID concept does provide a formal framework in which to select appropriate surface drainage, landscaping, and infiltration designs.

## 3.4 Microstorm Management

Management of microstorms (frequently occurring storms with high or low intensity and short duration) is one of the key strategies of LID. LID emphasizes treatment of small storms by taking advantage of multiple, distributed, small-scale storage, detention, infiltration, and evaporation functions within the site. Large events can be controlled by increasing the detention and retention volume of more centralized facilities. Wright and Heaney (2001) suggest the following guiding principles for the control of microscale storms:

- Minimize directly connected impervious area (DCIA).
- Increase flow paths and times of concentration.
- Increase ET and infiltration, but not at the expense of nuisance flooding.

## 3.5 LID Stormwater Management Framework

LID as a form of BMP in a highway system may be integrated into the overall stormwater management components of the highway. The characteristics of highway systems that favor integration of LID can be summarized as follows:

- LID favors the use of decentralized source control systems. Linear highway systems are typically decentralized already because the only available controllable drainage area is the right-of-way.
- The ET of microstorm runoff is a key strategy for reducing runoff volumes regardless of the infiltration potential at a site.
- Over 85% of state DOT roads are "rural" (see Table 1-2). As most rural roads use open drainage systems, it is reasonable to assume that the vast majority of them already control some portions of microstorms by soil soaking and ET and/or infiltration on the adjacent right-of-way. The major exceptions would be roads where there are steep slopes or other geotechnical elements necessitating a curb and gutter or where the roadside soils have low permeability.

Consequently, swale drainage or overland flow/dispersal tends to be the dominant BMP for the majority of highways. Many of the swale systems have not been optimized for water retention and water-quality treatment. A component of LID for these types of systems would be to develop design principles to maximize water retention, reduce runoff rates, and improve treatment.
- The 14.3% of state DOT roads that are not rural have curbs and gutters and associated closed drainage systems. Arguments have been advanced to reduce or eliminate curbs and gutters on low-use access roads and low-use parking areas (Li et al. 1998; Heaney et al. 2003). Curb-and-gutter drainage is much more essential in high-use state DOT transportation networks. Control of microstorms in these facilities must be developed as part of a closed drainage system.
- Unlike urban developers, who can view land use as a decision variable to reduce wet-weather impacts, state highway designers do not typically have the option of changing road locations. State highway designers can, and already do, use trading approaches (as applied to some NPDES and total maximum daily load [TMDL] permitting, for instance) to mitigate wet-weather impacts by more intensive controls elsewhere.

Applications of LID technology to the highway environment presented in this project incorporate the characteristics listed above. Detailed discussions of specific BMP and LID facilities are contained in the *Guidelines Manual* and *LID Design Manual*, respectively. The hydrologic analysis described in Chapter 10 of this report relies strongly on continuous simulation to evaluate the relative impact of microstorms. Additional review of the LID literature, background information, and design guidance are contained in the *LID Design Manual*.

# CHAPTER 4

# Stormwater Characterization

## 4.1 Overview

Identifying BMPs by unit operations and assessing BMPs partially on the basis of performance observed from monitoring data require an understanding and assessment of the water chemistry characteristics of an urban rainfall and runoff event (Sansalone et al. 1997; Sansalone et al. 1998; Glenn et al. 2002). Examples of anthropogenic constituents generated from traffic-related activities include significant loads of metals, particulate and dissolved solids, organic and inorganic compounds, and trash and debris (Sansalone et al. 1997). Deposition and accumulation of these pollutants generally result from traffic activities such as vehicular component wear, fluid leakage, and vehicular transport of material. However, the roadway itself may generate pollutants through processes such as pavement degradation and activities such as roadway maintenance (Sansalone et al. 1997). Influent water chemistry, characteristics, and components are important when looking at the overall BMP performance, effluent quality, and maintenance frequency, especially in areas with a high variability in water quality. In particular, stormwater *treatability* (defined later in this chapter) is vital to evaluation of removal effectiveness.

## 4.2 General Characteristics and Pollutant Sources

Stormwater runoff from urban land uses is a complex, heterogeneous mixture of constituents subject to variations in flow, concentrations, and mass loadings that sometimes vary by orders of magnitude during a single storm event. The concentration of constituents in stormwater runoff can be comparable to treated domestic wastewater; when untreated urban runoff is discharged directly to receiving waters, pollutant loadings can be much higher than loadings attributable to treated domestic wastewater (USEPA 2002a). Compared with treatment of drinking water, domestic wastewater, and industrial wastewater, treatment of stormwater poses uniquely difficult challenges because of the unsteady and stochastic nature of many interacting phenomena. These phenomena include anthropogenic activities that occur in the watershed, stochastic hydrology that is variable and unsteady between and during events, previous loadings on the urban surface, drainage conditions and design that influence parameters such as residence time, and the physical-chemical nature of urban surfaces in the watershed. Although these phenomena are unsteady and stochastic in stormwater runoff, they are relatively steady over short time periods for dry weather flows.

Stormwater pollutants often contribute to exceedances of water-quality standards and have been found to cause significant impacts to aquatic life in receiving waters. Most aquatic life impacts associated with urbanization are likely chronic effects related to habitat destruction, polluted sediment, and food web disruption. Public health impacts are generally related to pathogens in urban runoff, which are discharged into water supplies or waters used for recreation (USEPA 1999).

Stormwater runoff and pollutant discharges increase steadily with urbanization because of the increase in impervious surfaces (such as highways, roof tops, and driveways), which reduces infiltration of rainfall and runoff. Pollutants associated with urban runoff can be generally categorized as solids, oxygen-demanding substances, nutrients (nitrogen and phosphorus), pathogens, organics associated with fuels and other petroleum products (e.g., diesel and PAHs), metals, and synthetic (xenobiotic) organics. Generally, sediment is the most significant pollutant in water resources. The amount of sediment contributed to watercourses by urban construction is equivalent to the combination from sources such as forestry, mining, industrial, and commercial activities (USEPA 1999). Pollutants enter stormwater from a variety of sources in the urban landscape, as shown in Table 4-1. More specific information on pollutant sources and characteristics is provided in the Pollutant Fact Sheets of the *Guidelines Manual*.

Table 4-1. Common sources of stormwater pollutants.

| Pollutant | Potential Sources |
|---|---|
| Gross Solids, Sediment, and Floatables | Streets, lawns, driveways, roads, construction activities, atmospheric deposition, drainage channel erosion |
| Pesticides and Herbicides | Residential lawns and gardens, roadsides, utility right-of-ways, commercial and industrial landscaped areas, soil wash-off |
| Organic Materials/Oxygen Demanding Substances | Residential lawns and gardens, commercial landscaping, animal wastes |
| Metals | Automobiles, bridges, atmospheric deposition, industrial areas, soil erosion, corroding metal surfaces, combustion processes |
| Oil and Grease/ Organics Associated with Petroleum | Roads, driveways, parking lots, vehicle maintenance areas, gas stations, illicit dumping to storm drains, automobile emissions |
| Bacteria and Viruses | Lawns, roads, soil erosion, leaky sanitary sewer lines, sanitary sewer cross connections, animal waste, septic systems |
| Nitrogen, Phosphorus, and Other Nutrients | Lawn fertilizers, atmospheric deposition, automobile exhaust, soil erosion, animal waste, detergents |

Source: U.S. EPA 1999 (Preliminary Data Summary of Urban Storm Water BMPs).

Various site characteristics may affect stormwater quality, including the following:

- Climate—including antecedent dry period between storms, average rainfall intensity, storm duration, and amount of snowmelt. Arid and semi-arid regions generally experience longer dry periods than areas with higher rainfall amounts. During these dry periods, pollutants build up and subsequently run off in higher concentrations during storm events than they do in areas with higher rainfall amounts (USEPA 2002a).
- Geographic factors—including soil type, slope, land use patterns, and amount of imperviousness in the watershed (discussed in Chapter 5 of this report).
- Water chemistry—including the effect of pH, type of solids present, ionic strength, and dissolved organic matter.
- Existing source control practices—including sweeping, chemical storage methods, and landscape practices.

## 4.3 Sources of Stormwater-Quality Data

A substantial amount of stormwater-quality data has been collected throughout the United States since the mid-1980s. However, most of these data are not readily available and have not been subjected to rigorous statistical analysis. Some exceptions include the following:

- USEPA Nationwide Urban Runoff Program (NURP) data (described in more detail below).
- U.S. Geological Survey (USGS) National Stormwater Database, consisting of 1,123 storms for 98 stations in 20 metropolitan cities (USEPA 2002a).
- Camp, Dresser, and McKee (CDM) National Stormwater Database, consisting of NURP, available USGS data, and selected Phase I data (Smullen and Cave 2002). Analysis of the data concluded that pollutant concentrations from different land uses were not significantly different; therefore, all data were pooled.
- FHWA collection of stormwater runoff data from 31 highways in 11 states during the 1970s and 1980s (Driscoll et al. 1990). The database has been summarized for urban and rural areas for two highway traffic densities (greater than and less than 30,000 average daily traffic [ADT]) (WEF and ASCE 1998).
- NPDES Industrial Stormwater Data. Industrial NPDES permits require sampling and analysis of stormwater discharges associated with industrial activities. Data may be compiled by USEPA or other permitting authorities.
- Phase I MS4 Stormwater Data. Regional databases have been developed by various municipalities in the Los Angeles area, three counties in the San Francisco Bay Area, the Oregon Association of Clean Water Agencies, and the Dallas, Texas, area.
- Caltrans activities, available at www.dot.ca.gov/hq/env/stormwater/special/newsetup/index.htm, and discussed in Chapter 5 of this report.
- National Stormwater Quality Database (described in more detail below).

NURP was conducted from 1978 to 1983 and was the first comprehensive study to evaluate characteristics of urban runoff, similarities or differences among urban land uses, the extent to which urban runoff is a significant contributor to water-quality problems nationwide, and the effectiveness of management practices to control pollutant loads (USEPA 1983). Sampling was conducted in 28 communities at 81 sites for more than 2,300 discrete storm events. Although the NURP data did not indicate statistically significant differences in pollutant concentrations from different land uses (i.e., residential, commercial, and mixed), the data did show a significant difference between urban and nonurban sites. The NURP studies also found that geographic location, runoff volume, and other watershed factors were of little use in explaining overall site-to-site or event-to-event variability. Median stormwater pollutant concentrations (and coefficients of variation) for all NURP sites by land use are summarized in Table 4-2. The pollutants detected most frequently were copper, lead, and zinc.

A comprehensive study by Driscoll et al. (1990) evaluated FHWA stormwater runoff monitoring data from 31 highway sites in 11 states, incorporating a total of 993 separate storm events. A number of recent studies discussing BMP removal have used the Driscoll et al. (1990) analysis for comparative purposes. Within the testing scheme, mean concentrations of particulates, oxygen demand, nutrients, and heavy metals were evaluated for each of the sites and for the total study scheme, in order to determine approximate highway water quality. Annual average TSS concentrations ranged from 9 mg/L at a site in Florida to 409 mg/L in Colorado, yielding a mean concentration of 143 mg/L for all sites studied (Driscoll et al. 1990). For the nutrients observed, values for inorganic nitrogen, TKN, and phosphate were fairly consistent over all sites studied, with mean concentrations of 0.84 mg/L inorganic nitrogen, 1.79 mg/L TKN, and 0.435 mg/L phosphate. Metals studied include copper, lead, and zinc with mean concentrations of 0.052 mg/L, 0.525 mg/L, and 0.368 mg/L, respectively. The concentrations of all constituents studied were quite variable, but were meant to serve as a baseline for assessment of typical highway water-quality ranges.

A National Stormwater Quality Database (NSQD) is currently (2006) being developed and analyzed by the University of Alabama and the Center for Watershed Protection under a USEPA grant (Pitt et al. 2004, http://unix.eng.ua.edu/~rpitt/Research/ms4/mainms4.shtml). The database consists of nearly 10 years of stormwater outfall data collected by MS4 (municipal separate storm sewer system) permit holders throughout the United States. The final database and analysis will be published on the Web (USEPA Office of Water and Office of Wastewater Management and the Center for Watershed Protection's Stormwater Manager's Resources Center at www.stormwatercenter.net). Version 1.1 of the database contains data from 3,770 separate events from 66 agencies and municipalities in 17 states. Current data are mostly from the southern, Atlantic, central, and western parts of the United States; about 54% of the data are from communities located in Maryland, Virginia, Pennsylvania, North Carolina, Kentucky, and Tennessee. Subsequent phases of the project will concentrate on extending national coverage. The locations of municipal data that are currently in the database are shown in Figure 4-1, according to USEPA rain zones. The nine rain zones are based on precipitation event statistics including annual means of total storm volume, intensity, duration, and interval between storms. The database includes approximately 125 constituents, although 35 constituents are reported most frequently. Most of the data represent residential land use.

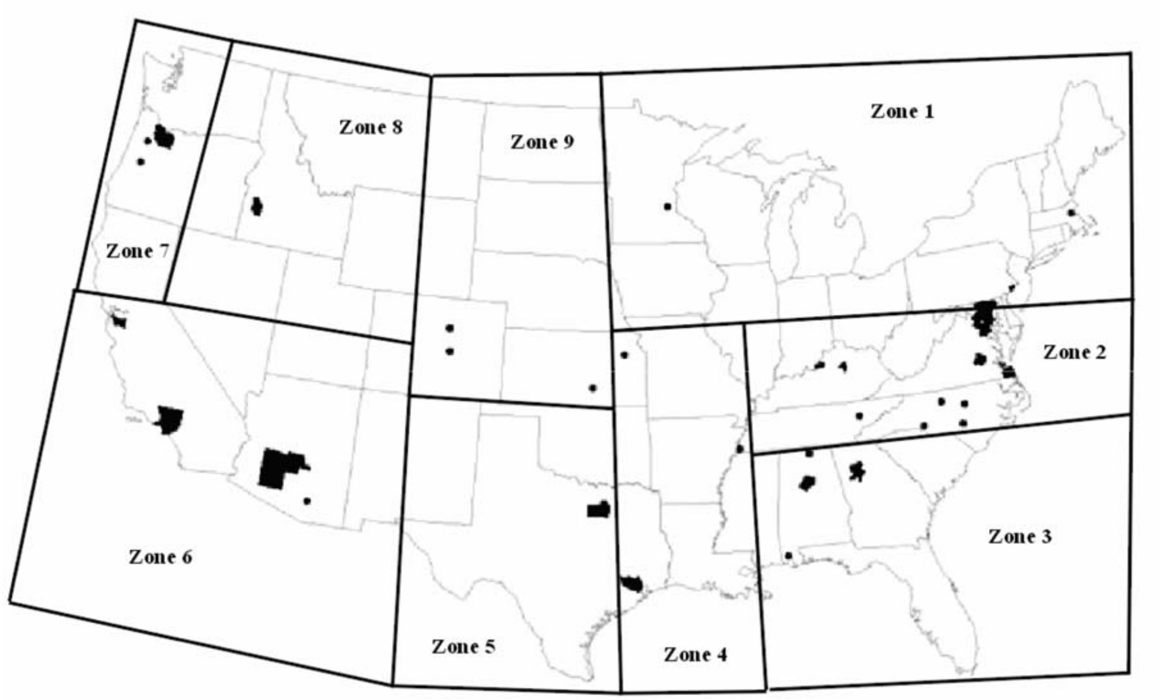
Analysis of the data will include an evaluation of the effects of the following parameters on pollutant concentrations:

- Land use,
- Rainfall amounts,
- Geographical area,

**Table 4-2. Median stormwater pollutant concentrations from the NURP study, by land use.**

| Pollutant | Units | Residential | | Mixed | | Commercial | | Open Space/ Nonurban | |
|---|---|---|---|---|---|---|---|---|---|
| | | Median | CV | Median | CV | Median | CV | Median | CV |
| BOD | mg/L | 10 | 0.41 | 7.8 | 0.52 | 9.3 | 0.31 | -- | -- |
| COD | mg/L | 73 | 0.55 | 65 | 0.58 | 57 | 0.39 | 40 | 0.78 |
| TSS | mg/L | 101 | 0.96 | 67 | 1.14 | 69 | 0.85 | 70 | 2.92 |
| Total Lead | µg/L | 144 | 0.75 | 114 | 1.35 | 104 | 0.68 | 30 | 1.52 |
| Total Copper | µg/L | 33 | 0.99 | 27 | 1.32 | 29 | 0.81 | -- | -- |
| Total Zinc | µg/L | 135 | 0.84 | 154 | 0.78 | 226 | 1.07 | 195 | 0.66 |
| TKN | µg/L | 1,900 | 0.73 | 1,288 | 0.50 | 1,179 | 0.43 | 965 | 1.00 |
| Nitrate + Nitrite | µg/L | 736 | 0.83 | 558 | 0.67 | 572 | 0.48 | 543 | 0.91 |
| Total Phosphorus | µg/L | 383 | 0.69 | 263 | 0.75 | 201 | 0.67 | 121 | 1.66 |
| Soluble Phosphorus | µg/L | 143 | 0.46 | 56 | 0.75 | 80 | 0.71 | 26 | 2.11 |

Note: CV = Coefficient of variation = standard deviation/mean; BOD = biochemical oxygen demand; COD = chemical oxygen demand; TSS = total suspended solids; TKN = total Kjeldahl nitrogen = organic nitrogen + ammonia nitrogen, -- = insufficient data.
Source: U.S. EPA 1983.



Source: Pitt et al. 2004.

***Figure 4-1. Locations of MS4 data in the National Stormwater Quality Database, by EPA rain zone.***

- Season (snowmelt data are not included),
- Watershed area percent imperviousness, and
- Time.

Additional factors that will be evaluated include the following:

- Occurrence and magnitude of first flushes,
- Effects of different sampling methods (e.g., use of grab sampling versus automatic sampling),
- Effects of infrequent wrong data in large databases,
- Appropriate methods to address values below analytical method detection limits, and
- Necessary sampling effort needed to characterize stormwater quality.

Examples of some preliminary findings of the data analysis are shown in Figures 4-2, 4-3, and 4-4. Box and whisker plots (for an explanation of box and whisker plots, see Section 8.5.4) for several constituents are shown in Figures 4-2 and 4-3 for different land use categories, including "freeways." Preliminary statistical analyses found significant differences for land use categories for all pollutants. Total Kjeldahl nitrogen (TKN), copper, lead, and zinc observations are lowest for open space areas, while freeway locations generally have the highest median values, except for phosphorus, nitrates (i.e., nitrate plus nitrate), fecal coliform, and zinc. The industrial sites have the highest reported zinc concentrations.

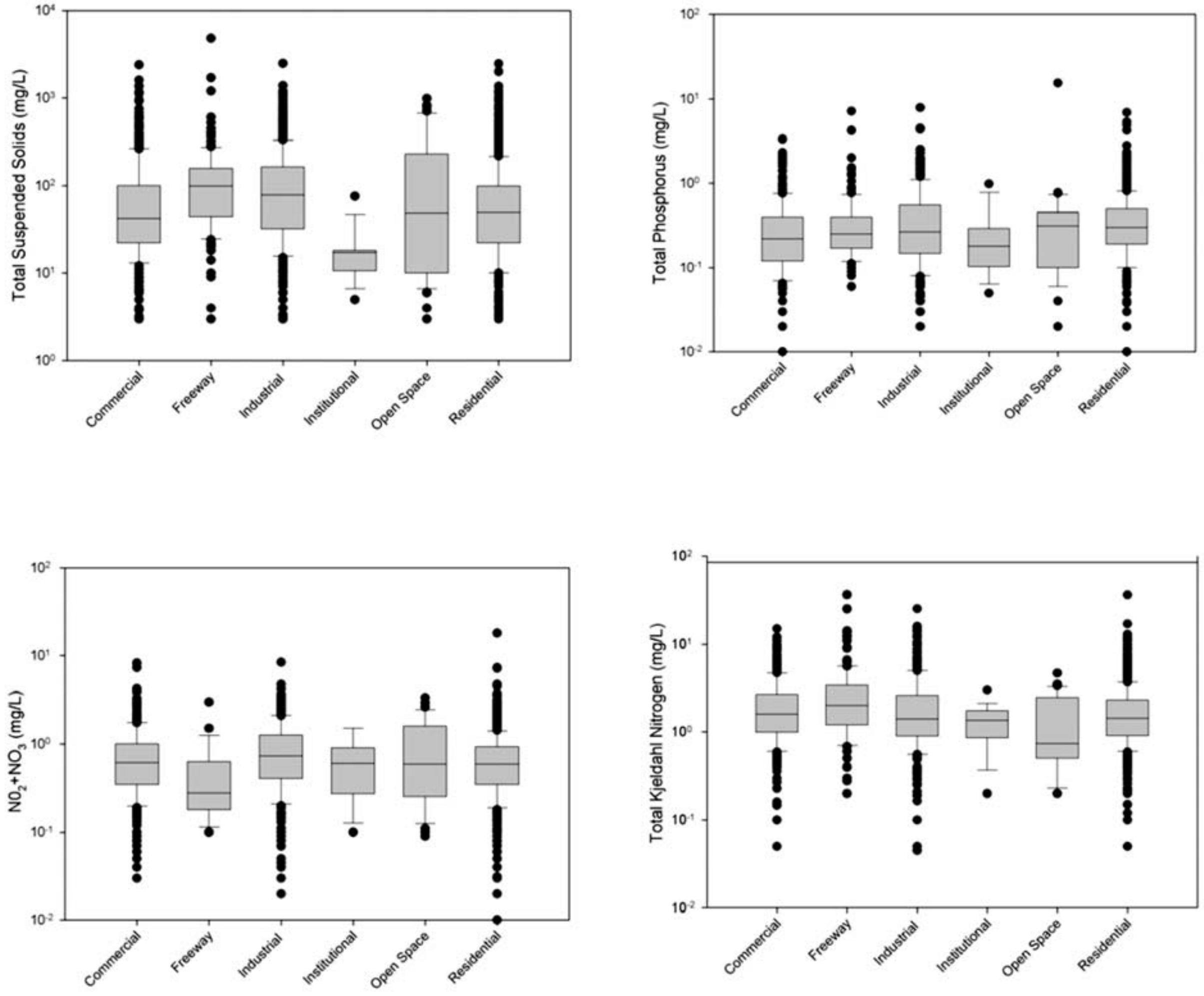
Selected residential data (TSS, total phosphorus, fecal coliform, and total copper) for the different USEPA rain zones are shown in Figure 4-4. Zones 3 and 7 (the wettest areas of the country) have the lowest concentrations for most constituents.

The NSQD will be used to develop a method to predict expected stormwater quality for a variety of significant factors and will be used to examine a number of preconceptions concerning the characteristics of stormwater, sampling design decisions, and some basic data analysis issues. These data are to serve as an updated benchmark for comparison with locally collected data, and they may also be used in lieu of general characterization monitoring for cases in which regional data have been included in the database.

## 4.4 Influence of Roadway Constituents

### 4.4.1 Overall Characteristics

Influent water chemistry, characteristics, and components are important when looking at the overall BMP performance,



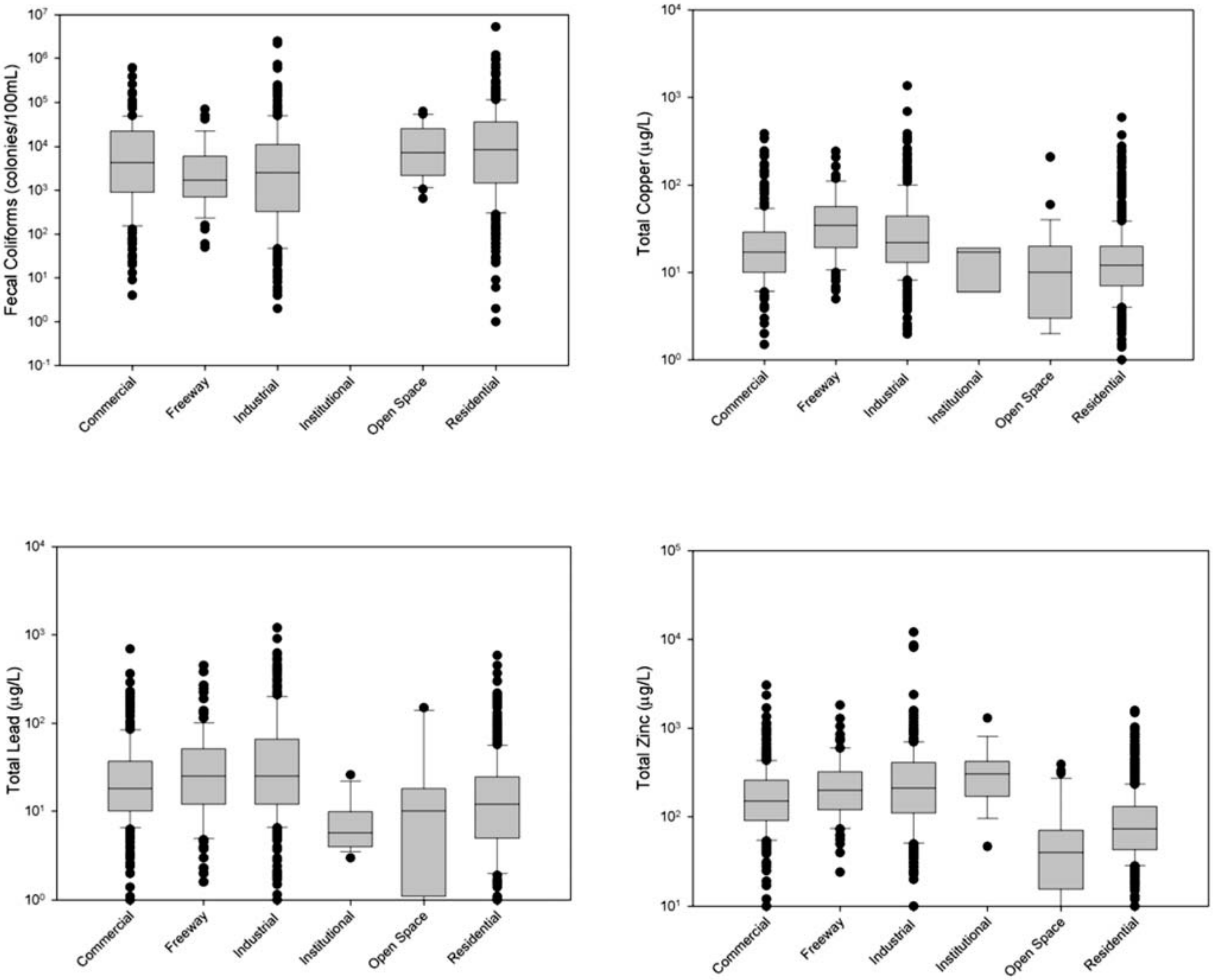
Note: $NO_2$ = nitrite. $NO_3$ = nitrate. Data represent homogenous land use site only; sites with mixed land use are not represented in this analysis.
Source: Pitt et al. 2004.

***Figure 4-2. Box and whisker plots for TSS, total phosphorus, and nitrite and nitrate ($NO_2$-N + $NO_3$-N), and TKN as a function of land use.***

effluent quality, and maintenance frequency, especially in areas that may observe a high variability in water quality. Influent chemical characteristics (such as pH and alkalinity) and hardness and hydrologic characteristics (such as initial and average pavement residence time [IPRT and APRT] and first-flush phenomena) are extremely important to consider when identifying constituent speciation and phasing (dissolved or suspended) (Sansalone et al. 1997; Glenn et al. 2002). Stormwater *treatability* is often defined as the settling velocity (or particle size and specific gravity) distribution of runoff constituents (see Section 4.5). Additional treatability information includes solubility and adsorptivity, but data on settleability are most commonly encountered. Larger, heavier particles are obviously easier to remove. Unfortunately, treatability data are relatively unusual in monitoring programs; however, numerous generalizations are possible, as described in the following sections.

### 4.4.2 Metals

Metals are of concern for urban runoff because of their relative solubility in natural waters, affinity for complexation with humic substances, and potentially toxic effects on and bioaccumulation in biota and aquatic organisms when they are at elevated concentrations (Strecker 1994). The pH and alkalinity of the rainfall are important characteristics to consider, specifically when looking at the partitioning and $K_d$ (linear sorption partitioning coefficient) values for a metal and the speciation and toxicity of the metals, because higher alkalinity and pH tend to drive partitioning toward the particulate-bound phase (Glenn et al. 2002). Typically, copper, zinc, cadmium, and lead are the primary metals monitored because they are generally detected at elevated concentrations in most urban roadway runoff locations, and they display

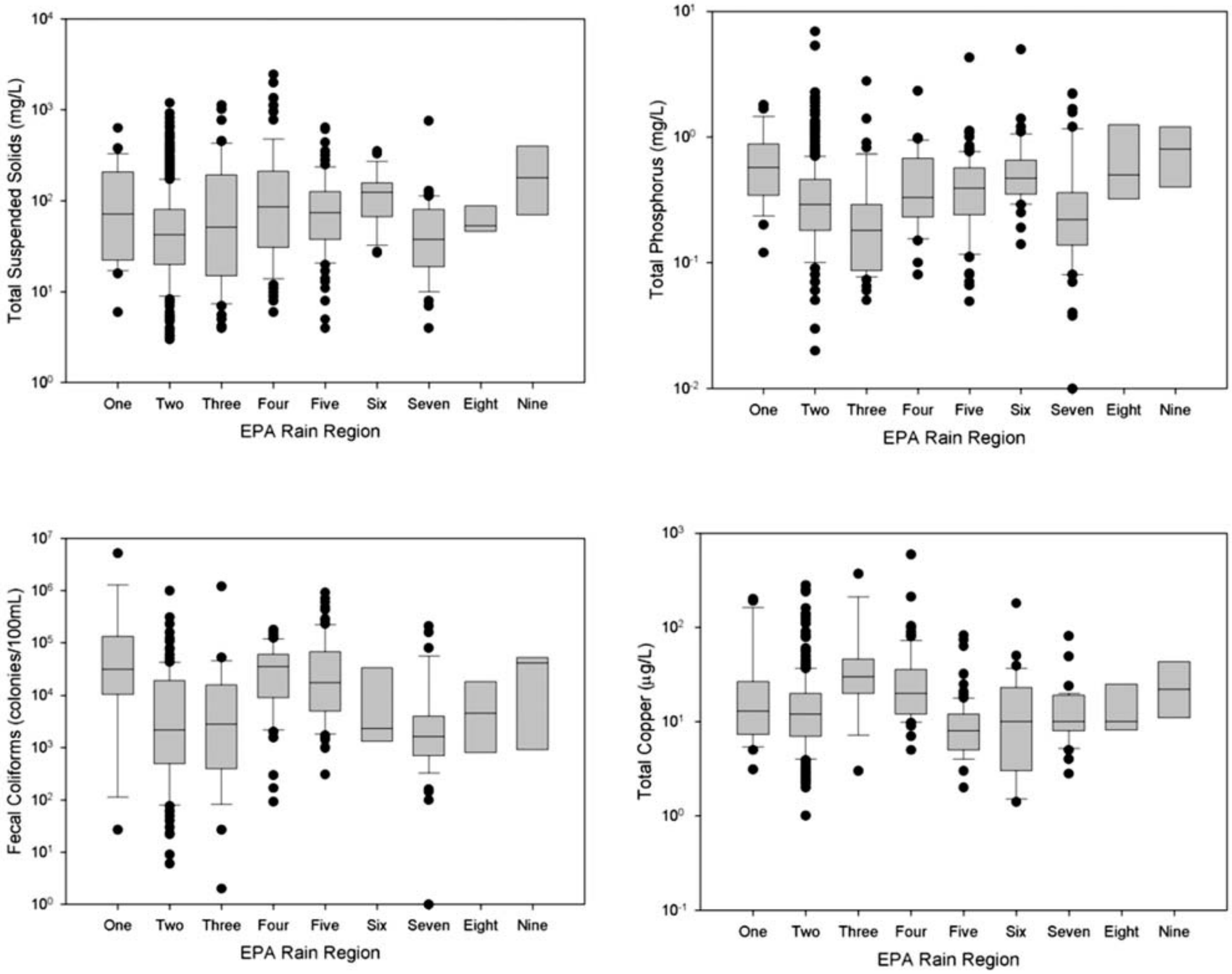


Note: Data represent homogenous land use site only; sites with mixed land use are not represented in this analysis.
Source: Pitt et al. 2004.

***Figure 4-3. Box and whisker plots for fecal coliforms, total copper, total lead, and total zinc as a function of land use.***

similar transport characteristics as other metals (Strecker 1994). If concentrations of metals are less than or equal to five times the detection limit, monitoring results for metals are often statistically insignificant. Because of this, the effectiveness of many BMPs in treating metals is often incorrectly reported and assessed when comparing influent and effluent values (Strecker 1994).

In urban roadway runoff, metals tend to partition into either dissolved or particulate-bound forms, and the partitioning tendencies of a metal indicate not only the probable forms found in wash-off but also the physicochemical mechanisms that are most effective for the metal's immobilization and ultimate removal via a BMP system (Sansalone et al. 1997). In a study conducted on an urban Cincinnati highway site, both the dissolved and particulate fractions of metal elements were measured, and it was determined that rainfall events with lower pH and higher average residence times generally resulted in significantly higher dissolved metal fractions (Sansalone et al. 1997). The low alkalinity of the asphalt pavement was found to have little effect on the pH of the runoff; thus, it did not significantly neutralize the runoff and affect the partitioning. However, the Portland cement concrete (PCC) pavement provided the alkalinity necessary to raise the pH significantly (Sansalone et al. 1997). In addition, it was found that metal elements such as lead, iron, aluminum, and chromium tended to be bound as particulates, while zinc, cadmium, and copper were predominately found in their dissolved form (Sansalone et al. 1997). However, other authors (Yonge et al. 2002) have found zinc primarily in the particulate-bound phase. With regard to partitioning, Glenn et al.



Source: Pitt et al. 2004.

***Figure 4-4. Example residential stormwater data for TSS, total phosphorus, fecal coliforms, and total copper by geographical area.***

(2002) found that dissolved mass, even for relatively insoluble metals, dominates particulate-bound mass at the edge of a highway shoulder, while major peaks in a runoff hydrograph tend to correspond to a decrease in the dissolved heavy metal mass, resulting from increased partitioning of metals to solids mobilized by higher flows.

The distinction between particulate and dissolved forms of a metal is increasingly important when analyzing BMPs on the basis of unit processes, specifically sedimentation. A study conducted at two sites in Washington State observed that in a wet pond setting, where sedimentation provides the primary means of removal, the effluent concentration of dissolved metals as a percentage of the total metals was as much as 2.5 times greater than the influent concentration of dissolved metals as a percentage of the total metals (Yonge et al. 2002). Therefore, sedimentation systems may not provide an effective treatment of dissolved metals constituents, and, in fact, sedimentation systems may become a source of dissolved metals if the redox potential of the system fluctuates.

Metals are readily transported in either dissolved or particulate form, and the concept of first-flush transport of metals via lateral pavement sheet flow was also investigated by Sansalone et al. (1997). Low rainfall intensity and low-flow events exhibited a pronounced first flush of dissolved cadmium (Cd), zinc (Zn), and copper (Cu) and a relatively weak first flush of dissolved lead (Pb), with relative strengths of Cd > Zn > Cu > Pb (Sansalone et al. 1997). In addition, for low rainfall intensity and low-flow events, the relative strength of the particulate-bound fraction first flush is Cu > Zn > Pb > Cd. These results are fairly consistent with the predicted partitioning characteristics of metals (low strength of first flush when metal is predicted to be in opposite partitioned form). For high-intensity and high-flow events, zinc and copper were the primary constituents observed in both the dissolved and particulate form of the first flush, and lead was dominant only in the particulate form (Sansalone et al. 1997). In general, zinc and copper were the primary metals observed during the first flush event in the Cincinnati study. In comparison, Yonge et al. (2002) found metals exhibiting the greater first-flush phenomena were lead and zinc, in the order of Pb > Zn > Cu > Cd. The stark differences in these results appear to be primarily due to differences in intensity of the storm events monitored. For the Sansalone et al. (1997) study, low-intensity events were monitored; for the Yonge et al. (2002) study, higher-intensity events were monitored. Of course, rainfall intensity would also affect pavement residence time, which could alter the pH and the dissolution of metals. These concepts are elaborated further below.

### 4.4.3 Solids and Sediment

Generally solids and sediment in urban runoff are characterized as either suspended, particulate, or dissolved, and the relative loads observed are influenced by factors including particle size, flows, climate, geology, and the vegetation of a drainage system (Strecker 1994). Excessive levels of solids and sediment in runoff may be attributed to high turbidity levels, stream bed occlusion due to deposition, loss of aquatic habitat, and stream channel modifications. Suspended solids have also been used as a surrogate for other contaminants that bind or sorb to fine particles, especially metals; therefore, TSS concentration is commonly correlated with other parameters, although it should not be the only parameter measured if additional monitoring options are available (Strecker 1994). In highway environments, pavement, tire, and vehicular abrasion are primary sources of solids, and solids may range in size from soluble, submicron particles to insoluble, gravel-size aggregate (Sansalone et al. 1997). It has been found that solids with a large surface-to-volume ratio better mediate partitioning and transport of other stormwater constituents, especially metals, and, thus, in order to predict such characteristics of solids present, specific surface area (SSA) is measured in addition to particle size distributions (PSDs) (Sansalone et al. 1998).

The overall transport of solids has also been found to be heavily influenced by traffic flow during storm events and preceding dry days. Sansalone et al. (1998) found that low runoff volume events (in high-traffic situations) typically exhibited a wash-off trend that is flow limited (more solids available for discharge than could be washed off); however, reducing the preceding dry days had a lowering effect on the amount of solids available for discharge and showed a trend similar to the high runoff volume events. In comparison, high runoff volume events in low-traffic situations typically show that wash-off of solids is mass limited (fewer solids available for further discharge) (Sansalone et al. 1998). Overall, these studies indicate the influence of vehicular traffic when looking at mass transport over a site: the greater the traffic volume, the lower the influence of actual runoff volume on actual mass availability and transport.

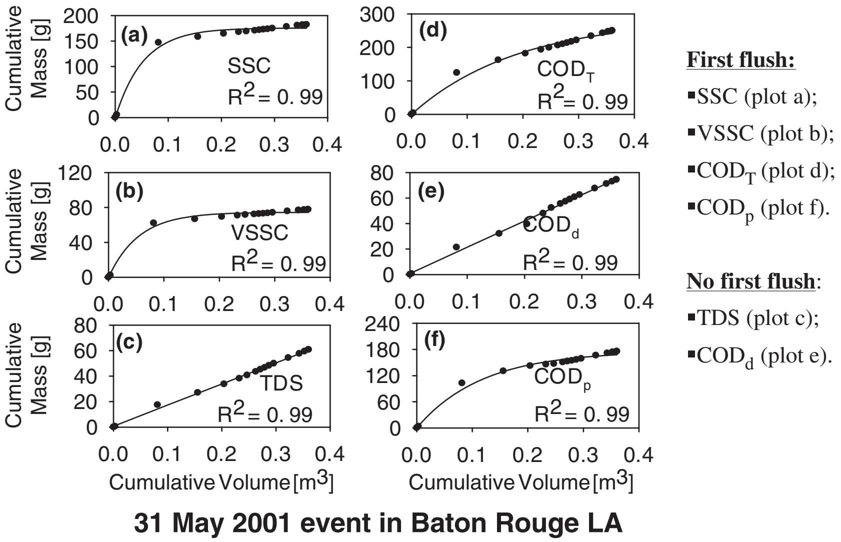
Partitioning of solids between the particulate and dissolved forms generally follows trends similar to those of metals and is heavily influenced by both pH and residence time: smaller pH values and longer residence times typically yield a higher fraction of dissolved particles (Sansalone et al. 1997). Sansalone et al. (1998) found that particle counts and diameters in runoff were strongly influenced by flow intensity (especially at higher flows) and thereby also influenced by traffic intensity. Smaller particles ($< 8$ μm) were rapidly washed off during high flows, and, even when the high flows had relatively short durations, a mass-limited condition was observed.

As with the metals, a first-flush phenomenon has been observed for both particulate and dissolved solids. In the Sansalone et al. (1997) study, it was found that dissolved solids typically exhibit a stronger first flush than suspended solids regardless of rainfall intensity or flow. Sansalone et al. (1998) confirmed this observation, as dissolved solids' first-flush strength was higher than that of suspended solids, and total solids displayed a weaker first-flush effect during low-flow events than during high-flow rate events.

A mass-to-volume curve is one method of displaying the relationship between mass transport and the storm flow event, in order to predict the strength of a first flush. The concept of a mass-to-volume curve is illustrated in Figure 4-5, which presents data from a 0.13-acre elevated section of Interstate 10 in urban Baton Rouge, Louisiana, with PCC paving. Exponential curves illustrate a first flush, while linear patterns represent the absence of a first flush. Notice that for the same event, some constituents exhibit a first flush, while others do not. In this case, particulate and particulate-bound constituents exhibit a first flush, and dissolved fractions do not.

Although not explained within the text of Sansalone et al. 1997 and Sansalone et al. 1998, transport of particulate solids may rely more heavily on rainfall intensity that may escalate during the storm event. Therefore, the typical low intensity of the first flush is more apt to transport dissolved solids. In general, solids and metals typically display consistent correlations between first and additional flush events, i.e., during the latter part of a storm (Hoffman et al. 1985).

Removal of solids and sediment is typically achieved with BMPs using sedimentation or filtration as the primary unit processes. Particle size distribution is an important characteristic to consider when determining the effectiveness of a BMP utilizing sedimentation and/or filtration. Sansalone et al. (1998) observed that when the ratio of media diameter to particle diameter is less than 10, particles are usually removed by surficial straining. When the ratio is between 10 and 20, particles tend to undergo filtration within the pore volume, and this ratio range generally contributes to a loss of filtration capacity of the



Note: SSC = suspended sediment concentration, VSSC = volatile suspended sediment concentration, $COD_T$ = total chemical oxygen demand, $COD_p$ = particulate COD, $COD_d$ = dissolved COD, TDS = total dissolved solids.

Source: John Sansalone, personal communication, 2004. Similar results may be found in Sansalone and Christina 2004.

***Figure 4-5. Illustration of a first flush (convex upward) or lack thereof (linear pattern).***

BMP if appropriate maintenance measures are not undertaken (Sansalone et al. 1998). Finally, with ratios greater than 20, little void space is filled by the particles, and sedimentation and filtration tend to become the dominant removal processes.

### 4.4.4 Petroleum Hydrocarbons

In roadway environments, oil and grease are prevalent organic constituents, but they are rarely measured because of difficulties in obtaining accurate, uniform samples for predicting event mean concentrations (EMCs). Petroleum hydrocarbons are generally present in five forms, only three of which are removable by flotation—free oil, dispersed or emulsified oil, and sorbed oil (Minton 2005). The two forms that are not readily removable with conventional stormwater treatment processes are (1) oil that has been stabilized by a surfactant like soap or detergent and (2) dissolved oil (Minton 2005). The free and dispersed oils exist as minute droplets about 10 to 100 μm in size, which may be sorbed to suspended solids or exist independently and produce a sheen that many jurisdictions do not allow (Minton 2005). Generally, flotation and sedimentation represent the primary processes for removal. Typical mean concentrations of petroleum hydrocarbons in stormwater range from 0.57 to 69 mg/L and are generally the result of vehicular exhaust and lubricating oils (Minton 2005).

Several factors influence the relative concentrations of hydrocarbons in an urban environment, including precipitation, land use, traffic volume, and population (Hoffman and Quinn 1987). Studies by Hoffman and Quinn (1987) and Hoffman et al. (1985) indicate that a majority of hydrocarbons in urban runoff are associated with particulate matter, regardless of land use, and partitioning between the particulate and soluble phases is typically a function of chemical properties, temperature, and time in solution. Particulate hydrocarbons are generally called aliphatic hydrocarbons and consist of normal and branched alkanes and cycloalkanes (Meyers 1987).

While a majority of treatable petroleum hydrocarbons are sorbed onto sediment because of their hydrophobic nature and high sorption coefficients, some also remain in solution, typically the less-dense gasoline products (Minton 2005). This partitioning affects the relative wash-off characteristics of petroleum hydrocarbons, although first-flush characteristics of petroleum hydrocarbons, regardless of partitioning, have been found to display peaks similar to those of solids and metals and increase according to the relative flow rate (Hoffman et al. 1985). The concentration of petroleum hydrocarbons during secondary flush situations tends to be more pronounced than the concentration of metals and solids, indicating that thorough transmittal of hydrocarbons during first-flush events does not readily occur, although eventually the source will be depleted and concentrations will significantly taper (Hoffman and Quinn 1987). Under snowmelt (as opposed to rainfall events), first-flush characteristics and patterns for petroleum hydrocarbons have been observed to differ from other pollutants.

Most pollutants exhibit lower loadings for snowmelt than for rainfall events; however, hydrocarbons have been observed to average 30% higher loadings for snowmelt (Hoffman and Quinn 1987).

Removal of hydrocarbons has been observed biotically under aerobic conditions, but typical removal practices involve flotation and sedimentation systems. Oil-water separators, detention ponds, and sand filters have all been used as removal methodologies for the particulate-based hydrocarbons. Biotic removal processes are found to most readily address the soluble, aromatic compounds with low atomic weights, and, generally, a high nutrient status and an aerated environment are the most important factors driving biological degradation (Fought and Westlake 1987).

### 4.4.5 Nutrients

Although nutrients are necessary for the growth and support of many organisms, excessive concentrations may over-stimulate biological growth and create problematic water-quality conditions such as hypoxia and eutrophication, and some nutrient forms may be toxic to organisms (e.g., un-ionized ammonia) (Strecker 1994). Nutrient removal processes depend upon a number of factors, including seasonal vegetation change, light intensity, temperature, sediment type, and sorption processes (O'Shea et al. 2002). Generally, nitrogen and phosphorus are the primary nutrients of concern because of their ability to enhance algal production, thus reducing the oxygen concentration in a water body. Nitrogen and phosphorus in stormwater are generally a result of runoff of lawn fertilizers, atmospheric fallout, and discharges from automobile exhaust and other combustion processes (Strecker 1994). Generally, three forms of nitrogen are measured and analyzed when looking at urban runoff: inorganic nitrogen (nitrite and nitrate), ammonia nitrogen, and total Kjeldahl nitrogen (TKN), which is the sum of ammonia and organic nitrogen (Strecker 1994). Because the treatability of nitrogen is a function of its form, it is desirable to have all three forms monitored, and they are generally reported in terms of their mass of nitrogen.

Three forms of phosphorus are also typically measured and analyzed: orthophosphate, which is the most biologically available, soluble phosphate (orthophosphate and organic phosphorus), and total phosphorus (Strecker 1994). Total phosphorus and orthophosphate are the typical forms included in monitoring regimes because they characterize both the total and bioavailable forms, and, just as forms of nitrogen are reported in terms of their mass of nitrogen, phosphorous and orthophosphate are generally reported in terms of their mass of phosphorus (Strecker 1994).

Removal of nutrients from stormwater may be addressed using a number of different unit processes; however, the extent to which a process may be effective is quite variable. Forms of nutrients fluctuate readily with different oxidation characteristics, sediment loads, and within the overall environment; for example, nitrate is the most oxidized form of nitrogen and the most mobile, which makes this form very difficult to remove with standard BMP systems. In the study by Yonge et al. (2002), in which two wet ponds in differing areas of Washington State were studied for removal performance, it was found that positive removal of TKN and ammonia occurred throughout the year, but a positive net removal of nitrate only occurred during the warm months that experienced algal growth. In the same wet pond study, it was observed that the average removal of phosphorus was poor throughout the year, with no net removal of orthophosphate and an average of 30% removal of total phosphorus. Bioswales and grass strips, employing more filtration and infiltration removal unit processes, tended to show a higher net removal of nutrients than systems primarily utilizing sedimentation for removal. In a study by Walsh et al. (1997), vegetated swales in Texas were found to exhibit an average total phosphorus removal of 35% and a total nitrogen (sum of nitrate, nitrite, and TKN) removal of 37%. A study by Yu and Stopinski (2001) found that for three storms in Virginia, total phosphorus removal exceeded 98%, while a controlled test site in Taiwan showed total phosphorus removal of 54% and a total nitrogen removal of 19%. A number of studies have found that swale length, as a function of residence time and hydraulic loading, as well as soil sorption characteristics, are important parameters when looking at the removal of nutrients via filtration and infiltration unit processes (Fletcher et al. 2002, Walsh et al. 1997, Yu et al. 2001).

In urban runoff, the first-flush phenomenon is often observed for nutrients, although with a much more variable pattern than for metals and solids because of the higher speciation frequency and the less-stable nutrient forms observed. Nitrate and orthophosphate were rarely observed by Yonge et al. (2002) during first-flush events and did not show significant strength, as orthophosphate was observed in only 18% of analyzed events. However, TKN, ammonia, and total phosphorus were readily observed in the first-flush events, with the strength of TKN and ammonia being greater than that of nitrate.

## 4.5 Stormwater Treatability

As discussed in previous sections, how amenable a particular pollutant is to treatment depends upon several factors, including the following:

- Partitioning (how much of the pollutant mass is associated with the dissolved fraction or the particulate-bound fraction).
- Settleability characteristics (settling velocity and/or particle size and specific gravity) of the particulate form.

- Speciation (the particular chemical form in which an element exists in water).
- pH and other elements of water chemistry (e.g., electrical conductivity, dissolved oxygen, and temperature).

Because many pollutants, such as heavy metals and phosphorus, are often found in particulate form, i.e., adsorbed to solid particles, the PSD of solids in stormwater is essential to determination of the relative treatability by sedimentation or filtration. It is easier to remove pollutants from stormwater if the pollutants are found in particulate form and the particles are large and settleable. When BMPs are arrayed in series, in the form of a "treatment train," the upstream devices will remove the largest, most settleable material first, making additional removal by sedimentation more difficult for downstream devices because only the finer particles remain. Hence, it is important to estimate the change in particle size distribution as water flows downstream through a treatment train. Thus, "treatability," within the discussion in this subsection, is primarily a function of the PSD.

Minton (2005) points out that it is important to distinguish among the PSDs based on particle number ($PSD_n$), volume ($PSD_v$), and mass ($PSD_m$). The $PSD_m$ may be computed from the $PSD_n$ based on assumptions described below. The $PSD_m$ is the most important characteristic from the standpoint of removal by sedimentation and sorption. Ultimately, the distribution of settling velocities must be measured or computed from the PSD in order to evaluate removal by sedimentation. This is illustrated later in this subsection.

Many investigators have documented treatability data in the form of particle settling velocity distributions for stormwater, including Whipple and Hunter (1981), Randall et al. (1982), Rinella and McKenzie (1982), USEPA (1986), Andral et al. (1999), and Deletic and Orr (2005). The terminal settling velocity occurs when particulates accelerate downward through the fluid until the settling velocity is constant and the upward drag force of the fluid and the downward gravitational force exerted on the particle reach equilibrium (Fair et al. 1968; James et al. 2003). Particle settling velocity distributions can also be determined from particle size distributions through the application of a simplified form of Stokes' law, which assumes spherical particles, but does not assume that settling occurs just as a laminar flow phenomenon, and computes the drag coefficient as a function of the Reynolds number (Fair et al. 1968). More sophisticated settling velocity computations may be performed with additional information on particle shape (Dietrich 1982; Jimenez and Madsen 2003).

Particle size distributions are completed every day in the field of geotechnical engineering through the application of sieves (yielding $PSD_m$ directly) for the larger particles (≥53 μm) and a hydrometer analysis for the smaller particles (Das 2002). Geotechnical applications are generally concerned with the distribution of the larger particles. Hydrometer analysis of small particles (less than 53 μm) generally takes a couple of days to complete, but can take up to a couple of weeks and therefore can be quite cumbersome.

Stormwater analysis usually is concerned with smaller particle sizes, which tend to have lower densities and nonspherical shapes, making settling velocities slower. The small particles in stormwater commonly have heavy metals attached to the small sediment sizes, making small sediment sizes more difficult to remove in settling basins (Pitt et al. 1995; Sansalone et al. 1995; Sansalone and Buchberger 1996). This is the reason for focusing on these small particles.

Stormwater is generally sampled to obtain an EMC for the constituents of concern. EMCs can be calculated by taking automated samples or grab samples at discrete points in time (time-weighted) or after a discrete volume of flow (flow-weighted). Stormwater samples are then sent to a lab where they can be analyzed for a range of constituents depending on local regulations and the monitoring program objectives. The stormwater samples could be analyzed for *E. coli*, fecal coliform, oil and grease, nitrogen (ammonia, TKN, and nitrate), phosphorus, biochemical oxygen demand (BOD), chemical oxygen demand (COD), hardness, metals (cadmium, copper, lead, mercury, silver, zinc, etc.), TSS, and total number of particles. Some stormwater monitoring may also include in situ monitoring to ensure that a BMP meets local, state, and/or national regulations. Stormwater characteristics analyzed in the field could include dissolved oxygen, pH, conductance, and temperature.

Total particles in a given sample are determined by a particle counter that separates the smaller particles (<100 μm) into different size fractions. With the particle size fractions ($PSD_n$) in hand, a particle settling velocity distribution can be computed by applying Stokes' law in an iterative process, in which the drag coefficient is a function of the Reynolds number (Fair et al. 1968; James et al. 2003). Necessary assumptions include the following:

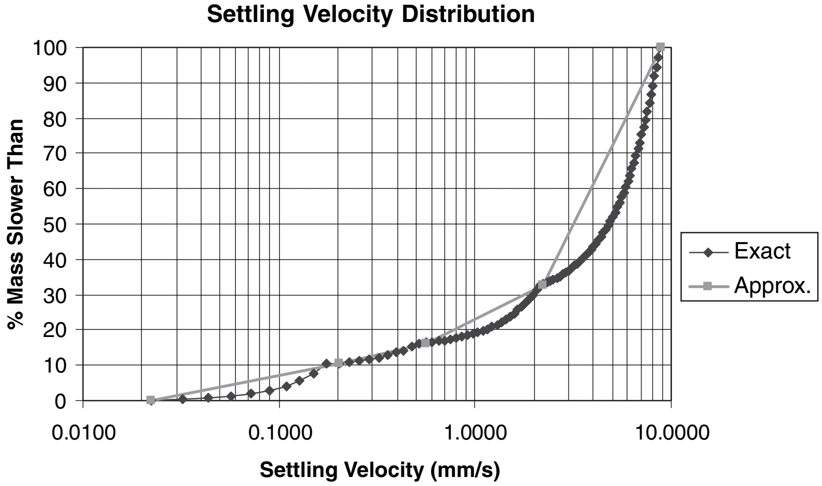
- Spherical particles (or else a relationship between drag coefficient and Reynolds number [Dietrich 1982; Jimenez and Madsen 2003]);
- Known specific gravity (usually 2.65 for sand, but can be less than 2 for colloids); and
- Distribution of particles within each counted range (usually assumed to be uniform).

For example, stormwater particle counts from a residential neighborhood in Portland, Oregon, are shown in Table 4-3, along with settling velocities computed under the assumptions just presented (Bureau of Environmental Services 2001b; Wells 2005). Settling velocities for the end points of the ranges are computed in Table 4-3 and plotted ("approximate") in Figure 4-6. Computations for every integer micron

**Table 4-3. Computation of particle velocity distribution from particle count data ($PSD_n$).**

| Particle Ranges (µm) | #Part/100mL* | Mass per Particle Range (mg)* | End Point Particle Size (µm) | Cumulative Mass (mg) | % Mass Slower Than | Settling Velocity (mm/s) |
|---|---|---|---|---|---|---|
| <5 | | | 5 | 0 | 0 | 0.0224 |
| 5–15 | 1,304,000 | 1.98 | 15 | 1.98 | 10.42 | 0.20 |
| 15–25 | 100,000 | 1.10 | 25 | 3.07 | 16.20 | 0.56 |
| 25–50 | 40,000 | 3.13 | 50 | 6.20 | 32.70 | 2.24 |
| 50–100 | 20,000 | 12.8 | 100 | 19.0 | 100.00 | 8.94 |
| >100 | 10,000 | 19.0 | ** | ** | ** | ** |
| Total Particles | 1,474,000 | | | | | |

* Sum of particles in the range.
** No additional computations possible because upper particle size end point not known for sizes > 100 um.
Source: Table based on sampling data of the Bureau of Environmental Services 2001b. Computations are from Wells 2005.



Note: "Exact" means computation for every integer size in range. "Approx." means computation only at range endpoints.
Sources: Bureau of Environmental Services 2001b; Wells 2005.

***Figure 4-6. Stormwater settling velocity distribution for Portland, Oregon, neighborhood.***

between the range end points are also shown in Figure 4-6 ("exact") from which it can be seen that end point computations should suffice for most computations. Note for this example that the size fraction greater than 100 µm is neglected because these particles will most likely settle out in a BMP designed to capture TSS—for example, a properly designed detention basin or pond. Data such as these (Table 4-3 and Figure 4-6) are used extensively in application of hydrologic screening results, as presented in Chapter 7 of the *Guidelines Manual.*

CHAPTER 5

# Influence of Roadway Land Management and Land Use Practices

## 5.1 Introduction

Proper BMP selection includes an assessment of the types and forms of stormwater constituents at a site and a determination of the proper unit processes to treat those constituents. It is also important to identify the sources and land areas contributing any additional stormwater volume and/or pollutant loads in order to identify source control measures and alternative development practices. Finally, identification of various land management and land use situations is important for determining BMP design and maintenance characteristics. The subsections that follow discuss the influence of impervious areas, land uses, and traffic volume on stormwater volumes and loads.

## 5.2 Directly Connected Impervious Area (DCIA)

Generally, the addition of impervious area as a result of increased development leads to an increase in stormwater runoff volume, higher peak flows, higher average temperature of runoff, collection of a larger mass of pollutants (due to lack of infiltration capacity), and an increased flooding hazard for downstream waterways (Minton 2005; Novotny 2003). Some impervious areas may be indirectly connected to the site drainage system by sheet flow over pervious and impervious surfaces for eventual discharge into gutters, catch basins, etc., while other areas, such as roadways and roofs with attached roof drains, may flow directly into the drainage system. Numerous studies have found that minimizing the DCIA by forcing runoff to travel over stable permeable surfaces (thereby slowing the runoff down and allowing for intermittent infiltration to occur) can yield a significant reduction in the volume and quality of stormwater runoff, especially for smaller storms (Urbonas and Stahre 1993). Site characteristics such as geology, soil type, vegetation, site slopes, groundwater levels, and weather patterns may influence the relative effects that reductions in DCIAs may have on a site (Field et al. 2000). Unfortunately, highways are the epitome of imperviousness, although porous pavement technology may be suitable for low-volume roads and parking lots. However, emphasis on infiltration, e.g., through LID techniques, can help to mitigate the unavoidable impervious impacts of highways, as will be discussed below.

Rainfall events from four sites in south Florida, including one highway site, were evaluated to determine the importance of the DCIA on the generation of urban runoff for smaller storm events (Lee 2003). Results were consistent with previous studies, indicating the result that the DCIA is responsible for between 50 to 100% of the total runoff and that DCIA runoff generally exceeds all other runoff for most land use types. Specifically, for the highway environment studied, the DCIA contributed only 18% of the total land area while yielding 80% of the total runoff. For the commercial development area studied, the DCIA contributed 98% of the total land area and essentially 100% of the total runoff volume (Lee 2003; Lee and Heaney 2003).

In residential settings, a majority of the DCIA is a result of connected roof downspouts and driveway areas. Huber and Cannon (2002) used the Storm Water Management Model (SWMM) as a means to model runoff events in a dense residential neighborhood in Portland, Oregon, and showed that infiltration of direct surface runoff from all roofs and driveway areas in their test site resulted in over a 50% reduction in total runoff volume. Lee (2003) found that high-density residential areas, with approximately 44% total area as DCIA, contribute approximately 70% of the total runoff over all rainfall events and a majority of runoff for 90% of the rainfall events. In comparison, low-density residential settings with 6% of the total area as DCIA contribute about 36% of the total runoff; however, significant runoff from such areas is only observed for larger storm events (Lee 2003).

Minimization of DCIA can be incorporated into both new design and retrofit scenarios. In new development, the use of

LID practices such as porous pavement, planter strips, and eco-roofs minimizes impervious areas on a site. Minimization of impervious areas allows for reduced flow rates, increased infiltration, increased ET, and increased groundwater recharge rates and therefore a reduction in the pollutant load reaching a BMP system and receiving water body. Retrofit practices, such as the disconnection or relocation of roof drains, may be possible in some older development areas, specifically in low-to-medium density residential areas and low-density commercial areas (Urbonas and Stahre 1993). Disconnection and relocation of roof downspouts to pervious areas allows runoff to discharge into landscaped areas for infiltration first instead of directly into the sewer system or onto the pavement or roadway area (Urbonas and Stahre 1993). This practice is not a panacea, however, since concerns over possible groundwater contamination and localized drainage problems must be addressed.

## 5.3 Land Use

Both the volume of runoff (because of varying impervious area percentages) and types of constituents that may be found on a site are influenced by type of land use (commercial, residential, highway, etc.). In addition, the setting for each land use type—urban or rural—may be indicative of the relative magnitude of pollutants at a site. Highways are one type of land use, but a particular highway may have both urban and rural settings. The concentrations of contaminants, especially metals and nutrients, have been found to increase as a highway's surrounding setting becomes increasingly urban (Driscoll et al. 1990).

The relative land use and urbanization implications for stormwater quantity and quality were extensively studied even before the establishment of NURP (USEPA 1983; Manning et al. 1977). From a water-quality perspective, increasing the urban areas within a watershed results in accelerated erosion and sediment transport because of alteration of the land surface, increased surface particulate matter from transportation and anthropogenic activities, and increased atmospheric depositional rates associated with industrial and energy production activities (USEPA 1983). As a function of urbanization, the type of land use within an urbanized setting (commercial, residential, or industrial) also influences the types of constituents and their loads (see Section 4.3). However, it is unclear whether there is an actual difference in concentration of constituents among land use types, for the overall relationship of mass to volume may be consistent even if the relative amounts from each site are not (Minton 2005). Generally, within an urban environment, high-density (apartment buildings) residential land use generates larger pollutant load accumulations and runoff volumes than low-density (single family homes and open space) residential land use. Apartment buildings generally have an increased associated population and a greater percentage of imperviousness and thus yield not only a greater volume of runoff because of less infiltration but also a higher rate of pollutant accumulation because of additional population, automobiles, and probable pollutant sources. Low-density residential land use typically has pervious surfaces incorporated into the land area and far fewer people and probable pollutant sources.

Hoffman and Quinn (1987) found that the type of land use (commercial, residential, highway, or industrial) had a strong effect on the discharge of petroleum hydrocarbons. Plots illustrating the discharge of hydrocarbons versus the relative rainfall showed a tapering of hydrocarbon discharge after about 20 mm of rainfall on residential and highway land use types, while commercial land use showed noticeable source depletion after about 32 mm of rainfall (Hoffman and Quinn 1987). Industrial land use did not show a tapering of hydrocarbon discharge, probably because of the much larger amount of discharge accumulating on the site as compared with the other land uses. For all land uses except industrial, there was a noticeable, yet variable, exhaustion of hydrocarbons during longer rainfall events (Hoffman and Quinn 1987).

Source control practices for stormwater management are beginning to focus on land use and urbanization policies as means of controlling runoff. With the use of zoning laws and urban growth boundaries, many local and state governmental organizations are able to control the rate at which rural lands are incorporated into urban areas. In addition, within urban areas, development activities aimed at maximum use of available area with minimal impact on the surrounding environment—characterized by a mixing of land uses, emphasis on green space, nodal development, diversity, and a reduction in highly impervious areas (parking lots and roadways)—are initiating a new development trend called "new urbanization" (Field et al. 2000). In contemporary land use planning, highways are often carefully managed from an environmental standpoint, including controls for stormwater, noise, and air pollution, as well as attention to aesthetics.

## 5.4 Traffic Volume

The distinction between urban and rural settings may directly influence stormwater constituents and volumes, and for highway settings, the distinction between urban and rural areas directly relates to the probable pedestrian and traffic volumes observed at a site. Some studies (Yousef 1985) have used average daily traffic as an indicator of traffic density, while others have investigated cumulative vehicles during a storm (Racin et al. 1982; Chui et al. 1982) in order to determine probable pollutant loading effects. In a study by Barrett et al. (1995a), three highway locations were compared to determine the effect of differing traffic volumes on the pollutant loading and runoff concentrations from the sites. The highways had traffic volumes ranging from 8,700 vehicles per day (in the rural setting) to 60,000 vehicles per day (in the highly urban setting) (Barrett et al. 1995a). The study found that higher concentrations of all constituents were measured at the high traffic volume site, and, when normalized for surface area, the highest mass accumulation and pollutant load was generated on the site with the highest traffic volume as well (Barrett et al. 1995a). Thus, increased urbanization surrounding a roadway resulted in increased pollutant mass accumulated, regardless of flow characteristics.

Mean highway TSS data from an FHWA study (Driscoll et al. 1990) and highway data from Baton Rouge, Louisiana, and Cincinnati, Ohio, (Sansalone et al. 1998) were analyzed for the impact of annual ADT by Teng and Sansalone (2004a, 2004b), as shown in Table 5-1. When mean TSS is plotted against ADT (as suggested by Rapp 2004), a weak but statistically significant (P = 3.6%) relationship may be seen (see Figure 5-1). However, an earlier analysis by Driscoll et al. (1990) of site *median* TSS EMC values for 16 highway sites from the FHWA study found no statistically significant correlation (at the 90% level) with ADT. Driscoll et al. (1990) reason that TSS sources from surrounding areas in addition to vehicular traffic could be responsible for accumulations on highway surfaces. Interestingly, the only pollutant showing a significant relationship with ADT in the analysis by Driscoll et al. (1990) was zinc.

In an analysis of data from the extensive 1997-to-2001 Caltrans highway runoff characterization study (www.dot.ca.gov/hq/env/stormwater/special/newsetup/index.htm), Kayhanian et al. (2003) found that, in general, EMCs from urban highways were greater than EMCs from nonurban highways, with the exception of TSS, COD, TDS, turbidity, ammonia, and diazinon, for which average EMCs were higher

**Table 5-1. TSS data for highways, summarized by Teng and Sansalone (2004a and 2004b).**

| Site | ADT ($\times 10^{-3}$) | Pavement* | Annual Rain (mm) | N** | TSS EMC | | |
|---|---|---|---|---|---|---|---|
| | | | | | Mean (mg/L) | Std. Dev. (mg/L) | Range (mg/L) |
| Denver (I-25) | 149 | ACC | 370 | 16 | 469.6 | 288 | 171–1185 |
| Efland, NC (I-85) | 26 | ACC | 1,090 | 34 | 24 | 13.6 | 7–57 |
| Miami (I-95) | 140 | ACC | 1,495 | 5 | 107.4 | 104 | 15–260 |
| Harrisburg (I-81) | 24 | PCC | 924.5 | 22 | 52 | 47.6 | 4–163 |
| Harrisburg (I-81) | 56 | PCC | 942.5 | 21 | 310.7 | 458.1 | 48-2160 |
| Little Rock (I-30) | 42 | ACC | 1,217.5 | 18 | 127.4 | 66 | 54–248 |
| Milwaukee (I-94) | 116 | ACC | 690 | 109 | 212.7 | 258 | 17–1860 |
| Milwaukee (I-794) | 53 | PCC | 1,495 | 30 | 169.7 | 114 | 26–475 |
| Nashville (I-40) | 88 | PCC | 1,125 | 31 | 215.2 | 106 | 52–478 |
| Seattle (I-5) | 53 | PCC | 655 | 119 | 124.9 | 97.7 | 14–552 |
| Vancouver, WA (I-205) | 17 | PCC | 975 | 86 | 43.5 | 38.2 | 2–254 |
| Baton Rouge (I-10) | 78 | PCC | 1,460 | 9 | 298.4 | 159 | 18–8735 |
| Cincinnati (I-75) | 117 | ACC | 1,020 | 13 | 130.7 | 57.2 | 29–259 |
| Mean of Sites: | 73.8 | | 1,009 | 37 | 172.2 | 122 | 2–8735 |

*ACC = asphalt cement concrete, PCC = Portland cement concrete.

** Number rainfall events sampled. Snowfall events not considered.

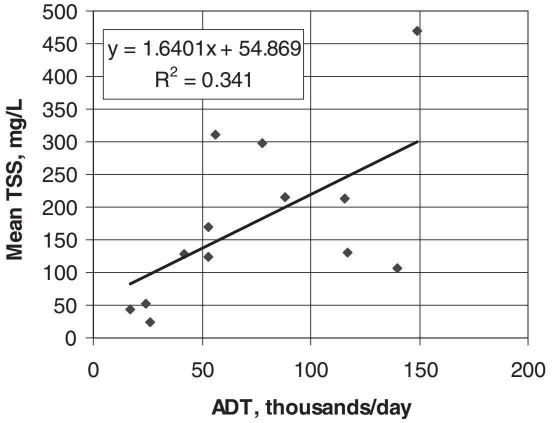


*Figure 5-1. Highway TSS concentrations versus ADT, from data of Teng and Sansalone (2004a and 2004b).*

on nonurban highways. The authors suggest that sources other than transportation-related sources must contribute to this latter group of constituents. Interestingly, no simple linear correlation was found between annual ADT and EMCs, including those known to be related to transportation activities (e.g., lead, copper, zinc, and oil and grease). However, ADT did contribute to significant multiple regression relationships when combined with other factors, such as antecedent dry period, seasonal cumulative rainfall, total event rainfall, maximum rainfall intensity, drainage area, and land use. (The latter three were generally the least important factors in the multiple regressions.) The multiple regression relationships developed by the authors are useful for EMC estimates based on these several independent variables, with the caveat that the data are heavily influenced by the majority of monitoring sites being located in Southern California.

## CHAPTER 6

# Influence of Hydrologic Characteristics

## 6.1 Introduction

Although various land management practices may influence the types and loads of stormwater pollutants, hydrologic characteristics will determine the relative transport of the contaminants to the BMP system. A number of hydrologic factors may vary the pollutant discharge during a storm event, including rainfall intensity, storm duration, and duration between rainfall events (antecedent dry days). Also, a number of site-specific factors affect the overall loading to a BMP system by influencing the relative partitioning of constituents and the delivery of the constituents to a site. Regional hydrologic influence on performance of BMPs is discussed in Chapter 10 of this report, and a detailed analysis is presented in Chapter 7 and Appendix C of the *Guidelines Manual*.

## 6.2 Urban Water Balance

As described in the previous chapter, urbanization replaces pervious surfaces that are generally vegetated with impervious surfaces. Furthermore, the process of construction and alteration of the land surface changes the nature of the soils and vegetation on the remaining pervious surfaces. The environment of a highway is particularly striking in this regard because of the heavy equipment and imported fill that are usually a part of the construction process. All of these activities drastically alter the vertical water balance among rainfall, infiltration, ET, and surface runoff. Before construction, native (or agricultural) vegetation may have transpired much of the rainfall, but roadside and other replacement vegetation in the urban setting may not behave similarly. If there is less ET, then more pressure is placed on infiltration to mitigate increased runoff from nearby impervious surfaces. Compacted soils may not easily perform this function (Pitt et al. 1999; 2001), although part of the BMP and LID design process is to enhance infiltration as much as possible. Vegetation that encourages ET (ideally without requiring extensive irrigation to maintain it during the dry season) provides a means to remove water to the atmosphere that might otherwise have to be infiltrated or else simply run off. For instance, experience with Portland's eco-roof program has shown that vegetated roofs reduce runoff even during the winter, when vegetation is relatively dormant and when there is considerable seasonal rainfall (T. Liptan, Portland Bureau of Environmental Services, personal communication, 2002). Where does this water go if it cannot infiltrate (into the roof!)? Enhanced ET is the answer, and ET will act to reduce runoff in most facilities for hydrologic source control.

With urbanization comes irrigation of planted vegetation, leading to dry-weather flow in areas that are otherwise deserts during most of the year, such as Southern California. This introduced artificial baseflow means that runoff may need to be managed during the whole year, not just during the rainy season. Possible advantages of having runoff during the whole year include the ability to maintain wetlands and wet ponds for treatment. Disadvantages include leaching of previously bound chemicals, such as nitrates and selenium (Strecker et al. 2002). If highway riparian vegetation is irrigated, this could also be a factor in BMP selection. Although irrigation is unusual along highways, it is not unknown, and drainage of the water table along highway embankments or cuts could have a similar effect (leaching of chemicals by the drainage effluent), at least temporarily, which might require mitigation.

## 6.3 Hydrologic Site Characterization

The discussion in the previous section, coupled with the common and unfortunate lack of constituent treatability data (see Section 4.5), underlines the need for site-specific hydrologic data for BMP and LID design. If a device relies upon infiltration, then infiltrometer tests should be conducted to quantify infiltration rates, especially for areas with disturbed soils (e.g., near highways). If ET will be encouraged (e.g., through vegetation), good local estimates of ET should be obtained (e.g., the U.S. Bureau of Reclamation's AgriMet web site for western states: http://www.usbr.gov/pn/agrimet/index.html). A characterization of soils in the catchment and particulates from the roadway will aid in estimating the effectiveness of sorption in reducing constituents such as heavy metals. Is a baseflow present that might leach chemicals from soils in the catchment and/or lead to a dewatering of soils in the highway embankment? What seasonality is exhibited in the precipitation records? All these factors (and more) affect BMP/LID design. A science-based approach to design including *measurement* of key parameters such as infiltration rates is recommended.

## 6.4 First-Flush Phenomenon

The first flush generally refers to the delivery of a disproportionately large load of constituents during the early part of a runoff hydrograph (Sansalone et al. 1997); this phenomenon has already been discussed in conjunction with specific pollutants in Section 4.4 and is recapped here. A number of jurisdictions base system sizing criteria on the treatment of the first flush, maximizing efficiency by using the system to achieve an overall net reduction of pollutants without treating the relatively clean water that discharges during the later stages of a storm event (Minton 2005). First-flush phenomena are discussed in numerous studies (Barrett et al. 1995a; Driscoll et al. 1990; Field et al. 2000; Glenn et al. 2002; Hoffman et al. 1985; Hoffman and Quinn 1987; O'Shea et al. 2002; Sansalone et al. 1997; Sansalone et al. 1998), and it has been noted that a first flush often has a variety of stormwater constituents such as hydrocarbons, metals, sediment, and nutrients. The extent to which a first flush is observed has been found to vary according to the flow event and the relative partitioning of constituents between particulate and dissolved phases.

A mass-to-volume curve (see Figure 4-5) is one method of displaying the relationship between mass transport and the storm flow event, in order to predict the strength of a first flush. Normalized with respect to time and based on the duration of the storm event, the mass and volume curves for the event are plotted simultaneously. The first flush occurs when the mass curve is above the flow volume curve (Sansalone et al. 1997). The ratio of the mass curve area to the flow curve area represents the strength of the first flush, and the relative slope of the mass curve represents the mass mobilization rate (Sansalone et al. 1997).

The first flush may or may not appear at a given site for a given constituent. For instance, solids may erode more readily later in a storm event, when soils are saturated (Sutherland and Jelen 2003). Generalizations cannot be made about whether or not there will "always" be a first flush for constituents in particulate, dissolved, or mixed forms; Christina and Sansalone (2002) emphasize the need to characterize any possible first-flush phenomenon on the basis of the particle size distribution of the constituent. But most importantly, BMP effectiveness can rarely be achieved with a system based on capturing just the early part of the storm event, even though this leads to more economical treatment (because a lower volume needs to be controlled). Better practice—or at least, more demonstrably justifiable practice—will usually be based on capture of a specified volume for all storms, as determined by a continuous simulation. This method is illustrated in Section 10.4.

Clearly, the variability of concentration and flow during a storm event strongly influences the selection of a BMP. High-rate devices, such as filters and some proprietary devices, are very susceptible to inefficiencies created by possible elevated concentrations late in a storm, whereas devices that typically store runoff from more than one event (e.g., ponds, wetlands) are less susceptible to these issues.

## 6.5 Pavement Residence Time

Pavement residence time generally refers to the lag time between rainfall and runoff increments and influences the partitioning of constituents and the loading dynamics for a BMP at a particular site. Generally, the pavement residence time is characterized as either the average or initial residence time. As described in Sansalone et al. 1997 and Sansalone et al. 1998, the initial pavement residence time (IPRT) refers to the lag time between the initial rainfall and initial runoff and is indicative of the time required to wet the pavement surface and fill depression storage before pavement runoff occurs. Generally, the IPRT has been found to be lowest for higher-intensity events, although studies have found that the IPRT is fairly consistent for most levels of intensity, only differing by a factor of 2 (Sansalone et al. 1997; Sansalone et al. 1998). The APRT is one measure of the time of concentration for a particular event, and, using hydrographs and hyetographs, APRT can be determined by calculating the mean time differential between each hydrograph and hyetograph centroid during a storm event (Sansalone et al. 1997). Generally, the lower the APRT, the higher the intensity of the event because of the shorter time associated with lateral sheet flow over the site. For the 0.07-acre site used in Sansalone et al. (1998), IPRT generally ranged from 3 to 14 min, with a mean time of 8 min, whereas the APRT ranged from 1.5 to 15 min, with a mean time of 5.2 min.

Residence time is an important hydrologic characteristic to consider when determining BMP loading from a runoff volume perspective and when sizing a volume-based BMP system to maintain a certain holding time. From a water-quality perspective, residence time has been shown to be important with regard to the partitioning of constituents, specifically for metals, sediment, and hydrocarbons. A longer APRT generally yields a higher dissolved fraction of sediment and metals (Sansalone et al. 1997; Sansalone et al. 1998), and, given that removal of dissolved constituents with BMP systems is generally a much more difficult process, this hydrologic characteristic should be considered in the BMP selection process. For example, largely pervious areas with long APRT (e.g., subdivisions and low-density residential areas) are often treated using a wet pond or other sedimentation facility because of aesthetic benefits, available land, lower relative cost, etc. However, sedimentation facilities are rarely able to remove dissolved pollutants via their primary FPC (sedimentation), and therefore other BMP alternatives for these types of areas should possibly be explored.

## 6.6 Flow Rate

The transport (or load or flux) of constituents off a surface is the product of concentration times discharge and thus is a function of catchment characteristics that influence discharge, including cover, slope, porosity, roughness, depressions, and the nature of the rainfall (Hoffman and Quinn 1987). The flow rate may be indicative of the amount of remaining mass available for discharge after the storm event because as the flow rate increases so does the mass of constituents that are able to be transported at a given rate (Hoffman and Quinn 1987). In general, BMP pollutant-removal efficiency, flow reduction capabilities, and overall effectiveness depend on the flow into and out of the system.

Flow rate and intensity influence the particle size distribution of sediment in a sample, in addition to the total mass carried during the event (Minton 2005). As mentioned in Section 4.4.3 Sansalone et al. (1997) found that particles smaller than 8 μm were rapidly transported during high-flow events, and a larger proportion of total mass for the site was transported. Low-flow events generally do not wash off as large a proportion of total mass, indicated by a presence of both total and dissolved mass still available for delivery (Sansalone et al. 1997). Generally, however, as flow rate increases, the proportion of larger particles also increases. Transport of pollutants such as metals and hydrocarbons is highly influenced by the sediment content in a sample and thereby also affected by flow rate. Hoffman et al. (1985) found that large peaks in loading rates of pollutants (TSS, hydrocarbons, lead, iron, copper, and chromium) are synonymous with higher flow rates.

CHAPTER 7

# Regional Drivers of BMP/LID Selection

## 7.1 Introduction

To select an appropriate BMP/LID system for a site, performance or hydrologic measures need to be considered along with the feasibility of design, installation, and implementation. A variety of regional factors or drivers influence the selection and/or location of a particular BMP/LID system. At the local level, competing political, economic, transportation, development, social and environmental objectives must be considered and reconciled by determining goals and objectives of the program, procedures to govern the overall effort, and specific operational requirements (American Public Works Association 1981). Goals and objectives regarding maintaining water resource uses and required water-quality criteria are often set forth by the states. However, local governments may require more specific objective statements to comply with these water-quality requirements when designing their stormwater management approach. Useful design criteria stem from clear and concise articulation of local stormwater management policy. In effect, the criteria represent the explicit and orderly tabulation of planning and engineering parameters which, when utilized by technical personnel, will result in a plan or facility that is consistent with the adopted state and local policies (American Public Works Association 1981). Special local and regional concerns could influence the BMP selection as well. For instance, BMP selection would be affected by local requirements/recommendations that indicated use of distributed (site-level, LID etc.) BMPs or a more centralized, regional-level BMP.

In this chapter, many nonhydrologic regional drivers are considered, all of which may impact the selection of BMP and LID controls for a highway project. At the conclusion of this chapter, an environmental checklist used by the Oregon Department of Transportation (ODOT) is provided by way of summation.

The regional and site-specific drivers can be divided into three primary categories: (1) physical drivers; (2) regulatory drivers; and (3) political, economic, and jurisdictional drivers. The drivers that influence BMP/LID selection and design are briefly described below.

## 7.2 Physical Drivers

### 7.2.1 Physical Constraints

The physical constraints of a potential BMP/LID location may significantly influence the selection and design of stormwater treatment and control facilities. These constraints depend on whether the stormwater project is a retrofit of an existing drainage system or simply a component of a larger highway improvement or construction project. For instance, a construction project with a new drainage system would be likely to have more options for integrating a stormwater treatment or control facility than an existing highway storm drain network.

Regardless of the type of project, all of the physical drivers that might influence the selection and design of a stormwater BMP should be carefully considered. Some of the most common physical drivers influencing BMP selection and design are space availability, existing infrastructure, imperviousness, hydraulic gradient, soils and geology, and groundwater.

### 7.2.2 Space Availability

A somewhat obvious consideration for BMP/LID selection and design is the amount of available space. In the highway environment, space availability may vary significantly, but typical open space areas include roadside embankments, medians, cloverleaves, and near on-ramps and off-ramps. In urban areas, highway right-of-way may be limited because of previous widening projects and build-out of surrounding land uses, while in rural areas there are often large open spaces adjacent to and in the medians of the primary travel lanes. However, the existence of open space does not necessarily mean that that space is available for a structural BMP, as planning for future expansions may take precedence over stormwater control projects. Even in rural areas, pressure to conserve agricultural and natural lands may take precedence over additional land for stormwater treatment. The only option for highly constrained urbanized or urbanizing areas may be subsurface devices that can be located within the storm drain system such as underground tanks/vaults, hydrodynamic devices, media filters, and catchbasin inserts. However, these types of devices generally provide a lower level of treatment and are more difficult to monitor and maintain than surface BMPs.

Detention-type BMPs usually require a larger footprint than flow-through-type BMPs, but the amount of space required for a particular BMP is directly dependent on the amount of runoff the BMP is expected to treat and the desired hydraulic retention time (HRT) for flows through the BMP. Because the runoff volume is directly proportional to the drainage area and the percent imperviousness, the size of the facility is a function of the size and land use characteristics of the catchment. The linear, directly connected, impervious nature of the highway environment often restricts the size of the catchment that can be reasonably treated with a single BMP. Therefore, rather than large regional facilities located near the downstream end of a watershed, a more distributed, LID approach to stormwater management is often more feasible. With the establishment of municipal partnerships, it may be possible to treat highway runoff in regional, offsite BMPs, which confers the benefit of centralizing maintenance activities.

### 7.2.3 Existing Infrastructure

One of the primary drivers for selecting and sizing a BMP for a site is the existing infrastructure. A retrofit to an existing drainage system is more restrictive than the construction of a new one. Also, the design of roadways and bridges and the presence of utilities may inhibit BMP selection and placement. Furthermore, concern over the structural integrity of roadways, shoulders, footings, bridge abutments, and retaining walls may discourage certain roadside infiltration/exfiltration practices. (See the discussion of highway structural integrity in the presence of water in Section 4.4 of the *LID Design Manual.*)

Different options for downstream drainage of stormwater may exist in urban areas. Should the highway drainage be connected to the existing storm sewer system? If the city must treat some of its stormwater, will highway drainage aggravate the problem, or will there be economies of scale in sharing resources (city and DOT), i.e., by cost-sharing? If a city is served predominantly by combined sewers, there may be every incentive to avoid additional flows to the combined system, since the cost of CSO control is much more than that of stormwater control.

### 7.2.4 Imperviousness

The significance of imperviousness, and especially DCIA, has been discussed in Section 5.2. Because roads and highways are the dominant source of imperviousness in urban areas, mitigation of runoff from pavement is an obvious need with regard to control of stormwater. With the exception of some porous pavement installations, runoff from pavement is unavoidable. If pavement runoff can be directed first to adjacent pervious areas, such as filter strips on the highway embankment, the pavement changes in classification from DCIA to non-DCIA, with good opportunities for reduction in runoff volume and pollutant load. This is a major goal of LID installations in the highway environment.

### 7.2.5 Hydraulic Gradient and Slope

The available hydraulic gradient at a site is another factor that must be considered when selecting and designing a BMP or LID facility. A slope that is not steep enough may cause ponding and backwater effects, which in turn may cause premature sedimentation and clogging of inlet pipes. A slope that is too steep may cause scour at the inlets and outlets of a facility. While some designs may be modified to accommodate larger slopes by using check dams and energy dissipaters, many BMPs will not function properly or cause slope failure if slopes are too great. For instance, unlined ponds should never be placed on hillsides, and a slope stability analysis should be conducted for any potential BMP location where slopes are greater than about 15%. Also, many types of BMPs require sufficient hydraulic head for proper operation. For example, swales must have sufficient longitudinal slope to avoid ponding. Furthermore, some inlet devices require a minimum amount of space between the inlet and storm drain invert in order to fit in the catchbasin. The ability to design a BMP treatment train is also extremely dependent on the available hydraulic gradient between the inlet and final discharge point.

A further consideration is the combination of land area, in a broader sense, and valley relief. In flat terrain, BMP facilities might be combined at an end-of-pipe location where there is room for both the collection system and the BMP. In steeper, narrower terrain, the drainage must collect all runoff, and there may simply not be enough room to construct a larger BMP (e.g., a pond or a basin). Such a facility would have to function like a small dam, and runoff quality controls would have to be integrated into the highway design itself, that is, close to the pavement. LID concepts are particularly useful in cases such as these. The impact of constraints on space is also discussed in Section 7.2.2.

### 7.2.6 Soil Properties

In addition to the slope, the types of soil and geologic formations at a site may dictate stormwater BMP type and design. Soils that are highly erosive and cut slopes that contain a slip plane that is prone to failure should be avoided. BMPs and LID facilities that rely on infiltration must have well-drained underlying soils, and the depth to bedrock must be sufficient so as not to cause excessive ponding. For BMPs designed to have a permanent pool, soils classified as Natural Resources Conservation Service (NRCS) hydrologic soil groups C or D may be desirable. If native soils are in soil groups A or B, a clay or geotextile liner would likely be needed to maintain the permanent pool. Soil is an integral part of the hydrologic cycle: it regulates the processes of surface runoff, infiltration, and percolation, and, through its capacity to store and release water, soil is a major controlling factor in ET.

The ability of surface soil layers to infiltrate and their capacity to store stormwater are important modeling and design parameters that are usually represented by two respective soil properties: hydraulic conductivity and water storage capacity. Hydraulic conductivity (sometimes inappropriately termed the coefficient of permeability) is the rate at which water flows through the soil pore structure under a unit gradient, given as a velocity, e.g., in./hr, mm/day, or gal/ft$^2$-day. Hydraulic conductivity is a function of the porosity and the connectivity of the pore spaces (usually characterized by the intrinsic permeability, a property only of the porous medium, with units of length squared), the degree of saturation, and the chemistry, temperature, and viscosity of the pore fluids (Freeze and Cherry 1979). Water storage capacity can be measured as the field capacity, the maximum fraction of soil that can potentially store water in the soil profile under the action of gravity. Water storage capacity is primarily a function of the soil porosity (volume of voids to volume of soil), temperature, and organic content.

A lower bound on water storage is the wilting point, the soil water fraction at which plants can no longer extract water for transpiration. The hydraulic conductivity, porosity, and field capacity, as well as the antecedent moisture condition (AMC), or degree of saturation, at the onset of a rainfall-runoff event, must be accurately accounted for during continuous simulation modeling and mass-balance operations.

Soil characteristics are extremely variable, even for locations just a few meters apart. Moreover, in urban areas, disturbed (often compacted) soils bear little resemblance in their physical properties to their natural state (Pitt et al. 2001). The importance of local, site-specific measurements of infiltration cannot be overemphasized. Guidelines to infiltrometer equipment and measurements are included in many hydrology books and on the Web.

### 7.2.7 Groundwater

A physical driver that may influence BMP/LID selection and design is groundwater quality and aquifer configuration. If the quality of the groundwater is limited and the depth to the aquifer is shallow, facilities that rely on infiltration should be avoided. Also, a basic understanding of the connectivity of groundwater resources may help determine the overall threat that a particular BMP may pose to receiving waters and drinking water supplies.

Several northern states and provinces use salt for control of snow in winter. Runoff of salty water can be a major problem for both surface and groundwater (Field et al. 1973). It is not clear that any BMP/LID device discussed in this project is suitable for control of salt contamination. Source control is the only practical solution.

## 7.3 Regulatory Drivers

### 7.3.1 Section 303(d) and TMDLs

The 1972 Federal Water Pollution Control Act Amendments, with subsequent amendments in 1977, are known generally as the Clean Water Act (CWA). The CWA as revised and amended further through year 2002 may be found at: http://www.epa.gov/region5/water/cwa.htm. Under Section 303(d) of the CWA, every 2 years, states, territories, and authorized tribes are required to develop lists of waters that are impaired or do not support one or more of their designated beneficial uses. This list is called the "303(d) list" because the process is described in Section 303(d) of the CWA. Waters are considered impaired if, through monitoring and assessment, it is determined that they do not meet established water-quality standards or objectives that have been approved by the USEPA. The law also requires that the regulatory agency (e.g., from a state, territory, or authorized tribe) establish priority rankings for waters on the 303(d) lists and develop TMDLs for these waters. A TMDL specifies the maximum amount (either as a load or concentration) of a pollutant that a water body can receive and still meet water-quality standards and allocates pollutant loadings or concentration limits among point and nonpoint pollutant sources. By law, the USEPA must approve or disapprove lists and established TMDLs. If the USEPA deems a submission inadequate, the USEPA must establish the list or the TMDL.

State DOTs may be directly affected by water bodies on 303(d) lists and waste load allocations (WLAs) established as part of TMDLs. If a receiving water body is listed as impaired for a particular stormwater constituent, stormwater management and control efforts must focus on removing that constituent. If a TMDL has been approved and a WLA for the DOT established, the level of stormwater management and control necessary to address the load allocated to a source can be estimated. However, if a water body is listed as impaired, but a TMDL has not yet been established, the DOT may have to provide the maximum level of control possible to ensure further impairment does not occur. In either case, if receiving waters are included on a 303(d) list, the type of BMP selected and the design components chosen for that BMP should be based on the unit operations and processes known to treat the impairing pollutants.

### 7.3.2 NPDES Permit Program

As authorized by the CWA, Section 402, the NPDES permit program controls water pollution by regulating point sources (i.e., discrete conveyances such as pipes or drainage ditches) that discharge pollutants into waters of the United States.

The NPDES permit program requires operators of large, medium, and small regulated municipal separate storm sewer systems (MS4s) to (1) obtain an NPDES permit and (2) develop a stormwater management program designed to prevent pollutants from being discharged into the MS4 (or from being dumped directly into the MS4) and local water bodies. A large MS4 is a system that is located in an area with a population of 250,000 or more. A medium MS4 is a system that is located in an area with a population between 100,000 and 249,999. Regulated small MS4s are defined as all small MS4s (MS4s not designated as medium or large) located in "urbanized areas" (UAs) as defined by the Bureau of the Census, and those small MS4s located outside of a UA that are designated by NPDES permitting authorities. An NPDES permit is also required for all construction sites that disturb an area greater than one acre in size.

Most states are authorized to implement the NPDES permit program, but the USEPA remains the permitting authority in a few states and territories and on most Indian land. State DOTs are usually designated as co-permittees to municipal NPDES permits issued from the state or the USEPA. However, in some cases, a separate statewide NPDES permit is issued directly to the state DOT (to the Oregon DOT, for example).

Regardless of who is designated as the principal permittee, NPDES permits place specific stormwater management, monitoring, and reporting requirements on state DOTs—requirements that may have a direct influence on BMP selection and design. The regional differences in NPDES permit requirements are dependent on regional and local regulations, as well as the designated quality or sensitivity of the receiving waters as established under the 303(d) and TMDL programs discussed above. For example, many NPDES permits require performance monitoring of stormwater BMPs. In these instances, it may be desirable for the inlet and outlet structures of the BMP to be designed to accommodate measurement of flow rates and collection of water-quality samples.

### 7.3.3 Section 404 Permit

Section 404 of the CWA establishes a program to regulate the discharge of dredge and fill material into waters of the United States, including wetlands. Activities in waters of the United States that are regulated under this program include fills for development, water resource projects (such as dams and levees), infrastructure development (such as highways and airports), and conversion of wetlands to uplands for farming and forestry. The USEPA and the U.S. Army Corps of Engineers (USACE) jointly administer the program. In addition, the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, and state resource agencies have important advisory roles.

Highway construction and stormwater management projects adjacent to or across waters of the United States may be required to obtain a Section 404 permit. The permit may have explicit requirements governing the types of activities, including stormwater treatment and discharge activities, allowed in and around the designated waters. Surface BMPs that require the placement of berms, dams, and embankments may be subject to a Section 404 Permit.

### 7.3.4 Water-Quality Criteria

CWA amendments, USEPA regulations, and state water-quality programs addressing point and nonpoint sources have evolved over the years as knowledge on the impacts of urban and highway development projects has accumulated. Several sections of the CWA apply to urban runoff, both as a point and nonpoint source of pollution, as well as to any activities that may disturb natural wetlands, regulated by Section 404 of the CWA. The relevance of these regulations to stormwater runoff and highway operations is described below.

The water-quality criteria developed in 1986 in accordance with the CWA are designed to be protective of water bodies that are beneficial to aquatic life. The USEPA national water quality, or National Toxics Rule (NTR), criteria are designed to be adjusted for site-specific conditions that properly consider the aquatic chemistry of the constituents of concern.

Also, state water-quality programs are required to designate uses for all state waters, establish criteria to meet those uses, and institute an antidegradation policy for waters that meet or exceed criteria for existing uses. The CWA also requires that state water-quality criteria must include both numeric standards for quantifiable chemical properties (e.g., the California Toxics Rule [CTR]) and narrative criteria or criteria based on biomonitoring. Some states have adapted the NTR criteria (e.g., Oregon). State and regional water-quality management plans are also required to identify priority point and nonpoint problems, consider alternative solutions, and recommend control measures. Ambient water-quality standards are to be supplemented by discharge standards in the form of effluent limitations applicable to point and nonpoint sources.

### 7.3.5 National Estuary Program

The USEPA administers the National Estuary Program under Section 320 of the CWA. This program focuses on all pollutant sources in geographically targeted, high-priority, estuarine waters. Through this program, the USEPA assists state, regional, and local governments in the development of comprehensive management plans that recommend priority corrective actions to restore estuarine water quality, fish populations, and other designated uses of the water (USEPA 1991).

### 7.3.6 Coastal Zone Act Reauthorization Amendments

In an effort to develop a more comprehensive solution to the problem of polluted runoff in coastal areas, Congress expanded the 1972 Coastal Zone Management Act (CZMA) in 1990 to include a new Section 6217 entitled "Protecting Coastal Waters." Section 6217 of the Coastal Zone Act Reauthorization Amendments (CZARA) requires that states with approved coastal zone management programs develop coastal nonpoint pollution control programs (coastal nonpoint programs). Section 6217 was envisioned with the idea that nonpoint source programs developed under Section 319 of the CWA would be combined with existing coastal management programs, in keeping with the successful state-federal partnership to manage and protect coastal resources achieved by the CZMA. By combining the water-quality expertise of state Section 319 agencies with the land management expertise of coastal zone agencies, Section 6217 was designed to more effectively manage nonpoint source pollution in coastal areas. To facilitate development of state coastal nonpoint programs and ensure coordination among states, administration of Section 6217 at the federal level was assigned to the National Oceanic and Atmospheric Administration (NOAA) and the USEPA.

### 7.3.7 Safe Drinking Water Act

Infiltration BMPs are a means of restoring infiltration capacity, thereby reducing the storm runoff volume and reducing the runoff pollutant load by settling and filtration processes. Underground injection control (UIC) is another effective measure for the subsurface disposal of runoff from roadways, roofs, and pavements. However, the regional water resources agencies must weigh the benefits of infiltration against potential negative impacts to groundwater resources and ensure that infiltration facilities are a viable long-term solution and meet the relevant regulatory criteria.

The primary objectives of the Safe Drinking Water Act of 1974 (SDWA), as amended extensively in 1984, are twofold: (1) to protect the nation's sources of drinking water and (2) to protect public health to the maximum extent possible, using proper water treatment techniques. Sections of the SDWA address the unique concerns related to underground sources of drinking water and controls for contamination of these sources. Section 1421 requires the USEPA to establish minimum requirements for effective UIC programs applying to five classes of wells. The USEPA has ruled that all states are required to submit a UIC program and that once the UIC program is established, all underground injections not authorized by a permit are unlawful and subject to penalties unless authorized by a permit. No injection will be authorized by permit if it results in the movement of fluid containing any contaminant into underground sources of drinking water, and such a permit will not be issued until the applicant can prove that discharge or disposal into the underground sources of drinking water will not affect drinking water integrity. This USEPA ruling has prompted states to develop multifaceted programs to protect groundwater resources and recharge areas that supply public water systems. Under these programs, wellhead protection strategies have also been developed. A provision of the SDWA requires protection of surface water discharges in areas designated as sole or principal source aquifers.

The SDWA set forth criteria for identifying critical aquifer protection areas (CAPAs), which are sole or principal source aquifers that are determined to be vulnerable to contamination because of local hydrologic or geologic characteristics and/or potential for contamination. Designating these areas as CAPAs allows states or municipalities to develop an areawide groundwater protection program. The program can identify actions in the protection area that would avoid adverse effects on water quality and place limits on activities and projects financially assisted by federal, state, or local governments that may contribute to degradation of such groundwater resources or to any loss of natural surface and subsurface infiltration and purification capabilities.

Areawide groundwater protection programs are essentially nonregulatory, but federal financial support for a project can be withheld if the project is deemed potentially harmful to the designated aquifer. Mitigation measures for activities that may contaminate the aquifer (including highway runoff) are typically required to ensure federal funding of the project. Any project in a sole-source aquifer area receiving federal financial assistance must be coordinated with the regional USEPA office. There are some principal aquifers in the country, such as the Edwards Aquifer in Texas, designated as the sole or principal drinking-water source for an area; contamination of these aquifers would create a significant hazard to public health. As a result, more strict regulations apply, and projects planned in the area of the aquifer are inventoried, reviewed, and approved by the general public, local authorities, state environmental agencies, and the USEPA.

### 7.3.8 Endangered Species Act

Another regionally influenced regulation that may drive the selection and design of stormwater treatment facilities is the Endangered Species Act (ESA) of 1973. The ESA, as amended, provides a means to protect endangered species and the ecosystems upon which they depend. The ESA directs all federal agencies to use their authority to advance the purposes of the ESA through programs designed to protect endangered species. These programs are necessarily based on habitat conservation and are thus very regional in nature. For example, in the Pacific Northwest, migration of anadromous fish must not be hindered, leading to prohibitions against hydraulic structures that block fish passage. Therefore, culverts designed for fish passage are common. If a highway drains to a perennial stream in the Pacific Northwest, it is likely that BMPs would have to be installed prior to entry of the drainage to the stream, in order not to inhibit fish passage. This requirement might rule out, for example, a combined or multipurpose control installed on the stream itself and lead to a set of smaller, distributed controls. Therefore, a careful review of the endangered species of an area, including their habitats, must be conducted during the selection and design of stormwater BMPs, particularly for projects discharging to receiving waters with federally listed species or for any BMP that may provide habitat for federally listed species. Constructed wetlands are a prime example of receiving waters with federally listed species.

### 7.3.9 Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA) gives the USEPA broad authority to regulate the disposal of hazardous wastes and encourages the development of solid waste management plans and nonhazardous waste regulatory programs by states. The USEPA promulgates regulations under RCRA, but as with many other federal acts, the states are encouraged to develop management programs and eventually take over enforcement responsibilities. To date, many states have chosen to allow the federal programs to suffice as the state program to avoid the expense of designing and enforcing programs. The U.S. DOT has enforcement responsibilities for the transport of hazardous wastes.

RCRA provisions may be relevant under some highway construction and maintenance projects, depending on the nature of the activity, proximity to receiving waters, and characteristics of the site. RCRA, or its state or local counterpart, applies to the proper storage, use, and disposal of solid wastes (e.g., plastics, scrap metals, wood materials, rubber, and plastic), petroleum or petroleum-based products (e.g., oils and greases), and other chemicals used in construction (e.g., detergents, paints, and solvents). Therefore, any highway construction activities that use these materials are subject to the provisions of RCRA for use and disposal. This would include vehicle and equipment maintenance and upkeep procedures at all facilities owned by DOTs.

### 7.3.10 National Wild and Scenic Rivers Act

The national Wild and Scenic Rivers Act (WSRA)establishes the Wild and Scenic River System, and its purpose is limited to protection of “certain selected rivers of the Nation, which, with their immediate environments, possess outstandingly remarkable scenic, recreational, geologic, fish and wildlife, historic, cultural, or other similar values” (WSRA, 16 U.S.C. § 1271). The act essentially provides a mechanism for determining whether a river (or river segment) can meet certain eligibility requirements for protection as a wild and/or scenic river (Corbitt 1990) and protects designated rivers from activities that may adversely impact their “remarkable scenic, recreational, geologic, fish and wildlife, historic, cultural, or other similar values.” The U.S. Department of the Interior has ultimate authority for administering the program, but states can designate rivers to be included in the system. The act’s framers intended for most rivers on private land to enter the Wild and Scenic River System through the state designation and management provisions (Doppelt et al. 1993). However, the U.S. Department of Agriculture administers and designates rivers in the national forests (Corbitt 1990).

It is the intent of WSRA to preserve “selected rivers or sections thereof in their free-flowing condition to protect the water quality of such rivers and to fulfill other vital national conservation purposes” (WSRA, 16 U.S.C. § 1271). In planning for the use and development of water and land resources, federal agencies must consider potential wild and scenic river areas (Corbitt 1990). For the purposes of WSRA, water resource actions are defined as any project or action that could affect the free-flowing characteristics of the river, e.g., dredge/fill operations and placement of riprap (USEPA Region 2 1993). Under Section 7(a) of the WSRA, federal actions on water resources are prohibited if they result in a direct adverse effect on the characteristics that result in a river’s WSRA classification. The U.S. Department of the Interior has determined that actions within a quarter mile or within the visual field of the designated river could have a direct impact (USEPA Region 2 1993).

As of 1993, 32 states have conservation programs of some form in which rivers or river segments, and their associated riparian environments, are protected under state wild and scenic rivers legislation. As a result, many state regulations prohibit or restrict dams, protect designated rivers from channelization or diversion, or require land use planning, water-quality and waste control, transportation planning, and local zoning. Each state maintains its own administration over designated rivers or river segments through a state or regional authority, such as the USEPA Region, National Park Service, or other state environmental agency. Authority is often delegated to local jurisdictions through the establishment of riverine or river corridor commissions.

Highway construction and operations near designated river segments are subject to restrictions developed by the state. Even if such activities are temporary, any disruptions to the normal flow of the river (e.g., dams and drainage alteration), increased sediment loads (construction areas) or significant increases to pollutant loads (e.g., increased runoff volume) may be restricted by a state-enacted WSRA regulation. Through the National Environmental Policy Act (NEPA) (discussed in Section 7.3.11) and/or permitting processes, the state DOT should be notified if its actions are subject to restriction under the WSRA.

### 7.3.11 NEPA

NEPA establishes judicially enforceable obligations that require all federal agencies to identify the environmental impacts of their planned activities. The NEPA legislation and its requirements provide the framework under which environmental impacts of all substantial federal projects are evaluated and have been the starting point from which many other environmental regulations are applied and enforced. Any major effort that involves federal funding, oversight, or permits, such as highway operations and projects, is subject to the NEPA process to ensure that environmental concerns are considered and documented in an environmental impact statement (EIS) before implementation.

### 7.3.12 Regulatory Acceptance of BMP Practices

As demonstrated in the discussion above, the implementation of highway projects, including those with and without BMPs, is subject to a wide variety of regulations that may affect the selection and design of BMPs. Unfortunately, the lengthy environmental assessment and review process, as required by NEPA, will often cause significant delays (on the order of years) in the implementation of highway projects, some of which are essential infrastructure upgrades to reduce congestion and improve environmental quality. The primary causes of these delays are twofold: (1) the redundancy of environmental assessment and review requirements in federal, state, and local laws and (2) the proposed project design features or mitigation measures that are not acceptable to the regulating authorities.

Bureaucratic inefficiencies and jurisdictional overlap that cannot be addressed at the project level cause significant delay of highway project implementation. However, steps are being made to address this issue. For instance, President Bush signed Executive Order 13274 on September 18, 2002. This order is intended to enhance environmental stewardship and streamline the environmental review and development of priority transportation infrastructure projects. In accordance with the order, the U.S. DOT developed the Transportation Infrastructure Streamlining Task Force to (1) monitor and assist agencies in their efforts to expedite the review of transportation infrastructure projects and issue permits or similar actions, as necessary; (2) review projects, at least quarterly, on the list of priority projects designated by the Secretary of Transportation; and (3) identify and promote policies that can effectively streamline the approval process for transportation infrastructure projects, in compliance with applicable law, while maintaining safety, public health, and environmental protection. States that wish to have a highway project designated a priority project must submit nominations to the Secretary of Transportation. Projects added to the priority list generally are of national or regional importance, have a high level of support among state and local elected officials, and have been or are likely to be delayed by the federal agency review and coordination process.

Insufficient assessment of the potential environmental impacts or unfamiliarity with the proposed project design features or mitigation measures by the regulatory community are the other primary causes of highway project implementation delay. Depending on how the EIS is presented for a project, stormwater BMPs and LID facilities may be considered either project design features or mitigation measures. In either case, it must be demonstrated that the project will not cause significant water-quality impact with the implementation of the proposed controls. For new and innovative stormwater treatment technologies, it may be difficult to demonstrate effect on water quality because of a lack of third-party evaluations. This presents a significant roadblock to the evolution of stormwater BMPs, including many LID practices.

Some regulatory agencies have begun testing and providing lists of acceptable treatment technologies. For example, under the Environmental Technology Verification (ETV) Program—Wet Weather Flow Technologies Area, the USEPA approves innovative treatment technologies through performance verification and dissemination of information (www.epa.gov/etv/index.html). Some state regulatory agencies have developed similar programs, such as the "Stormwater Best Management Practices Demonstration Tier II Protocol for Interstate Reciprocity," which has been endorsed by California, Massachusetts, New Jersey, Pennsylvania, and

Virginia (Virginia Department of Conservation and Recreation 2001; California Environmental Protection Agency 2001), and the "Guidance for Evaluating Emerging Stormwater Treatment Technologies, Technology Assessment Protocol—Ecology (TAPE)" for the Washington Department of Ecology (WADoE 2002). While these programs are beginning to test and approve/disapprove innovative technologies, many proprietary BMPs have yet to be verified. If a proposed BMP is not verified, the level of acceptance by the regulatory agency may be limited, even if the fundamental unit processes provided by the BMP can be theoretically demonstrated.

## 7.4 Political, Economic, and Jurisdictional Drivers

### 7.4.1 Economic and Planning Factors

State DOTs must justify and prioritize the expenditure of their annual budgets. As one example, the procedure for transportation system planning used by ODOT is outlined below (Oregon Department of Transportation 2001):

- Step 1–Identify project statement of work, timeline, staffing requirements, oversight responsibility, and budget.
- Step 2–Assign staff or hire a consultant with necessary expertise.
- Step 3–Clearly define what the consultant (or staff if the TSP is prepared in-house) needs to do to prepare the plan.
- Step 4–Develop a stakeholder/public involvement program.
- Step 5–Review plans, policies, regulations, and standards.
- Step 6–Inventory the transportation system.
- Step 7–Describe current conditions and identify deficiencies.
- Step 8–Determine future travel demand, capacity, deficiencies, and needs.
- Step 9–Develop and evaluate system alternatives that eliminate deficiencies and meet needs.
- Step 10–Select a preferred alternative.
- Step 11–Prepare the TSP (write the plan).
- Step 12–Develop a transportation improvement program and a transportation finance program.
- Step 13–Develop/adopt local and county ordinances.

In almost all cases, stormwater quality control is implemented as a part of new projects or major highway renovation projects. The authors are unaware of significant capital projects implemented only on the basis of environmental concerns such as stormwater.

The goal of capital planning is to make the best use of available funds to achieve agency strategic goals and objectives. These goals may include the management of a portfolio of capital assets to achieve performance goals with the lowest life-cycle costs and least risk. As a result, an agency's capital planning plays a significant role in the implementation of BMP/LID systems within any jurisdiction.

The construction and maintenance costs of BMPs are important factors in BMP selection. The construction cost of BMPs under consideration could be determined based on cost surveys, local experience, or regionally adjusted national average cost data, such as that provided by the RSMeans company. These cost data could be normalized to compare different BMP options on the basis of acres of impervious area treated. In addition, life-cycle costs, including operation and maintenance costs, should be added to the cost equation. Although all BMPs require routine maintenance and inspection, some BMPs require more effort than others. Factors such as frequency of scheduled maintenance, chronic maintenance problems (e.g., clogging), and failure rates add to the overall cost of BMP implementation.

### 7.4.2 Public Acceptance (Aesthetics, Property Values)

Public acceptance of a BMP can be measured by market and preference surveys, reported nuisance problems, visual aesthetics, and the potential impact a BMP would have on the neighborhood property values. Some BMPs, such as biofilters, are unobtrusive and in general tend to look more natural and therefore be more easily disguised than other BMPs. In contrast, dry ponds and infiltration basins that accumulate trash, debris, and sediment loads may have a more negative aesthetic impact. Odors, mosquitoes, weeds, and litter can all be potential problems in stormwater BMPs. However, negative aesthetic impacts can be nullified through regular maintenance to remove debris and a good landscaping plan.

### 7.4.3 Property Ownership

The ownership of property may also have a significant effect on the selection and design of a BMP or LID facility. The most strategically located parcel for a BMP may be privately owned or owned by a public agency other than the DOT implementing the BMP. In these instances, the property must be purchased or an access agreement established. Implementation costs can be significantly increased if property must be purchased. Also, some agencies may be resistant to certain BMPs on their property. Intra-agency conflicts may also be a concern. For instance, the maintenance department may own land that the watershed management department would like to use for a BMP project. While this kind of situation is generally easier to work out than some others, there may be conflicting planned uses for the property that must be negotiated.

### 7.4.4 Health and Safety

BMPs could potentially create a public health hazard by increasing habitat availability for the aquatic stages of mosquitoes and by creating harborage, food, and moisture for other reservoir and nuisance species. Emerging public health threats, such as the detection in 2001 of the exotic Asian tiger mosquito and the westward expansion of mosquito-borne West Nile virus illustrate the importance of cooperation and partnership at all levels of government. The public health powers of state departments of health and safety, including the power to abate public nuisances, and those of local mosquito and vector control agencies must be considered. For example, eight mosquito species have been collected from Caltrans BMP structures, four of which are vectors of human disease (Metzer 2001). Of the eight different BMP technologies implemented by Caltrans, those that maintained permanent sources of standing water in sumps or basins provided excellent habitat for mosquitoes and frequently supported larger populations of mosquitoes than other designs. In contrast, BMPs designed to drain rapidly provided less-suitable habitats and rarely harbored mosquitoes. Information on what factors in BMPs are most conducive to mosquito production and which species utilize these structures should be considered. Based on these findings, appropriate engineering modifications should be made or an adequate vector control plan should be developed to minimize the potential of certain BMPs to produce or harbor vectors.

In addition to minimizing stormwater treatment structures' production or harboring of vectors, it is critical that these structures do not create public health hazards. Depending on their depth, detention BMPs can pose safety hazards, particularly to children, if they are not properly signed and fenced. Designs that utilize gentle side slopes and shallow basin depths should be considered if fencing is not used.

### 7.4.5 Watershed Approach

The watershed approach is the fundamental biophysical unit that links stormwater releases to several regulatory issues, including TMDLs and quality of aquatic habitat. Through this approach, managers are able to gain a more complete understanding of overall water quality and environmental conditions in a receiving stream and the stressors that affect those conditions. In addition to the environmental payoff, watershed approaches can save time and money. Whether the task is monitoring, modeling, issuing permits, or reporting, a watershed framework offers many opportunities to simplify and streamline the workload. For example, the USEPA, under the CWA's Section 319 nonpoint source grants program, provides more flexibility to states to focus on high priorities when they identify waters and their watersheds that are impaired by nonpoint source pollution. States can also use watershed planning to help simplify the CWA Section 404 wetlands regulatory program in several ways, including advanced identification, greater use of general permitting, and use of collective wetlands permitting procedures. States and communities are given greater flexibility in operation of mitigation banks for wetlands and in implementation of effluent trading programs when these efforts are established within the context of a watershed management plan, and this flexibility can lead to a more cost-effective achievement of water-quality goals.

Stormwater management practices are installed in watersheds and subwatersheds to compensate for the hydrological changes caused by new and existing development. These practices are used to delay, capture, store, treat, or infiltrate stormwater runoff. An important choice is determining the primary stormwater objectives for a subwatershed that will govern the selection, design, and location of stormwater management practices at individual sites. While specific design objectives for stormwater management practices are often unique to a subwatershed, the general goals for stormwater management practices are often the same and include the following:

- maintain groundwater quality and recharge;
- reduce stormwater pollutant loads;
- protect stream channels;
- prevent increased overbank flooding; and
- safely convey extreme floods.

While many advances have been made recently in innovative stormwater management designs, their ability to maintain resource quality in the absence of other watershed protection tools is limited. In fact, stormwater management practices designed or located improperly can sometimes cause secondary environmental impacts that are more severe than the impacts that the stormwater management design was meant to mitigate. Key questions for stormwater management in the context of an overall watershed management plan include the following:

- What is the most effective mix of structural and nonstructural BMPs that can meet subwatershed goals?
- Which hydrologic variables need to be managed in the subwatershed?
- What are the primary stormwater pollutants of concern?
- Which BMPs should be avoided because of their environmental impacts?
- What is the most economical way to provide stormwater management?
- Which BMPs are the least burdensome to maintain within local budgets?

### 7.4.6 Planning and Development

BMP planning and development occur on both a watershed level and a site level. Among other environmental planning and management goals, watershed planning also provides the following:

- A list of BMPs, LID facilities, and other mitigating measures and their locations in a watershed;
- Hydrology and hydraulic modeling to determine the BMP/LID size;
- The selection of ecosystem features at a BMP/LID facility; and
- A conceptual and detailed layout of BMPs and LID facilities for upstream, site, and downstream aspects.

These factors provide conditions and features that drive the selection and design of a BMP facility. Because of the diversity of models and evaluation methods at the project and watershed scale, linkages between the assessment of road impacts and overall watershed conditions are often difficult to make.

Long-range planning and control for future land use are also typically included in wellhead protection programs. Any highway projects, including maintenance operations or BMP implementation, may therefore be subject to additional planning and analysis and possibly permitting if the projects are within the recharge area and the state or local wellhead protection rules apply.

### 7.4.7 Contextual Design

Land use planning trends and movements such as Traditional Neighborhood Design, Historic Preservation, or overlay districts for "Green Cities" may dictate or influence the physical appearance, location, and type of BMPs that are permitted in the corridor. Planning considerations such as reduction of heat island effects may also influence the location and type of vegetation in the design corridor.

### 7.4.8 Archaeological and Cultural Impacts

Archaeological resources are locations of prehistoric and historic human activity that contain artifacts or distinct features (ODOT, undated, and see Appendix B). Paleontological findings, such as dinosaur bones, are also covered under this category. Various state and federal laws may apply. For example, Section 4(f) of the Department of Transportation Act of 1966 refers to any effect on a historic property, historic bridge, park, wildlife and waterfowl refuge, or public recreation area, if the project includes federal funds. Most DOTs provide resources for these types of eventualities.

### 7.4.9 Wetland and Aquatic Habitat Mitigation

Regulatory requirements for mitigation require regulators to determine how much restoration or compensating preservation is enough to offset permitted wetland or habitat losses.

The CWA's Section 404 regulates the discharge of dredged or fill material into waters of the United States, including wetlands. The USACE is responsible for processing Section 404 permits and analyzing impacts associated with proposed projects that include the discharge of dredged or fill material into jurisdictional waters. Under 40 CFR Part 230, the USACE reviews proposals using a "sequencing" procedure: avoidance, minimization, and finally compensation for unavoidable impacts. When an applicant proposes a project with unavoidable impacts, the USACE often requires the applicant to provide compensatory mitigation. The mitigation package can include different types of mitigation, including on-site and off-site mitigation or in-kind and out-of-kind mitigation. However, provision of the mitigation package is the responsibility of the applicant (33 CFR Part 320 et seq.).

The USACE reviews and approves the proposed mitigation plan in accordance with USEPA regulations (40 CFR Part 230). In most cases, the applicant provides the USACE with one mitigation plan for review. The decision of the USACE to accept on-site or off-site, in-kind or out-of-kind, mitigation is based on a review of the applicant's proposed mitigation plan, not on a comparison of several mitigation sites. The USACE will review the applicant's mitigation plan and determine whether the proposal meets regulatory requirements or must be modified (which can include changes to the plan, additions, or reductions in specific types of mitigation). In making a determination that a proposed plan is acceptable, the USACE must consider not only the environmental factors, but practicability factors as well (33 CFR 320 et seq.; 40 CFR 230 et seq.).

Several documents currently provide guidance on compensatory mitigation for the Section 404 permit program, and they are discussed below. The Section 404(b)(1) guidelines of the CWA are regulations that govern the evaluation of permit applications. Other documents provide guidance concerning the use of on-site and off-site, in-kind and out-of-kind, compensatory mitigation. These are the following:

- "Memorandum of Agreement Between the Environmental Protection Agency (EPA) and the Department of Army Concerning the Determination of Mitigation Under the Clean Water Act Section 404(b)(1) Guidelines" (Mitigation MOA) (USEPA and U.S. Department of the Army 1990).
- "Federal Guidance for the Establishment, Use and Operation of Mitigation Banks" (Banking Guidance) (U.S. Department of Defense et al. 1995).

- "Federal Guidance on the Use of In-Lieu-Fee Arrangements for Compensatory Mitigation Under Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act" (ILF Guidance) (U.S. Department of the Army et al. 2000).
- *Regulatory Guidance Letter (RGL) 02-2*, "Guidance on Compensatory Mitigation Projects for Aquatic Resource Impacts Under the Corps Regulatory Program Pursuant to Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act of 1899" (USACE 2002).

The revision of "Mitigation of Impacts to Wetlands and Natural Habitat" (23 CFR 777) became effective March 30, 2001 (see U.S. DOT 2000). The revised regulation includes legislative, regulatory, technical, and policy developments that have occurred since 1980. The revision broadens the scope of the regulation to encompass all wetland mitigation projects eligible for federal participation, not just those involving privately owned wetlands, and updates the regulation to implement the provisions of TEA-21 (Transportation Equity Act for the 21st Century), which expanded the mitigation banking eligibility provisions established by the Intermodal Surface Transportation Efficiency Act (ISTEA). The revised regulation specifies that its provisions apply to all projects funded under the provisions of Title 23 of the United States Code. This revision also addresses the added funding eligibility for highway projects funded under Title 23 that impact natural habitats. Finally, the rule includes a provision requiring that existing wetland and habitat mitigation banks be given preference for use in establishing compensatory mitigation if the highway project impacts occur within a bank's service area.

The wetland and natural habitat mitigation provisions in TEA-21 deal with issues of eligibility, that is, how and when federal-aid highway funds can be used for mitigation banking. TEA-21 and the FHWA wetland regulation state that to the maximum extent practicable, preference should be given to the use of mitigation banks. TEA-21 and the FHWA wetland regulation also require the following four conditions be met:

1. The wetland impact occurs within the service area of an existing mitigation bank;
2. The mitigation bank contains sufficient credits to offset the impact;
3. The mitigation bank used has been approved as adhering to the "Federal Guidance for the Establishment, Use and Operation of Mitigation Banks" (U.S. Department of Defense et al. 1995); and
4. The eligibility preference be "In accordance with all applicable Federal law (including regulations). . ." (U.S. DOT 2000, § 777.9[a][4]).

Condition #4 means that Section 404 permit conditions apply to the banking preference. If the Section 404 permit conditions and the regulatory decision of the USACE indicate a specific wetland bank (whether public or private) is an acceptable alternative for compensatory mitigation, the provisions in TEA-21 require that the bank be used as compensatory mitigation for a project's wetland impacts to the greatest extent practicable. If, on the other hand, the Section 404 final decision is that the use of a particular bank would not be acceptable as mitigation, then Condition #4 above would not be met, and banking would not be binding.

The TEA-21 provisions and "Mitigation of Impacts to Wetlands and Natural Habitat" (23 CFR 777) do not make a distinction between mitigation banks that are publicly funded operations and those that are privately funded operations. Therefore, the regulation does not state a preference for one particular type of bank over another. If a project has wetland impacts that occur within the service area of two or more banks, the decision as to which bank to use is made on the basis of other considerations, such as the following:

- cost,
- compensation for lost or impacted wetland functions, and
- acceptability under regulatory decisions.

### 7.4.10 Direct and Indirect Ecological Impacts

Direct physical impacts to sensitive ecological and habitat areas such as wetlands and wildlife corridors are measured and evaluated under regulatory programs that often have a benchmark or threshold of acceptable impacts from road construction. Regulatory thresholds or mitigation requirements for permitting may not address the entire range of impacts to receiving waters or habitats. For example, road improvements and additional traffic capacity may help facilitate additional development, or redevelopment, in the watershed so that there will be additional cumulative impacts in the watershed. The question of indirect impacts is an area of contention in environmental planning in which the engineer designing the stormwater system is not likely to be directly involved. Practitioners should refer to the policies of their own department and to the policies of the FHWA regarding indirect impacts. The latter may be found in "Executive Order 13274, Indirect and Cumulative Impacts, Draft Baseline Report" (U.S. Department of Transportation and ICF Consulting 2005).

### 7.4.11 Permit Processing and Review Criteria

State and local BMP programs are often designed to have consistent methods and standard techniques for the design of stormwater control systems. This approach may be in conflict with tributary strategies, TMDLs, and watershed trading policies because of administrative limitations on altering BMP designs and penalties of time delays for waivers that are required to develop or alter designs that meet the specific overall permit or resource protection goals in the watershed.

### 7.4.12 Jurisdictional Overlap (Intra-agency and Intradepartmental)

Many, if not most, watersheds encompass areas within more than one jurisdiction. A stormwater management plan for watersheds encompassing more than one jurisdiction may have to be developed with the involvement of more than one agency, department, or even state. In such cases, a committee should be established early in the planning process. The committee should include key members representing each agency and department to ensure that stormwater management planning is conducted in the spirit of cooperation and good faith. The priorities of each participating agency should be fully disclosed in advance so that they are incorporated in the planning objectives. Successful compacts or agreements usually have some central authority or mandate to ensure that strategies in the watershed will be implemented.

## 7.5 A Typical Summary Checklist

The Oregon DOT's environmental checklist (ODOT, undated) may be used as a guide to most of the regional drivers summarized above. The list, available at http://egov.oregon.gov/ODOT/HWY/BRIDGE/docs/LAPM/lapm_05.pdf is appended as Appendix B and includes federal, state, and local regulations that must be addressed as well as other potential concerns. While this checklist is for any highway project, it also serves as a guide for regulatory and other guidelines that may affect BMP/LID implementation. Most DOTs probably have posted guidelines similar to those of the Oregon DOT that should be consulted for information specific to an individual state. A useful guide to regulatory requirements for each of the 50 states is the Stormwater Resource Locator: www.envcap.org/swrl/.

## CHAPTER 8

# Performance Evaluation

### 8.1 Methodology Options

A variety of methods may be used to assess the efficiency and effectiveness of a given BMP, but it is important to understand the constraints and assumptions of any method before selecting it. For example, many effectiveness models measure efficiency on a storm-by-storm, pollutant-load basis, which assumes that for any given storm, the influent and effluent volumes are equal, and the outflow is directly related to the inflow. However, many systems using a permanent pool of water (wetlands and wet ponds) may not experience complete permanent pool displacement during all storm events, which invalidates storm-by-storm comparisons for removal percentages (Strecker et al. 2001).

Another factor that may influence performance measures of a given BMP, especially if the performance measure is an efficiency ratio or removal percentage, is the influent concentration. The efficiency ratio, which is one definition for removal fraction, R, is

$$\begin{aligned}\text{Efficiency ratio} &\equiv \text{Removal fraction}\\ &\equiv R = 1 - \text{EMC}_{\text{out}}/\text{EMC}_{\text{in}}\end{aligned} \qquad (8\text{-}1)$$

where the inflow and outflow EMCs are usually defined as averages of the individual events (averages of n sampled storm events, for instance). When using the efficiency ratio method, a lower influent concentration may lead to the mischaracterization of a BMP as less effective because the relative removal percentage may be far less than if a higher influent concentration was observed. Thus, as influent concentrations vary, the relative removal percentage may be a measure of the cleanliness of the influent, not the performance of the system. Especially for systems reliant on settling as their primary removal process (e.g., ponds), TSS "removal" is almost entirely a function of influent concentration combined with particle size distribution (Strecker et al. 2001). That is, TSS effluent concentrations can range widely for most ponds, and the ratio of effluent to influent concentration simply decreases as the influent concentration increases. Because of its reliance upon influent concentrations, the efficiency ratio method does not account for the performance of a BMP that results in relatively constant effluent EMC levels independent of inflow conditions (e.g., media filters). Currently, the International BMP Database (www.bmpdatabase.org ) employs the efficiency ratio method to calculate the relative performance of the BMPs, but the robustness of this method is limited, as just mentioned, and does not provide a process level characterization of the system performance.

An abridged discussion of alternative methods for evaluation of BMP EMC data is included in Section 8.5. A broader discussion may be found in GeoSyntec et al. 2002, Brown 2003, and Minton 2005.

### 8.2 Use of EMC

Most available monitoring information is in the form of EMCs, used to depict the average, flow-weighted concentration of a constituent over the total length of a storm event. EMCs can be used to assess not only solids and sediment but also most other constituents (nutrients, metals, and hydrocarbons) as well. EMC is defined as the total pollutant load (mass) divided by the total runoff volume for an event of specified duration, as indicated in Equation 8-2:

$$\text{EMC} = \overline{\text{C}} = \frac{\text{M}}{\text{V}} = \frac{\int \text{C(t)Q(t)dt}}{\int \text{Q(t)dt}} \qquad (8\text{-}2)$$

In Equation 8-2, C(t) and Q(t) are the time-variable concentration and flow measured during a runoff event. M represents the total pollutant mass, and V represents the total runoff volume. In practice, EMCs are determined from a laboratory analysis of a flow-weighted composite of several samples collected during a storm. Instantaneous concentrations during an event may vary greatly from the calculated EMC, but use of the EMC ensures that the relative mass of pollutant in a system during a storm is accurately represented (Huber 1993). EMCs are also the primary means of reporting monitoring information within the International BMP Database because of the highly variable and error-prone nature of intrastorm data collection (grab samples). The variability among EMC data is generally statistically defined by either the standard deviation or coefficient of variation (Minton 2005).

## 8.3 Use of the International BMP Database Web Site for Data Acquisition

The primary goals of the International BMP Database project are to facilitate efficient data entry, provide useful queries of stored data, and deliver relevant performance information in a comprehensive and applicable manner through a user-friendly interface (Strecker et al. 2001). The project, which began in 1996 under a cooperative agreement between ASCE and the USEPA, now has support and funding from a broad coalition of partners including the Water Environment Research Foundation (WERF), ASCE's Environmental and Water Resources Institute (EWRI), FHWA, and the American Public Works Association. Wright Water Engineers, Inc. and GeoSyntec Consultants maintain and operate the database and web site. The web site (www.bmpdatabase.org) and its related documents are a comprehensive collection of reports and analyses of water quantity and quality measurements previously conducted for a variety of BMP performance studies (Quigley et al. 2002). Evaluation of the BMP data to date has indicated that BMP pollutant-removal performance is best assessed by determination of

- The amount of runoff that is prevented, i.e., disposed of on-site,
- The amount of runoff that is captured/bypassed by the BMP, and
- The effluent quality of the treated runoff (Quigley et al. 2002).

Within this chapter, summary responses to these three items are presented. Methods for analysis of quality data are not included herein. Refer to GeoSyntec et al. (2002) and Burton and Pitt (2002) for a thorough discussion of statistical and other data analysis methods.

Issues associated with use of the data include obtaining a large enough number of samples to achieve statistically significant results, acquisition of correct flow measurement data, and the typographical and organizational formatting problems that arise when data are submitted by many contributors (Quigley et al. 2002).

A summary (April 2004) is presented in Table 8-1 of statistical analyses that are available from the International BMP Database team for some common stormwater parameters and for BMP categories that have enough data to allow for useful analysis to be conducted relative to the scope of this project. For example, the range of locations at which statistical analyses have been performed for suspended solids is 11 (for detention ponds) to 21 (for retention ponds). In other words, there are enough performance data to compare different BMP types with each other using box plots and other statistical criteria. Although most of these locations will not be highway sites, the comparisons should still be relevant to highway applications. Results of these comparisons are presented for individual pollutants in the Pollutant Fact Sheets, included in Appendix A of the *Guidelines Manual*.

## 8.4 Search for Intra-Event Data

Early in this study, a considerable effort was devoted to searching for good intra-event data for a variety of BMPs for use in characterizing fundamental unit processes at work in the devices. In addition to a complete physical description of the BMP and its catchment, an ideal data set would include influent and effluent hydrographs and pollutographs, stormwater treatability, and an indication of the character of the water within the device during an event. Such a data set would include several storms. No such ideal data set was found, but 11 candidates were selected from a thorough review of the International BMP Database (see Table 8-2). These 11 sites include 21,134 individual data records. Table 8-3 and Table 8-4 are expanded versions of Table 8-2, including information on the respective studies from which the data were extracted, the type of data available in each study, and other relevant information such as the number of storms studied, water-quality constituents examined, a catchment description, and notes regarding data collection and sampling.

All but one of the studies (Dayton Ave. biofilter) include both flow and water-quality intra-event data. With the exception of the U.S. 183, Walnut Creek, and Seton Pond data, which were made available electronically by Dr. Michael Barrett at the University of Texas at Austin, all of the intra-event data were entered by hand from hard copies of the respective studies or, in the case of hydrologic data for the Moyewood Pond and Dayton Ave. biofilter, digitized from hard copy graphical displays. All hand-entered data were checked for errors, record by record. The maximum values for each field were also examined to minimize errors caused by missing decimal points (the most common mistake identified). Assessment of these corrections indicates that the percentage of identified errors in hand-entered data was less than 1% for most studies.

**Table 8-1. Number of detailed statistical analyses by common stormwater parameter for various BMP categories.**

| | | Parameter Name | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BMP Category | Data | Solids, Total Suspended | Cu, Dissolved | Cu, Total | Zn, Dissolved | Zn, Total | Pb, Dissolved | Pb, Total | Cd, Dissolved | Cd, Total | P Total | Nitrate Nitrogen, Total | Nitrogen, Ammonia Total | Nitrogen, Kjeldahl, Total | Nitrogen, Total |
| Biofilter | Count of Inflow n | 17 | 11 | 14 | 11 | 17 | 11 | 17 | 7 | 8 | 18 | 15 | 1 | 12 | 4 |
| | Count of Outflow n | 17 | 11 | 14 | 11 | 17 | 11 | 17 | 7 | 8 | 18 | 15 | 1 | 12 | 4 |
| Detention Basin | Count of Inflow n | 11 | 6 | 12 | 6 | 13 | 6 | 12 | 4 | 7 | 10 | 7 | | 6 | 4 |
| | Count of Outflow n | 11 | 6 | 12 | 6 | 13 | 6 | 12 | 4 | 7 | 10 | 7 | | 6 | 4 |
| Hydrodynamic Device | Count of Inflow n | 13 | 6 | 9 | 6 | 11 | 6 | 8 | 4 | 5 | 9 | 2 | 4 | 3 | 1 |
| | Count of Outflow n | 13 | 6 | 9 | 6 | 11 | 6 | 8 | 4 | 5 | 9 | 2 | 4 | 3 | 1 |
| Media Filter | Count of Inflow n | 18 | 16 | 18 | 16 | 18 | 16 | 18 | 8 | 9 | 17 | 16 | 8 | 15 | |
| | Count of Outflow n | 18 | 16 | 18 | 16 | 18 | 16 | 18 | 8 | 9 | 17 | 16 | 8 | 15 | |
| Retention Pond | Count of Inflow n | 21 | 4 | 13 | 4 | 17 | 5 | 16 | 1 | 10 | 20 | 4 | 9 | 12 | 6 |
| | Count of Outflow n | 21 | 4 | 13 | 4 | 17 | 5 | 16 | 1 | 10 | 20 | 4 | 9 | 12 | 6 |
| Wetland Basin | Count of Inflow n | 12 | 1 | 2 | 2 | 7 | 3 | 6 | 1 | 2 | 13 | 6 | 8 | 6 | 10 |
| | Count of Outflow n | 12 | 1 | 2 | 2 | 7 | 3 | 6 | 1 | 2 | 13 | 6 | 8 | 6 | 10 |

Source: International BMP Database (http://www.bmpdatabase.org/) April 2004.

Table 8-2. BMPs with intra-event data as of July 2003.

| BMP Name | Location | BMP Type | Hydrologic Data | Water Quality Data |
|---|---|---|---|---|
| Seattle METRO Retention Pond | Bellevue, WA | Retention pond | Yes | Yes |
| Whispering Heights Residential Pond | Bellevue, WA | Detention basin | Yes | Yes |
| Moyewood Pond | Greenville, NC | Detention basin | Yes* | Yes |
| Demonstration Urban Stormwater Treatment (DUST) Marsh System A | Freemont, CA | Wetland channel | Yes | Yes |
| DUST Marsh System C | Freemont, CA | Wetland channel | Yes | Yes |
| Barton Creek Square Shopping Center Pond | Austin, TX | Detention basin | Yes | Yes |
| U.S. 183 at MoPac Expressway, Grass Filter Strip | Austin, TX | Biofilter | Yes | Yes |
| Walnut Creek Vegetative Buffer Strip | Austin, TX | Biofilter | Yes | Yes |
| Seton Pond Sedimentation Facility | Austin, TX | Detention basin | Yes | Yes |
| Queen Anne's Pond | Centerville, MD | Wetland channel | Yes | Yes |
| Dayton Ave. Biofilter—Grass Swale | Seattle, WA | Biofilter | Yes* | No |

*Hydrograph data digitized from graphical displays

Generally, there were two primary issues affecting the usability of the data for the International BMP Database. First, several of the studies had sparse data or large sections of absent data for certain water-quality constituents and/or certain monitored runoff events. The proportion of records with missing water-quality and/or flow data was particularly high for the Queen Anne's Pond study. Others with some missing data were the U.S. 183 study, the Walnut Creek study (gaps in concentrations of bacteria and some metals), and the Seton Pond study (missing concentration, flow, and/or time of sample data). For all the studies, records with no reported concentration or load, and/or no flow data were not considered for this project.

Second, several studies, particularly the Queen Anne's Pond study, included flags on reported data (such as letters next to sample IDs and/or flags on water-quality data), but no explanation of their meaning. For all studies, the following assumptions were made for commonly encountered flags:

- Data such as "<10" indicate values known to be less than value shown,
- Data such as ">10" indicate values known to be greater than value shown,
- Data such as "–0.3" indicate non-detects, with the reported value representing the detection threshold, and
- Data reported as "NA" or "—" indicate missing data.

In spite of gaps in bacteriological and some metals data, three sites in Austin, Texas (U.S. Hwy. 183, Walnut Creek, and Seton Pond), and the site on Moyewood Pond in Greenville, North Carolina, had the best documented and most complete data. Hydrologic and water-quality data from these sites in Austin and Greenville were used for preliminary assessment of EMC evaluation techniques and for testing of the SWMM for application for hydrologic screening (Brown 2003).

Another potential source of intra-event BMP performance information is proprietary BMP makers. However, virtually all of the data are EMCs and the quality-assessment/quality-control (QA/QC) procedures for these studies are generally not well documented.

Other research investigated during the course of this study include research conducted by the Wisconsin Department of Natural Resources (Personal communication, Roger Bannerman, Wisconsin Department of Natural Resources, Madison, Wisconsin, 2003; www.dot.wisconsin.gov/library/research/docs/quarterlyreports/0092-00-03.pdf), City of Griffin, Georgia (Keller 2002), the U.S. Geological Survey literature review of highway-related stormwater studies (Granato 2003), and the *Runoff Water Quality Knowledge Base for Windows* CD-ROM prepared by GKY Associates (2001). Results from the first two studies were not available in time to be included in this report, and none of these sources yielded any better data sources than the ones from the International BMP Database described above, although future review is warranted. Some Caltrans data were used later in this study for evaluation of swales, filter strips, and detention ponds. Essentially, evaluation of all the data is incorporated into the Pollutant Fact Sheets, included in Appendix A of the *Guidelines Manual*. A broad summary is presented in Section 8.6. Section 8.5 provides descriptions of recommended methods for evaluating the effectiveness of individual BMPs. The methods are illustrated using data from one of the three Austin, Texas, studies discussed above. Data from all three Austin sites and

## Table 8-3. Extended summary table of candidate intra-event sites.

| BMP Name | BMP Type | Study Name | Author(s) | Approx. # of Storms w/Sufficient Data | Water Quality Constituents | Catchment Description | Hydrologic Data | WQ Data | TSS | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Particle Size Distribution? | Settling Velocity? |
| Seattle METRO Retention Pond | RP | Operation of Detention Facilities for Urban Stormwater Quality Enhancement | Dally et al. 1983 | 6 | grease and oil, TSS, TP, TCd, SolCd, TPb, SolPb, TZn, SolZn, | bus parking lot/ maintenance | Yes | Yes | No | No |
| Whispering Heights Residential Pond | DB | Operation of Detention Facilities for Urban Stormwater Quality Enhancement | Dally et al. 1983 | 4 | TSS grease and oil, | subdivision | Yes | Yes | No | No |
| Moyewood Pond | DB | An Evaluation of Pollutant Removal by a Demonstration Urban Stormwater Detention Pond | Stanley 1994 | 8 | TSS, VSOL, FSOL, NH4, NO3, PO4, TKN, TDP, PN, PP, DOC, POC, Cr, Cd, Ni, Pb, Cu, Zn, fecal coliform BOD, COD | residential and commercial | Yes (see Comments) | Yes | No | Yes |
| Demonstration Urban Stormwater Treatment (DUST) Marsh System A | WC | Urban Stormwater Treatment at Coyote Hills Marsh | ABAG 1986 | 7 | pH, EC, TDS, TSS, BOD, oil/grease, NH4, NO3, TKN, Ortho-P, TP, Cd, Cr, Cu, Pb, Mn, Ni, Zn | general urban (Fremont, CA) | Yes | Yes | Yes | No |
| DUST Marsh System C | WC | Urban Stormwater Treatment at Coyote Hills Marsh | ABAG 1986 | 7 | pH, EC, TDS, TSS, BOD, oil/grease, NH4, NO3, KN, Ortho-P, TP, Cd, Cr, Cu, Pb, Mn, Ni, Zn | general urban (Fremont, CA) | Yes | Yes | Yes | No |
| Barton Creek Square Shopping Center Pond | DB | Effects of Runoff Controls on the Quantity and Quality of Urban Runoff at Two Locations in Austin, Texas | Welborn and Veenhis 1987 | 6 | COD, BOD, fecal coliform strep, DS (180 degC), DS (105 degC), VDS, TN, NO2+NO3, NH4, POC, Cd, Fe, Pb, Zn | shopping center | Yes | Yes | No | No |
| U.S. 183 at MoPac Expressway—Grass Filter Strip | BF | Use of Vegetative Controls for Treatment of Highway Runoff | Walsh et al. 1997 | 15 | TSS,turbid, fecal colif, strep, ecoli, COD, TOC, NO3, TKN, TP, Zn, Pb, Fe, Cu | highway | Yes | Yes | No | No |
| Walnut Creek Veg. Buffer Strip | BF | Use of Vegetative Controls for Treatment of Highway Runoff | Walsh et al. 1997 | 23 | TSS,turbid, fecal colif, strep, ecoli, COD, TOC, NO3, TKN, TP, Zn, Pb, Fe, Cu | highway | Yes | Yes | No | No |
| Seton Pond Sedimentation Facility | DB | The Effectiveness of Permanent Highway Runoff Controls: Sedimentation/Filtration Systems | Keblin et al. 1997 | 9 | TSS,turbid, COD, TOC, NO3, TKN, TP, Zn, Fe | highway | Yes | Yes | No | No |
| Queen Anne's Pond | WC | The Use of Artificial Wetlands in Treating Stormwater Runoff | Athanas and Stevenson 1991 | 14 | NO3, NO2, TN, TDN, PO4, TP, TDP, TSS, ON, OP, PN, PP, NO3+NO2, NH4 | high school | Yes | Yes | No | No |
| Dayton Ave. Biofilter—Grass Swale | BF | Dayton Avenue Swale Biofiltration Study | Goldberg et al. 1993 | 7 | No pollutographs | urban (Seattle, WA) | Yes (see Table 8-4) | No | No | No |

Note: RP = retention pond, DB = extended detention basin, WC = wetland channel, BF = biofilter, T = total, Sol = soluble, EC = electrical conductivity, VSOL =volatile solids, FSOL = fixed solids, TKN = total Kjeldahl nitrogen, TDP = total dissolved phosphorus, PN = particulate nitrogen, PP = particulate phosphorus, DOC = dissolved organic carbon, POC = particulate organic carbon, DS = dissolved solids, VDS = volatile dissolved solids, TN = total nitrogen, TDN = total dissolved nitrogen, ON = organic nitrogen, OP = organic phosphorus, PN = particulate nitrogen, and PP = particulate phosphorus.

## Table 8-4. Sampling method and additional comments on candidate intra-event sites.

| BMP Name | Sampling Method | Comments |
|---|---|---|
| Seattle METRO Retention Pond | Outflow measured in V-notch flume. Pond height measured using nitrogen gas pressure differential. Stevens A-35 water level recorder and stilling well were installed to record flume stage. Manning 4040 discrete water quality sampler was installed to sample discharge from the flume. The samplers are capable of taking 24 one-liter samples at carrying time increments. | Good data, some printing errors identified. Study text details lab calibration of special stage-discharge relationship for flume used to measure flow. |
| Whispering Heights Residential Pond | Stevens A-35 float type water level recorder in 12" stilling well used to measure the water level in the pond. 6" orifice at outlet controlled discharge. Manning 4040 discrete automatic samplers with adjusted one-liter intake capacities were used. Outflow samples were collected directly upstream of outlet. | Good data, some printing errors identified. Study text details lab calibration of special stage-discharge relationship used to measure flow based on pond surface elevation. |
| Moyewood Pond | WQ sampled automatically (ISCO Model 2700). Inflow at 15-min intervals for first 2 hrs and every hour thereafter. Outflow every hour. Every other WQ sample discharged when delta TSS was "small" in order to reduce lab costs. | Hydrologic data in graphical form only. Points digitized and flow volumes for each sample interpolated. Two pages of data missing (end of storm 7, beginning of storm 8) and pages missing from summary of analysis methodology in text. Water quality sampling period does not always exactly overlap with available flow data; as a result, several water quality records have no corresponding flow data. |
| Demonstration Urban Stormwater Treatment (DUST) Marsh System A | Flow rate computed from stage-discharge relationship. Water quality measurements from grab samples. | DUST Marsh A and C in series. A is 5-acre lagoon system. Time of samples provided as "sampling periods," separately from tabulated data. It is assumed that each sample was taken at the end of the corresponding sampling period. |
| DUST Marsh System C | Flow rate computed from stage-discharge relationship. Water quality measurements from grab samples. | DUST Marsh A and C in series. C is wetland channel. Treats flows from System A and System B. No inlet data for System B, only outlet data. Time of samples provided as "sampling periods," separately from tabulated data. It is assumed that each sample was taken at the end of the corresponding sampling period. |
| Barton Creek Square Shopping Center Pond | WQ and discharge data collected immediately upstream and downstream of pond. Manning X System Level Transmitter and Recorder was used at the inflow and outflow stations to measure stage. Manning S-4050 automatic water samplers were used to collect WQ samples. The sampler intake was located near the bottom of the channel and was activated when the stage rose to a predetermined level (not specified). Two one-liter bottles were sampled at every interval. | Data difficult to interpret. No clear methodology for when multiple intra-event samples taken. Extracted data limited to those events where >3 intra-event data are clearly evident. |
| U.S. 183 at MoPac Expressway, Grass Filter Strip | Isco 3700 samplers and Isco 3230 bubbler flow meters used to measure water quality and flow at the inlet and outlet of the filter strip. | Data provided electronically by Michael Barrett. Inflows and outflows have different number of storms. Several records missing flow and/or water quality data. |
| Walnut Creek Vegetative Buffer Strip | Isco 3700 samplers and Isco 3230 bubbler flow meters used to measure water quality and flow at the inlet and outlet of the filter strip. | Data provided electronically by Michael Barrett. Inflows and outflows have different number of storms. Several records missing flow and/or water quality data. |
| Seton Pond Sedimentation Facility | Isco 3700 sampler drew inflow samples at 15, 45, 75, 135, and 195 min, after flow depth in influent channel reached 2.5 cm, and every 60 min thereafter, if necessary. Isco 3700 sampler drew outflow samples at 5, 120, 240, 600 and 960 min after activation. Isco 3230 bubbler flow meters measured flow at inlet and outlet. | Data provided electronically by Michael Barrett. Inflows and outflows have different number of storms. Several records missing flow and/or water quality data. |
| Queen Anne's Pond | No information available. | Irregular data. Data from both inlets not provided for many storms. No annotation explaining flags marking many records, unclear whether these are dupes, problematic samples, or other. Only flow volumes provided for majority of storms (no time data), with no clear way of translating into hydrograph. |
| Dayton Biofilter— Grass Swale | Flow measured using an automatic flow meter connected to a pressure transducer, installed at the inlet and outlet (H-flumes). | Hydrologic data in graphical form only. Points digitized and flow volumes for each sample interpolated. No "start of event" time given in study, so assumed that lower scale of x-axis represented beginning of event. One of the eight monitored storms not used due to known obstruction in flow path, affecting flow data. |

the Greenville site were evaluated by Brown (2003), whose study may be consulted for more detail.

## 8.5 Evaluation of Quality Performance for Individual BMPs

### 8.5.1 EMC Data for U.S. 183 Filter Strip

As described in the previous section, University of Texas researchers (Walsh et al. 1997) collected performance data for a major highway median filter strip in northwestern Austin, Texas (see Table 8-5 and Figure 8-1). Although most of the data were obtained from the International BMP Database, considerable help in obtaining and interpreting the data was provided by Professor Michael Barrett of the University of Texas. Data for three parameters—TSS, nitrate, and total zinc—will be used to illustrate some EMC evaluation procedures, although several other constituents were sampled as well (see Table 8-3). These three parameters were chosen because they were available for multiple studies evaluated during the project. The basic data used for the comparisons that follow are shown in Table 8-6. There are at least 19 EMC data points for each of the three parameters, which is more data than is usually available for BMP evaluation studies. Note, however, that flows were not sampled for all events for which quality was sampled and that more effluent samples were collected than influent samples. The results of simple statistical analysis of the data are also shown in Table 8-6. The total zinc data illustrate a detection limit issue, with seven effluent EMCs at 0.002 mg/L. Methods of dealing with data at the detection limit are given by Burton and Pitt (2002). For instance, because of the huge data-handling requirements within the International BMP Database, all records flagged as nondetects are assigned one-half the reported detection limit, although Helsel and Hirsch (1992) advocate more robust methods based on the characteristics of observed data greater than the detection limit. However, following the methods of Walsh et al. (1997), detection limit data points herein are kept at detection limit values in order to be conservative (higher EMCs than might otherwise be occurring) for effluent BMP quality.

**Table 8-5. Characteristics of the U.S. 183 filter strip.**

| Characteristic | U.S. 183 |
|---|---|
| Centerline length (m) | 356 |
| Width of entire median (m) | 14.9-19.5 |
| Filter strip treatment length (m) | 7.5-8.8 |
| Average median side slope (%) | 12.10% |
| Average centerline slope (%) | 0.73% |
| Drainage area ($m^2$) | 13,000 |
| Average daily traffic | 111,000 |
| Impervious drainage area (%) | 52% |
| Impervious roadway area (%) | 100% |

Source: Brown 2003, using data from Walsh et al. (1997).

Source: Walsh et al. 1997.

*Figure 8-1. Vegetated filter strip at U.S. 183 site.*

Simple removal efficiencies (see Equation 8-1) are also shown in Table 8-6, based on average effluent and influent EMCs. The efficiency ratio weights all EMCs equally, regardless of the magnitude of the storm, and therefore will yield inconsistencies if the EMC varies significantly with the storm volume or if the pollutant loads are not necessarily proportional to the storm volume. For the three tabulated pollutants, however, removal does occur.

### 8.5.2 Scatter Plot

Methods for analysis of EMC data have been evaluated in detail by GeoSyntec Consultants et al. (2002), Huber et al. (2006), and Minton (2005). Prior to an evaluation involving a "removal" estimation or formal statistical procedure, or prior to the more sophisticated effluent probability method used in this study, a simple plot of storm event effluent EMC versus influent EMC should be conducted for a qualitative estimate of effectiveness. Hypothetical data are shown in Figure 8-2 to illustrate possible relationships. If the data plot at less than a 45° line (effluent = influent), some removal is occurring. If removal occurs and the line is approximately linear, then

$$\mathrm{EMC_{out}} = (1 - \mathrm{R}) \cdot \mathrm{EMC_{in}} \tag{8-3}$$

where R = removal fraction. If the relationship is nonlinear, particularly, if apparent removal increases with higher influent concentration (as illustrated in Figure 8-2), then it can be inferred that removal is a function of influent concentration. However, if effluent EMCs are relatively constant (the square data points in Figure 8-2) and not a function of influent EMCs, then "percent removal" is a poor way to characterize the BMP performance, and effluent quality itself is the key characteristic. This property (EMC distribution) may in turn

**Table 8-6. Water-quality data (EMCs) for the U.S. 183 filter strip.**

| Storm No. | Date | Inflow Volume, L | Outflow Volume, L | TSS in mg/L | TSS out mg/L | $NO_3$* in mg/L | $NO_3$ out mg/L | T-Zn** in mg/L | T-Zn out mg/L |
|---|---|---|---|---|---|---|---|---|---|
| 9 | 5/27/1996 | --*** | 60,390 | -- | 4 | -- | 0.65 | -- | 0.011 |
| 10 | 4/5/1996 | -- | 74,350 | -- | 18 | -- | -- | -- | 0.003 |
| 11 | 4/22/1996 | -- | 42,120 | -- | 5 | -- | 0.8 | -- | 0.002 |
| 12 | 5/27/1996 | 117,310 | 148,880 | 127 | 56 | 1.21 | 0.54 | 0.294 | 0.022 |
| 13 | 5/30/1996 | 176,250 | 254,830 | 7 | 56 | 5.21 | 4.61 | 0.002 | 0.115 |
| 15 | 6/22/1996 | 6,800 | 62,330 | 247 | 38 | 3.29 | 2.71 | 0.459 | 0.002 |
| 16 | 6/25/1996 | 18,480 | 115,950 | 117 | 50 | 5.66 | 3.71 | 0.285 | 0.003 |
| 18 | 8/11/1996 | -- | 170,400 | -- | 58 | -- | 0.64 | -- | 0.002 |
| 19 | 8/22/1996 | 5,940 | 35,410 | 31 | 3 | 2.66 | 0.31 | 0.279 | 0.002 |
| 20 | 8/23/1996 | 15,260 | 149,470 | 17 | 5 | 0.8 | 0.2 | 0.03 | 0.002 |
| 21 | 8/29/1996 | 3,680 | 151,690 | 22 | 59 | 1.12 | 1.4 | 0.146 | 0.002 |
| 22 | 9/18/1996 | 32,320 | 103,090 | 135 | 7 | 2.25 | 1.32 | 0.123 | 0.002 |
| 23 | 10/17/1996 | 18,400 | -- | 64 | -- | 1.15 | -- | 1.04 | -- |
| 24 | 10/27/1996 | 6,320 | -- | 312 | -- | 0.47 | -- | 1.099 | -- |
| 25 | 11/7/1996 | 30,600 | 222,390 | 81 | 14 | 0.53 | 0.2 | 0.126 | 0.025 |
| 26 | 11/24/1996 | 25,660 | 294,980 | 40 | 6 | 0.41 | 0.19 | 0.022 | 0.026 |
| 28 | 12/15/1996 | 55,180 | 475,340 | 98 | 7 | 0.55 | 0.25 | 0.093 | 0.022 |
| 29 | 2/7/1997 | -- | 161,420 | -- | 7 | -- | 1.12 | -- | 0.044 |
| 30 | 2/12/1997 | 10,110 | 257,940 | 133 | 5 | 0.46 | 0.78 | 0.23 | 0.027 |
| 31 | 3/11/1997 | -- | 122,090 | -- | 17 | -- | 0.17 | -- | 0.11 |
| 32 | 3/25/1997 | 20,490 | 175,860 | 328 | 6 | 0.43 | 0.41 | 0.44 | 0.07 |
| 33 | 4/2/1997 | 12,360 | 65,380 | 522 | 6 | 1.63 | 0.68 | 0.69 | 0.05 |
| 34 | 4/25/1997 | 3,830 | 426,570 | 146 | 4 | 2.47 | 0.32 | 0.35 | 0.07 |
| 35 | 5/9/1997 | 152,400 | 462,050 | 389 | 21 | 0.91 | 0.42 | 0.48 | 0.05 |
| 36 | 5/27/1997 | 87,389 | 301,330 | 159 | 19 | 0.94 | 0.48 | 0.41 | 0.07 |
|  | n | 19 | 23 | 19 | 23 | 19 | 22 | 19 | 23 |
|  | average | 42,041 | 188,446 | 157 | 20.5 | 1.692 | 0.996 | 0.347 | 0.032 |
|  | std. dev. | 52,456 | 130,775 | 141 | 20.7 | 1.568 | 1.181 | 0.313 | 0.035 |
|  | CV**** | 1.248 | 0.694 | 0.903 | 1.009 | 0.927 | 1.186 | 0.901 | 1.091 |
|  | median | 18,480 | 151,690 | 127 | 7 | 1.12 | 0.59 | 0.285 | 0.022 |
|  | R (Eqn. 8-1) | -- | -- | -- | 0.87 | -- | 0.41 | -- | 0.91 |

* $NO_3$ = nitrate
** T-Zn = total zinc
*** -- = no available data.
****CV = coefficient of variation = standard deviation / average.
Source: Walsh et al. 1997.

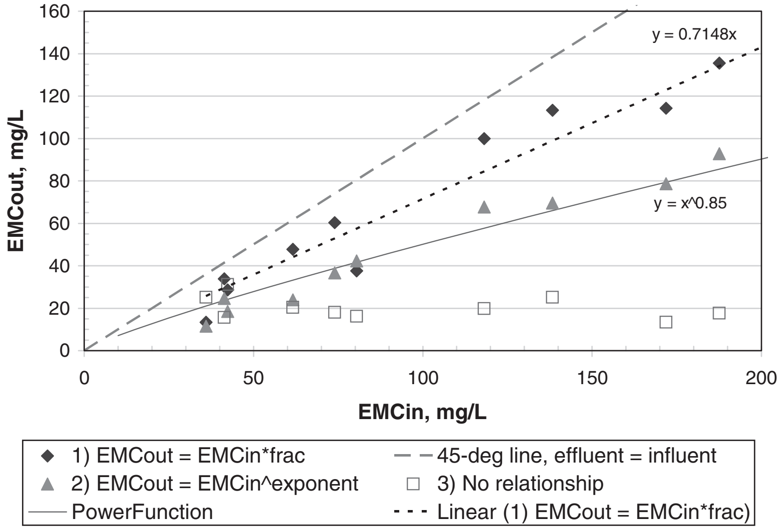


*Figure 8-2. Scatter plot of hypothetical data to illustrate possible relationships between effluent and influent EMCs.*

be characterized by a frequency distribution, as exemplified by the effluent probability method (EPM) (see Section 8.5.3). In any event, scatter plots are useful for such qualitative evaluation and are shown for the U.S. 183 data in Figures 8-3, 8-4, and 8-5.

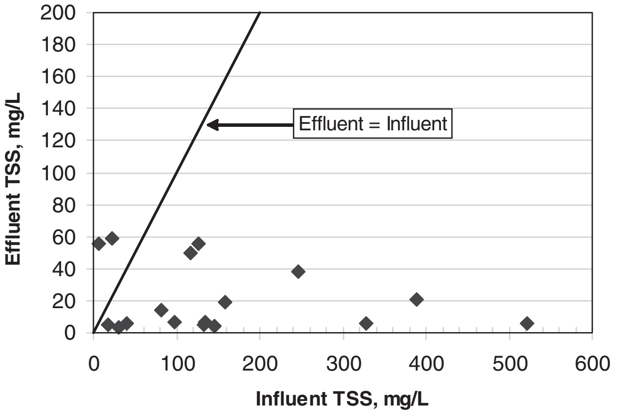
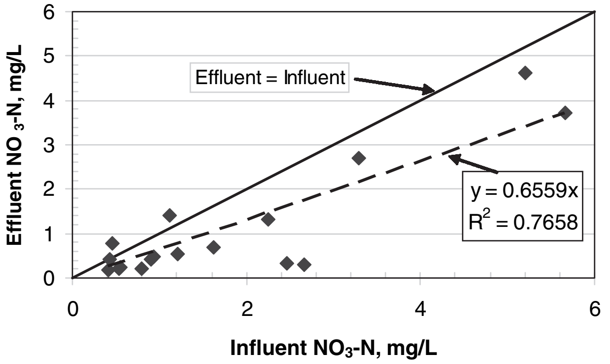


*Figure 8-3. Effluent versus influent TSS EMCs for U.S. 183 filter strip.*



Note: Trend line intercept is forced through zero.

*Figure 8-4. Effluent versus influent nitrate ($NO_3$-N) for U.S. 183 filter strip.*

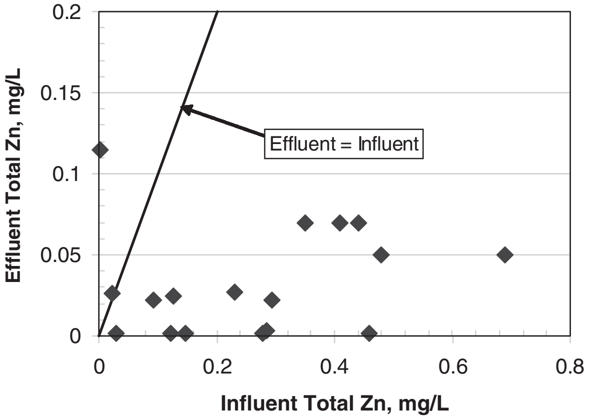


*Figure 8-5. Effluent versus influent total zinc for U.S. 183 filter strip.*

In the scatter plots of TSS and total zinc for U.S. 183, the effluent concentrations are essentially flat and seemingly not influenced by the influent concentration (see Figures 8-3 and 8-5, respectively). No functional removal relationship is apparent; what is apparent is that effluent EMCs are much lower than influent EMCs The frequency distributions provided by the EPM are an excellent means to provide such a characterization of effluent EMCs.

With respect to nitrate (see Figure 8-4), removal is less, which is to be expected for a dissolved constituent. A trend line, forced through zero, has a relatively high $R^2$ value, but the statistical significance cannot be evaluated (because of the forced zero intercept). A trend line not forced through zero is $y = -0.202 + 0.719x$, for which $R^2 = 0.78$ and for which $p = 3 \times 10^{-6}$ (highly significant). However, the intercept is not significant ($p = 0.41$). Hence, one definition of removal fraction for nitrate would be 1 – slope, in the range of 0.28 – 0.35 (*at this site only*; nitrate is poorly removed by most BMPs). These values are somewhat lower than the efficiency ratio removal fraction computation of 0.41 (see Table 8-6).

Although an EMC reduction does occur for the majority of BMPs and constituents (see the *Guidelines Manual*, Appendix A, "Pollutant Fact Sheets"), the relationship can often only be characterized by a significant difference between EMC medians or through the use of other nonparametric statistical tests. These tests will also be illustrated below.

### 8.5.3 EPM

The EPM is straightforward and provides a clear, but qualitative picture of BMP effectiveness. The EPM consists of a lognormal probability plot (although any distribution could be used for which probability paper exists, including normal) of EMC versus either probability of occurrence or percent exceedance (equivalent to the cumulative distribution function). Probability plots are among the most useful pieces of information that can result from a BMP evaluation study (Burton and Pitt 2002). The authors of *Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater BMP Database Requirements* (GeoSyntec et al. 2002) strongly recommend that the stormwater industry accept probability plots as a standard "rating curve" for BMP evaluation studies as they provide a visual representation of the frequency distribution of both influent and effluent quality.

Lognormal plots are ordinarily used because the lognormal distribution has been found to be a good fit for most stormwater EMC data (USEPA 1983; Driscoll 1986; Smullen and Cave 2002; George 2004), although the normal distribution has been found to be a better fit for pond effluent data in some studies (Van Buren et al. 1997). One advantage of normality, either of the logs or of the untransformed data, is that parametric statistical tests can be applied, such as the t-test, chi-square test, and analysis of variance. Statistical tests used to compare data sets typically require normality in the data sets, and some also require the data sets to have equal variances. Lognormal (and normal) probability plots can also be used for qualitative guidance because the occurrence of two curves with the same slope indicates the same variance of the data.

The most basic test for normality is whether or not the data plot as a straight line on normal probability paper (or versus equivalent values of the standard normal variate, z) (Burton and Pitt 2002; Bedient and Huber 2002). Tests for normality itself include tests directly related to probability plots, such as the probability plot correlation coefficient (PPCC) (Vogel 1986) and the Shapiro-Wilk test (Helsel and Hirsch 1992). Tests not related to probability plots include the Kolmogorov-Smirnov test and the chi-square test (Benjamin and Cornell 1970; Helsel and Hirsch 1992). However, the latter two (Kolomogorov-Smirnov and chi-square) are less powerful in a statistical sense than tests that use probability plots; moreover, the plots themselves yield great qualitative information, as discussed below. It is interesting to note that if ranked data are plotted against standard normal variates ("z-values") obtained from the inverse of the plotting position probability (Bedient and Huber 2002) using MS Excel, the linear fit of data (untransformed or logarithms) obtained using MS Excel's "trend line" option provides the required PPCC. The PPCC can then be tested for statistical significance (Vogel 1986; Helsel and Hirsch 1992). The critical values of the correlation coefficient (found in Vogel 1986 and Helsel and Hirsch 1992) account for the inherent correlation between two ranked data sets (order statistics). If normality, and, in some cases, equal variance, is ensured among the respective data sets, parametric tests can be employed to test the difference between the means (and medians if normally distributed) of the data sets.

Parametric and nonparametric statistical tests should be conducted after the probability plots are generated to indicate if perceived differences in influent and effluent mean EMCs are statistically significant (the level of significance should be provided rather than just noting whether the result was significant, e.g., a 95% significance level). Helsel and Hirsch (1992) provide an excellent primer on parametric and nonparametric methods with applications to water resources and water quality. Many parametric and nonparametric tests are included in standard statistical software.

Limited *quantitative* assumptions can be made simply on the basis of the effluent probability plots themselves. Unlike the X-Y scatter plots in Figures 8-2 through 8-5, probability plots arrange the data on the basis of ranked quantiles, not by event. Influent and effluent values for a given quantile (cumulative frequency) are assumed to be temporally independent (values associated with the same storm event would be sheer coincidence). Even if the distribution of effluent values lies wholly underneath the influent distribution, there is no guarantee that effluent concentrations were less than influent concentrations for every sampled event.

However, the range of both influent and effluent quality can be determined on the basis of the concentration range between given percentile values. In addition, the normality and equal variance among the data sets can be qualitatively observed, although any inferences about variance must be confirmed through quantitative statistical testing. Finally, when influent and effluent EMC medians are separated by less than the standard deviation of either the influent or effluent EMC data, this is a qualitative indication of minimal removal. Examples of effluent probability plots are shown for the U.S. 183 data in Figures 8-6 through 8-8.

The abscissa in each plot is the standard normal variate, z, or the inverse of the cumulative distribution function, F(z), of the N(0,1) distribution (normal, with mean = 0 and variance = 1), corresponding to

$$F(z) = \int_{-\infty}^{z} \frac{e^{-\frac{u^2}{2}}}{\sqrt{2\pi}} du \tag{8-4}$$

Tabulated values of either F(z) or $z^{-1}(F)$ may be found in any statistics book and may also be obtained from the Excel functions NORMDIST() or NORMINV(), respectively. Quartiles for 25%, 50% (median), and 75% correspond to z = -0.674, 0, and +0.674, respectively, and are shown on the three EPM plots.

Regression lines (Excel trend lines) are also shown for each plot, corresponding to

$$\ln \text{EMC} = \overline{\ln \text{EMC}} + S_{\ln} \cdot z \tag{8-5}$$

in which it is clear that the average of the logarithms of the EMCs ($\overline{\ln \text{EMC}}$) is the intercept, and the standard deviation of the logarithms of the EMCs ($S_{\ln}$) is the slope. Because Excel can only provide an exponential fit when using a vertical log scale, the exponential equation is given on the plots. Hence, the average of the logarithms is the log of the coefficient, and the standard deviation of the logarithms is the number in the exponent. For example, for TSS effluent, $\overline{\ln \text{EMC}} = \ln(12.452) = 2.52$, and $S_{\ln} = 0.9935$. As a matter of interest, the least squares regression trend lines for these data are almost indistinguishable from lines that would show the method of moments fit for the lognormal distributions. Hence, the latter fits are not shown.

One other aspect of the EPM method is that all influent and effluent data points are included in the analysis (all EMC values tabulated in Table 8-6) whereas only the lesser number of matched pairs (both values sampled for the

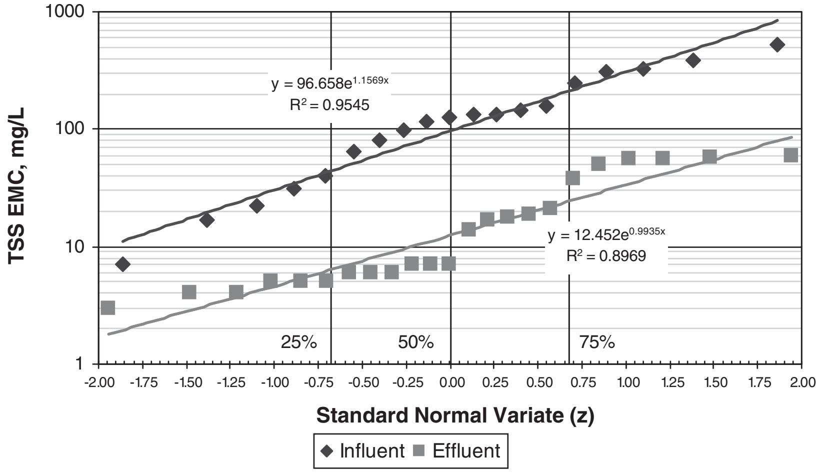


*Figure 8-6. EPM plots for TSS for U.S. 183 filter strip, with quartile locations also shown.*

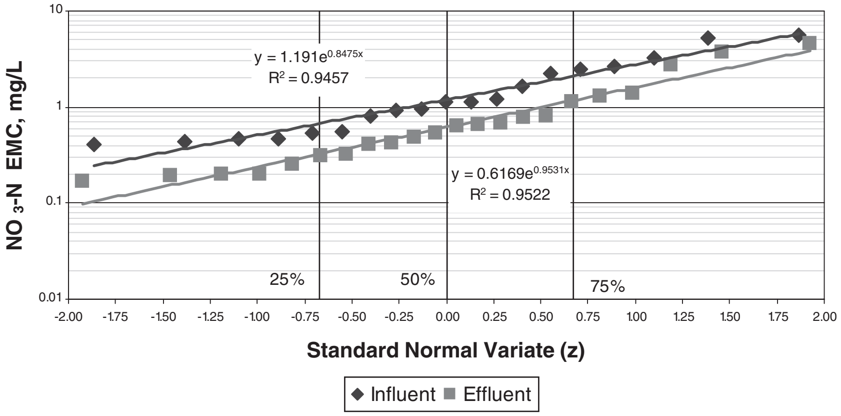


*Figure 8-7. EPM plots for nitrate for U.S. 183 filter strip, with quartile locations also shown.*

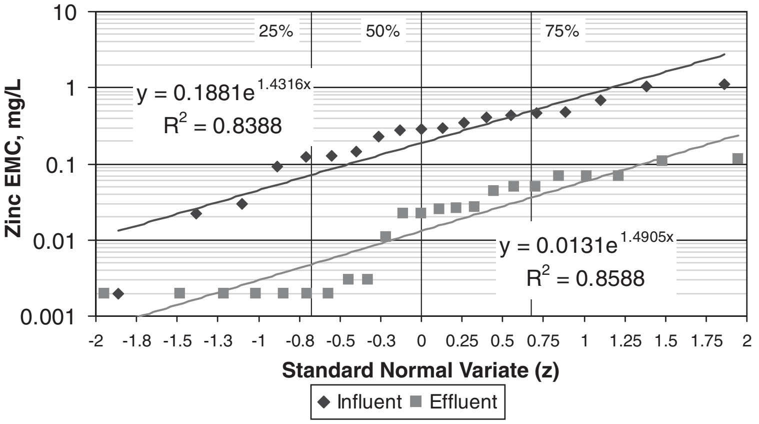


*Figure 8-8. EPM plots for total zinc for U.S. 183 filter strip, with quartile locations also shown.*

same event) can be shown on scatter diagrams. This once again emphasizes the point that data values shown for the same quantiles do not necessarily (and are not even likely to) correspond to the same storm event.

Examination of the EPM plots for TSS and total zinc (see Figures 8-6 and 8-8 and) suggests that the slopes of the influent and effluent lines are very similar, indicating similar variances (of the logs) for the two parameters. Moreover, the separation of the influent and effluent frequency distributions is very clear, the significance of which will be tested subsequently. Interestingly, as will be shown subsequently as well, only the lognormal fit of the effluent TSS EMC distribution is statistically significant, that is, the logs of the influent TSS EMCs fail two normality tests. The implication is that a parametric t-test may not be used to compare means, leading to use of the nonparametric Kruskal-Wallis test later. Overall, the U.S.183 filter strip shows obvious removal of TSS and total zinc, with significance tests to follow.

A final element of the EPM plot for total zinc (see Figure 8-8) is the evidence of detection limit data, with seven values at 0.002 mg/L forming a flat line at the lower left part of the effluent EMC distribution. As mentioned previously, in reality, values may be less than 0.002 mg/L; hence, the plot conservatively overestimates the magnitudes of effluent EMCs.

The EPM for nitrate (see Figure 8-7) also shows a tendency toward similar variance of the logs, but with less separation between influent and effluent EMCs than is the case with TSS and total zinc. Both the influent and effluent log (EMC) values fail normality tests; thus, only a nonparametric comparison may be used to test the significance of the separation of the influent and effluent EMCs.

Finally, for illustrative purposes, EPM plots for the hypothetical data of Figure 8-2 are shown in Figure 8-9. Although the figure illustrates separation of data sets as before, there is almost no way of discerning the possibility of a functional relationship from the EPM. Only the scatter plot shows the linear (series 1), power function (series 2), and lack of relationship (series 3) qualitatively evident in Figure 8-2.

The qualitative inferences from the EPM may also be obtained from other descriptive statistics, such as box plots (see Section 8.5.4), as well as obtained quantitatively through the parametric t-test and nonparametric comparisons of medians. However, the EPM has the advantage of illustrating the lognormal (or other distribution) fit of the data, rather than simply certain quantiles, as with box plots. The primary problem with the EPM is that certain quantitative assumptions, such as removal and performance at or around a certain concentration value, cannot be made unless data points are entered as matched pairs (e.g., as in scatter plots of effluent versus influent EMC). With the Caltrans BMP study and assessment (Caltrans 2003), this discrepancy was called out and discussed, indicating that interpretation of these plots should be performed in conjunction with related analyses, such as scatter plots. Another concern raised with the EPM is its ability to provide sufficient information regarding BMP selection. In areas requiring a set removal percentage, use of the EPM may not adequately portray whether a BMP is capable of meeting that performance standard (Caltrans 2003).

### 8.5.4 Box and Whisker Plots

Most statistical software will provide what is known as a box plot or box and whisker plot, representing quantiles, extremes, and confidence limits of the data. So-called notched box and whisker plots are used in Appendix A of the *Guidelines Manual* and will be illustrated here for the U.S. 183 data. An explanation (taken from the same appendix) is shown in conjunction with Figure 8-10.

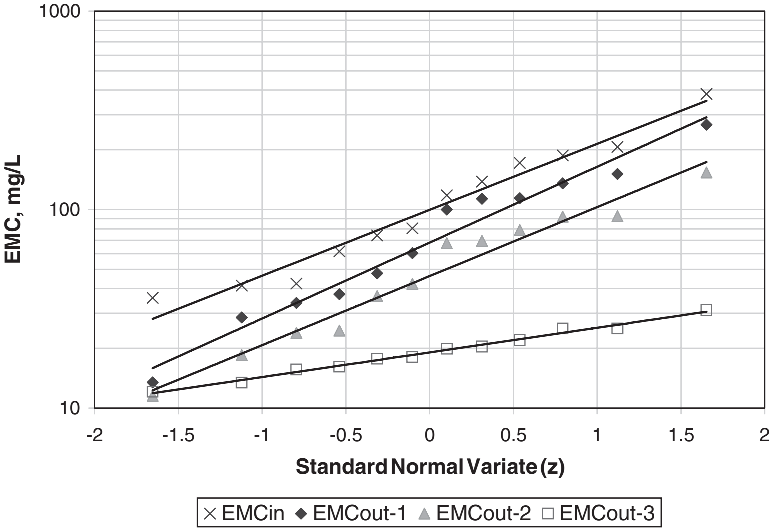
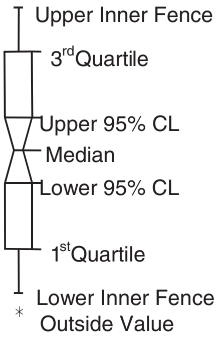


***Figure 8-9. EPM analysis of hypothetical data shown in Figure 8-2.***



Note: CL = confidence level.

***Figure 8-10. Box plot definitions.***

The notches encompass the 95% confidence interval of the median and provide a nonparametric means of assessing the difference between the centers of multiple distributions. A logarithmic scale was determined to be best suited for plotting most data. The log-scale box plots were created utilizing the following method to calculate the upper and lower confidence levels:

1. The natural logs of the EMC are sorted in ascending order.
2. The upper and lower quartiles (i.e., the 75th and 25th percentiles) are calculated, following Tukey (1977).
3. The confidence interval of the median is calculated based on the upper and lower quartiles, following McGill et al. (1978).
4. The inner quartile range (IQR) is defined as the difference between the upper (third or 75%) quartile (also, approximately, the upper hinge) and the lower (first, or 25%) quartile (also, approximately, the lower hinge). The lower inner fence is the lower quartile minus 1.5 × IQR, and the upper inner fence is the upper quartile plus 1.5 × IQR.
5. By taking the exponent (value = $e^{\log}$), the upper and lower confidence levels are translated back to arithmetic space. These values are used to delineate the upper and lower bounds of the notch on the box plots.

Many useful explanations of such arcane statistics may be found on the Web; one of many sites with explanations of box plot ingredients is available at: http://www.xycoon.com/index.htm. For the distributions of averaged EMCs by BMP category and the distributions of individual EMCs by BMP category, the arithmetic values of the upper confidence level and lower confidence level of the median are provided in the table that accompanies each summary. All the box plots shown in Appendix A of the *Guidelines Manual* were prepared with SYSTAT software.

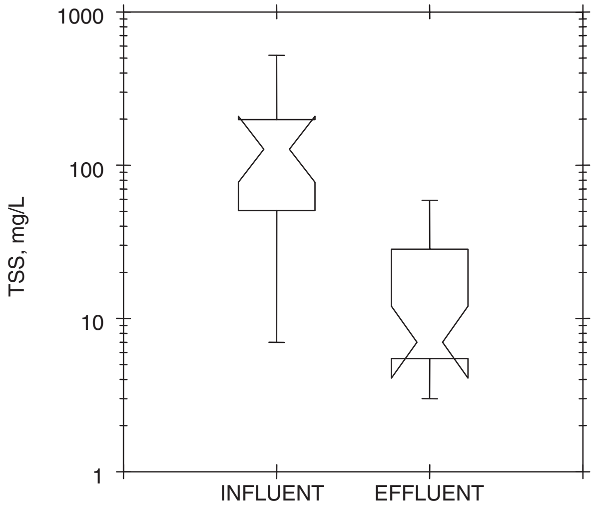


***Figure 8-11. Box plot comparison of influent and effluent EMCs for U.S. 183 TSS data.***

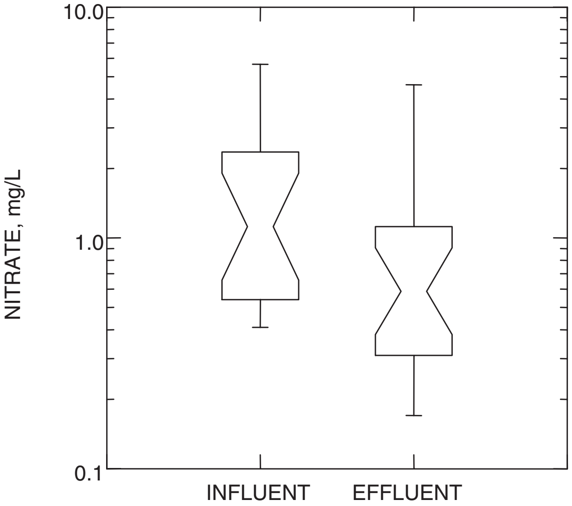


***Figure 8-12. Box plot comparison of influent and effluent EMCs for U.S. 183 nitrate data.***

Notched box and whisker plots for the three constituents of the U.S. 183 site are shown in Figures 8-11 through 8-13. The plots summarize inferences that may be made from the frequency distribution plots of the EPM. For instance, for influent TSS data, the lower quartile of about 50 mg/L and the upper quartile of about 200 mg/L may also be read off the EPM plot (see Figure 8-6). The lower confidence limit on the median for effluent TSS is less than the lower quartile, resulting in the reversal of the lines at the bottom of the box plot. Only the influent total zinc data have any data points (one) less than the lower inner fence (evidently a detection limit value).

Overlapping confidence intervals are an indication that medians are not significantly different. From the three box plot figures, it is to be expected that TSS and total zinc medians are significantly different, whereas it is not clear about nitrate medians. The performance of definitive tests is discussed in the next section. Because of the confidence interval presentation, it is generally easier to determine the significance of differences in medians from box plots than from the EPM plots, and the box plots nicely summarize the range of

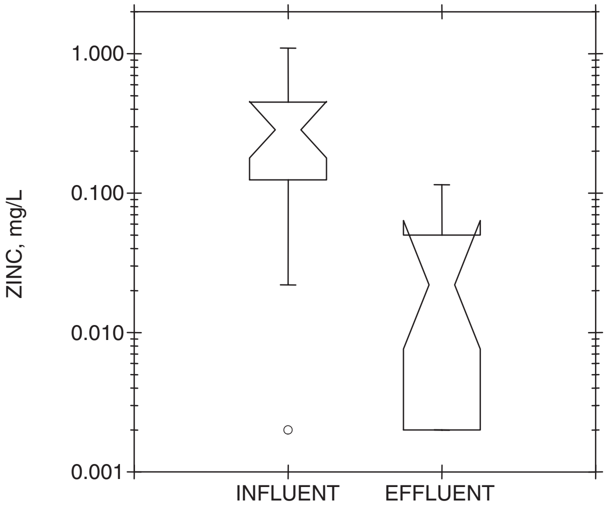


***Figure 8-13. Box plot comparison of influent and effluent EMCs for U.S. 183 total zinc data.***

data. Hence, box plots are used to concisely compare performance among BMPs in terms of effluent EMCs in the *Guidelines Manual*, Appendix A. On the other hand, the EPM plots show all data points and also illustrate the normality, or lack of it, of the data. EPM plots also give a better visual sense of the variance of the data. (When plotted with frequency on the abscissa and magnitude on the ordinate, a steeper slope means greater variance.)

### 8.5.5 Tests of Normality and Equality of Variance

One way to evaluate BMP performance is to determine whether there is a statistically significant difference between the means (or medians) of the data sets (e.g., between influent and effluent EMCs within this chapter or among different BMPs in Appendix A of the *Guidelines Manual*), beyond the qualitative evaluations made from the EPM plots and box plots. Selection of the appropriate test to assess these differences depends on the normality of the influent and effluent data sets, and, in some cases, on the equal variance of the two data sets. George (2004) summarizes several methods for evaluation of normality of the data (or their log transforms), two of which, the probability plot correlation coefficient (PPCC) method and the Shapiro-Wilk test, will be demonstrated in this section. In addition, three different variance tests (the Levene test, the Cochran test, and the Bartlett test) will be run on the individual *log-transformed* influent and effluent data sets for each constituent to test for equal variance.

Based on the R-values obtained for the least squares trend line, the PPCC test was conducted to test for normality of the log-transformed influent/effluent data for U.S.183 (Vogel 1986; Helsel and Hirsch 1992). The correlation coefficient is simply the square root of the $R^2$ value determined from the least squares trend line shown on the EPM plots (see Figures 8-6 through 8-8). The null hypothesis ($H_0$) is that the data are normally distributed, and failure to reject the null hypothesis means that the data set may be assumed to be normal. However, rejecting the null hypothesis does not *prove* normality especially for small sample sizes (Helsel and Hirsch 1992). A Type I error (probability of accepting a false hypothesis) significance level, alpha ($\alpha$, or often "p") of 0.05, is used for the normality assessment (Helsel and Hirsch 1992). Based on the sample size and alpha level, critical correlation coefficients can be obtained from tables provided by either Vogel (1986) or Helsel and Hirsch (1992) and compared to calculated correlation coefficients to determine whether or not to reject the null hypothesis. The PPCC test for normality maintains an advantage over other normality tests (Kolomogorov-Smirnov test and chi-square test) in that the probability plots may help to illustrate the results, and the test may be conducted over a continuous scale (Vogel 1986; Helsel and Hirsch 1992). George (2004) demonstrates the application of several methods for evaluation of the frequency distribution of EMCs.

As sample size increases, it is more difficult to show, based on the correlation coefficient, that the normal distribution cannot be rejected; this is because the critical correlation coefficient increases while the actual correlation coefficient may or may not increase with sample size. For instance, critical R values at the 95% level ($\alpha = 0.05$) range from 0.879 ($n = 3$) to 0.939 ($n = 15$) and higher (for higher sample size n). Therefore, with small data sets ($n < 25$), departures from normality must be large in order to reject the null hypothesis that the data are normally distributed (Helsel and Hirsch 1992).

Ranked data are inherently correlated, i.e., the ranked EMCs increase monotonically with the increasing standard normal variates (a function of increasing cumulative frequencies). The correlation embedded in this comparison is included in the PPCC significance test. The numerically derived critical values for the test reflect expected "spurious correlation."

In order to compare available normality tests, results of the PPCC test may be compared with the results of the commonly encountered Shapiro-Wilk normality test, available in the StatGraphics statistical computer program. The Shapiro-Wilk test also uses probability plots to determine correlation coefficients, which describe the regression between the actual data and their normal variates or z values (Helsel and Hirsch 1992). The principal difference between the Shapiro-Wilk and PPCC tests is that the former compares values of $R^2$ to critical values whereas the latter compares R-values. The StatGraphics program was used to compute Type I–error p-values for the log-transformed data for each constituent at each site, and the respective p-values were compared with the predetermined alpha value of 0.05. As in the PPCC test, in the Shapiro-Wilk test, if the p-value exceeds 0.05, then the null hypothesis that the data are normally distributed cannot be rejected; nonetheless, being unable to reject the hypothesis that the data are normally distributed does not ensure normality.

As shown in Table 8-7, the hypothesis that the data are normally distributed is confirmed for nitrate influent and effluent EMCs and for TSS influent EMCs. In order to use parametric tests to assess the difference between the means of two samples (influent and effluent), both the influent and effluent data sets must be normal; here, this is true only for nitrate. The Shapiro-Wilk results coincide with the PPCC results for these data, which is not necessarily the case with other data. When the two tests disagree, professional judgment (or other statistical tests) may be used to assess normality.

Although it is not always required, equal variance between two data sets is sometimes necessary for a number of parametric tests as well. Equal variance is not required for the parametric one-tailed t-test used in this report, but equal variance is used for other forms of the t-test. In order to compare the statistical verification of equal variance with the effluent probability plots (see Section 8.5.3), Table 8-8 contains the results of three different variance assessments: the Cochran's C test, the Bartlett test, and the Levene test, all included in the StatGraphics computer program. P-values that signify the correlation between influent and effluent data for each pollutant were compared with the alpha value of 0.05, and, if any of the three tests conducted calculated p-values lower than 0.05, there is a statistically significant difference among the standard deviations at the 95% confidence level (StatGraphics). Not surprisingly, on the basis of the EPM plots, the hypothesis of equality of influent and effluent log EMC variance is not rejected, for all three parameters.

**Table 8-7. Normality test comparison using the PPCC and Shapiro-Wilk tests.**

| **Normality Test Comparison**<br>Null hypothesis ($H_0$) =<br>data are lognormally distributed | **U.S. 183 Filter Strip** | |
|---|---|---|
| | Influent | Effluent |
| **Total Suspended Solids** | | |
| Sample Size (N) | 19 | 23 |
| Actual Correlation Coefficient R | 0.977 | 0.947 |
| Critical Correlation Coefficient R* | 0.949 | 0.956 |
| Alpha (α) | 0.05 | 0.05 |
| Shapiro Wilk P-value | 0.4284 | 0.0085 |
| *Reject Null Hypothesis (Y/N)* | | |
| PPCC Normality Test | N | Y |
| Shapiro Wilk Test | N | Y |
| **Nitrate** | | |
| Sample Size (N) | 19 | 22 |
| Actual Correlation Coefficient R | 0.972 | 0.976 |
| Critical Correlation Coefficient R* | 0.949 | 0.954 |
| Alpha (α) | 0.05 | 0.05 |
| Shapiro Wilk P-value | 0.1698 | 0.225 |
| *Reject Null Hypothesis (Y/N)* | | |
| PPCC Normality Test | N | N |
| Shapiro Wilk Test | N | N |
| **Total Zinc** | | |
| Sample Size (N) | 19 | 23 |
| Actual Correlation Coefficient R | 0.916 | 0.927 |
| Critical Correlation Coefficient R* | 0.949 | 0.956 |
| Alpha (α) | 0.05 | 0.05 |
| Shapiro Wilk P-value | 0.0058 | 0.0012 |
| *Reject Null Hypothesis (Y/N)* | | |
| PPCC Normality Test | Y | Y |
| Shapiro Wilk Test | Y | Y |

**Table 8-8. Results of the comparison of variance testing.**

| **Variance Assessments**<br>Null hypothesis ($H_0$) =<br>variance of logs is the same | **U.S. 183 Filter Strip** |
|---|---|
| **Total Suspended Solids** | |
| Alpha (α) | 0.05 |
| Cochran's C test (p-value) | 0.606 |
| Bartlett test (p-value) | 0.607 |
| Levene test (p-value) | 0.930 |
| *Reject Null Hypothesis (Y/N)* | N |
| **Nitrate** | |
| Alpha (α) | 0.05 |
| Cochran's C test (p-value) | 0.868 |
| Bartlett test (p-value) | 0.868 |
| Levene test (p-value) | 0.904 |
| *Reject Null Hypothesis (Y/N)* | N |
| **Total Zinc** | |
| Alpha (α) | 0.05 |
| Cochran's C test (p-value) | 0.885 |
| Bartlett test (p-value) | 0.886 |
| Levene test (p-value) | 0.287 |
| *Reject Null Hypothesis (Y/N)* | N |

## 8.5.6 Statistical Verification of EMC Differences

### *8.5.6.1 Overview*

In order to interpret qualitative EPM plots and box plots, parametric and/or nonparametric statistical tests may be used to determine whether a significant difference exists between the influent and effluent data sets (or among EMC data for different BMPs, etc.). Parametric tests typically require that the data be normally distributed and thus have either a normal or lognormal probability density function (PDF), as determined previously, and some tests may require that the variance of sample sets be the same and constant over a range of values (Burton and Pitt 2002). If parametric test requirements are met, parametric tests should be used because they have greater statistical power (Burton and Pitt 2002). Generally, nonparametric methods of determining distributions and processing data are used when normal or lognormal PDFs are determined not to be a valid method for describing the observed data because the data do not fit a particular distribution function or because the sample size was too small. Nonparametric methods may be used in cases in which the frequency distribution parameters of the variable of interest are not known (Helsel and Hirsch 1992) or when the influent and effluent data sets have different distributions. Helsel and Hirsch (1992) recommend performing both parametric and nonparametric tests for small sample sizes to protect against the potential loss of power of parametric tests when distributional requirements are not met.

The parametric test employed for the statistical analysis of the log-transformed data is the one-tailed t-test for unequal variance. This t-test does not necessarily require equal variance, although the hypothesis of equal variance of EMC logarithms is not rejected for the three data sets considered herein. The one-tailed t-test (as opposed to the two-tailed t-test) is deemed acceptable because the effluent concentration is predicted to be less than the influent concentration for all plots. The one-tailed t-test is used to assess the difference between the means for the one constituent, total zinc, for which the influent and effluent log-transformed data sets are both normal, based on the results of both the PPCC and Shapiro-Wilk tests. The nonparametric test employed to test the difference between the medians was the Kruskal-Wallis test, and this test was used on all site/constituent combinations.

### *8.5.6.2 One-Tailed t-test Results*

Results of the Excel version of the one-tailed t-test for unequal variance for the log-transformed nitrate data for U.S 183 in Austin are given in Table 8-9. The t-test assumes a null hypothesis that the means of the two groups of data are equal. It may be seen that the critical value for rejection of equality of means (p-value) is well below the predetermined value of alpha = 0.05. Hence, "removal" of nitrate by the filter strip is verified by the t-test, even though removal was questionable on the basis of the scatter plot, EPM plot, and box plots. This result is also confirmed by the nonparametric test described below.

### *8.5.6.3 Kruskal-Wallis Test Results*

Nonparametric methods of data analysis typically allow for processing of more random data and assume nothing is known about the frequency distribution of the data set (Helsel and Hirsch 1992). These methods do not rely on the estimation of parameters, such as mean and standard deviation, to assist in describing the distribution of variables. The Kruskal-Wallis nonparametric test will be illustrated for the three data sets. The rank-sum nonparametric test (Helsel and Hirsh 1992) could also be used when just two data sets are being compared, but the Kruskal-Wallis test (suitable for comparison of two or more groups of data) is very similar and more easily available in the StatGraphics software used in this study. The null hypothesis for the analysis is that the medians of the two data sets (influent and effluent EMCs) are equal. The results of the Kruskal-Wallis test are reported in Table 8-10 for a 95% significance level (alpha = 5%).

**Table 8-9. t-test results for natural log-transformed nitrate at U.S. 183 in Austin, TX.**

| Nitrate | Influent | Effluent |
|---|---|---|
| Mean | 0.174815 | –0.52241 |
| Variance | 0.711655 | 0.768261 |
| Observations | 19 | 22 |
| t Stat | 2.5842 | |
| P(T≤t) one-tail | 0.006810 | |
| t-critical one-tail | 1.684875315 | |

$H_0 = \mu(x) = \mu(y)$

**Reject Null Hypothesis**

#1 t critical < t stat

#2 P(one-tail) < 0.05

Equality of medians is rejected for all three constituents. Although equality of nitrate medians may not be rejected for many sites and BMPs, for these results, equality of medians is rejected and nitrate removal is confirmed by the Kruskal-Wallis test; however, the p-value for nitrate is much higher than the p-value for the other two constituents. A p-value > 0.05 would lead to acceptance of the hypothesis of equal medians and therefore no removal. The results of the Kruskal-Wallis test are consistent with the earlier t-test result as well. The bottom line for the three constituents monitored at U.S.183 in Austin and evaluated herein is that the filter strip BMP removes all three.

Other nonparametric tests, such as the Hodges-Lehmann test, are similar in character to the Kruskal-Wallis test (Helsel and Hirsch 1992) and have not been pursued further herein. Other graphical techniques are also available, such as quantile-quantile plots (Helsel and Hirsh 1992) for comparison of frequency distributions of two different data sets. Again, the reader may access the cited literature for further information on other comparison options.

## 8.5.7 Simulation of EMC Removal

Section 8.5 thus far has illustrated statistical methods of evaluating EMC data. However, in Section 8.7 of this chapter and Chapter10, the use of computer models to simulate highway runoff quality and BMP performance is discussed, in particular, the USEPA SWMM model. At this point, it is appropriate to discuss briefly the most common method for

**Table 8-10. Kruskal-Wallis test results for difference between the medians.**

| **Kruskal-Wallis Test**<br>Null hypothesis ($H_0$) =<br>medians of data sets are equal | **U.S. 183 Filter Strip** |
|---|---|
| **Total Suspended Solids** | |
| Alpha (α) | 0.05 |
| P-value | 5.60E-05 |
| *Reject Null Hypothesis (Y/N)* | Y |
| **Nitrate** | |
| Alpha (α) | 0.05 |
| P-value | 0.010693 |
| *Reject Null Hypothesis (Y/N)* | Y |
| **Total Zinc** | |
| Alpha (α) | 0.05 |
| P-value | 7.1E-06 |
| *Reject Null Hypothesis (Y/N)* | Y |

simulation of BMP quality treatment in SWMM and how this method might be adapted to produce frequency distributions similar to those observed earlier for the U.S. 183 filter strip. This discussion is based on three reports and papers by Huber et al. (2004, 2005, 2006).

Although it is not the only option available, the most straightforward method for treatment simulation in versions 4 and 5 of SWMM (Huber and Dickinson 1988; Rossman 2004) is the use of a conceptual continuous-flow, stirred-tank reactor, or CFSTR. Conceptually, the CFSTR represents all treatment or removal processes that act to reduce EMCs of constituents as they pass through the BMP (see Figure 8-14). This method does not account for beneficial losses of water by infiltration and ET, which act to reduce loads (product of flow × concentration), especially for LID facilities. However, SWMM simulation also accounts for storage changes during inflows to and outflows from the facility.

The main removal mechanism available with version 5 of SWMM (http://www.epa.gov/ednnrmrl/models/swmm/index.htm) is first-order decay, for which a CFSTR conceptualization (for constant volume, to simplify the explanation) is

$$C(t) = C_o e^{-kt} \tag{8-6}$$

where
$C(t)$ = effluent concentration,
$C_o$ = initial concentration,
$k$ = first-order decay coefficient (1/time), and
$t$ = hydraulic detention time.

In Equation 8-6, t (hydraulic detention time) is applied on a time-step basis in SWMM to reflect changes in concentration as a function of dynamic changes in inflow concentrations and other parameters. The point is that the only option for outflow concentration is to decrease toward zero; this would mean a reduction at every time step toward zero. However, as has been shown for U.S. 183 in Austin, some BMPs and constituents interact so that there is a limiting effluent EMC, or rather, a frequency distribution of effluent EMCs for which the concentrations do not approach zero and which remains relatively constant regardless of the influent EMCs. The U.S. 183 TSS and total zinc are excellent examples of this phenomenon. However, according to Equation 8-6, a CFSTR will always reduce concentrations. A solution to this dilemma recommended by Wong et al. (2002), for use in their MUSIC model and easily available in version 5 of SWMM, is to employ Kadlec and Knight's (1996) k-$C^*$ model for a CFSTR (The k-$C^*$ model is also available in the spreadsheet model of Heaney and Lee [2006], which was used extensively in this project),

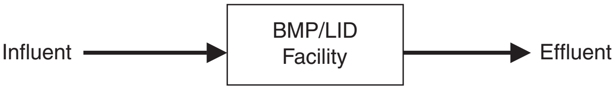


*Figure 8-14. Conceptualization of BMP/LID facility treatment.*

$$C_{out} = C^* + (C_{in} - C^*)e^{-kt} \tag{8-7}$$

where
$C_{out}$ = effluent concentration,
$C_{in}$ = influent concentration,
$C^*$ = minimum effluent EMC,
$k$ = first-order decay rate, and
$t$ = detention time.

Here, the concentration tends not toward zero but toward $C^*$, which can represent an "irreducible minimum" effluent concentration (Minton 2005). An advantage of this formulation is that concentrations downstream along a treatment train or series of removal locations cannot be reduced beyond the minimum $C^*$. Wong (2002) reports $C^*$ values for TSS for "sedimentation basins" = 30 mg/L, ponds = 12 mg/L, vegetated swales = 30 mg/L, and wetlands = 6 mg/L. Barrett (2004a, 2004b) reports values on the order of 20 mg/L for ponds and 20 to 50 mg/L for swales (the latter based largely on Caltrans studies). When the swale is designed with a filter strip component, e.g., as part of a highway embankment, primary removal in the filter strip–swale combination is usually via the vegetated filter strip. However, removal in swales alone also occurs by filtration and sedimentation when the flow depth is less than the height of the vegetation.

One other advantage of the k-$C^*$ model as an easy conceptualization of BMP treatment is that the $C^*$ value may be approached both from above (dirty inflow) and below (clean inflow). When SWMM is run on a time-step basis with widely varying influent concentrations, the simulated effluent EMCs trend towards a distribution about $C^*$ (Huber 2006). The limitation of the k-$C^*$ model is verifying that pollutant removal follows a first-order decay and then estimating the decay coefficient for the particular BMP.

## 8.6 Overall Hydrologic and Water-Quality Performance Estimation

### 8.6.1 Introduction

Evaluating the practicability of candidate BMPs requires consideration of several site-specific variables including expected performance for target pollutants, hydrology and hydraulics, surface and subsurface space availability, maintenance, costs, and aesthetics. Other factors include safety (see *Guidelines Manual* and *LID Design Manual*), regional constraints (see Chapter 7), and downstream impacts (see Section 10.2.3). Many such variables are discussed in Chapters 2 through 7. This section addresses in detail one of the most important practicability factors: treatment performance in terms of meeting hydrologic, hydraulic, and water-quality goals. A full practicability assessment for each candidate BMP, based on the various relevant factors, is presented in Chapter 6 of the *Guidelines Manual*. As many practicability factors are highly site-specific, not all factors that could be relevant are included. The design engineer should build on the information presented in previous chapters to account for site-specific conditions as much as possible. Estimating the treatment performance of a BMP requires an evaluation of (1) runoff volume reductions, (2) capture efficiency, and (3) expected effluent quality for target constituents.

## 8.6.2 Volume Reduction

There is certainly a basis for factoring in volume and resulting pollutant load reductions into performance estimates, particularly when TMDLs are involved. The infiltration capacity of the soil within or beneath a BMP influences volume reduction primarily through infiltration to subsurface and, combined with vegetation, ET. Soils with a high fraction of clays will prevent significant stormwater volume reductions because of their poor infiltration capacity. If stormwater volume reductions are a goal for a detention basin, soils can be amended to improve the capacity for infiltration. 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 from the next event.

It is expected that wet ponds and wetland basins or channels 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. If the soil has high infiltration capabilities, a liner will be necessary to maintain the water quality of the pool during the wet season. Because of the need to maintain a permanent wet pool for optimal pollutant removal in a constructed wetland, little volume reduction can be expected because of infiltration losses. However, volume reductions would be expected in biofilters because of drier, more-permeable soils and complete vegetative cover.

The limited study data available show an average volume reduction of 30% and 38% in dry detention basins and biofilters, respectively, while wet ponds (retention ponds) and wetland basins achieve an average volume reduction of 7% and 5%, respectively (see Table 8-11) (Strecker et al. 2004a, 2004b). Based on this analysis, detention basins (dry ponds) and biofilters (vegetated swales, overland flow, etc.) appear to contribute significantly to volume reductions, even though it is likely that they are not designed specifically for this purpose. Assuming a capture efficiency (discussed in Section 8.6.3) of 80%, a dry detention basin could be expected to reduce stormwater runoff volumes by about 25% on average. The actual volume reduction depends on the infiltration characteristics of the soils and local ET rates.

**Table 8-11. Volume losses in various BMPs.**

| BMP Type | 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 |
| Wetland Channels | 1.00 |

Source: Strecker et al. 2004a, 2004b.

## 8.6.3 Capture Efficiency

The capture efficiency (percent of stormwater runoff treated) of an on-line, volume-based BMP (e.g., detention facility) is primarily a function of the volume of the facility and the hydraulic design of the outlet structure (e.g., brimfull or half-brimfull emptying time of the detention facility). (This concept is also discussed in Chapter 10 of this report and Chapter 7 of the *Guidelines Manual.*) A properly designed, storage-based BMP should generally result in capture efficiencies satisfying regulations (e.g., on the order of 70 to 90% of the long-term flows from the watershed). Untreated stormwater runoff volumes that bypass the detention facility will therefore generally be less than 30% of the runoff volume, ideally on the order of 10 to 20%.

For volume-based BMPs, the bypassed, untreated flows occur most often from the tail end of the storms. Depending on the pollutant and the runoff characteristics of the watershed, these bypasses will frequently have lower pollutant concentrations because the majority of accumulated pollutants are discharged earlier in the storm. This higher pollutant loading at the beginning of a storm event is referred to as the first-flush effect (see Sections 4.4 and 6.4). However, for many pollutants and under the varied rainfall conditions found seasonally and geographically around the United States, a first-flush effect may not exist. First flush is frequently oversimplified for the complex phenomena of pollutant source loading to runoff.

**Design volume (depth).** In the simplified sizing approaches frequently used in regulatory environments, the design depth (inches) is the depth of runoff over the catchment that results in a runoff volume equivalent to the storage design volume of a detention basin. The runoff volume for the tributary area is a function of the watershed size and runoff coefficient; the runoff coefficient is a function of the impervious fraction and soil type(s) in the tributary area to the basin. Larger design depths result in a larger percentage of the stormwater runoff captured by the basin. However, as design depths become excessively large, only marginal improvements are gained. Given that drain time criteria remain constant, very large design depths are undesirable because the smaller, more frequent storms will pass quickly through the basin without receiving sufficient detention time for sedimentation to occur (see Section 10.2 and *Guidelines Manual* Chapter 7). A proper design depth provides nearly complete treatment of smaller, more frequent storms and captures significant portions of larger storms. Continuous simulation screening results are provided in the *Guidelines Manual*, Appendix C; these results show percent capture versus design depths for 30 locations in the United States.

**Drawdown rate.** The drawdown rate is the average outflow rate (cfs) at which a detention facility is emptied. Often the upper third of the detention basin is emptied in half of the detention time (from full pool), while the lower two-thirds is emptied in the remaining detention time. This scenario creates storage capacity quickly for the next storm event, if the next storm occurs before the basin is completely empty (storm interevent times are typically within 24 hr or between 24 and 48 hr). Slower drawdown of the lower half of the pool promotes effective treatment for smaller storm events that would not completely fill the detention basin. Typical detention times to achieve sedimentation and removal of associated pollutants range from 24 to 72 hr. Shorter detention times (e.g., 24 hr) create storage volume more quickly, resulting in a higher capture efficiency, but do not allow as much time for sedimentation. An appropriate detention time should be determined on the basis of the expected particle size distribution in stormwater runoff and typical storm interevent times. Longer detention times are appropriate for treating runoff with a large fraction of fine particles. Shorter detention times are more appropriate for stormwater runoff with fewer fines, or in areas with storms that occur in series with short interevent times. These trade-offs are discussed in Chapter 10 of this report and Chapter 7 of the *Guidelines Manual*. A maximum drain time of 36 hr from a brimfull condition is often an appropriate compromise between the removal efficiency of particles and capture efficiency of stormwater runoff volumes. Drawdown at maximum is the seasonal mean time between precipitation events in a watershed.

**Flow rate.** Flow-based treatment systems, such as most swales, are frequently sized on the basis of the calculation of a peak-flow estimate derived from a design event, unit hydrograph, or rainfall/runoff model. One major disadvantage of flow-based design is that it does not normally account for the volume of the runoff hydrograph. A flow-based system is best sized to capture a required runoff volume (say 80%) by methods presented in Section 10.3, summarized as follows:

1. Plot the historical or simulated hydrograph for its full-time base of months or years.
2. Choose a range of flow rates (represented by horizontal lines on the hydrograph).
3. Integrate along the hydrograph to find the volume beneath each flow rate (beneath each horizontal line). Convert the volume to percent of total volume under the hydrograph. This percentage is the percent of runoff volume treated by (runoff flowing through) the device at a given maximum inflow rate.
4. Plot flow rate versus percent runoff volume captured, as in Figure 10-17.

The plot yields the particular inflow rate necessary to treat a specified percent runoff volume (e.g., 80%) and vice versa. Based on this runoff hydrograph analysis, the flow-based system could then be sized for the flow rate that would capture the runoff volume to be treated. Flow-based treatment systems are evaluated in Appendix C of the *Guidelines Manual* for 30 locations in the United States.

## 8.6.4 Pollutant Removal

### *8.6.4.1 Summary Data*

Median effluent quality for various BMPs is shown in Table 8-12 for common target constituents. The data are from the International BMP Database (www.bmpdatabase.org). Data summaries by typical stormwater pollutants are also provided in the pollutant fact sheets (see Appendix A of the *Guidelines Manual*). The degree of pollutant removal, of course, depends on the pollutant species/form and the extent to which appropriate unit operations occur within the treatment system. In addition, design features such as pond depth or use of a forebay can significantly affect effluent quality.

### *8.6.4.2 Suspended Solids*

Larger suspended solids can be removed effectively by gravitational sedimentation, screening, or surficial straining. For most well-designed BMPs that incorporate these unit operations, the median effluent concentrations range from 20 to 25 mg/L, provided the concentration and characteristics (e.g., particle size distributions) of influent suspended solids

**Table 8-12. Median of average effluent concentrations of BMPs.**

| Constituents | Detention Pond | Wet Pond | Wetland Basin | Biofilter | Media Filter | Hydrodynamic Devices |
|---|---|---|---|---|---|---|
| Suspended Solids | 41.35*<br>(30.8–55.5) | 19<br>(12.9–28.0) | 19.68<br>(16.6–23.4) | 24.6<br>(15.0–40.3) | 25.47<br>(14.7–44.3) | 40.34<br>(18.4–88.7) |
| Total Cadmium | 1.3<br>(0.8–2.2) | 0.31<br>(0.05–2.0) | xx** | 0.25<br>(0.21–0.34) | 0.31<br>(0.16–0.59) | 1.65<br>(1.05–2.6) |
| Dissolved Cadmium | 0.41<br>(0.22–0.76) | xx | xx | 0.22<br>(0.11–0.43) | 0.24<br>(0.18–0.33) | 0.93<br>(0.27–3.2) |
| Total Copper | 18.9<br>(16.6–21.5) | 6.92<br>(4.7–10.3) | xx | 10.01<br>(5.6–17.9) | 9.81<br>(8.1–11.8) | 14.13<br>(11.1–18.1) |
| Dissolved Copper | 14.72<br>(10.4–20.9) | 5.09<br>(3.1–8.3) | xx | 7.66<br>(4.7–12.5) | 7.95<br>(6.6–9.7) | 8.63<br>(3.3–22.9) |
| Total Chromium | 2.85<br>(1.7–4.8) | 1.78<br>(0.5-6.7) | xx | 2.18<br>(1.2–4.0) | 1.46<br>(0.9–2.3) | xx |
| Total Lead | 15.02<br>(9.5–23.8) | 6.68<br>(2.9–15.6) | 3.25<br>(1.9–5.6) | 6.95<br>(4.2–11.7) | 5.5<br>(3.5-8.6) | 12.98<br>(4.2–40.2) |
| Dissolved Lead | 2.33<br>(1.7–3.3) | 4.16<br>(2.0–8.9) | xx | 1.35<br>(0.5–3.6) | 1.42<br>(1.0–1.9) | 2<br>(0.6–6.5) |
| Total Zinc | 85.26<br>(50.6–143.7) | 28.63<br>(21.4–38.3) | 118.73<br>(32.8–429.5) | 39.44<br>(28.2–55.2) | 64.96<br>(45.3–93.2) | 89.66<br>(74.4–108.1) |
| Dissolved Zinc | 43.99<br>(20.0–96.6) | 16.89<br>(2.6–109) | xx | 31.96<br>(26.7–38.3) | 57.14<br>(37.7–86.6) | 45.17<br>(29.6–68.9) |
| Total Phosphorus | 0.3<br>(0.2–0.44) | 0.16<br>(0.12–0.21) | 0.15<br>(0.07–0.33) | 0.32<br>(0.24–0.43) | 0.14<br>(0.11–0.17) | 0.19<br>(0.07–0.51) |
| Dissolved Phosphorus | xx | 0.07<br>(0.04–0.13) | 0.07<br>(0.03–0.18) | xx | xx | xx |
| Total Nitrogen | xx | 1.17<br>(0.77–1.78) | 2.42<br>(1.46–4.0) | 0.69<br>(0.37–1.29) | xx | xx |
| Nitrate-Nitrogen | 0.64<br>(0.37–1.09) | 0.48<br>(0.11–2.05) | 0.46<br>(0.16–1.28) | 0.5<br>(0.36–0.68) | 0.82<br>(0.68–0.97) | xx |
| Total Kjeldahl Nitrogen | 1.87<br>(1.46–2.39) | 0.84<br>(0.68–1.04) | 1.33<br>(0.84–2.11) | 1.6<br>(1.42–1.8) | 1.79<br>(1.45–2.2) | 4.68<br>(1.97–11.12) |

* All units in mg/L; values in parentheses are the 95% confidence intervals about the median.
** xx = lack of sufficient data to report median and range.
Source: International Stormwater BMP Database (http://www.bmpdatabase.org/).

do not significantly deviate from typical stormwater. Well-designed treatment systems that incorporate wet pools and wetland vegetation typically exhibit good effluent quality for suspended solids. Available data suggests that these BMPs can typically achieve effluent concentrations of around 20 mg/L. Well-designed biofilters and media filters also perform well in achieving low concentrations of effluent suspended solids.

The presence of a permanent wet pool is a feature of a wet pond/wetland system. Incorporating even a small permanent wet pool can significantly improve the sediment removal performance of a BMP by providing long periods of retention during smaller storms. Long retention times during small events allow for appreciably more sediment removal than dry facilities that typically have very limited detention times during small events. Generally, settleable solids composed of inorganic particles in the 25- to 75-μm range are effectively removed by quiescent gravitational sedimentation.

For biofilters and media filters, gravity settling and filtration are the primary removal mechanisms for suspended sediments. Direct filtration can usually be effectively accomplished at concentrations less than 50 mg/L, but generally requires some level of pretreatment in urban runoff, in which solids concentrations are frequently above 100 mg/L and can exceed 1,000 mg/L depending on the site, loading, and hydrology. Generally, suspended inorganic particles less than 25 μm require some natural or enhanced coagulation/flocculation followed by sedimentation and/or filtration.

Available data suggest that TSS effluent concentrations are significantly higher (i.e., the quality of the effluent is poorer) for dry detention basins (which drain after each event and generally lack a significant littoral zone) and hydrodynamic BMPs (flow-through systems that rely on centrifugal forces to provide treatment). However, as noted, dry detention basins have been shown to provide considerable reduction in effluent volume (up to 30%), which may translate into lower total mass loading of TSS downstream.

#### *8.6.4.3 Trace Metals*

The important forms of trace metals from a treatability and regulatory perspective are total, dissolved, and particulate-bound metals. If trace metals are bound to organic or inorganic particulates, viable unit operations include sedimentation and filtration either as unit operations separate from coagulation/flocculation or in combination with coagulation/flocculation as pretreatment to these operations. If trace metals are present as a dissolved complex, precipitation could be effective. If trace metals are present as a dissolved ionic species such as $Cu^{2+}$, $Pb^{2+}$, or $Zn^{2+}$, surface complexation (including adsorption) could be effective. Well-designed wet ponds, biofilters, and media filters can provide better effluent quality than detention ponds and hydrodynamic devices (see Table 8-12). BMPs that are effective in removing trace metals also are typically good at removing fine particulates.

#### *8.6.4.4 Nutrients*

Treatability for phosphorus is a function of whether phosphorus is present in particulate or dissolved form. In dissolved form, phosphorus may readily undergo surface complexation reactions, sorption, or precipitation (see Section 4.4.5). Uptake by vegetation and microbes is another mode by which dissolved phosphorus is effectively removed. Media or soils containing iron, aluminum, or hydrated portland cement can be very effective at removing dissolved phosphorus species through surface complexation or precipitation. If phosphorus is bound to organic or inorganic particles, viable unit operations include sedimentation and filtration either alone or in combination with pretreatment using coagulation/flocculation.

As shown in Table 8-12, media filters, wet ponds, and wetland basins report the lowest median effluent concentrations of total phosphorus, although only wet ponds show a statistically significant difference between median influent and effluent values (i.e., the BMP affected total phosphorus concentrations). Although median effluent levels for dissolved phosphorus are the lowest for wetland basins, the available data are insufficient to reliably differentiate the performance of various BMPs.

Nitrogen compounds exist in dissolved form and as particulate-bound species. Treatability success for nitrogen species, as with other constituents in stormwater, is highly dependent on the form and species of nitrogen present. Treatability for nitrogen also depends on the presence of specific bacteria that mediate nitrogen transformations. Physical operations such as sedimentation have played an insignificant role with respect to treatment of nitrogen as compared with microbially mediated transformations. Microbial decomposition of organic matter mineralizes nitrogen as ammonia, which can be oxidized to nitrite and nitrate. Nitrate can be reduced to nitrogen gas by anaerobic bacteria for complete removal from the system. Median effluent quality of total nitrogen, TKN, and nitrate-nitrogen are summarized in Table 8-12. However, available data on removal of nitrogen species are insufficient to draw definitive conclusions about BMP performance based on average effluent concentrations.

Filters, ditches, and dry ponds typically exhibit poor nitrate removal and, in many cases, have been shown to export nitrate. In these BMPs, organic nitrogen is converted to nitrate in the mineralization and nitrification processes; however, the aerobic conditions are not favorable for denitrification. Thus, these BMPs may export more nitrate than is present in the influent. Conversely, in wet ponds and wetland basins, plants, algae, and other microorganisms take up nitrate as an essential nutrient. However, nitrogen is also released back into the system upon death or decay of the organisms.

## 8.7 Methodology Options Using Process Simulation Models

Simulation models provide an opportunity to analyze details of several BMP options, including treatment trains and the ability of some BMPs to evapotranspire and/or infiltrate runoff. For example, the Storage/Treatment Block of version 4 of SWMM (Huber and Dickinson 1988; Roesner et al. 1988) contains a process-oriented approach for evaluating the effectiveness of BMPs. (This is demonstrated in Chapter 7 of the *Guidelines Manual* and discussed in Section 8.5.7.) All treatment systems employ some mix of physical, chemical, and biological processes to achieve some effluent quality and/or removal efficiencies. For wet-weather controls, many of the BMPs include temporary storage of stormwater. When stormwater is stored temporarily, it is vital to include in the analysis the dynamics of the filling and emptying of these devices because these have a major impact on the amount of runoff treated and removal efficiencies. For example, detention time is difficult to estimate because it depends on the mixing regime (e.g., CFSTR or plug flow) and how the outlet control is operated (e.g., drawdown regime). In addition, some of the stormwater detained in a pond in a warm, arid area of the country may evaporate before the next storm event, thereby increasing the overall performance of the BMP. An infiltration system may receive irrigation water between storm events, thereby reducing its ability to infiltrate runoff during the next storm event.

Simulation models also allow one to evaluate a long-term rainfall record to assess how much stormwater is treated by the BMP and how much is bypassed or processed by the BMP at the lower, water-quality design flow rate, and the higher, flood control rate at which higher flows (and resulting short detention times) will result in minimal or ineffective treatment. For example, swales are not effective at flow rates above a certain level (often the flow rate that results in a flow depth which covers the vegetation). Any flows with rates above the design flow rate should be considered as a "bypass" during a BMP performance analysis. Thus, evaluations of the performance of a BMP must take into consideration how much of the rainfall record is treated, controlled, or eliminated. An additional option for simulation of the rainfall record for these kinds of evaluations is the spreadsheet model of Heaney and Lee (2006).

Various SWMM components allow the user to perform continuous simulations over extended periods of time in order to integrate treatment process and hydraulic dynamics. Heaney and Nix (1979) summarize the basic ideas behind this approach. Medina et al. (1981a, 1981b) present a more complete description of the process dynamics for doing continuous simulation. Nix (1982) presents a comprehensive evaluation of statistical and process-oriented approaches for evaluating storage-release systems. Goforth et al.(1983) compare a process simulator with a statistical approach for estimating BMP performance. Nix and Heaney (1988) describe how to optimize the size and release rate of stormwater control devices. Finally, Nix et al. (1988) describe a more detailed process approach for evaluating suspended solids removal by relating it to particle sizes and detention times. In addition to using the Storage/Treatment Block of version 4 of SWMM, Huber (2001) and Huber et al. (2006) show how the performance of many of the BMPs can be simulated using the Runoff Block of version 4 of SWMM. The newest version of SWMM is version 5, which was developed with a graphical user interface by the USEPA (www.epa.gov/ednnrmrl/models/swmm/index.htm; Rossman 2004). In general, version 5 of SWMM is much easier to use than version 4; however, version 5 lacks some version 4 functionality, specifically the ability to simulate sedimentation using sedimentation theory with a plug flow assumption. Versions 4 and 5 of SWMM applications are outlined in Chapter 10 of this report and presented in detail in Chapter 7 and Appendix E of the *Guidelines Manual*.

Continuous simulation modeling is an important tool in assessing BMP performance. A number of efforts have improperly applied flood design hydrology approaches to substantiate hydraulic performance (Strecker et al. 2001). SWMM is far from the only continuous simulation tool available; the Hydrologic Simulation Program—Fortran (HSPF) (Bicknell et al. 1997) is an example of a very widely used model for simulation of runoff and water quality from rural and urban watersheds. Another widely used model (for hydrology only) is the well-known HEC-HMS model (www.hec.usace.army.mil/), which can also be used for long-term, period-of-record (i.e., continuous) simulation. Model choice (also discussed in Section 10.5.2) is based on model capabilities and often on user familiarity. Both factors led to the use of SWMM in this project.

CHAPTER 9

# BMP Selection Guidance Methodology

## 9.1 Introduction

The BMP selection and conceptual design methodology presented in this report is driven by well-defined stormwater management goals and a solid understanding of site characteristics, constraints, and water-quality conditions. As opposed to other design approaches that recommend the selection of typical BMPs based solely on documented performance factors such as percent removal, effluent quality and/or percent capture, the approach presented herein is to first select the unit treatment processes that address the pollutants of concern and stormwater management goals and then individually select the components of a BMP treatment system based on those unit processes. The steps of the BMP selection and conceptual design methodology include the following: (1) problem definition, (2) site characterization, (3) identification of fundamental process categories, (4) selection of BMPs, LID elements, and other treatment options, (5) practicability assessment of candidate treatment systems, (6) sizing the conceptual BMP design, and (7) development of a performance monitoring and evaluation plan. The sections that follow briefly describe each component of the methodology; these components are presented in detail in the *Guidelines Manual*. At the end of Chapter 9, the methodology is summarized in a detailed flow chart in Figure 9-1 (chapter and section numbers in Figure 9-1 refer to the *Guidelines Manual*).

## 9.2 Problem Definition

The design of any engineering system requires a clear definition of the problem. Without clear descriptions of the highway runoff issues that need to be addressed at a particular site, including the desired results, it is difficult (if not impossible) to evaluate the steps needed to select and design a practicable and cost-effective runoff treatment system. Typical stormwater objectives in urban and highway areas are listed in Table 9-1. The title of the table, "Urban runoff management objectives checklist," reflects the fact that runoff can be generated from several sources not directly connected to rainfall, such as baseflow, car washing, etc. Hence, stormwater control must be integrated with overall urban or highway runoff control.

The problem definition should include a detailed description of the overall project, including whether the project is solely a stormwater retrofit project or is part of a larger highway-improvement or construction project. All project objectives (including those unrelated to stormwater) should be carefully identified and ranked. Since project objectives often conflict (e.g., water quality and flood control, cost, and safety), clearly defining the relative importance of these objectives is essential to the coordination of planning and design activities among the various project managers, subcontractors, and stakeholders. A worksheet template for such an evaluation is included in Appendix D of the *Guidelines Manual*.

## 9.3 Site Characterization

After the project has been described and the objectives identified, the next step in any highway construction, improvement, or retrofit project is to characterize the site conditions and constraints. This step is critical for the assessment and identification of feasible solutions to the runoff management problem. Site conditions may significantly influence the treatability and manageability of highway runoff. With careful characterization of the hydrologic, geologic, and anthropogenic factors that affect runoff quantity and quality, appropriate and feasible selection and design alternatives can begin to be identified. Assessing site characteristics should involve identifying opportunities and, to a certain extent, constraints that influence the selection and design of highway runoff treatment systems. Opportunities for incorporation of LID techniques that emphasize pollutant source control through infiltration, interception, ET, and reduction of directly connected impervious area should also be identified when characterizing the site conditions. The highway engineer must

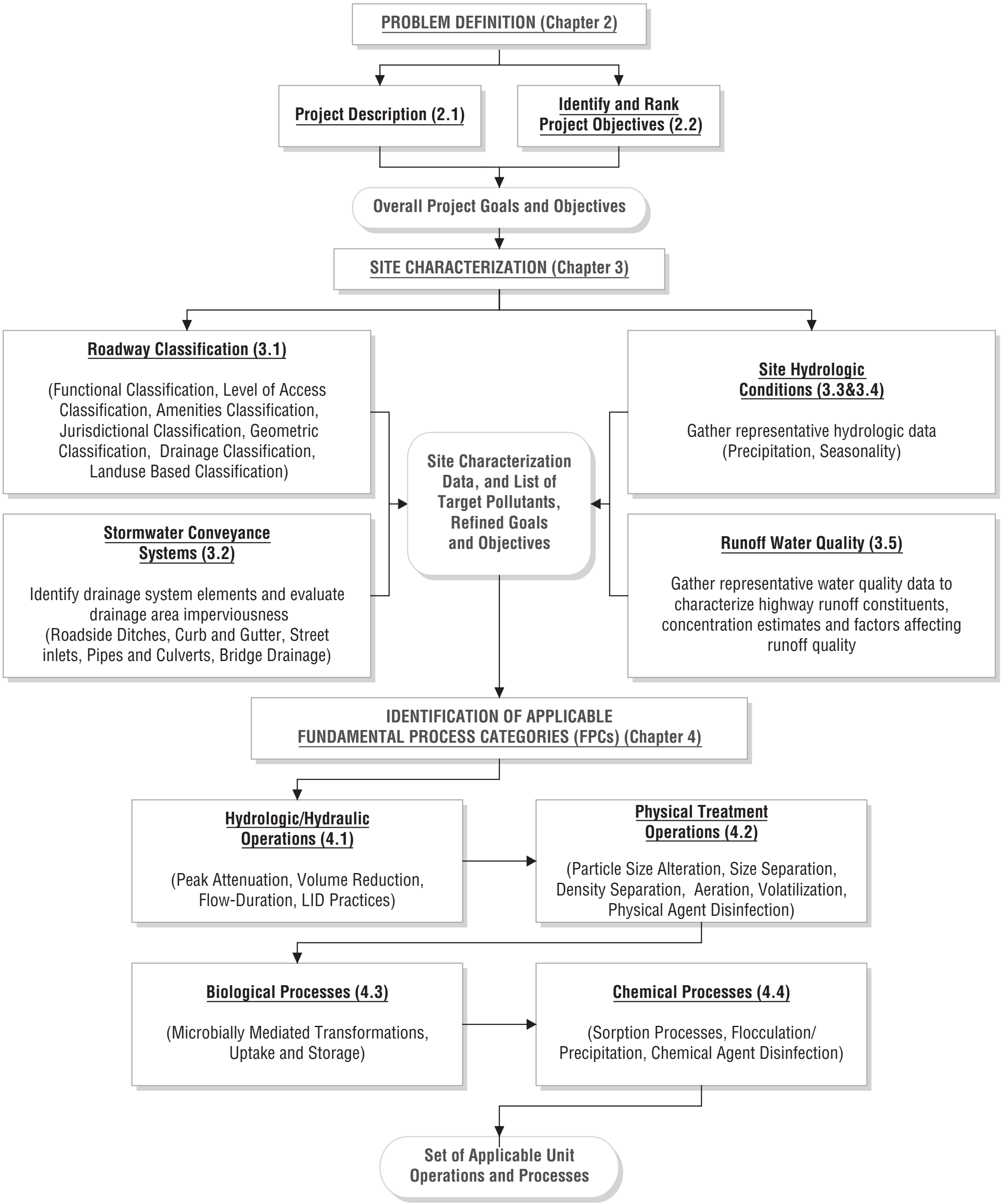


***Figure 9-1. Conceptual stormwater treatment system design methodology flow chart.***

be open to alternative designs that do not significantly alter the safety or structural integrity of the project.

## 9.4 Identification of FPCs

After site conditions, constraints, and influent water quality and hydrology have been determined and/or estimated, the unit processes that are available to reduce or treat the pollutants of concern should be identified and qualitatively ranked on a scale according to how well those processes reduce runoff volumes/rates or treat the pollutants of concern. Site-specific information on soils and associated infiltration rates is especially critical because of their high variability and their importance as major components of LID.

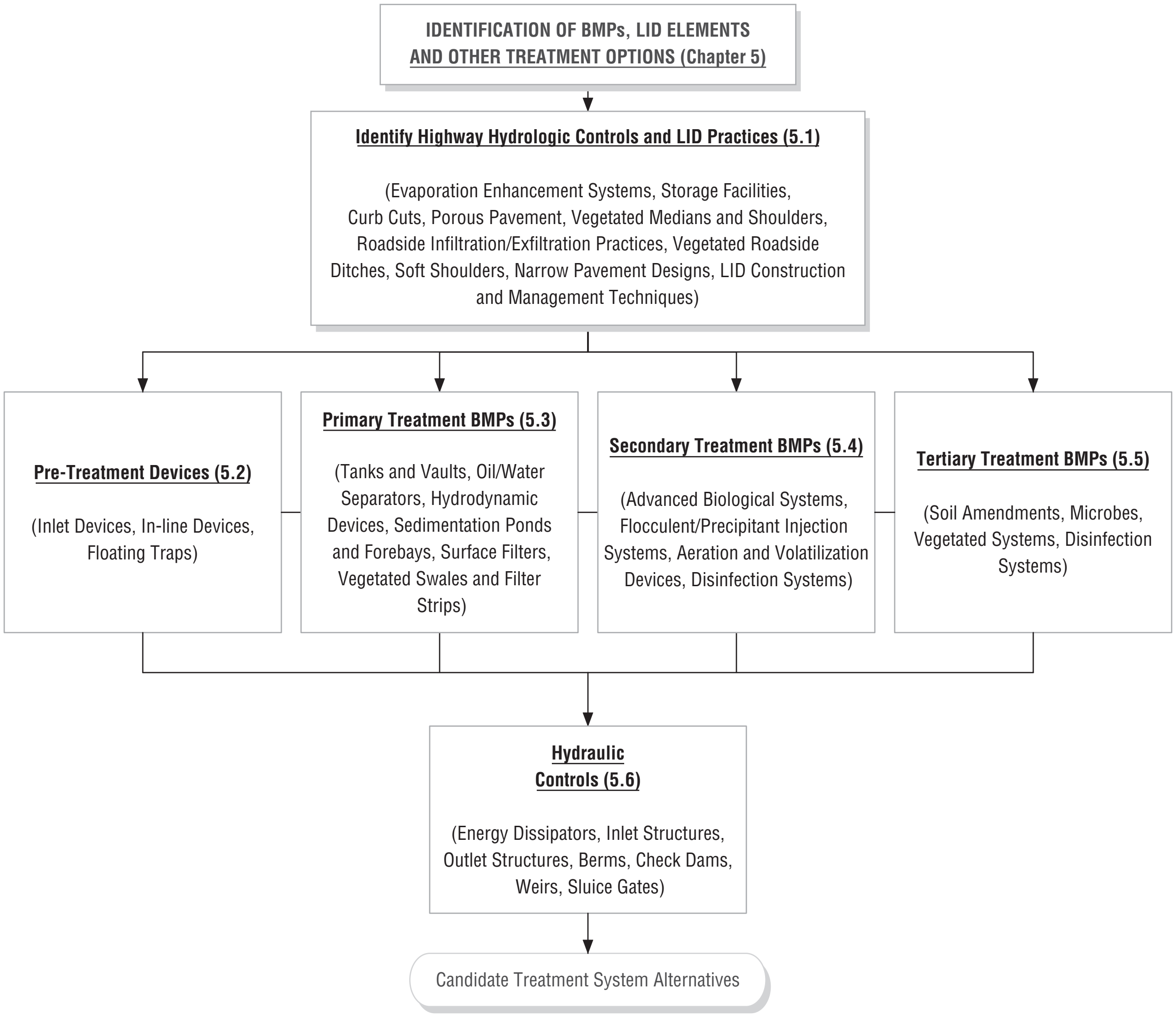
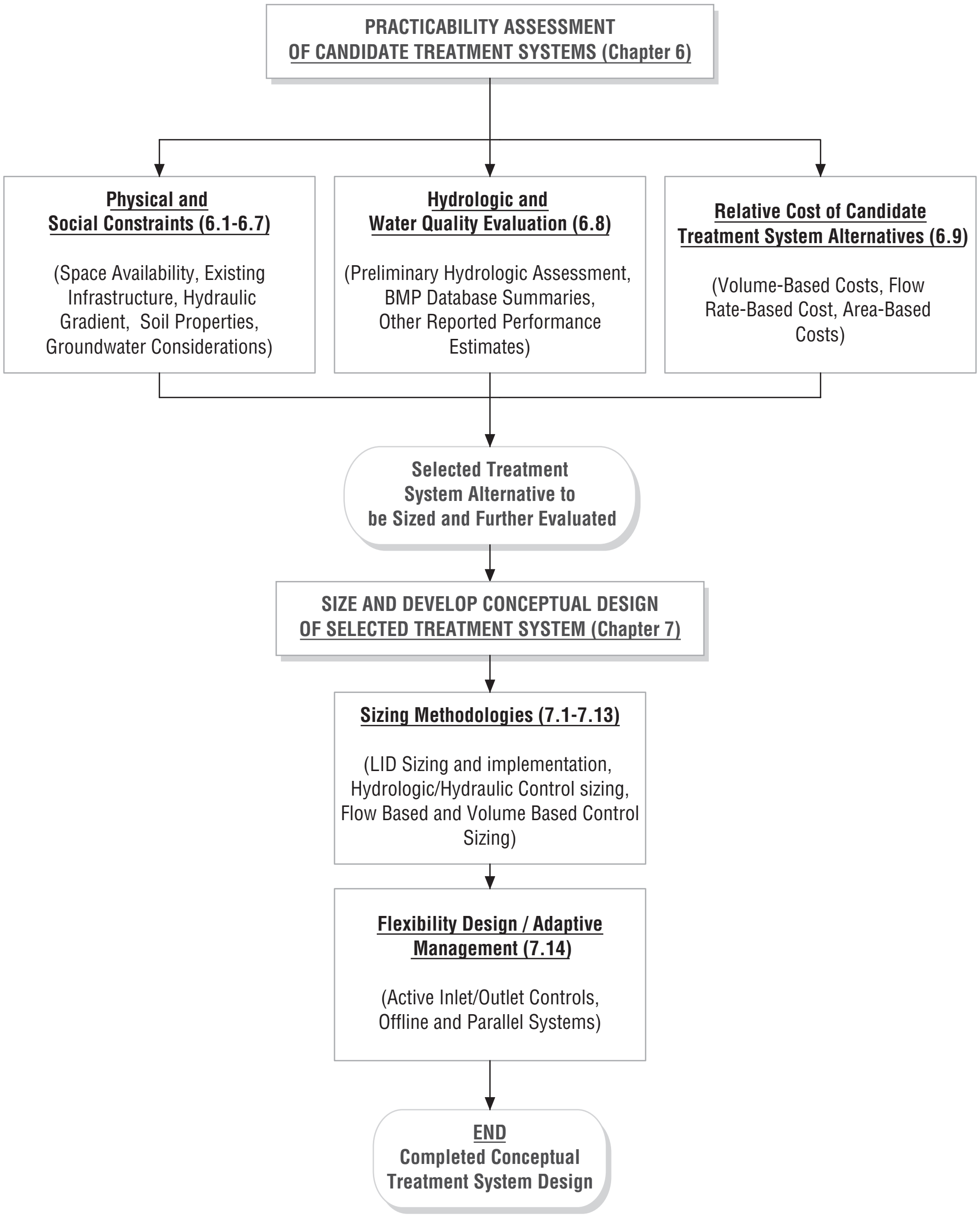


***Figure 9-1. (Continued).***

Many unit treatment processes applicable to stormwater treatment have been previously developed in the fields of water and wastewater engineering. UOPs can be divided according to four FPCs (see Sections ): (1) hydrologic operations, (2) physical operations, (3) biological processes, and (4) chemical processes. Hydrologic operations, which are essentially a subset of physical operations, include the principles of flow attenuation (e.g., peak shaving and detention) and volume reduction (e.g., infiltration and ET). These are the two fundamental principles of LID. Physical operations, as referred to in this report, include the principles of particle size alteration (e.g., comminution), size separation and exclusion (e.g., screening and filtration), density separation (e.g., sedimentation and flotation), aeration and volatilization, and natural disinfection (e.g., ultraviolet light and heat). Biological processes include the principles of microbially mediated transformations (e.g., redox reactions resulting from microbial respiration) and uptake and storage (e.g., bioaccumulation). Chemical processes include the principles of sorption (e.g., ion exchange and surface complexation), coagulation and flocculation (e.g., particle agglomeration and precipitation), and chemical agent disinfection (e.g., chlorine and ozone). The selection of any one of these UOPs should be based on the characteristics of the target pollutants in relation to specific stormwater management goals. Such a characterization is presented for a variety of pollutants in the pollutant fact sheets in Appendix A of the *Guidelines Manual*.

## 9.5 Selection of BMPs, LID Elements, and Other Treatment Options

Once the UOPs available for addressing the runoff management goals have been identified, individual BMPs, LID facilities, and other BMP treatment systems can be selected. Some BMPs may include a higher level of runoff treatment or control than other BMPs, so it is important to understand, at



Note: Chapter and section numbers refer to the *Guidelines Manual*.

***Figure 9-1. (Continued).***

least at a fundamental level, the relationship between BMP design and UOPs. With an understanding of the physical (including hydrologic), biological, and chemical processes that typically occur in stormwater BMPs, supported by BMP performance monitoring data, candidate BMPs can be compared and selected. If a single BMP does not provide all of the desired UOPs, then a BMP treatment system or treatment train may need to be developed. Table 5-1 in the *Guidelines Manual* provides a mapping of FPCs, UOPs, associated pollutants, and common stormwater BMPs. An examination of this table reveals that several BMPs and combinations of BMPs may provide similar levels of stormwater treatment and control. Therefore, the next step is to consider the project constraints and site conditions that may favor one BMP alternative (or BMP combination) over another.

## 9.6 Practicability Assessment of Candidate Treatment Systems

Once alternative BMPs or BMP/LID systems have been selected, the practicability of implementing each alternative should be considered. Determining the practicability of

**Table 9-1. Urban runoff management objectives checklist.**

| Category | Typical Objectives of Urban Runoff Management Projects |
|---|---|
| Hydraulics | Manage flow characteristics upstream, within, and/or downstream of treatment system components |
| Hydrology | Mitigate floods; improve runoff characteristics (peak shaving) |
| Water Quality | Reduce downstream pollutant loads and concentrations of pollutants |
| | Improve/minimize downstream temperature impact |
| | Achieve desired pollutant concentration in outflow |
| | Remove litter and debris |
| Toxicity | Reduce acute toxicity of runoff |
| | Reduce chronic toxicity of runoff |
| Regulatory | Comply with NPDES permit |
| | Meet local, state, or federal water quality criteria |
| Implementation | Function within management and oversight structure |
| Cost | Minimize capital, operation, and maintenance (life cycle) costs |
| Aesthetic | Improve appearance of site and avoid odor or nuisance |
| Maintenance | Operate within maintenance and repair schedule and requirements |
| | Design system to allow for retrofit, modification, or expansion |
| Longevity | Achieve long-term functionality |
| Resources | Improve downstream aquatic environment/erosion control |
| | Improve wildlife habitat |
| | Achieve multiple-use functionality |
| Safety, Risk, and Liability | Function without significant risk or liability |
| | Function with minimal environmental risk downstream |
| | Contain spills |
| Public Perception | Clarify public understanding of runoff quality, quantity, and impacts on receiving waters |

candidate BMPs for a site is not a decision based specifically on performance or hydrologic measures, but rather on feasibility of design, installation, and implementation. A variety of factors exist that must be taken into account by engineers when initially selecting a particular BMP system design to pursue, including performance for target pollutants, hydrology and hydraulics, surface and subsurface space availability, maintenance, costs, and aesthetics. Other factors include safety, regional constraints, downstream impacts, land use allocations, safety and human health concerns, regional and climatic concerns, and overall project budget (cost considerations). Most of these factors are discussed in Chapters 5, 6, and 7 of this report. Each BMP alternative should be evaluated according to these practicability factors, and at least one alternative should be selected for preliminary sizing. Such factors are included in practicability assessment tables in Appendix D of the *Guidelines Manual*.

## 9.7 Sizing the Conceptual BMP Design

The design of a selected BMP treatment system must address the project goals and objectives as well as the design requirements of the regulating authority. Several methods exist for hydrologic design including the following: flow-attenuation design, volume-reduction design, and flow-duration design. Flow attenuation, also referred to as peak shaving, is typically achieved with storage and controlled release, but increasing the flow path may also be feasible. Volume reduction is possible through infiltration and ET, both of which are highly dependent on site-specific conditions including soils, vegetation, and climate. Flow duration seeks to reduce both the magnitude and the time period of flow by incorporating the principles from flow attenuation and volume reduction. The applicability of any of these design methods depends on whether the system is volume-based, such as detention basins, or flow-based, such as swales. These facilities can be sized using a hierarchy of procedures including simple design storm approaches, rainfall frequency analyses, and continuous runoff simulation. Continuous simulation is generally the preference for water-quality-based design because it permits optimization for design on the basis of minimum cost, minimum downstream discharge, minimum downstream pollutant load, and a variety of other possibilities using a long-term hydrologic record that is presumably representative of the life of the BMP. This may be done heuristically with models such as SWMM or in a more integrated fashion (i.e., incorporating optimization) with spreadsheet models. The continuous simulation approach is described in Chapter 10 of this report and in Chapter 7 of the *Guidelines Manual*. Continuous simulations can be performed to develop general sizing and design criteria on a subregional basis, the results of which could then be used to direct the engineer to more detailed design procedures. An analytical hierarchy is described in Section 10.5.4.

## 9.8 Development of a Performance Monitoring and Evaluation Plan

Stormwater BMP monitoring projects are initiated to address a broad range of programmatic, management, regulatory, and research goals. Monitoring goals are often focused on the achievement of objectives (including hydrology/hydraulics and water quality) downstream of the facility. This monitoring and evaluation effort (not shown on the flow chart in Figure 9-1) may be used to determine the degree to which these objectives are met. Multiple methods, all with different cost and time structures, can be used for sampling including manual and automated methods for collecting grab samples as well as time-weighted and flow-weighted composite samples. Depending on the specific treatment system and the goals of the monitoring program, several samples may need to be collected at multiple locations during multiple storm events to obtain data useful for determining the actual performance.

## CHAPTER 10

# Hydrologic Evaluation for BMP/LID Selection

## 10.1 Design Guidance

Apart from the *LID Design Manual*, specific BMP design guidance is not an objective of this project since good help is available, as listed below. However, BMP/LID selection inherently involves hydrologic and hydraulic considerations, discussed in this section.

Stormwater treatment system design involves both the *mechanism* for hydrologic and hydraulic controls as well as the *design criteria* for determining the runoff volume and/or flow rate for which to design. Hydrologic and hydraulic design guidelines with various levels of detail are included in the following:

- *Design and Construction of Urban Stormwater Management Systems* (WEF and ASCE 1992),
- *Municipal Storm Water Management* (Debo and Reese 2003),
- *Surface Water Design Manual* (King County 1998),
- *Stormwater Collection Systems Design Handbook* (Mays 2001),
- *Stormwater Treatment: Biological, Chemical, and Engineering Principles* (Minton 2005),
- *Urban Storm Drainage Criteria Manual* (Urban Drainage and Flood Control District 1999),
- *Stormwater: Best Management Practices and Detention for Water Quality, Drainage and CSO Management* (Urbonas and Stahre 1993),
- *Stormwater Management Manual for Western Washington* (Washington State Department of Ecology 2001),
- *Urban Runoff Quality Management* (WEF and ASCE 1998), and
- *Stormwater Best Management Practice Design Guide* (Clar et al. 2004).

Several of the references listed above are based in part on one of the original guidelines produced for the Metropolitan Washington Council of Governments by Schueler (1987). In addition to the above references, many cities and other public agencies provide good, localized design guidelines, such as the Stormwater Management Manual provided by the Bureau of Environmental Services in Portland, Oregon (BES 2004). A useful compendium of Web sites and BMP documents is available from the California State Water Resources Control Board at www.swrcb.ca.gov/rwqcb2/news_items/Tobi%20Reference%20Attachment%20sept%206.doc.

Several methods can be employed for sizing hydrologic and hydraulic controls including flow attenuation, volume reduction, and flow duration. Stream power and shear stress methods can also be used.

## 10.2 Sizing Hydrologic/Hydraulic Controls

### 10.2.1 Flow-Attenuation Design

Many stormwater regulations require postdevelopment hydrograph peaks to be no greater than predevelopment peaks, as indicated in Figure 10-1. At the downstream end of the catchment or subarea, this peak-shaving reduction is almost always accomplished simply through storage with a controlled release. The combination of storage and hydraulic outlet configuration may be adjusted through simple storage routing to achieve the desired peak reduction. For example, storage-indication, or modified-Puls routing works well and is easily performed on a spreadsheet (Bedient and Huber 2002). The greater the available storage volume, the greater the peak reduction that is possible. If the outlet capacity is too large, the hydrographs for events with peak flows under the capacity are simply passed through the storage volume with minimal reduction.

After passing through the storage unit, the duration of medium flows is attenuated compared with the duration of medium flows in the incoming (likely the predevelopment) hydrograph. However, the attenuated postdevelopment hydrograph still has a greater volume than does the predevelopment hydrograph.

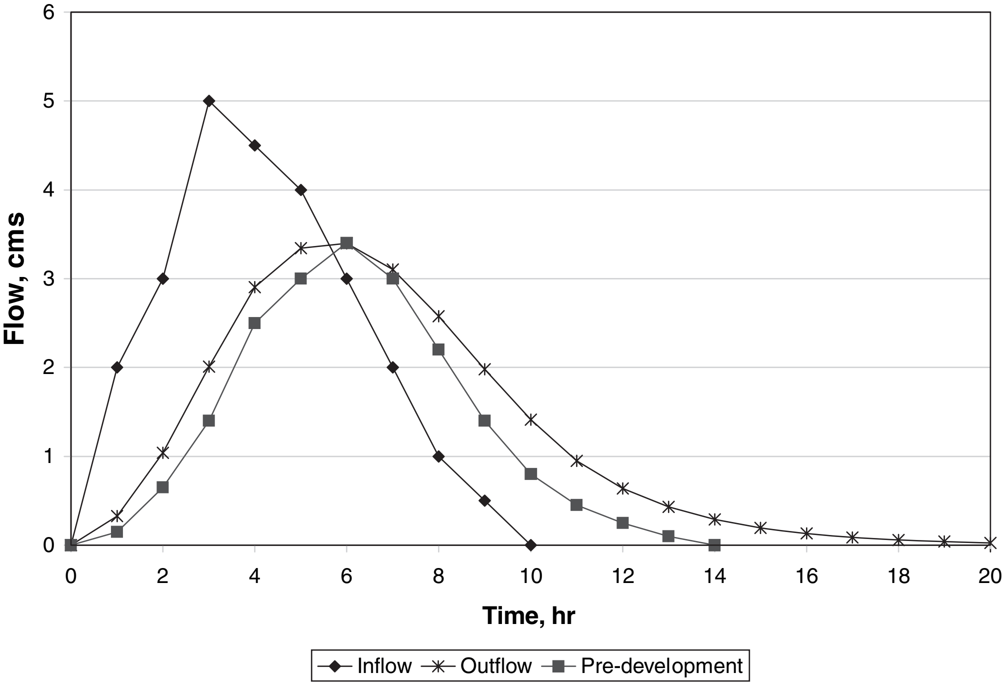
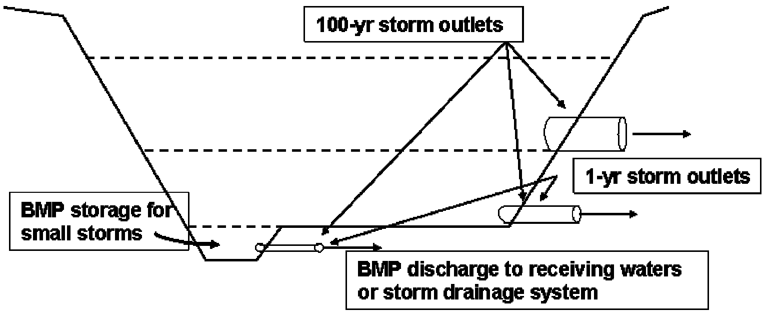


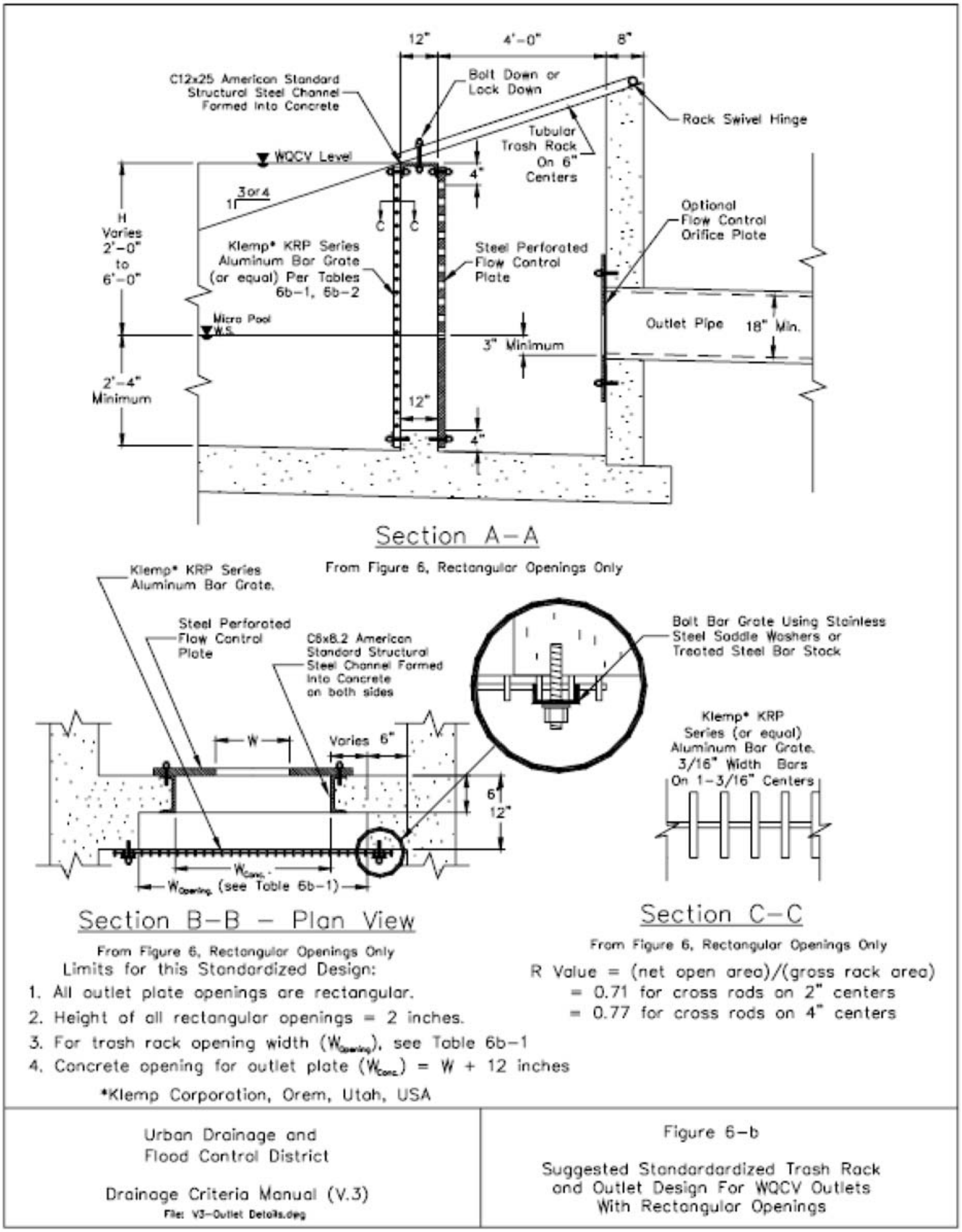
*Figure 10-1. Typical peak flow reduction (peak shaving) resulting from storage.*

If a storage basin is configured to detain large storms, with large outlet capacity, small storms will essentially pass through unmodified. However, control of small storms is one of the cornerstones of water-quality control. Hence, extended-detention ("dry") basins can be configured with multiple outlets, as indicated in Figure 10-2. The smallest and lowest volume is designed to contain and hold, for an extended period, the frequent "small" storms (i.e., depths less than a few tenths of an inch) that make up 80 to 90% of most rainfall events at most locations in the United States (WEF and ASCE 1998). The low-flow outlet is often a pipe with a small diameter (with protection against clogging), perforated riser, or filter drain and is used to drain this detention volume over, typically, a 24- to 72-hr period, as a goal. (If detention is too long, the basin may not be empty before the next storm event.) A somewhat larger outlet may be installed at an intermediate depth (labeled "1-yr storm outlet" in Figure 10-2) to reduce peak flows of larger events. Finally, an outlet for larger storms (with potential for flooding) is added (all of which are labeled "100-yr storm outlets" in Figure 10-2) in the form of a weir or emergency spillway (or large pipe). Of course, all outlets contribute to drainage of the facility during very large events. But if the 100-yr outlet is placed at the bottom of the structure, small events will pass through unmodified, with no water-quality control. Typical outlet structures for these purposes are illustrated in Figure 10-3. An outlet rating curve (outflow versus depth) is constructed as the sum of the outflow from the various hydraulic outlet components; the outlet rating curve is then used in the storage-routing procedure for design.



Reprinted with permission from L.A. Roesner (diagram presented to authors in informal presentation in 2003).

*Figure 10-2. Outlet configuration for multiple-objective stormwater control.*



Limits for this Standardized Design:

1. All outlet plate openings are rectangular.
2. Height of all rectangular openings = 2 inches.
3. For trash rack opening width ($W_{Opening}$), see Table 6b-1
4. Concrete opening for outlet plate ($W_{Conc.}$) = W + 12 inches

*Klemp Corporation, Orem, Utah, USA

R Value = (net open area)/(gross rack area)
= 0.71 for cross rods on 2" centers
= 0.77 for cross rods on 4" centers

Note: WQCV = water quality control volume. See source documentation for details and tables referenced in the figure.
Source: Urban Drainage and Flood Control District 1999 (Vol. 3, Figure 6b, p. SD-13).

***Figure 10-3. Typical outlet structures used in detention basins.***

Peak-flow reduction may also be accomplished upstream in the watershed through "hydrologic source control" mechanisms (including components of LID) that reduce the volume of the runoff hydrograph and delay the peak through distributed storage. In addition to infiltration systems, bioretention areas and extended detention basins have been shown to reduce runoff volumes. The volume of storage in the collection network (pipes and channels) should be included in estimates of peak-flow attenuation from the whole catchment. For example, highway drainage is often routed through pipes or channels to a concentrated discharge point. This is usually accomplished through flow routing down the drainage network.

### 10.2.2 Volume-Reduction Design

Volume reduction is possible in two ways: (1) upstream reduction in runoff, for example, through hydrologic source control, and (2) BMPs that emphasize infiltration and ET. LID options are described in sources such as Prince George's County 2000, Puget Sound Action Team 2003, and Urban Drainage and Flood Control District 1999, to name a few, and detailed design guidelines are presented in the *LID Design Manual*.

BMPs reduce runoff volumes through the combined mechanisms of infiltration and ET. ET is facilitated through an ample free water surface and/or plants that transpire from the near-surface soil layers or by soil soaking and drying. Wetlands and retention ponds obviously promote ET via a free water surface and transpiration. To a lesser extent, bioswales and controls that hold and store water at or near the ground surface will also promote ET via soil soaking and drying, including transpiration. Infiltration occurs through any permeable surface that is not saturated or, if saturated, that is able to respond to an applied gradient, to the extent that the permeable surface is not reduced by clogging because of sediment in the influent. Water that is retained in shallow soils after wetting can be evaporated between storm events. For this purpose, ponds, wetlands, and devices designed to promote infiltration are often part of a treatment train, with a sediment forebay or gross pollutant trap upstream of the primary facility.

Issues of sediment accumulation and maintenance specific to infiltration devices are discussed in the *Guidelines Manual* as are data relevant to design for infiltration and ET. Infiltration estimates based solely on native soils are the easiest to obtain but are subject to large variation in areas of disturbed soils, which include practically all urban areas and construction sites for BMPs. Hence, it is preferable that infiltration estimates be made on the basis of field infiltrometer tests of representative soils. Some recent studies illustrate the effect of compaction on infiltration rates (Pitt et al. 1999; Pitt et al. 2001).

### 10.2.3 Flow-Duration Control

The flow-duration method seeks to minimize the difference between predevelopment and postdevelopment (pre-highway and post-highway) magnitudes of flows discharged from the watershed and predevelopment and postdevelopment cumulative time periods during which each flow level persists. This approach incorporates principles from both flow attenuation (e.g., conveyance and detention) and volume reduction (e.g., infiltration and ET), while taking into account the distribution of flows with time. Changes in flow duration are most easily detected from comparison of the predevelopment and postdevelopment flow-duration curves.

Comparing several different stormwater management strategies, including flow attenuation, volume reduction, and flow-duration matching, Palhegyi and Bicknell (2004) suggest that, of the three, flow duration offers the best means of limiting modification of downstream hydraulic conditions. While designing for flow attenuation over a range of design storm sizes accounts, in part, for potential impacts to downstream morphology from both large and small runoff events, it does not address the increased frequency of potentially erodible discharges. Volume reduction, in turn, fails to regulate the intensity of runoff from the watershed. By matching both the magnitude and frequency of flows under postdevelopment conditions to those assumed for the predevelopment watershed for potential erosive flow rates, flow duration helps govern the overall amount of "work" done on the downstream channel.

As predevelopment hydrographs are modified through storage for peak reduction (see Figure 10-1), the duration of moderate and low flows is extended over what would have occurred naturally because of the volume increase. The increase in volume caused by urbanization and development requires an increase in low flows to release the stored inflows. This means that the duration of low flows is increased both because of the redistribution of the hydrograph shape (higher flows converted to lower flows through storage) and because of the increase in low flows necessary to account for the higher volume of runoff. The extended duration of some of these low flows can be highly erosive, especially when these flows are near bank-full flows (often a 1- to 2-yr storm).

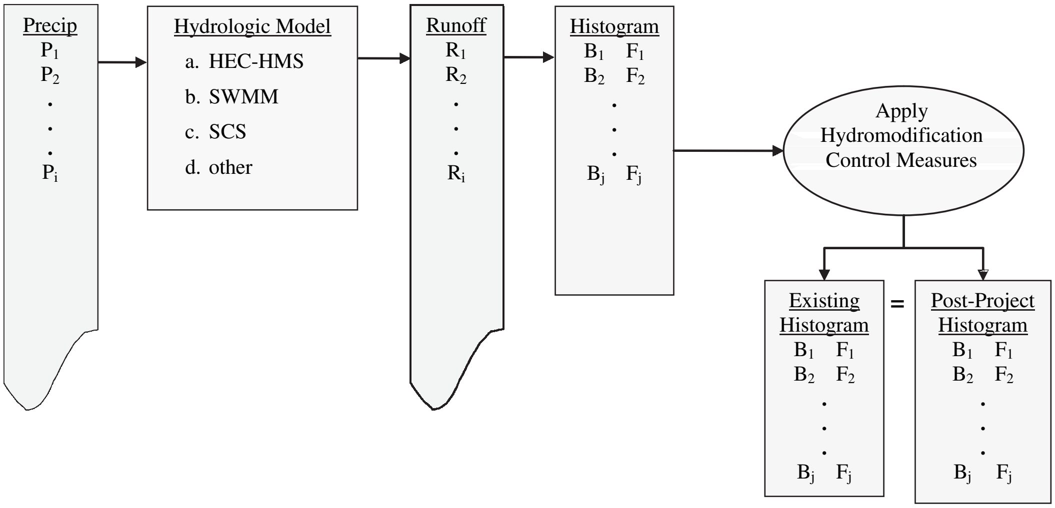
Matching flow duration for the full range of stormwater runoff events is thought to be the most effective method for protecting streams from increases in erosive flows with development (SCVURPPP 2004). Another effective method is the stabilization of the stream. The steps involved in flow-duration control design include the following:

1. Estimating stormwater runoff from the preproject and postproject sites using a long-term precipitation record,
2. Generating flow-duration curves from the results, and

3. Designing a storage-release system that discharges post-project runoff that matches the preproject flow-duration characteristics.

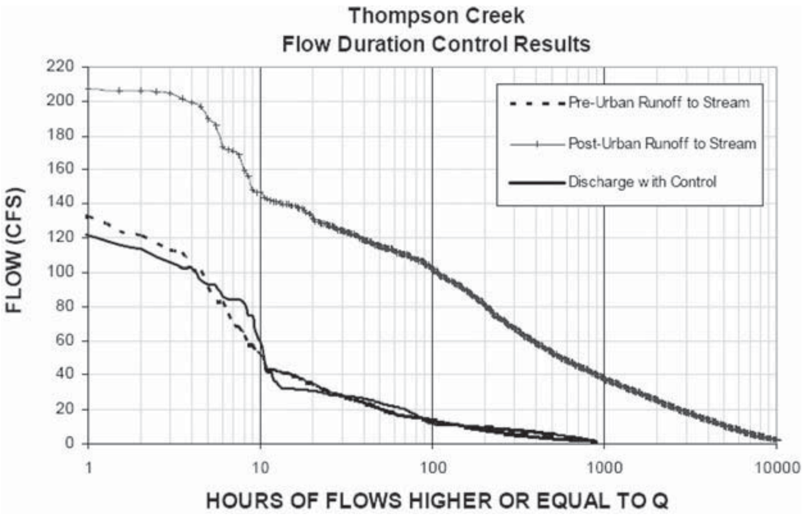
The flow-duration design methodology is illustrated in Figure 10-4. Rather than analyzing single storm events (either water-quality size or smaller flood control size), flow duration requires an analysis of the full probability distribution of runoff derived from a continuous hydrologic simulation. Flow-duration curves (or alternatively histograms) of predevelopment and postdevelopment conditions are constructed to determine the reduction in flow rate for each flow-duration time interval to be achieved by a control facility for those flows considered to be potentially erosive. An example of flow-duration curves for a 716-acre catchment in California generated using a full range of storms in a 50-yr continuous simulation is provided in Figure 10-5. As illustrated, the continuous simulation approach closely reproduces the preproject flow-duration curve for flows above potentially erosive flows.

An example similar to that of Figure 10-5 is provided by Nehrke and Roesner (2001). The approach is that postdevelopment runoff may be controlled through design of storage and outlet controls so that excessive erosion is prevented. If the goal is maintenance of downstream flow-duration relationships within a certain frequency range—for example, to maintain geomorphologically significant flow relationships, say in the 1- to 2-yr return period range—then outlets may be designed appropriately for that purpose. While not very



Note: $B_i$ represents different bins (class intervals) for flow ranges, and $F_i$ represents the corresponding frequencies.

*Figure 10-4. Illustration of the flow-duration methodology.*



Source: SCVURPPP 2004.

*Figure 10-5. Example comparison of flow-duration control design.*

common today, flow-duration design criteria are becoming more popular with regulatory agencies. For example, King County, Washington, has a flow-control criterion requiring postdevelopment flow durations to match predevelopment flow durations for 50% of the 2-yr through 50-yr peaks (King County 1998). Santa Clara County, California, is considering a similar criterion requiring flow-duration controls be designed so postdevelopment discharge rates and durations match pre-development discharge rates and durations for 10% of the 2-yr peak up to the 10-yr peak (SCVURPPP 2004).

Another downstream criterion might be maintenance of stream power relationships for erosion control. Erosion potential (Ep) is measured as an increase in the effective work index above the predeveloped conditions. Maintaining the in-stream Ep is similar to maintaining flow duration in that maintaining flow duration also maintains work and the erosion potential. However, maintaining the Ep can be accomplished in ways other than maintaining flow duration. In other words, the shape of the flow histogram can change as long as the total effective work remains the same between predevelopment and postdevelopment.

Ep can be calculated as follows:

$$Ep = \frac{W_{unstable}}{W_{stable}} \tag{10-1}$$

where

Ep = erosion potential,

$W_{unstable}$ = work index for a stream section determined to be unstable, and

$W_{stable}$ = work index for a stream section determined to be stable.

$$W = \sum_{1}^{n} (\tau_i - \tau_c)^{1.5} \cdot \Delta t \tag{10-2}$$

where

W = index of total effective work done over the length of flow record;

n = length of flow record;

$\tau_i$ = applied hydraulic shear stress, computed as $\rho \times g \times d \times S$ (force/area)(where $\rho$ = water density, g = gravitational acceleration, d = depth of water, and S = stream slope);

$\tau_c$ = critical shear stress that initiates bed mobility or shear erosion (force/area); and

$\Delta t$ = duration of flows (hours).

The critical shear stress is based on the least-resistant boundary material observed. Critical values of shear stress and velocity for the stream bed and stream bank provide a measure of the stream's resistance to erosion. For different bed material sizes, critical values of shear stress and velocity for bed mobility can be estimated two ways: (1) using Shield's equation and (2) using permissible velocity tables published in *ASCE Manual of Practice No. 77* (WEF and ASCE 1992).

The success of flow-duration matching for erosive flows depends not only on detailed analyses, but also on good design and construction of facilities. There is still some question as to whether good design and construction can be accomplished on a project-by-project basis, especially for smaller developments. For example, a small error in the final placement of a weir structure could mean that the facility will not be effective. Flow duration may only be successful if applied on a regional scale by entities that can better ensure that proper design and construction takes place.

In watersheds that are already partially built out and where stream erosion is already occurring, the most cost-effective approach to addressing stream erosion issues may be to install grade and bank stabilization projects in the stream. Controlling runoff from new development will not solve existing problems; therefore, the best use of funds may be to help the stream adjust to its new flow regime.

## 10.3 Sizing Flow-Based Treatment Systems

Flow-based, or flow-limited, controls contain very limited or no storage volumes and include sand filters, filter strips, some swales, infiltration trenches, and some infiltration basins as well as some proprietary devices, such as the StormFilter and Bay Saver, that are better described by a limitation on their maximum treatable inflow rate than by a limitation on their maximum treatable inflow volume. For proprietary devices, sand filters, and infiltration trenches, a bypass mechanism is sometimes provided, either external to the device or included in its design, so that high flows (higher than the design flow for treatment) are bypassed around the device. On the other hand, the entire hydrograph must usually pass through a swale—high flows as well as low flows—but the swale will only function well as a pollutant-removal device for low flows. An infiltration basin is often essentially a form of extended detention, which may be designed for a desired outflow into the soil (and atmosphere), but which is usually designed on the basis of volumetric considerations (discussed in Section 10.4).

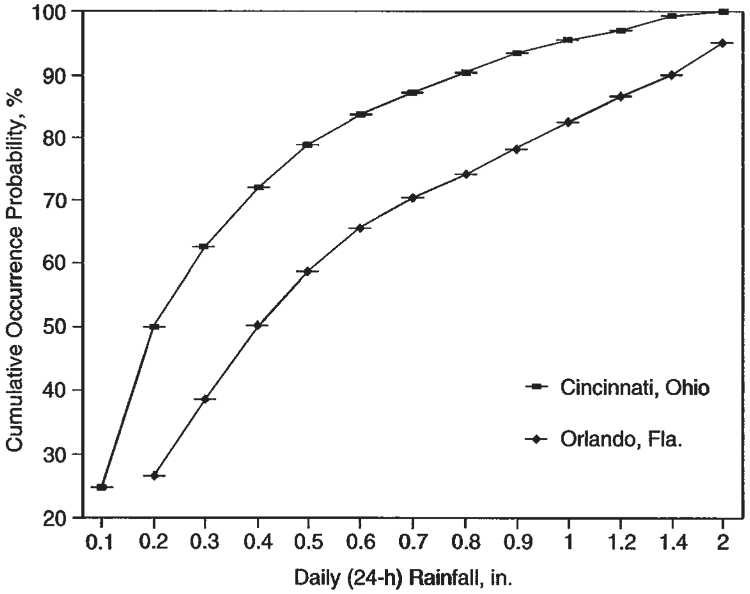
The level of sophistication for sizing both flow-based and volume-based devices varies considerably. In many municipalities, a "water-quality event" or "BMP volume" (see Figure 10-2) may be defined by the local department of public works. For instance, on the basis of continuous simulation or a simple frequency analysis of rainfall totals, a depth of, say, 0.9 in. in 24 hr may be chosen as the "water-quality design event." The rainfall would be converted to a design storm through application of a Natural Resources Conservation Service (NRCS) dimensionless hyetograph, such as a Type II distribution for the U.S. Southeast or a Type I-A distribution for the U.S. Pacific Northwest

(Bedient and Huber 2002; King County 1998). The design storm may be converted to a design hydrograph by a variety of standard hydrological techniques, such as a unit hydrograph, Soil Conservation Service (SCS) methods (e.g., SCS methods TR-20 and TR-55), Santa Barbara Unit Hydrograph, time-area method, and so forth. Alternatively, the hyetograph may be input to a model. (All of these methods are inferior to the continuous simulation approach, discussed subsequently, but are currently more commonly encountered.) The resulting runoff hydrograph is then used to determine a peak flow for sizing of the flow-based device. The peak will necessarily be quite low compared with flood runoff events, that is, the flow-based device will control the frequent small events, as discussed earlier. However, because of the inherent "peakedness" of hydrographs developed from NRCS flood-based design hyetographs, designing a flow-based device to treat up to even this lower peak has almost no technical basis in terms of targeting appropriate treatment sizes. That is, the artificially high peak flow, even for the low water-quality design rainfall event, generally results in an over design for flow-based BMPs compared with continuous simulation approaches. Once the required flow for the device is determined, the device is then sized according to infiltration rates and other criteria to accept such a flow (WEF and ASCE 1998). Devices that rely on infiltration must be diligently maintained to prevent clogging.

In the absence of a prespecified water-quality rainfall event, regression relationships developed by Guo and Urbonas (1995, 1996) and documented by WEF and ASCE (1998) may be used to obtain a design storm depth for locations in the United States. For purposes of flow-based systems, the depth must be assigned a duration in order to distribute it in time, after which standard hydrologic techniques again may be used to estimate a runoff hydrograph. The distribution in time is not necessarily straightforward, since "real" storms do not have convenient durations such as 24 hr. However, if daily rainfall totals are used, frequency diagrams of the type shown in Figure 10-6 may be used to obtain a 24-hr (midnight to midnight or sometimes 8:00 a.m. to 8:00 a.m.) rainfall total corresponding to a specified percent exceedance. Again, this is a somewhat arbitrary method for determining treatment flow rates.

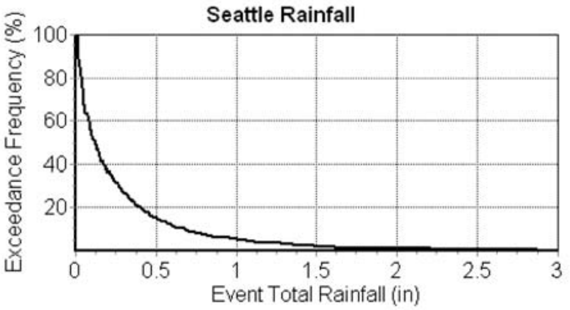
Another approach to setting a design storm size is to conduct a frequency analysis of the actual rainfall data by separating the hourly values into events using a minimum interevent time (MIT) criterion. The duration of such events is the "real" duration and not necessarily 24 hr. The separation criterion varies, but 6 hr is often employed. That is, rainfall occurrences separated by 6 hr or more are considered separate events (see Bedient and Huber [2002] for an explanation). Although commonly employed, an MIT of 6 hr may be too long for BMPs without storage receiving runoff from small, impervious catchments of the type used for highways. This is because such catchments will respond without "memory" of the previous storm after just a short drying time. On the other hand, rainfall data for a catchment in combination with a storage device may be better analyzed using an MIT that reflects the overall response of the catchment plus storage, such as 24 to 72 hr.

Example plots for Seattle, Washington (1948 to 2002 hourly rainfall) are shown in Figure 10-7 and Figure 10-8. Figure 10-7



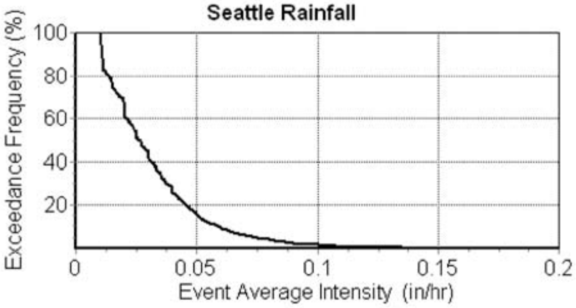
Note: Upper curve is Cincinnati and lower curve is Orlando.
Source: WEF-ASCE 1998, p. 171.

***Figure 10-6. Cumulative frequency distribution of daily precipitation for two U.S. cities.***



Note: SWMM5 analysis and output graph for time period 3/1948 – 10/2002.
Maximum event depth was 4.80 in. on 4/3/1991 (duration = 53 hr).
MIT separation = 6 hr.

***Figure 10-7. Rainfall storm event depth versus exceedance frequency for Seattle, WA, NCDC Station 457473.***



Note: SWMM5 analysis and output graph for time period 3/1948 – 10/2002.
Maximum event intensity was 0.29 in./hr on 9/17/78 (duration = 2 hr).
Minimum possible average intensity is 0.01 in/hr. Minimum interevent time (MIT) separation = 6 hr.

***Figure 10-8. Rainfall storm event average intensity versus exceedance frequency for Seattle, WA, NCDC Station 457473.***

shows event depths and Figure 10-8 shows event average intensities. Depths and intensities corresponding to specified frequencies may be obtained from such graphs and used in the standard hydrologic techniques previously described. The actual events may be extracted from the historic record for use as design hyetographs of a specified frequency.

Guo and Urbonas (2002) suggest that the exponential distribution may be used to fit cumulative probabilities such as those in Figure 10-6 and Figure 10-7:

$$F(d) = \text{prob}(d \le D) = 1 - e^{-D/D_m} \qquad (10\text{-}3)$$

where

$F(d)$ = cumulative frequency distribution,
$d$ = storm event depth,
$D$ = particular event depth of interest, and
$D_m$ = mean storm event depth = reciprocal of exponential distribution parameter.

Exceedance frequency, as shown in Figures 10-7 and 10-8, is 100 – F, where F would be expressed as a percent.

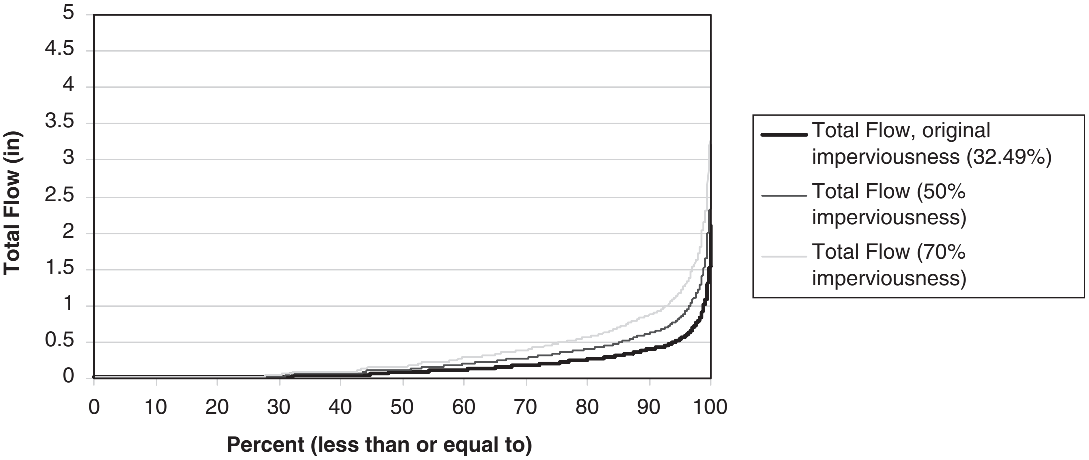
Several figures refer to an MIT. Values separated by ≤ MIT are aggregated into one event. An MIT of 6 hr is commonly used for rainfall analysis but may be too long for BMPs without storage receiving runoff from small, impervious catchments of the type used for highways.

The vexing problem of how to assign a duration leads to the most sophisticated procedure discussed herein: continuous simulation for selection of design events. The idea of continuous simulation is to run a calibrated model for the period of record of historic rainfall and to perform a statistical analysis of the resulting hydrographs (and sometimes on the resulting pollutographs if quality is simulated). Hourly rainfall data dating back to about 1948 are available at most first-order weather stations in the United States. Available at a smaller number of stations and dating back to about 1972 are 15-min data, which are better suited for urban analyses. Such data may be obtained from the National Climatic Data Center (NCDC) at www.ncdc.noaa.gov/oa/ncdc.html.

Unfortunately, the one-hundredth of an inch (0.01-in.) resolution data are typically only available for a few years out of the period of record because of a change in instrumentation at most stations in the 1980s. Among other difficulties, it is much harder to define the starting and stopping times for low-intensity rainfall when a tipping bucket gauges tips only at every tenth of an inch. Furthermore, if the smallest resolution is 0.1 in. in 15 min, the smallest rainfall intensity available to drive a model is 0.4 in./hr. This affects simulations sensitive to short residence times, namely simulations for peak flows and for infiltration off highways. Methods for dealing with the rainfall resolution issue are discussed in Chapter 7 of the *Guidelines Manual*.

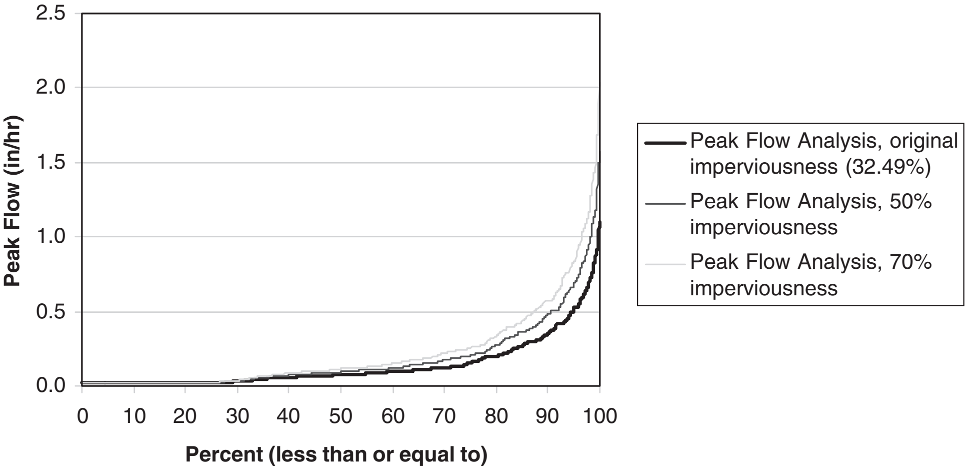
Although calibration is clearly desirable, it is seldom possible. Fortunately, in the urban environment and particularly on highways, the imperviousness of catchments usually means that more credible simulations may be performed even without calibration. Simulations performed by competent modelers are generally no less credible than reliance on heuristic parameter estimation, such as the time of concentration, which is required for simpler techniques. Continuous simulation methods are discussed in Section 10.5.

The most common way to present continuous simulation results is through a plot of magnitude versus percent of time the magnitude is less than or equal to the indicated value. As part of this project, Brown (2003) performed continuous simulations for the Moyewood Pond urban catchments in Greenville, NC (200 acres) (Stanley 1994, 1996) and the Walnut Creek highway catchment in Austin, TX (26 acres) (M. Barrett, personal communication, 2003; Walsh et al. 1997) using calibrated SWMM models. Continuous simulation results for the Greenville site for storm event runoff depth and storm event maximum flow are shown in Figure 10-9 and Figure 10-10, respectively. Simulations were based on 15-min rainfall data, and a 6-hr MIT was used for defining individual storm events from the resulting



MIT separation = 6 hr.
Source: Brown 2003.

***Figure 10-9. Runoff depth frequency relationship for Moyewood Pond Catchment, Greenville, NC.***



Note: MIT separation = 6 hr.
Source: Brown 2003.

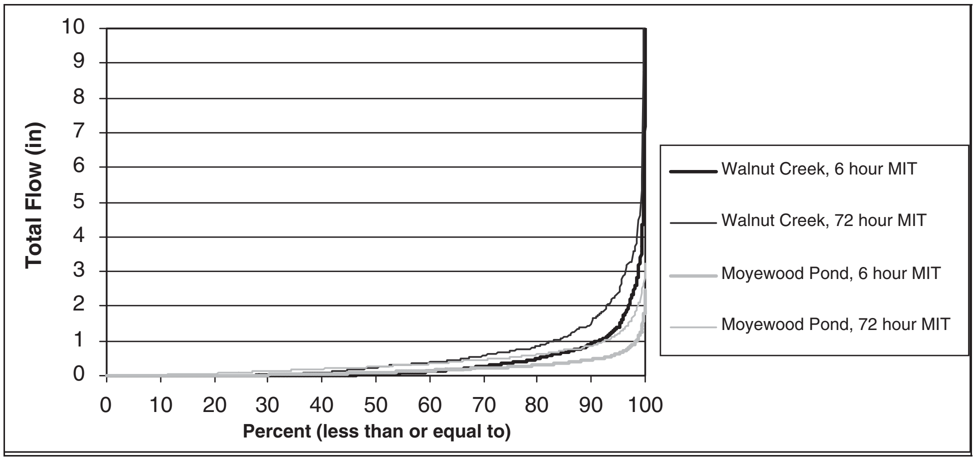
***Figure 10-10. Runoff peak flow frequency relationship for Moyewood Pond Catchment, Greenville, NC.***

hydrographs. For example, the 90% runoff depth and normalized maximum flow for the actual 33% imperviousness of the site is about 0.4 in./hr and 0.3 in./hr, respectively. The magnitudes obviously increase with imperviousness.

Total runoff depths and peak flows are compared for the two catchments in Figure 10-11 and Figure 10-12, respectively. Event depths and peak flows increase with increasing MIT, as expected. Magnitudes are clearly higher for the site in Austin, Texas, than for the site in Greenville, North Carolina, an outcome that might not be intuitive. Additional detail on the Greenville, North Carolina, and Austin, Texas, simulations is provided by Brown (2003) and Brown and Huber (2004).

Once again, an exponential fit may be obtained to the curves in Figures 10-9, 10-10, 10-11, and 10-12, as suggested by Guo and Urbonas (2002). The curves may be made dimensionless by dividing by the mean runoff event depth or mean runoff event peak flow.

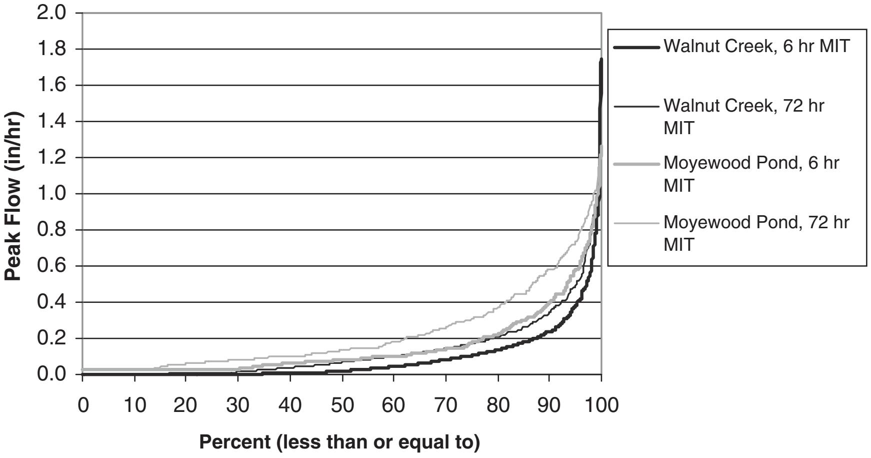
The results of Figures 10-9, 10-10, 10-11, and 10-12 offer ways to select design peaks and volumes on the basis of allowable frequency (e.g., 80%) if local regulations permit such an approach. In all cases, somewhere in the vicinity of the “knee of the curve” is an attractive choice because it becomes less cost-effective to capture the peaks and volumes for extreme events at that point. Guo and Urbonas (1996) offer a criterion for selection of an optimum point on the knee of the curve, which is to use the location at which incremental change in dimensionless capture ratio equals the incremental change in dimensionless runoff volume or peak. Capture ratio may be in the form of number of events captured or cumulative volume captured. However, the volume basis is likely to be a



| Continuous Simulation Characteristics | Moyewood Pond 38% Impervious | Walnut Creek 38% Impervious |
|---|---|---|
| Precipitation- total (in) | 911.25 | 751.70 |
| Average yearly (in/yr) | 28.48 | 30.09 |
| Infiltration- total (in) | 560.49 | 346.21 |
| Average yearly (in/yr) | 17.52 | 13.85 |
| Evaporation- total (in) | 50.98 | 70.09 |
| Average yearly (in/yr) | 1.59 | 2.80 |
| Runoff- total (in) | 310.88 | 342.28 |
| Average yearly (in/yr) | 9.72 | 13.69 |

Note: Average values are low because of missing data in the 15-min rainfall records used to drive the model. Evaporation is low because of runoff from pavement and predominant infiltration into sandy soils. Moyewood Pond simulation period: 5/13/71–1/1/03. Walnut Creek simulation period: 12/1/75–12/1/00.
Source: Brown 2003.

***Figure 10-11. Total runoff depth comparisons between regions and MIT values, based on Walnut Creek and Moyewood Pond (Greenville) site simulations at constant 38% imperviousness.***

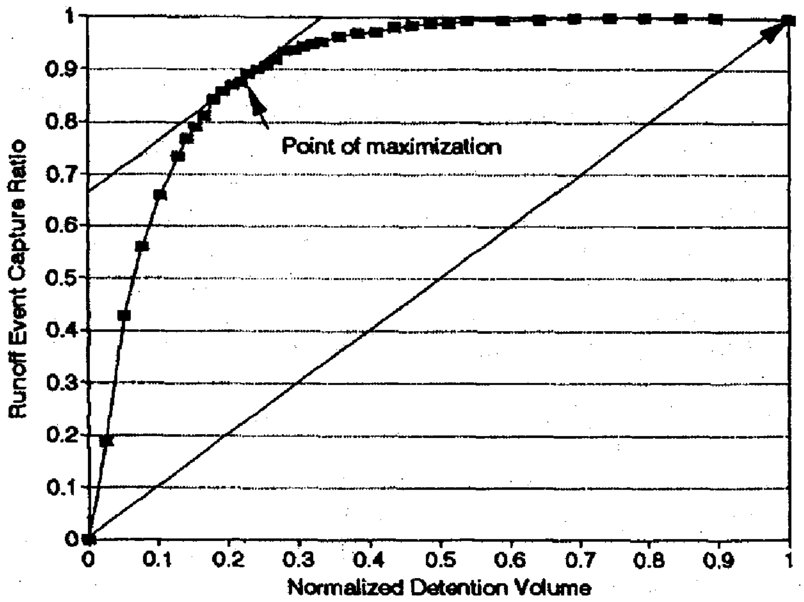


Note: Peak flow frequencies also provide insight about downstream impacts.
Source: Brown 2003.

***Figure 10-12. Peak flow comparison between regions and MIT values, based on Walnut Creek and Moyewood Pond (Greenville, NC) site simulations at constant 38% imperviousness.***

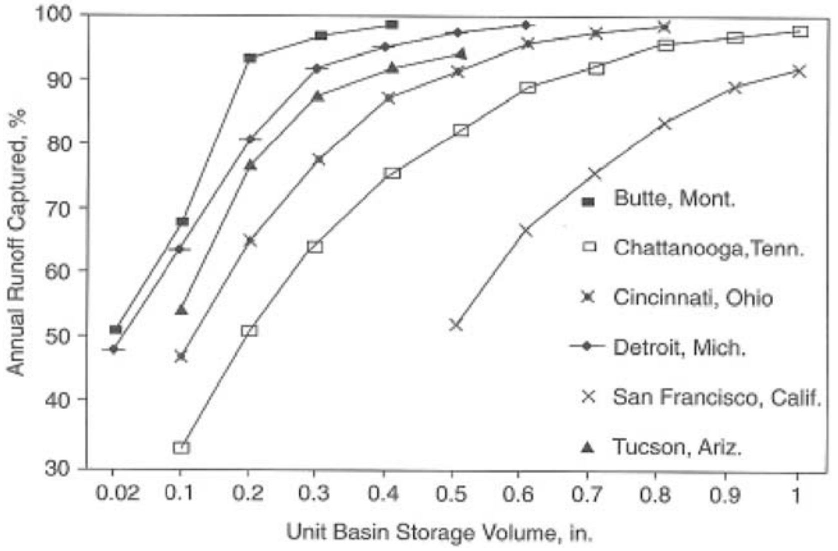
more robust method. Runoff volume or peak is made dimensionless by dividing by the mean storm event magnitude. While this method does use a long-term rainfall record, it is inferior to a continuous simulation approach because it does not account for the sequence of events, which affects the ability of the BMP to process more or less volume than its full capacity during individual events. The Guo and Urbonas (1996) selection criterion is illustrated in Figure 10-13.

Use of different models and simulation options leads to similar results presented in different ways. For example, Hydrologic Engineering Center STORM model simulations for six cities in which storage volumes necessary to detain runoff for 24 hr were determined by continuous simulation are summarized in Figure 10-14. Additional details are given in WEF and ASCE (1998). Heaney et al. (1977, 1979) present STORM model results in another way, providing the control



Note: Based on equating slopes of normalized detention to runoff event capture ratio (Guo and Urbonas 1996). The detention volume is normalized by dividing by the volume of the mean annual runoff event.

*Figure 10-13. One criterion for design detention volume selection.*



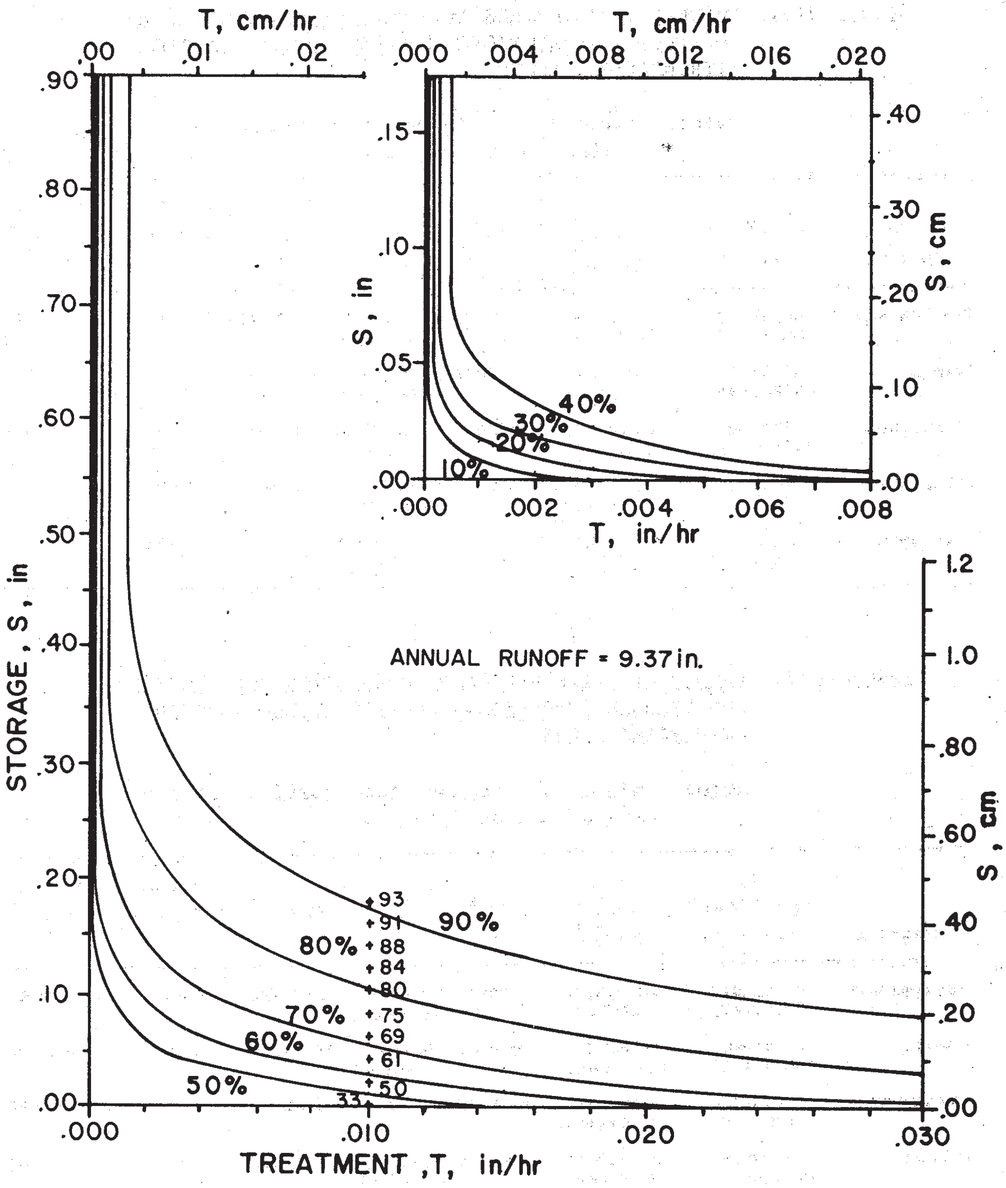
Source: WEF and ASCE 1998, p. 173.

*Figure 10-14. Runoff capture rates versus unit storage volumes at six study sites.*

effectiveness of different combinations of storage and treatment. Results for San Francisco, California, are shown in Figure 10-15, from which further cost optimization may be performed. "Level of control" means percentage of generated BOD that is removed by the treatment unit.

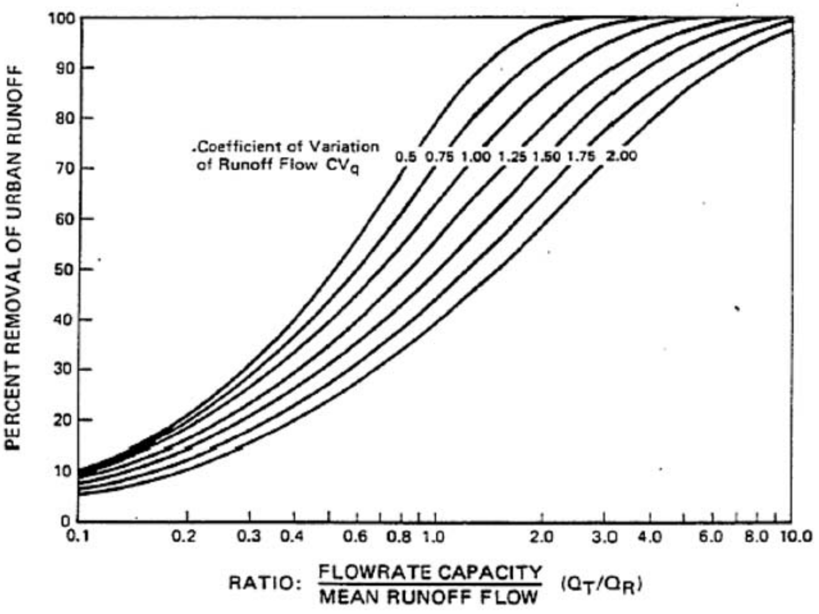
Driscoll et al. (1986) presented a method for sizing flow-based treatment systems that have a maximum flow capacity in which all flows above the capacity are bypassed (e.g., infiltration systems and hydrodynamic devices). The method determines the long-term volumetric capture of a device that captures all inflows up to a treatment capacity, $Q_T$, for situations in which storm flows are gamma distributed. Figure 10-16 illustrates the effect of normalized treatment capacity (treatment capacity, $Q_T$, divided by mean runoff flow rate, $Q_R$) and the coefficient of variation of runoff flow rates ($CV_q$) on long-term capture efficiency (Driscoll et al. 1986).

For ease of application by the practitioner, results of continuous simulations are provided in Appendix C of the *Guidelines Manual* for 30 locations in 15 hydrologic regions throughout the United States. As explained in detail in Chapter 7 of the *Guidelines Manual*, the simulations were computed for a 4-acre impervious catchment in a manner similar to the development of Figures 10-9, 10-10, 10-11, and 10-12. The results may be used for *screening purposes* for sizing flow-based



Source: Heaney et al. 1977.

*Figure 10-15. Storage-treatment combinations for given levels of control for BOD removal.*



Source: Driscoll et al. 1986.

***Figure 10-16. Average long-term performance for a flow-capture device.***

BMPs within the 15 different hydrologic regions. Results for four locations are compared in Figure 10-17. Flow magnitudes may be scaled up (or down) linearly on the basis of impervious area. Differences in the frequency relationships are apparent for the four locations. Results for infiltration-based controls, i.e., a filter strip, are also provided in Appendix C of the *Guidelines Manual* for the 30 locations as a function of infiltration rate and slope of the filter strip. A comparison of five locations is shown in Figure 10-18 for one infiltration rate and slope; again, regional differences are very apparent.

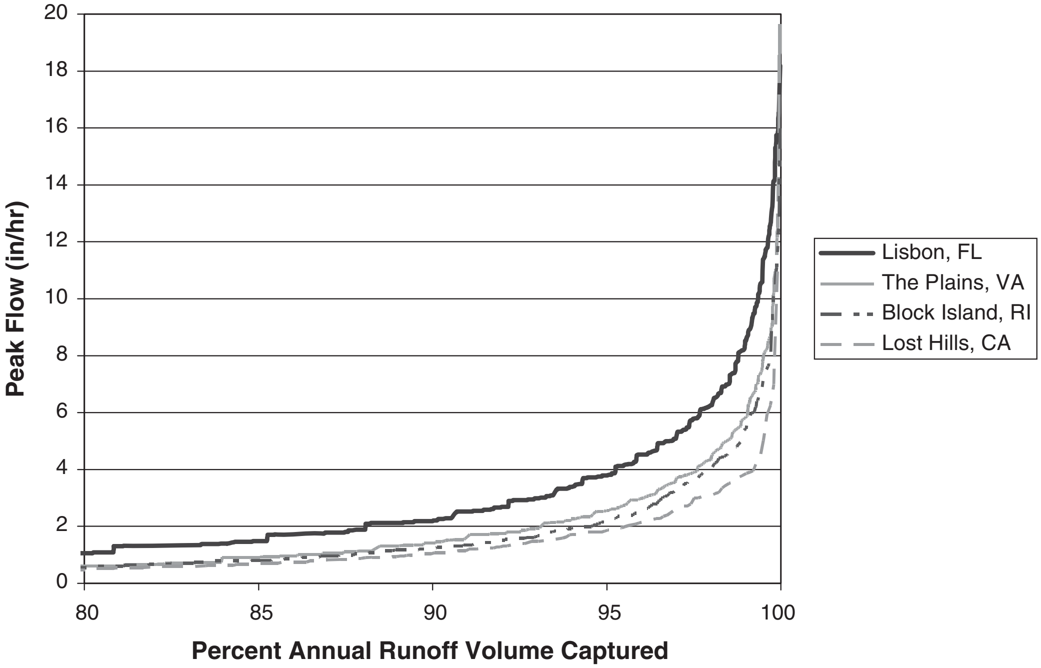
This section has summarized various ways in which frequency results for rainfall intensity (see Figure 10-8), peak-flow magnitude (see Figures 10-10 and 10-12) and combinations (see Figure 10-15) may all be used to size flow-based controls. Volume-based controls use similar information and are discussed in the next section.

## 10.4 Sizing Volume-Based Treatment Systems

Volume-based systems are somewhat simpler to size than flow-based systems from a hydrologic point of view because only a total runoff volume (or equivalent depth over the catchment) is needed to determine the required storage volume. For example, from a frequency analysis of rainfall events at many locations, Driscoll et al. (1989) produced contours of storm event depths (with MIT = 6 hr) for the United States (see Figure 10-19). Such a map summarizes information obtained by many simulations of the type shown for just one site in Figure 10-7. WEF and ASCE (1998) present runoff estimation techniques that rely in part on a runoff coefficient applied to the rainfall event contours shown in Figure 10-19 for runoff volume estimates. Obviously, better site-specific information on volume-frequency relationships may be obtained by analysis of local rainfall records (to improve on Figure 10-19); the best information is obtained by analysis of simulated runoff to produce site-specific runoff volume-frequency relationships as shown in Figures 10-9, 10-11, 10-14, and 10-15.

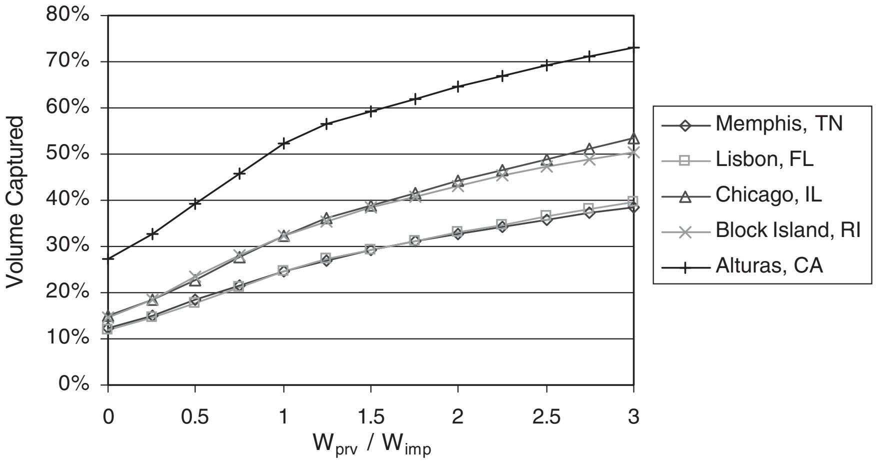
Driscoll et al. (1986) provide a method for sizing off-line volume-based systems in which storm volumes are gamma distributed that is similar to the sizing methodology for flow-based systems. Figure 10-20 illustrates the effect of normalized treatment volume (treatment volume, $V_E$, divided by mean runoff volume, $V_R$) and the coefficient of variation of runoff volume ($CV_{VR}$) on long-term volumetric capture efficiency (Driscoll et al. 1986).

The USGS has produced regression relationships for runoff flows and volumes at many locations in the United States. Examples include Laenen (1983) for urban areas in western Oregon and Franklin and Losey (1984) for Tallahassee, Florida. Relationships for the United States are summarized by Sauer et al. (1983). These regression relationships provide good peak flow and runoff volume estimates for ungauged watersheds; unfortunately, the lowest return period for estimates is 2 yr, which is much too high for most stormwater-quality designs. However, these regression relationships may be used to check sizing for flood control.



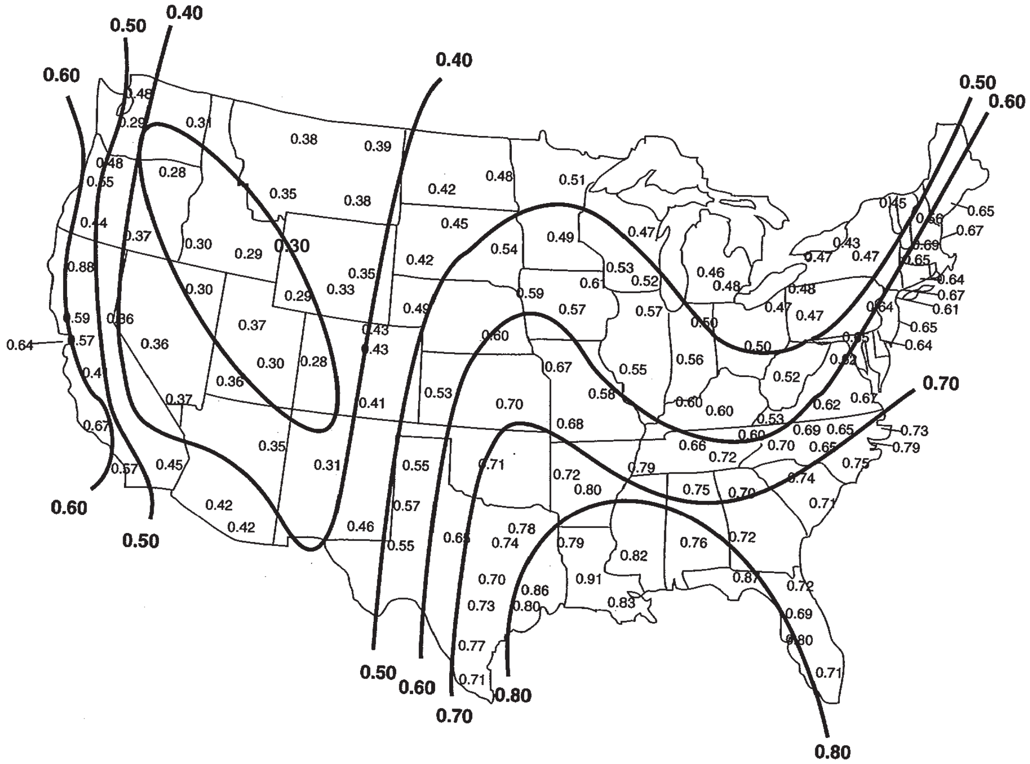
Note: Top curve is Lisbon, FL, 2nd curve is The Plains, VA, 3rd curve is Block Island, RI, and bottom curve is Lost Hills, CA. Only results for control > 80% are shown, for clarity (see *Guidelines Manual*, Chapter 7).

***Figure 10-17. Scheme 1 peak-flow frequency analysis comparing four U.S. locations.***



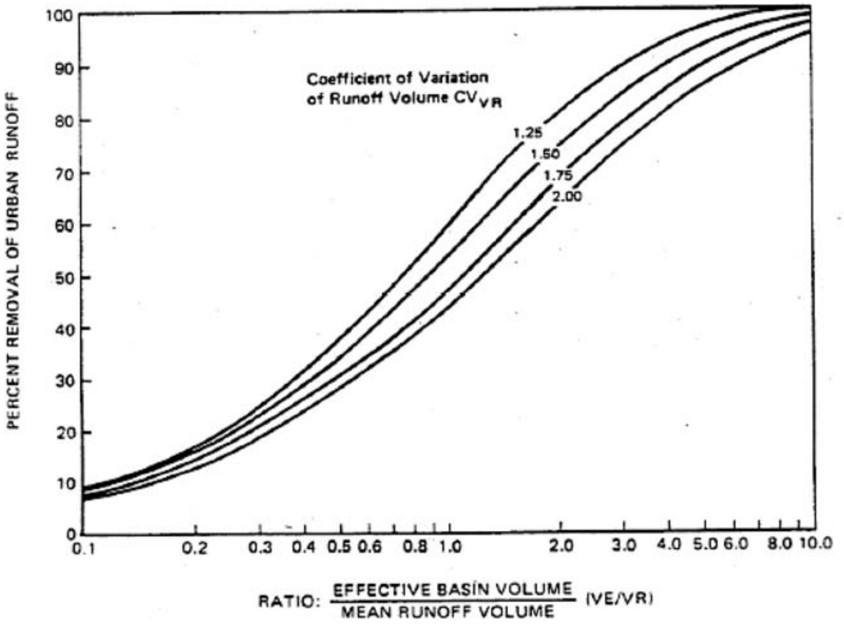
Note: Constant infiltration rate of 0.2 in./hr and filter strip slope of 0.1. The abscissa is the ratio of the width (flow path length) of the pervious filter strip, $W_{prv}$, to the width of the tributary impervious catchment, $W_{imp}$ (see *Guidelines Manual*, Chapter 7).

***Figure 10-18. Filter-strip effectiveness comparison for five U.S. locations.***



Source: Driscoll et al. 1989.

***Figure 10-19. Mean storm precipitation over the United States based on 6-hr MIT.***



Source: Driscoll et al. 1986.

***Figure 10-20. Average long-term volumetric capture efficiency for detention systems.***

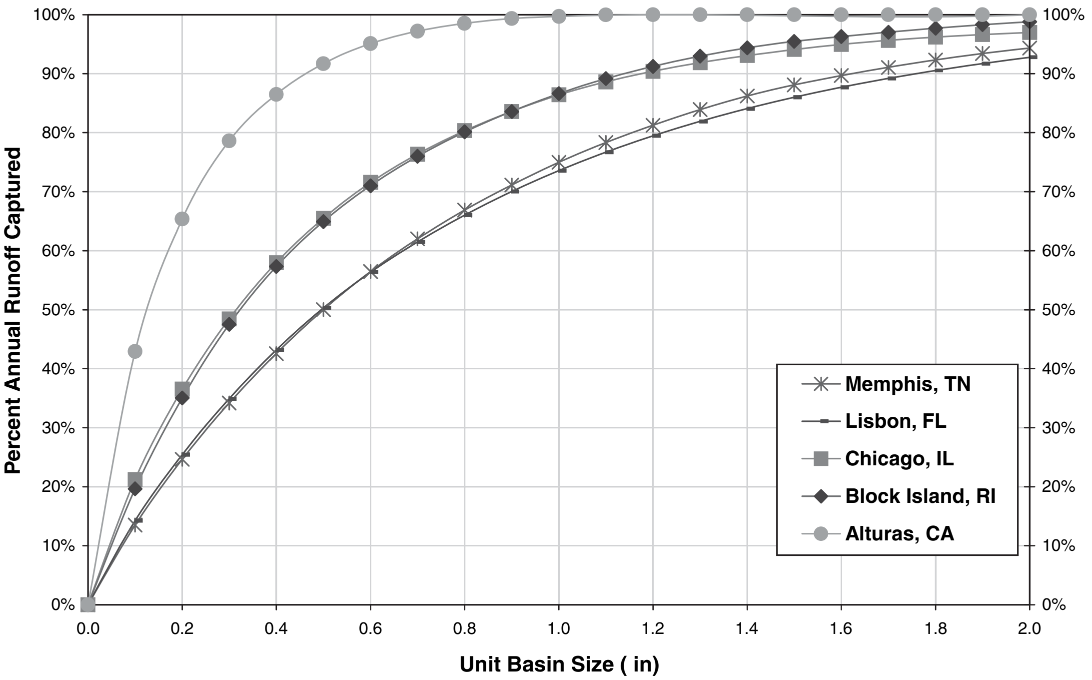
Continuous simulations provide more than just a depth or flow rate that corresponds to a certain frequency. The output (hydrographs and pollutographs) may be analyzed for the parameter of interest, including runoff event depth, average flow, maximum flow, duration, interevent time, pollutant load, pollutant EMC, pollutant maximum concentration, and so forth. Events corresponding to return periods or frequencies of interest may be selected as design events for modeling or for hyetograph input into simpler hydrologic procedures (Bedient and Huber 2002). Although continuous modeling generally involves the most effort, continuous models are getting easier to use, and spreadsheet procedures are also available, as will be discussed in Section 10.5. Models also have the ability to simulate series-parallel arrangements of BMPs. They are most appropriate for evaluating the hydrologic and hydraulic performance of a treatment system. Water-quality simulations must be used with caution so that simulation of downstream controls reflects the removal of heavier particles by upstream controls. Hence, treatment train configurations may be analyzed by continuous simulations if careful attention is paid to the impacts of controls in a series, especially the notion of maintaining the knowledge of the particle size distribution while moving downstream through the treatment train.

To summarize, both flow-based and volume-based sizing may be performed based on a hierarchy of procedures beginning with 24-hr rainfall depths, for example, specified by a local agency. Standard hydrologic techniques may be applied to begin with, then a frequency analysis of rainfall to obtain design depths and intensities can be performed, and, finally, continuous simulation modeling can be performed for hydrograph- and pollutograph-based analyses.

Screening results for the United States for evaluation of volume-based controls are presented in Appendix C of the *Guidelines Manual*. As described earlier for flow-limited controls, continuous simulations were performed for a standard impervious catchment (described in Appendix C of the *Guidelines Manual*). Volume-based controls were simulated as off-line storage, for which the annual percent capture of the off-line device is presented regionally, and on-line storage, for which effectiveness in TSS removal is a function of detention time. Evaluation of the latter involves simulation of particle removal within the device, as explained in Appendix C of the *Guidelines Manual*.

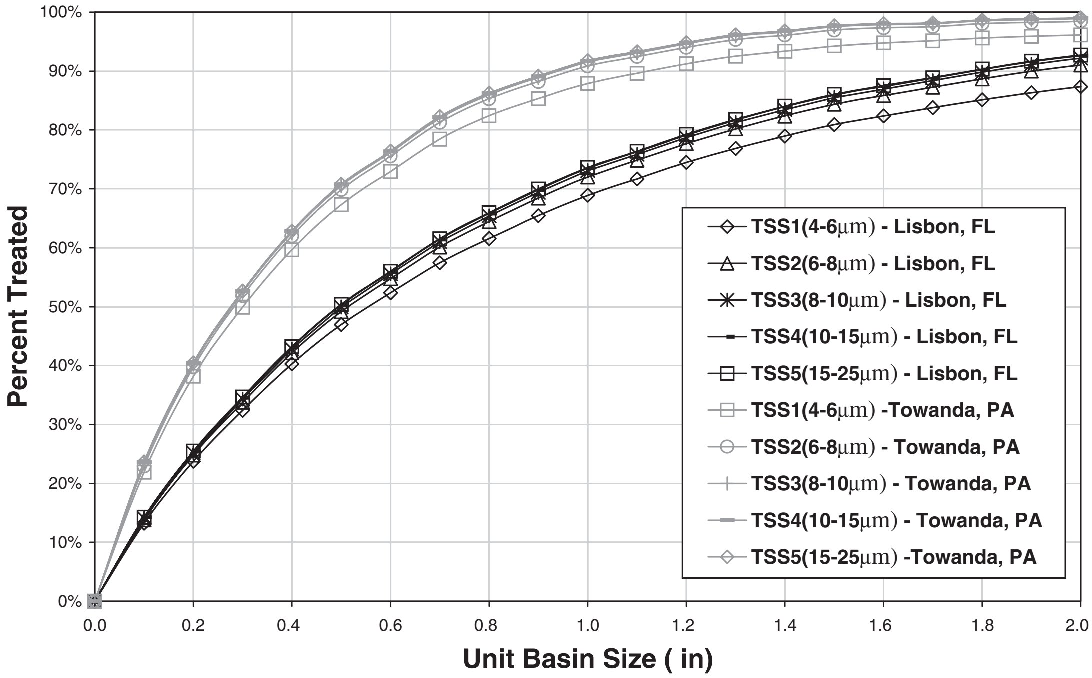
Example regional comparisons for off-line controls are shown in Figure 10-21, and example regional comparisons for on-line controls are shown in Figure 10-22. As Figure 10-21 shows, generally, a given basin size captures a greater percent annual runoff volume in a dry area, such as Alturas, California, than it does in a humid area, such as Memphis, Tennessee. Similarly, it can be seen in Figure 10-22 that for the same unit basin size, on-line detention is more effective (for TSS removal) in Towanda, Pennsylvania, than it is in Lisbon, Florida. Screening results for 30 locations in the United States are provided in Appendix C of the *Guidelines Manual*.

With respect to sizing of treatment systems, site-specific analysis is always best (preferable to general screening



Note: For off-line storage, for five different locations (72-hr drawdown time). Unit basin size is inches over the catchment area (watershed inches).

*Figure 10-21. Percent annual runoff volume capture as a function of unit basin size.*



Note: Unit basin size is defined as inches over the catchment area. Two sites are compared: Lisbon, FL (lower curves) and Towanda, PA (upper curves). Particle size ranges are defined in the *Guidelines Manual* Chapter 7, with "TSS5" being largest and "TSS1" being smallest.

***Figure 10-22. Percent TSS removed as a function of unit basin size.***

results). Application of continuous simulation for this purpose is discussed in Section 10.5; examples are provided in Appendix B of the *Guidelines Manual.*

## 10.5 Performance Verification and Design Optimization

### 10.5.1 Introduction

After a stormwater treatment system is properly sized, it may be desirable to analyze the hydrologic performance to ensure that it will meet runoff management goals. Depending on the level of detail and the methods used for sizing, much of this analysis may have already been done. However, in most cases, detailed continuous simulations coupled with cost-benefit analyses would not have been completed during preliminary design stages. The subsections that follow describe some methods for verifying the performance of a treatment system and optimizing its design.

### 10.5.2 Modeling and Models

Hydrologic methods for evaluation of regional hydrologic impacts on treatment system performance have been discussed in Section 10.4 and in Section 8.7. These often begin with "classical single-event methods," such as the rational method for peak flows and unit hydrographs, SCS (now NRCS) methods for losses and hydrographs, the Santa Barbara Unit Hydrograph method, and so forth. In almost all cases, the resulting hydrographs are driven not by actual monitored rainfall, but by synthetic design storms, typically NRCS dimensionless hyetographs (e.g., Type I-A for the Pacific Northwest and Type II for the Southeast). As discussed earlier, a 24-hr duration is usually assigned; assigning a 24-hr duration is based on convenience rather than hydrologic considerations. Although event methods could certainly be applied to other design hyetographs derived from monitored rainfall, they rarely are. In addition to the issue of the rainfall driver, the question of initial conditions also arises, because event methods are sensitive to AMCs that affect infiltration and depression storage. Initial conditions may be handled in a consistent way when applying the SCS method (i.e., through choice of antecedent moisture condition—AMC I, II, or III), but more often than not they are ignored or worst-case (saturated) conditions are assumed, leading to an overly conservative design. Event hydrographs may then be passed through trial layouts of a treatment system for hydraulic design. Of course, such methods cannot account for water storage in the system between events. These methods are embedded in several versions of commercial software and are routinely accepted by the hydrologic engineering profession in spite of the issues just mentioned.

The alternative to event methods is continuous simulation, using any of several models. Software for this purpose includes federally supported models such as (Singh 1995; Singh and Frevert 2006):

- EPA Storm Water Management Model (www.epa.gov/ednnrmrl/models/swmm/index.htm)
- HEC-HMS (www.hec.usace.army.mil/)
- HSPF (http://water.usgs.gov/software/surface_water.html)

Continuous simulation may also be performed by several other models, even in a spreadsheet format, such as shown by Heaney and Lee (2006). Continuous models (which may also be used to simulate single-storm events) are driven by a period-of-record precipitation file and should provide for soil moisture accounting, ET, regeneration of depression storage, and infiltration capacity, etc.

Apart from a better estimate of the overall water budget for the catchment, continuous models also permit the user to simulate the interaction of storage capacity and storm runoff volumes and/or pollutant loads so that estimates can be made about how often the device will still contain water when the next event arrives. Results may be presented in a frequency format, as illustrated in Section 10.4 (and in Appendix C of the *Guidelines Manual*), so that the percentage of annual runoff and/or pollutant load captured by (or passed through) a control device may be determined as a function of device capacity and outlet structure design. This information can then be used to develop sizing requirements so that continuous simulations would not need to be performed for each BMP.

Depending on the model, several forms of output may be analyzed statistically, such as runoff peaks, volumes, and durations as well as water quality parameters such as loads, EMCs, peak concentrations, etc. That is, the analysis may be performed on the parameter of interest, not just on one or two hydrologic parameters. Because large events are inherently included in the simulation, safety factors for flood control or other device purposes may also be determined during the course of the evaluation. Finally, it is well established that the frequency of a runoff parameter, such as peak flow, will be different than the frequency of the rainfall event that caused it (primarily because of variable antecedent conditions as well as precipitation durations and intensities). Hence, frequency analysis can be separated from analysis of rainfall frequencies, in the form of an intensity-duration-frequency (IDF) curve, or even in the more sophisticated analysis of rainfall event parameter frequencies of the type described in Section 10.3.

Finally, continuous modeling permits optimization for design on the basis of minimum cost, minimum downstream discharge, minimum downstream pollutant load, and a variety of other possibilities. This may be done heuristically, with models such as SWMM, or in a more integrated fashion, with the spreadsheet models of Heaney and Lee (2006). Continuous modeling also allows for an estimate of the number of hours ("wet hours") a control is in use and the amount of sediment removed for computation of operation and maintenance costs, as well as expected maintenance needs. Estimates of residuals or solids removed by a device will also be useful for operation and maintenance evaluations.

While continuous modeling affords several technical advantages, there are disadvantages as well. Continuous modeling generally requires more effort in assembling the necessary long-term precipitation input, from the NCDC, as well as in statistical interpretation of the multiyear hydrographs (and sometimes the corresponding pollutographs). Additional training may be required for use of the necessary models. Event modeling with synthetic design storms is easily reviewed by agencies because much of it involves relatively prescribed parameter selection. Event models are available from many public and commercial software suppliers, and descriptions of the incorporated hydrologic techniques, such as the SCS method, may be found in any hydrology text. Commercial software also often includes reservoir routing and simple storage design options. Oversight agencies often strongly suggest, if not absolutely require, certain event modeling techniques, which can make the leap to continuous simulation more difficult. On the other hand, such local guidance (e.g., Urban Drainage and Flood Control District 1999; Washington State Department of Ecology 2001) often provides invaluable information on local parameters, suitable design conditions, and methods adapted to that particular region.

Again, continuous simulations can be performed to develop general sizing and design criteria on a subregional basis (e.g., *Guidelines Manual*, Appendix C), and the results can be used for simpler design requirements, which could then be effected using event models. Alternatively, an agency could look at the results of treatment-system sizing using event-based methods as a starting point for design via continuous simulation to refine the design criteria and adjust the event-based storm size (or release hydrograph) accordingly.

### 10.5.3 Modeling Data Requirements

Data requirements for modeling include required input for the model itself as well as calibration and verification data (monitored hydrographs and pollutographs). Unfortunately, calibration and verification data are routinely *un*available, especially for an undeveloped site. In this situation, the modeler should still compare results with data from the nearest or most appropriate site for which data are available, including data produced by the USGS, numerous agencies in response to NPDES requirements, state transportations agencies and departments of transportation (e.g., Caltrans), universities, and so forth. Sensitivity analysis should also be performed on the model to help determine the most important parameter needs and to help evaluate uncertainty in the output.

Continuous hydrologic model input data typically include the following:

**Rainfall input.** NCDC long-term precipitation data are available in four formats:

- 15-min, 0.01-in. resolution;
- 15-min, 0.10-in. resolution;
- 1-hr, 0.01-in. resolution; and
- 1 hr, 0.10-in resolution.

Records at individual stations may be combinations of the above formats. There is no easy way to find out what kind of record is available for an individual station other than downloading and analyzing the data set. For continuous modeling of urban areas, the 15-min precipitation records (NCDC data set TD 3260) with a resolution of 0.01 in. are preferable and should be used unless data of shorter time increments are available locally. The NCDC 15-min data typically begin at about 1972, whereas hourly data can start as early as 1948. However, the relative unavailability of 15-min data at 0.01-in. resolution can be a problem for small catchments with short response times, such as highway pavement. ET data are needed to compute the vertical water balance; one source is Farnsworth and Thompson (1982). If the additional complication of snowmelt is simulated, appropriate meteorological data (e.g., temperature, wind speed, etc.) are needed to compute melt.

**Catchment data.** These include area, directly connected and other imperviousness, depression storage, slope, roughness, infiltration values or other loss parameters (such as SCS curve numbers), shape factors (such as time of concentration), etc. Additional soil properties may be needed to model soil moisture levels. *Site-specific measurements are the best way to determine infiltration properties of disturbed soils.*

**Data for flow routing, if simulated.** These include channel/pipe connectivity, shape, dimensions, slope, roughness, invert and ground elevations, etc. If hydraulic structures are simulated, their hydraulic characteristics obviously must be provided. For small catchments (up to several acres), it may not be necessary to simulate flow routing, but for larger urban watersheds, the storage, delay, and attenuation provided by the drainage system should be accounted for.

**Data for simulation of controls.** These include stage-area-volume-discharge information for storage devices, infiltration properties for swales and filter strips, ET, hydraulic considerations, etc. If water quality in controls is simulated, additional information may include unit operation performance, outlet EMC frequency distribution, treatability data (distribution of sizes and/or settling velocities), sorptive properties, and so forth, depending strongly on the model used.

Good maps and drainage plans are an essential part of the data preparation effort. If spatially oriented data are included in a geographic information system (GIS) for a locality, this effort will be greatly facilitated. Soil survey maps and reports are always useful.

The importance of site-specific data cannot be overemphasized. For example, infiltration into soils is notoriously variable in space, with infiltrometer measurements that may differ even for closely spaced samples. Urban soils are likely to have been compacted and to not reflect infiltration characteristics for nearby undisturbed soils (Pitt et al. 1999; Pitt et al. 2001). Because infiltration is a key parameter for the evaluation of effectiveness of such common devices as swales, site-specific infiltrometer data are essential and are not that costly. Similarly, the effectiveness of any stormwater control is a function of the treatability of the stormwater (see Section 4.5). Obviously, the larger and heavier the particles, the easier it is for any device to remove them. Therefore, it is important to have settling velocity or particle size data on the expected influent. Finally, an analysis of a treatment train must account for the fact that upstream devices will remove the largest material first, and performance of downstream devices will be affected accordingly. For example, in watersheds that are effectively swept regularly, the runoff may be expected to be cleaner prior to input into a treatment system. Likewise, if a bioswale discharges to a wetland treatment system, the wetland will receive input loads that are lower than they would be if the bioswale were not there.

The developers of the International BMP Database (Strecker et. al. 2001) have recommended that stormwater treatment system performance be assessed according to (1) the amount of runoff prevented by the BMP, (2) the amount of runoff treated (and not treated), and (3) the resulting effluent quality of treated runoff. Using these descriptors will help one evaluate performance through several possible measures and not overestimate treatment system performance on the basis of a single measure.

### 10.5.4 Recommended Process Modeling Methodologies

This guidance recommends the following hierarchy for modeling:

1. Continuous simulation, using a model suited to the task, such as the ones discussed in Section 10.5.2. Depending on the objective, it may not be necessary to simulate water quality as well as water quantity because water-quality simulation is much more difficult and uncertain. However, if water quality is not simulated (e.g., sedimentation), then the results for storage effectiveness are

less accurate because the trade-off between maximizing volume captured and maximizing load captured is not explicitly included. The volume captured can be maximized by shortening the detention time, but water-quality control will be improved if detention time is increased. Continuous simulation models can be used to simulate the effects of using simpler methods for sizing treatment systems. For example, continuous simulations can be conducted on potential event-based model sizing methods to ascertain the capabilities of the event-based models and establish sizing requirements to which the event-based models are applied.

One step down from continuous simulation is the derived distribution approach, in which the frequency distributions (probability density functions) of runoff and quality are derived analytically (although sometimes numerical solutions are incorporated). The derivations are based on transformation of the input rainfall frequency distribution using functional relationships among rainfall, runoff, and quality. The techniques are developed in considerable detail by Adams and Papa (2000). The frequency distributions of runoff and quality resulting from these techniques could also be derived from the results of continuous simulation.

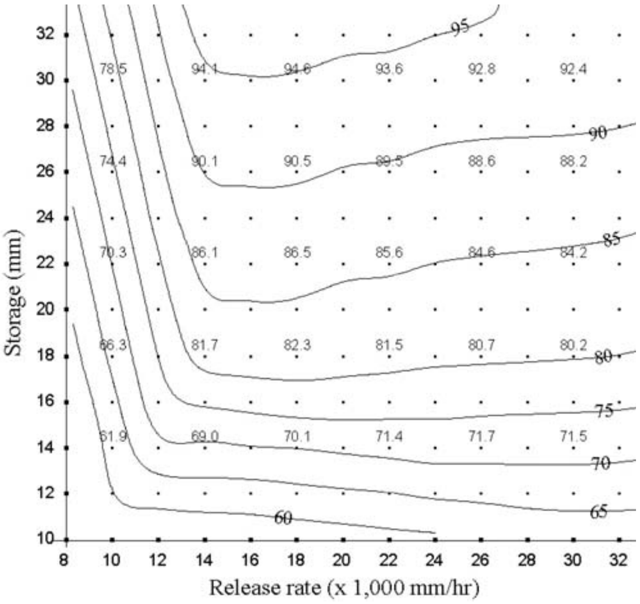
2. Event models of "classical" hydrology, using site-specific data. These models should only be used when verified with a continuous simulation approach to determine what the potential results of wet-weather controls may be over the entire spectrum of runoff hydrographs. This is especially critical when designing systems for reducing downstream erosion.
3. Generalized regional guidelines of the type discussed in Sections 10.3 and 10.4. These can include simplified methods provided by WEF and ASCE (1998) and the extensive regional, but general, continuous simulation results provided in the *Guidelines Manual* (see Chapter 7 and Appendix C). These regional guidelines might also provide a starting point for event and continuous models.

Guidance with regard to the generalized results has been provided in Section 10.3 and 10.4. This guidance will not cover the standard hydrologic procedures referred to in Option 2 above because they are documented in dozens of texts and stormwater manuals. Nor will descriptions of screening methods already provided by WEF and ASCE (1998) and similar sources be covered because these sources are readily available, and no improvement can be made on the presentation made in the originals. However, much has been implied herein about the advantages of continuous simulation for analysis of wet-weather controls; documentation of this recommended approach is provided in Appendices E and F of the *Guidelines Manual*.

### 10.5.5 Optimization Methodologies

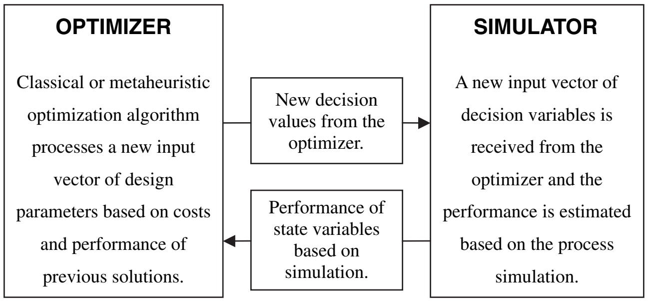
Heaney and Lee (2006) and Lee et al. (2005) summarize how spreadsheet-based process simulations can be linked with cost data, performance standards, and optimization software to find the actual "best" management practice(s). Pack (2004) develops these methods for infiltration systems, and Rapp (2004) develops them for storage/release systems. The results of process simulation, in which performance is measured in terms of percent pollution control as a function of the size of the storage volume and release rate, are illustrated in Figure 10-23 (Lee et al. 2005). Each point on the figure represents a simulation run. The percent pollutant control for selected runs is also included. The isoquants (contours) in Figure 10-23 show the various combinations of storage volume and release rate that yield a given percent pollution removal over the simulated period (note the similarity to Figure 10-15). For example, the 85% isoquant shows that storage can be reduced significantly if the release rate is increased from 0.010 to 0.015 mm/hr. However, further increases in the release rate (decreasing the detention time) require more storage. Thus, the portion of this isoquant for which release rates exceed 0.015 mm/hr is technically inefficient. The least-cost combination for 85% removal is the one that minimizes the life-cycle cost for storage volume plus release rate. The optimal solution can be determined graphically (for two variables) or by using the Solver optimization software in Excel.

A schematic of the flow of information between the simulator and the optimizer is shown in Figure 10-24. This process can be repeated for all performance levels to derive



Source: Lee et al. 2005.

***Figure 10-23. Pollutant control as a function of the assumed storage volume and release rate.***



Source: Lee et al. 2005.

***Figure 10-24. Linkage between the simulator and the optimizer.***

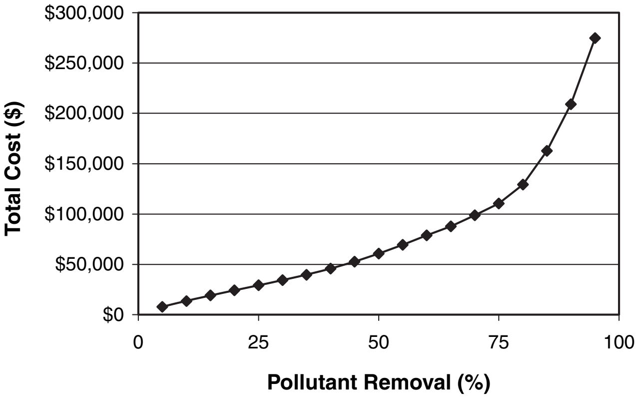


***Figure 10-25. Illustrative performance curve for a storage/release treatment system.***

the final cost-effectiveness curve that shows total costs as a function of the percent pollutant removal (see Figure 10-25) (Rapp 2004). This performance curve is typical. Incremental costs of control typically increase rapidly beyond about 80% pollutant removal.

## 10.6 Flexible Design/Adaptive Management

### 10.6.1 Concepts

The design methodologies described herein focus attention on selection of specific treatment train designs that are anticipated to perform within specified constraints and to achieve established project goals. However, these estimates need to be refined on the basis of the results of actual operation. The concepts of flexible design and adaptive control and management are important and effective components of implementation and should not be overlooked. These concepts can be quite powerful in situations in which effluent quality and downstream hydraulic performance are direct measures of project success, and these concepts allow for changes to be made in system function well after implementation. Continuous simulation of various designs requires the specification of how the system will be operated. It also provides valuable estimates of system behavior across the entire spectrum of flow conditions. Often these approaches only minimally increase capital costs for a project, and they can often significantly increase the likelihood of achieving project goals.

Flexible design is defined here as having unit operations that can be readily adjusted or modified following construction or installation to achieve variations in system function and performance. Adaptive management is a means for managing these flexible design elements to allow for changes in implementation to be made on the basis of information obtained from monitoring the effectiveness and performance of a treatment system. Ideally, adaptive management and flexible design go hand in hand and are integral and intentional components of the physical design of a treatment system.

### 10.6.2 Design Elements

Many unit operations lend themselves to a flexible design approach. The obvious examples include hydraulic controls that can be manipulated to

- Achieve longer or shorter residence times or to match complex water-quality performance goals.
- Match predevelopment flow-duration curves in the receiving water.
- Adjust, split, divert, or redirect flows between downstream processes or BMPs.
- Adjust the configuration of the physical outlet to permit fish passage.
- Increase or decrease peak-discharge flow rates.
- Increase or decrease the quantity of water diverted for infiltration.
- Increase or decrease the drainage area flowing to specific facilities through simple modifications such as additional swales, curb-cuts, gutters, and so forth.

Flexible hydraulic designs frequently include the use of controls such as adjustable stop-log structures, adjustable weir plates, valves and gates, and interchangeable orifice and weir plates.

Many other unit operations and BMPs can incorporate components of flexible design to allow for adaptive management of the system. Some examples are the following:

- Allowing for additional storage volume. This could include, for example, designing additional storage that may be used only if expected performance is not achieved or for flexibility in the use of flood storage for water-quality treatment.
- Setting aside additional site area for future treatment processes.

- Allowing for an increase or decrease in the quantity of vegetation in the system as well as varying vegetation management strategies, such as altering vegetation type or species to achieve water-quality benefits. (Different plant species have varying pollutant-removal capacities and tolerances. Adjusting plant composition and density within the treatment site can maximize plant cover and pollutant uptake.)
- Incorporating outlet adjustments that allow water level to be maintained during drought conditions. Having an adjustable low-flow control is particularly important during times of drought and low baseflow in vegetated and wetland systems.
- Being able to change filter media or loading rates to treat specific pollutant needs.
- Being able to increase or decrease maintenance to preserve treatment effectiveness.

The design engineer needs to pay particular attention to making all of the other design components compatible with flexible design elements. For example, the capacity of outlet structure conveyance systems downstream of an adjustable stop-log structure must allow for safe passage of the maximum possible flow independent of the setting.

### 10.6.3 Inherently Safe and Inherently Functional Design

Flexible design requires the use of inherently safe and inherently functional designs. Inherently safe designs do not allow the flexible or adjustable component of the system to be set so that the setting results in an unsafe condition. Likewise, inherently functional designs do not allow a flexible control element to be set so that the element results in a condition that compromises the functionality of the system from either a water-quality or operational perspective. For example, the concept of inherently functional design could be used to limit the size of a pipe leading from an adjustable flow splitter to an off-line wetland system on the basis of the maximum flow rate that the wetland system might tolerate without incurring damage to vegetation or that could result in the export of accumulated sediments. This approach sets an upper limit on the flow rate to be diverted to the wetland system.

# CHAPTER 11

# Summary, Conclusions, and Recommendations

## 11.1 Objectives

Highway-drainage engineers and environmental professionals require a straightforward and simple-to-apply method for evaluation of potential BMP and LID strategies for management of stormwater runoff. The main purpose of NCHRP Project 25-20(1) has been to provide results and examples of a method that has been developed and documented by the project team. This summary includes a brief description of the critical elements of the project and key conclusions and recommendations for future research efforts. The principal investigators believe these conclusions and recommendations will be valuable for evaluation of BMP and LID facilities and for the successful integration of LID into linear transportation projects from the perspective of water-quality and hydrologic and hydraulic design and analysis. Section 11.2 of this report includes a brief summary and discussion of key hydrologic considerations. Section 11.3 includes the conclusions of the research and recommendations for future research efforts. In most instances, the term “BMP” is used to describe practices for control of stormwater and other runoff from highways and urban areas.

## 11.2 Summary of BMP Evaluation Methodology

BMP evaluation methodology, outlined in Chapter 9, is holistic (encompassing all aspects of the problem) and uses the following three procedures:

- Practicability analysis. This provides an assessment of critical selection factors (e.g., reliability, safety, aesthetics, costs, and maintenance). The practicability analysis is presented in detail in the *Guidelines Manual*, but some elements of this analysis are also incorporated into Chapters 5, 6, and 7 of this report.
- Performance analysis. This is based on monitored BMPs. The procedures and results are presented in Chapter 8 of this report.
- Hydrologic analyses. These are the methods used to evaluate runoff treated and runoff bypassed and to conduct a frequency analysis of design parameters (e.g., volume and peak flow) on a regional basis. These methods are described in Chapter 10, and hydrologic analysis related to BMP performance is described in Chapter 8.

The hydrologic evaluation addresses the first two of the three BMP performance questions presented by Strecker et al. (2001):

- How much runoff is prevented, i.e., disposed of, on-site?
- How much runoff that does occur is captured/bypassed by the BMP?
- What is the effluent quality of the treated runoff?

The third performance question is addressed through the use of EMC performance evaluations that are discussed in Chapter 8. Simulation modeling (see Chapter 10) can be used to provide both site-specific and regional analyses for runoff prevented (i.e., runoff prevented or eliminated by a BMP) and runoff bypassed through the use of long-term, continuous simulation.

Several figures of Sections 10.3 and 10.4 provide examples of design (sizing) guidelines for capture of any desired percentage of runoff. Similar curves could be developed for standard sets of imperviousness to reflect various highway pavement percentages and for multiple locations. Further details, as well as applications to 30 U.S. locations, are presented in Chapter 7 of the *Guidelines Manual*. The following design criteria were used in the analysis:

- Design for a specified peak flow that enters and is processed through or potentially bypasses the BMP.

- Design for a specified loss by infiltration and ET for an overland flow BMP.
- Design of an off-line BMP for capture of a specified volume of runoff, for a specified drawdown time. This design incorporates the trade-off between the goal of longer retention of stormwater and the goal of having storage available for succeeding storm events.
- Design of an on-line BMP for capture of a specified volume of runoff, for a specified drawdown time. This design depends on sedimentation theory, i.e., to evaluate the trade-off between greater capture with a high release rate and greater TSS removal with a low release rate. Design results can be presented on the basis of either percent removal of TSS (based on treatability, e.g., particle size distribution) or on TSS effluent EMC (event mean concentration).

The results of this analysis are used to derive the BMP/LID selection and conceptual design methodology applied in the *Guidelines Manual* and outlined in Chapter 9. The methodology includes the following:

1. Problem definition;
2. Site characterization;
3. Identification of fundamental process categories;
4. Selection of BMPs, LID Elements, and other treatment options;
5. Practicability assessment of candidate treatment systems;
6. Sizing the conceptual BMP design; and
7. Development of performance monitoring and evaluation plan.

The following conclusions and recommendations are drawn from this research report, the *Guidelines Manual*, and the *LID Design Manual*.

## 11.3 Conclusions and Recommendations

Conclusions and recommendations are presented here grouped into four topic areas: BMP/LID Design and Implementation, Monitoring Needs, Modeling Needs, and General.

### 11.3.1 BMP/LID Design and Implementation

1. **Conclusion.** Fundamental unit processes of environmental engineering may be applied along with empirical data to significantly improve the evaluation and selection guidance for BMP and LID facilities. Treatment of stormwater, like treatment of water and wastewater, relies on hydrologic/hydraulic and physical, biological, and chemical operations. The difference in application lies mainly in the different characterizations of stormwater and water for water and wastewater treatment. For some operations and processes, empirical data must still be employed, but hydrologic/hydraulic performance of BMPs, as well as settling performance, can be well represented by unit processes. For predicted pollutant concentrations and loadings, a combination of unit-process and empirical-data approaches can be used to significantly improve selection and design guidance.

   **Recommendation.** The drainage engineer should use fundamental UOPs to guide his/her selection of treatment systems for control of stormwater. A particular advantage is the focus on UOP selection based on specific targeted pollutants, as opposed to a "one size fits all" approach with typical BMP performance data. It is also recommended that guidance and requirements for stormwater BMPs based on UOP approaches be combined with empirical approaches as they have been in this project. Adhering to simple design rules only, such as using a 24-hr precipitation analysis for sizing and considering all BMPs equal, will not result in meeting water-quality goals in most cases.
2. **Conclusion.** LID concepts are already an unplanned component of highway designs with open drainage systems that encourage stormwater infiltration at or near the point at which the precipitation occurs. The performance of these systems can be enhanced significantly by incorporating straightforward LID methods such as additional ET, surface roughening, and enhancement of soils and vegetation to promote infiltration.

   **Recommendation.** Use LID methods to maximize on-site control of stormwater, typically by infiltration, for new and existing conveyance systems (a retrofit for the latter). Show the result in terms of the proportion of the highway right-of-way that controls stormwater on site as a way of demonstrating to regulators that the highway control system is achieving a high degree of control.
3. **Conclusion.** State and local governments often apply site-development BMP regulatory approaches to highways and require linear projects to use site-development BMPs. Although this approach may be convenient from a regulatory standpoint, in many cases, the BMPs are less effective or not efficient. Moreover, they are sometimes impossible to design according to the site-development criteria, which results in significant design modifications or waivers.

   **Recommendation.** The highway and regulatory communities should work together to develop a consistent and realistic set of BMP design criteria that will meet water-quality and drainage standards for control of wet-weather impacts.

4. **Conclusion.** There are limits to the effectiveness and efficiency of using a limited set of BMPs within the right-of-way to address water-quality impairments. Furthermore, different agencies within a state may adopt BMP strategies (e.g., regional, end-of-pipe, and LID) that are exclusive of each other. Effective structural and nonstructural techniques outside of the right-of-way may be a better use of resources to address known impairments.

   **Recommendation.** Hybrid approaches that combine on-site and off-site strategies, such as stream stabilization, wetland restoration, and stormwater banking, should be explored. Within the context of the BMP/LID stormwater management framework, agencies should develop common metrics, or policies, for BMPs and other strategies that use trading approaches (as is done for some NPDES permitting) to mitigate local wet-weather impacts by more intensive controls elsewhere. This can be used to develop more flexible and effective regulatory schemes.

### 11.3.2 Monitoring Needs

1. **Conclusion.** Characterization of stormwater for purposes of evaluating its treatability depends most strongly on settleability data for pollutants associated with particulates, that is, a frequency distribution of particle size/specific gravity or frequency distribution of settling velocities (see Section 4.5). Currently, such data are rarely available; however, they are essential for design of efficient control strategies, especially treatment trains.

   **Recommendation.** Treatability data should be collected from the tributary catchment (e.g., highway) prior to detailed drainage design (but see also next conclusion/recommendation). Collected data should include, at a minimum, EMCs of all pollutants of concern and their speciation and particulate solids characteristics and especially particle size distribution. Intra-event water-quality data can also be used to identify the presence or absence of a first flush and what pollutants are in the first flush. A related need is to identify and evaluate accurate and applicable methods for monitoring the particle size distribution of suspended sediment concentrations.
2. **Conclusion.** The characterization and treatability data discussed in the recommendation above will require extra effort and expense to collect (and for a new highway would be impossible to collect). This is not likely to occur on a voluntary basis because transportation agencies have limited resources and only minimal standards for monitoring are currently required by permits.

   **Recommendation.** Collect regional treatability data that are representative of combinations of soils, land use, and highway traffic. Make these data available for design as a default to collection of site-specific treatability data in every case. This might be done by state DOTs or regulatory agencies.
3. **Conclusion.** The collection of intra-event stormwater monitoring data within BMPs is relatively rare (e.g., based on the International BMP Database). Although 11 candidate sites were identified during this project (see Section 8.4), none of them included monitoring of all variables necessary to characterize the unit operation mechanisms by which water quantity was reduced and pollutants removed as a storm was routed through the BMP.

   **Recommendation.** Mechanistic understanding of BMP performance can only be obtained through funding of research that fully instruments and monitors a set of BMPs of different kinds (e.g., ponds, detention, and swales) so that within-storm analyses can be completed.
4. **Conclusion.** In spite of the lack of fully monitored BMPs in the sense just described, several studies offer quantity and quality performance data sufficient to support BMP selection guidance. These include studies entered into the International BMP Database as well as the comprehensive Caltrans data sets (many of which have been entered into the International BMP Database) and other studies.

   **Recommendation**. Data from the International BMP Database, the Caltrans data sets, and other studies should be analyzed and published in a timely way to support highway and other urban drainage professionals as they seek to refine stormwater control options. Examples include the analysis of Caltrans data by Kayhanian et al. (2003), analysis of International BMP Database data by Barrett (2004a) and Strecker et al. (2004a, 2004b), and analysis of NPDES data by Pitt et al. (2004).
5. **Conclusion.** The water-quality performance of BMPs is typically characterized by a percent removal of given constituents, implying that the effluent EMC is some fraction of the influent EMC. However, especially for particulate-bound pollutants, percent removal usually increases for higher influent EMCs, and effluent EMCs often are essentially functionally unrelated to influent EMCs. In this case, the frequency distribution of effluent EMCs is a suitable way of characterizing performance.

   **Recommendation.** BMP quality performance should be evaluated by several measures (see Chapter 8) to ensure that the data are being properly interpreted. The effluent probability method is a good way of representing the quality performance when effluent EMCs are not functionally related to influent EMCs.
6. **Conclusion.** DOTs and other agencies construct water-quality control facilities, but they typically do not engage

in postconstruction performance monitoring. The coordination between the design and construction process has not been adequately studied. It is not clear whether designs are always constructed to plans, whether materials meet specifications, and what effect the construction process has on the BMP. The long-term effectiveness of BMPs is poorly understood. Guidelines for the type, frequency, and effectiveness of maintenance programs need to be developed. A continuing need exists for postconstruction monitoring data.

**Recommendation.** DOTs and other agencies should monitor at least a subset of different types of BMP/LID facilities to obtain regional performance data for a variety of BMP types and watershed conditions. Such data should eventually be entered into the International BMP Database. Monitoring should include maintenance needs and operation and maintenance (and construction) costs. Costs evaluated should represent the net cost difference for the project, including LID measures in new or expansion projects. Many LID techniques can reduce other infrastructure needs.

7. **Conclusion.** Monitoring that does occur, valuable as it is, is usually for new control facilities, often at new construction sites. However, DOTs and other agencies are often called upon to provide water-quality retrofits for existing runoff locations. A retrofit project may not be designed to the optimal size or location that is specified in a design manual.

   **Recommendation.** Retrofit facilities should be monitored to evaluate performance under constrained (e.g., space and fixed upstream configuration) settings and resources.
8. **Conclusion.** BMP performance data for facilities in operation during the winter in cold climates are relatively uncommon.

   **Recommendation.** Additional cold-climate BMP performance data are needed. In particular, data are needed on the periodic melt-runoff events that do occur, even during the middle of winter.
9. **Conclusion.** Performance of storage facilities for multipurpose objectives of flood control and water-quality control depends heavily on the design of the outlet structure.

   **Recommendation.** Innovative hydraulic designs of such structures should be widely published by agencies responsible for their design. Attainable storage-discharge rating curves should be included that promote extended detention for water-quality control while releasing flood volumes within prescribed drawdown time limits. Design templates should also be provided.
10. **Conclusion.** Site-specific hydrologic data are needed for efficient (i.e., cost-effective and within performance constraints) design of BMP and LID facilities. Such data include infiltration rates, ET values, soil moisture and bulk density, losses in nonconcentrated overland flow situations, and precipitation records. The goal is to make the best water balance estimates possible. Thus, even if EMC reduction is subject to great variability, some insurance of protection of receiving water may still be obtained through hydrologic source controls, whenever it is possible to significantly reduce runoff volumes.

    **Recommendation.** Measure infiltration rates (e.g., with a double-ring infiltrometer) on-site, and use the nearest precipitation and ET records available. Because soil characteristics are notably heterogeneous, perform the relatively inexpensive infiltrometer tests at enough locations to characterize the catchment and/or BMP/LID facility. Postconstruction infiltration data should also be collected to check for the need for soil amendments or tilling.
11. **Conclusion.** Infiltration estimates for BMP and LID facilities depend not only on soil type and land use but on the nature of disturbances and construction in the vicinity of the project, especially near highways. Although infiltrometer and other hydrologic data are seldom collected during highway construction, geotechnical data on compaction, grain size distribution (sieve analyses), bulk density, and other soil properties often are collected.

    **Recommendation.** Research is needed to relate data commonly collected at construction sites to hydrologic data needed to assess BMP/LID performance. The studies by Pitt et al. (1999, 2001) are examples of addressing such needs.
12. **Conclusion.** The lack of consistent precipitation records at 15-min intervals and 0.01-in. resolution hampers continuous modeling of small, flashy, highly impervious catchments such as highways. The available 15-min, 0.1-in. resolution data are insufficient to evaluate systems with times of concentration and water parcel travel times that are often less than 15 min. Microstorm peaks can be missed when rain gauges tip only at every tenth of an inch.

    **Recommendation.** Encourage the National Weather Service and other agencies to record precipitation data at 15-min or more frequent intervals at the 0.01-in. resolution because such records would be very useful to drainage engineers. The 0.01-in. data at 5-min intervals of some regional networks (e.g., Portland, Oregon) are much better for assessment and design.

### 11.3.3 Modeling Needs

1. **Conclusion.** Regulatory agencies typically rely on single-event modeling techniques (e.g., SCS methods TR-55,

TR-20) or less-sophisticated methods (e.g., Rational Method) to determine BMP effectiveness. Continuous simulation models, although they are the most complicated analysis option, offer great advantages (that the project team believes to be essential) related to annual performance estimates of BMP/LID facilities. For instance, percent control of annual runoff volume can be estimated directly from such models, which is not possible with any level of accuracy with a design storm approach. Continuous simulation models are well documented and readily available to the engineering community.

**Recommendation.** Highway-drainage engineers and related professionals should use state-of-the-art tools to refine their design methods. A bridge between the design storm approach and the continuous modeling approach should be developed to ease the transition to the latter. Continuous models can be incorporated into spreadsheet or other decision support systems along with preprocessed local precipitation data and other local data.

2. **Conclusion.** While very good hydrologic and hydraulic continuous simulation models suitable for highways and urban areas are available in the public domain (e.g., HSPF, HEC-HMS, and SWMM), these models are not as capable at simulating most treatment processes as models designed specifically for simulation of fundamental treatment processes in wastewater treatment plants. Moreover, often in hydrologic and hydraulic simulation models (including proprietary stormwater models) water quality is not simulated at all (e.g., HEC-HMS). The urban/drainage engineer is often required to simulate BMP quality performance and needs reliable tools for this purpose.

   **Recommendation.** Simulation models of the type mentioned above should be enhanced for the urban and highway-drainage engineer for more accurate simulation of physical, biological, and chemical unit operations within water-quality control facilities for stormwater and urban runoff in general. If unit process approaches are not well-enough documented for the problem at hand, then more refined empirical approaches should be included.
3. **Conclusion.** The fate and transport of sediment as stormwater passes through a BMP is critical for evaluation of the removal performance of most BMPs for many parameters of concern. This is particularly true for treatment trains, in which upstream devices may perform the bulk of the particulate removal.

   **Recommendation.** Stormwater models need to be enhanced for better simulation of scour, deposition, and transport of sediment in urban and highway settings. Particulates should be tracked as they progress through a treatment train.
4. **Conclusion.** The output of continuous simulation models often includes only long-term hydrographs and pollutographs with some additional statistical summaries. The output of such models could easily be coupled with optimization techniques that can seek least-cost control strategies within specified constraints. The spreadsheet model of Heaney and Lee (2006) demonstrates such model integration within a simplified simulation/optimization framework.

   **Recommendation.** Enhance continuous simulation models by incorporating optimization techniques directly into the models so that the optimizer can direct the simulation trials toward the best solution.
5. **Conclusion.** Generalized performance results for BMPs as a function of hydrologic inputs have been produced as part of this study (see Chapter 7 and Appendix C of the *Guidelines Manual*). However, regionalization was based solely on meteorological parameters such as rainfall depth, duration, and interevent time (Driscoll et al. 1989). Regionalization of runoff quantity and quality results should be based on a coupling of meteorological characteristics and hydrological and water-quality characteristics of the catchment.

   **Recommendation.** Research should be performed to develop regionalization or other clustering parameters based not only on rainfall but on catchment characteristics (e.g., time of concentration), residence time in BMP storage, soil types, traffic density/type, etc., as these catchment characteristics are determined to be applicable for this purpose. Selection of MIT for separation of quantity and quality events can also depend on these factors.

### 11.3.4 General

1. **Conclusion.** The authors of this report have observed something of a separation between water-resources and environmental professionals in the highway arena and water-resources and environmental professionals in the broader urban setting. Highway professionals communicate primarily through the annual Transportation Research Board conference and in the *Transportation Research Record*, whereas similar professionals within the urban drainage community tend to communicate through the American Society of Civil Engineers (ASCE) and its conferences and journals. (In actuality, both sets of professionals engage more broadly in professional societies and activities than implied here.) Both sets of professionals produce an extensive amount of "gray literature" (e.g., professional reports) that may or may not see wide dissemination outside of these professionals' immediate community. Highway research is often funded by highway-related agencies such as DOTs and the NCHRP,

whereas the USEPA has funded much of the stormwater and urban flows research applicable to the broader urban setting. Highway engineers may find it difficult to deviate from AASHTO standards, even when such deviation is likely to lead to improved stormwater control.

**Recommendation.** Highway engineers and drainage and water-quality professionals in similar urban settings should work toward better communication through common meetings, common journals, and broader acceptance of techniques developed outside their narrower professional circles. In this way, innovation developed within the broad community of water resources and water-quality professionals can benefit all practitioners.

Additional research needs are listed in the final chapter of the *Guidelines Manual* and in Strecker et al. (2005).

*Abbreviations and acronyms used without definitions in TRB publications:*

| | |
|---|---|
| AASHO | American Association of State Highway Officials |
| AASHTO | American Association of State Highway and Transportation Officials |
| ACRP | Airport Cooperative Research Program |
| ADA | Americans with Disabilities Act |
| APTA | American Public Transportation Association |
| ASCE | American Society of Civil Engineers |
| ASME | American Society of Mechanical Engineers |
| ASTM | American Society for Testing and Materials |
| ATA | American Trucking Associations |
| CTAA | Community Transportation Association of America |
| CTBSSP | Commercial Truck and Bus Safety Synthesis Program |
| DHS | Department of Homeland Security |
| DOE | Department of Energy |
| EPA | Environmental Protection Agency |
| FAA | Federal Aviation Administration |
| FHWA | Federal Highway Administration |
| FMCSA | Federal Motor Carrier Safety Administration |
| FRA | Federal Railroad Administration |
| FTA | Federal Transit Administration |
| IEEE | Institute of Electrical and Electronics Engineers |
| ISTEA | Intermodal Surface Transportation Efficiency Act of 1991 |
| ITE | Institute of Transportation Engineers |
| NASA | National Aeronautics and Space Administration |
| NCFRP | National Cooperative Freight Research Program |
| NCHRP | National Cooperative Highway Research Program |
| NHTSA | National Highway Traffic Safety Administration |
| NTSB | National Transportation Safety Board |
| SAE | Society of Automotive Engineers |
| SAFETEA-LU | Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005) |
| TCRP | Transit Cooperative Research Program |
| TEA-21 | Transportation Equity Act for the 21st Century (1998) |
| TRB | Transportation Research Board |
| TSA | Transportation Security Administration |
| U.S.DOT | United States Department of Transportation |

## APPENDIX A

# Acronyms and Abbreviations

| | |
|---|---|
| ADT | (annual) average daily traffic |
| AMC | antecedent moisture condition |
| APRT | average pavement residence time |
| ASCE | American Society of Civil Engineers |
| BOD | biochemical oxygen demand |
| BMP | best management practice |
| Caltrans | California Department of Transportation |
| CAPA | critical aquifer protection area |
| CDM | Camp, Dresser, and McKee |
| CFSTR | continuous-flow, stirred-tank reactor |
| COD | chemical oxygen demand |
| CSO | combined sewer overflow |
| CTR | California Toxics Rule |
| CWA | Clean Water Act |
| CZARA | Coastal Zone Reauthorization Amendments |
| CZMA | Coastal Zone Management Act |
| DCIA | directly connected impervious area |
| DOT | department of transportation |
| EIS | environmental impact statement |
| EMC | event mean concentration |
| EPM | effluent probability method |
| ESA | Endangered Species Act |
| ET | evapotranspiration |
| ETV | environmental technology verification |
| EWRI | Environmental and Water Resources Institute |
| FPC | fundamental process category |
| GIS | geographic information system |
| HEC-HMS | Hydrologic Engineering Center, Hydrologic Modeling System |
| HRT | hydraulic retention time |
| HSPF | Hydrologic Simulation Program Fortran |
| IDF | intensity duration frequency |
| I/I | infiltration and inflow |
| IMP | integrated management practice |
| IPRT | initial pavement residence time |
| IQR | inner quartile range |
| LID | low-impact development |
| MIT | minimum interevent time |
| MS4 | municipal separate storm sewer system |
| NCDC | National Climatic Data Center |
| NDMA | N-nitrosodimethylamine |
| NEPA | National Environmental Policy Act |
| NOAA | National Oceanic and Atmospheric Administration |
| NPDES | National Pollutant Discharge Elimination System |
| NRCS | Natural Resources Conservation Service |
| NSQD | National Stormwater Quality Database |
| NTR | National Toxics Rule |
| NURP | Nationwide Urban Runoff Program |
| ODOT | Oregon Department of Transportation |
| PAH | polycyclic aromatic hydrocarbon |
| PCC | portland cement concrete |
| PDF | probability density function |
| PPCC | probability plot correlation coefficient |
| PSD | particle size distribution |
| PSD$_m$ | particle size distribution based on mass |
| PSD$_n$ | particle size distribution based on number |
| PSD$_v$ | particle size distribution based on volume |
| QA/QC | quality assessment/quality control |
| redox | oxidation-reduction |
| RCRA | Resource Conservation and Recovery Act |
| SBMC | sorptive buoyant media clarifier |
| SC | surface complexation |
| SCS | Soil Conservation Service |
| SDWA | Safe Drinking Water Act |
| SQID | stormwater quality improvement device |
| SSA | specific surface area |
| SSO | sanitary sewer overflow |
| SUDS | sustainable urban drainage system |
| SWMM | Storm Water Management Model |
| TAPE | Technology Assessment Protocol – Ecology |

| | |
|---|---|
| TCE | trichloroethene |
| TDS | total dissolved solids |
| TKN | total Kjeldahl nitrogen = organic nitrogen plus ammonia nitrogen |
| TMDL | total maximum daily load |
| TSC | treatment system component |
| TSP | transportation system planning |
| TSS | total suspended solids |
| UA | urbanized area |
| UIC | underground injection control |
| UOP | unit operation and process |
| USACE | U.S Army Corps of Engineers |
| USEPA | U.S. Environmental Protection Agency |
| USGS | U. S. Geological Survey |
| WaDOE | Washington Department of Ecology |
| WEF | Water Environment Federation |
| WERF | Water Environment Research Foundation |
| WLA | waste load allocation |
| WSRA | Wild and Scenic Rivers Act |