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# Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring



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16. Abstract

This report builds on recent FHWA manuals by expanding and presenting additional data, design criteria, and monitoring study results on stormwater best management practices (BMPs) implemented in ultra-urban areas. An extensive literature search was performed along with a comprehensive analysis of documented information currently available, with the focus on identifying new and successful technologies for ultra-urban areas. Factors used to identify ultra-urban BMP studies included:

- Limited space available for BMP implementation (less than 0.5 ha [1 ac]).
- Drainage area imperviousness greater than 50 percent.
- Property value of land more than $215 per square meter ($20 per square foot).
- Location of BMP in right-of-way (only available space).
- Existence of build-out conditions at the site (lot-line to lot-line development).

The purpose of this report is to provide a planning-level review of the applicability and use of new and more traditional BMPs in ultra-urban areas. This report focuses on the unique characteristics specific to ultra-urban settings and provides specific guidance for selecting and siting stormwater management technologies. The information is structured in an informative, user-friendly format, with case studies highlighting examples of BMP monitoring throughout the country and tables illustrating the characteristics of each BMP to facilitate comparison and identification of specific technologies appropriate to a given site. BMP information is provided in fact sheets, which address applicability, effectiveness, siting and design, maintenance, and cost considerations. The report is organized into separate chapters that address ultra-urban considerations, BMP design information tailored to the ultra-urban environment, monitoring program design, and BMP selection.


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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| NOTE: Volumes greater than 1000 l shall be shown in $m^3$. | | | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5(F-32)/9 or (F-32)/1.8 | Celcius temperature | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.71 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact)** | | |
| °C | Celcius temperature | 1.8C + 32 | Fahrenheit temperature | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

# ULTRA-URBAN BEST MANAGEMENT PRACTICES

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# 1. INTRODUCTION AND PURPOSE

Best management practices (BMPs) are used to mitigate the effects of highways and roads on local conditions, in terms of both water quantity and water quality effects. BMPs are used to reduce peak flows, to reduce runoff volumes, and to reduce the magnitude and concentrations of constituents in runoff. Numerous studies have been done on the effectiveness of BMPs, although past studies have emphasized more traditional BMPs such as wet and dry ponds and vegetative practices. A new, emerging area of BMPs includes technologies for highly urbanized, highly impervious ("ultra-urban") areas. Many of these practices use existing stormwater and wastewater technologies, modifying them to fit into the ultra-urban environment.

The purpose of this document is to provide a planning-level review of the applicability and use of new and more traditional BMPs in ultra-urban areas. This report is the result of extensive research to identify and document BMP practices in ultra-urban areas. The term "ultra-urban" has been used to describe metropolitan areas of the country where space for stormwater BMP implementation is limited (Bell, 1996). The goal of ultra-urban technology is to provide cost-effective, low-maintenance solutions to stormwater management problems in the ultra-urban environment.

This document is not intended to be a design manual. Other recent manuals by the Federal Highway Administration (FHWA) provide design guidance for more traditional BMPs, while design specifications for new, commercially available BMPs can be obtained from their manufacturers. This report supplements the other recent FHWA manuals, which are described below, by expanding and presenting additional data, design criteria, and monitoring study results on BMPs implemented in ultra-urban areas. *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996) was developed to support highway practitioners by synthesizing the results of past documentation and research on highway stormwater runoff into a unified user's manual on water quality impact assessment and mitigation. *Urban Drainage Design Manual Hydraulic Engineering Circular 22* (Brown et al., 1996) was developed to provide a comprehensive and practical guide for the design of storm drainage systems associated with transportation facilities. *Retention, Detention, and Overland Flow for Pollutant Removal from Highway Stormwater Runoff; Volume I: Research Report* (Dorman et al., 1996a) and *Volume II: Design Guidelines* (Dorman et al., 1996b) were developed to provide design guidelines and specifications for measures to reduce or eliminate the impacts of highway runoff on surface waters.

## 1.1 BACKGROUND

The water quality impact of runoff from highways and developed land is an environmental concern that is addressed by both state and Federal Department of Transportation (DOT) personnel tasked with stormwater management responsibilities. A number of current regulatory requirements, at the Federal, state and local levels, set the framework for stormwater management (Young et al., 1996). The box below lists some of the Federal programs which, along with state and local regulatory requirements, need to be incorporated into stormwater management planning considerations. A brief discussion of selected relevant programs is presented below.

The National Environmental Policy Act (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

## Regulatory Framework

- National Environmental Policy Act (NEPA)
- Clean Water Act: National Pollutant Discharge Elimination System (NPDES)
- Clean Water Act: Nonpoint Source Pollution Control Program (Section 319)
- Coastal Zone Act Reauthorization Amendments (CZARA)
- State regulatory requirements
- Local regulatory requirements

process to ensure environmental concerns are considered before implementation.

The Clean Water Act contains the primary mechanism for protecting and improving water quality. The purpose of the Clean Water Act is "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" by declaring unlawful the unregulated discharge of pollutants into all waters of the United States. The Act makes the states and the U.S. Environmental Protection Agency (EPA) jointly responsible for identifying and regulating both point sources and nonpoint sources of pollution. The Act allows for both environmental quality-based approaches (water quality standards) and technology-based approaches (treatment processes and BMPs) to water quality control. Water quality management planning is focused on priority water quality issues in geographic areas. A number of relevant programs operate under the Clean Water Act, including Water Quality Certifications (section 401), the National Pollutant Discharge Elimination System (NPDES) (Section 402), and the Nonpoint Source Pollution Control Program (section 319).

The purpose of section 401 of the Clean Water Act is to ensure that federally permitted activities comply with the Act and appropriate state laws. Any applicant for a Federal permit for an activity that could result in a discharge of a pollutant to a state's waters is required to obtain certification from the state where the activity will occur. The state certifies that the materials or pollutants discharged comply with the effluent limitation, water quality standards, and other applicable state laws.

Amended section 402 of the Clean Water Act authorizes the NPDES program, under which discharge permits are granted by EPA or by states with EPA-approved programs. The NPDES permit program regulates any discharges by point sources, including stormwater discharges (except for agricultural stormwater runoff and return flows from irrigated agriculture) from municipalities serving a population of 100,000 or more. The overall approach to controlling stormwater runoff from local roads and highways is through stormwater management programs developed by municipalities. Many state DOTs participated in the NPDES permitting process where they were designated as permittees by EPA or the states.

In 1987, Congress amended the Clean Water Act to focus greater national efforts on nonpoint sources. Congress enacted section 319, which established a national program to control nonpoint sources of water pollution. Under section 319, states address nonpoint pollution by assessing nonpoint source pollution problems and causes within the state and developing and implementing management programs to control nonpoint source pollutants. The management programs include BMPs for different categories of sources, a schedule of implementation milestones, and appropriate regulatory measures. Section 319 authorizes EPA to issue grants to states to assist them in implementing these management programs.

Congress enacted the Coastal Zone Act Reauthorization Amendments of 1990 (CZARA) to address several concerns, one of which was the impact of nonpoint source pollution on coastal waters. To participate in the CZARA program, each coastal state must develop a Coastal Nonpoint Pollution Control Program for implementing management measures for nonpoint source pollution to restore and protect coastal waters, working in close conjunction with other state and local authorities (USEPA, 1993). The central purpose is to strengthen the links between Federal and state coastal zone management and water

**CZARA Management Measures for Urban Areas**

- Roads, highways, and bridges
- Runoff from developing areas
- Runoff from construction sites
- Runoff from existing development
- On-site disposal systems
- General sources (households, commercial activities, and landscaping)

quality programs and enhance state and local efforts to manage land use activities that degrade coastal waters and coastal habitats. CZARA identified distinct source categories of nonpoint pollution, one of which is urban areas. Areas addressed by the management measures for urban areas are listed in the box below.

Programs developed in response to the Federal regulations vary significantly among states. Activities associated with the construction, operation, and maintenance of roads and highways are also subject to state regulations and programs addressing nonpoint source pollution (USEPA, 1992). Most states have refined their nonpoint source management programs to include BMPs that have proven effective in their area for mitigating water quality impacts. Among the projects most often included in state nonpoint source programs are:

- Production of guidance materials on stormwater management that include the application of BMPs, planning guidance, permitting requirements, and monitoring practices.
- Demonstration projects for particular BMPs under differing land use practices.
- Groundwater and surface water monitoring programs to expand water quality and nonpoint source impact assessments, and provide ongoing water quality data to measure nonpoint source program performance and BMP efficiency.

In large metropolitan areas, watersheds often extend over more than one community and potential problems related to runoff may affect more than one jurisdiction. Intergovernmental cooperation is required in these situations to provide effective stormwater management. Typically in these situations, the local public works agency has the ultimate responsibility for implementation, maintenance, and enforcement of nonpoint source programs. DOTs need to be aware of state and local regulations and their implication for a DOT's activities. Frequently, the DOT will join with local municipalities in developing stormwater management programs and applying for permits. The responsibility for stormwater management related to highway runoff becomes shared between the DOT and the local jurisdictions.

The DOT must determine the relative contribution that its activities make to the total stormwater system within the local jurisdiction and what structural components of the system will be the DOT's responsibility. Once this has been established, the DOT typically determines the runoff volume and constituents associated with these areas, assesses the potential impacts, and establishes a series of structural and nonstructural measures to control the impacts. Establishing the performance of BMPs in ultra-urban areas provides key information for DOT personnel that will aid them in evaluating structural and nonstructural measures.

## 1.2 REPORT DEVELOPMENT

This report was developed based on an extensive literature search and a comprehensive analysis of documented information currently available. Search criteria were used to identify stormwater BMP monitoring studies that address ultra-urban areas. The focus of the data gathering and analysis effort was to identify new and successful technologies for ultra-urban areas. The following factors were used to distinguish between studies addressing ultra-urban BMPs and studies addressing urban BMPs:

- Limited space available for BMP implementation (less than 0.5 ha [1 ac]).
- Drainage area imperviousness greater than 50 percent.
- Property value of land over $215 per square meter ($20 per square foot).
- Location of BMP in right-of-way (only available space).
- Existence of build-out conditions at the site (lot-line to lot-line development).

Also identified was literature that provided the most recent information available addressing some or all of the issues regarding BMP design and evaluation in ultra-urban settings, including issues such as:

- Stormwater quality, particularly highway and roadway runoff characteristics.
- Site considerations.
- Design criteria.
- Constituent removal effectiveness.
- Operation and maintenance requirements.
- Issues related to the design or operation of the system.
- Monitoring protocols and sampling methods.
- Conclusions and possible recommendations for areas of additional study.

The literature review built on previous compilations, including *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996), *Guidance Specifying Management Measures For Sources Of Nonpoint Pollution In Coastal Waters* (USEPA, 1993), *Design of Stormwater Filtering Systems* (Claytor and Schueler, 1996), and *A Review and Evaluation of Literature Pertaining to the Quantity and Control of Pollution from Highway Runoff and Construction* (Barrett et al., 1995), among others, along with original abstract listings with particular emphasis on recent material and reports. Contacts with stormwater personnel across the country, including academic, state and local government, and DOT personnel tasked with stormwater management, were also used to locate recent studies and additional "gray" literature, those monitoring studies that are not identified through the typical literature search process. In addition, design manuals from various jurisdictions across the country and studies evaluating design criteria for stormwater BMPs were reviewed.

The studies identified in the literature review included monitoring done on stormwater BMPs in an ultra-urban setting and monitoring done on BMPs in urban settings applicable to ultra-urban sites. These studies were entered into a database to facilitate review and analysis of the study results and evaluation of new and innovative technologies. This CD-ROM database describes these selected monitoring studies on stormwater BMPs. The information can be accessed in a number of ways: by study title, by location, by general BMP type, by specific BMP type, and by drainage area size.

The identified studies evaluate stormwater BMPs in both urban and ultra-urban settings and address various design factors in both laboratory (bench-scale) and field settings. Relating the results of these studies to other geographic areas of the country requires comparison and evaluation of site conditions and specific factors that affect the effectiveness of stormwater BMPs. Monitoring protocols and data evaluation techniques significantly affect the representativeness of data and their transferability to other regions of the country.

Of the stormwater BMPs evaluated, most of the studies have concentrated on detention/retention ponds and wetlands. However, recent studies on various filtering systems and water quality inlets appear to be broadening the scope of stormwater BMP evaluation. With a limited number of studies conducted on each technology, defining the performance of each BMP in different regional settings is a difficult task. This report focuses on the unique characteristics specific to ultra-urban settings and provides specific guidance for selecting and siting stormwater management technologies in ultra-urban settings.

# 1.3 REPORT ORGANIZATION

This report illustrates various technologies available for use in ultra-urban settings, and it provides specific design criteria and reported effectiveness of various BMPs where possible. The information is structured in an informative, user-friendly format, with case studies highlighting examples of BMP monitoring throughout the country and tables illustrating the characteristics of each BMP to facilitate comparison and identification of specific technologies appropriate to a given site. The report is organized into separate chapters that address ultra-urban considerations, BMP design criteria, monitoring program design, and BMP selection. The reader can review the report in its entirety, or it can be used as a reference for specific areas of interest.

The specific design criteria for each BMP build on the information presented in the FHWA Manuals: *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996), *Urban Drainage Design Manual Hydraulic Engineering Circular 22* (Brown et al., 1996), and *Retention, Detention, and Overland Flow for Pollutant Removal from Highway Stormwater Runoff; Volume II: Design Guidelines* (Dorman et al., 1996b). When appropriate, and to avoid redundancy between the documents, the reader is referred to the FHWA manuals and other selected sources for additional design information.

Chapter 2 presents the characteristics of ultra-urban areas, including stormwater quantity and quality characteristics, land use description, and an overview of BMPs that can be used in ultra-urban areas. The concerns typical of ultra-urban areas are addressed to highlight factors that may need to be considered when siting BMPs in ultra-urban areas.

Chapter 3 includes specific design information, tailored to the ultra-urban environment, for both structural and nonstructural BMP technologies. These criteria can facilitate determination of the feasibility of various BMPs for a given site. The BMP information addresses applicability, effectiveness, siting and design, maintenance, and cost considerations. Comparison tables are provided at the beginning of the chapter, and a section on innovative technologies (those whose performance was still under evaluation at time of publication) is also provided.

Chapter 4 addresses the process of designing a BMP monitoring program through a discussion of the four different phases involved—planning, design, implementation, and program evaluation. A thorough discussion of ultra-urban runoff characterization is provided to aid in targeting specific runoff constituents in the ultra-urban environment. Methods for monitoring the effectiveness of stormwater BMPs are presented, along with data evaluation techniques and quality control measures. Case study examples of selected BMP monitoring studies are provided in Chapter 5.

Chapter 5 contains selected BMP monitoring studies chosen because they illustrate one or more of the objectives of a monitoring program discussed in Chapter 4, and provide excellent examples of the type of information that can be gained from a BMP monitoring program.

Chapter 6 uses the information presented in the previous chapters to present a decision-making framework for effectively selecting BMPs, based on the goals and objectives of the program, siting considerations, and implementation costs.

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# 2. STORMWATER MANAGEMENT IN THE ULTRA-URBAN ENVIRONMENT

## 2.1 INTRODUCTION

The objective of this chapter is to provide a description of the characteristics of the ultra-urban environment and the types of best management practices (BMPs) typically found in ultra-urban areas. To characterize ultra-urban areas, water quality constituents typically found in stormwater runoff are defined. An overview of typical urban stormwater BMPs is presented, along with a description of the physical characteristics and BMP design considerations specific to the ultra-urban environment. Additional design criteria for each technology are presented in Chapter 3.

Federal, state, and local agencies responsible for watershed management and pollution control programs are increasingly becoming aware of the significant effects that urbanization has on the natural balance between stormwater runoff and the ecosystem of wetland and stream systems. Land use changes from agricultural to urban (urbanization) result in the conversion of pervious spaces, such as vegetated and open forested areas, to increased areas of impervious surface, resulting in increased runoff volumes and pollutant loadings.

As urbanization occurs, the quantity of stormwater runoff from the surrounding watershed increases due to the reduction in the amount of pervious spaces available to infiltrate rainwater and snowmelt. The greatly increased runoff volumes and the subsequent erosion and sediment loadings to surface waters that accompany these changes are of concern. Hydrologic and hydraulic changes result from site clearing, grading, and the addition of impervious surfaces and maintained landscapes. Hydrological changes to the watershed are directly related to an increased amount of impervious surface. Roads, parking lots, sidewalks, rooftops, and other impervious surfaces decrease the infiltrative capacity of the ground and result in changes to peak runoff frequency, time to peak, runoff volume, and runoff velocity, disturbing the receiving stream channel and wetlands. Stream channels respond by either increasing their cross-sectional area to accommodate the higher flows or down-cutting the channel. This channel instability begins a cycle of streambank erosion and habitat degradation, and may increase the frequency and severity of flooding.

In response to these detrimental ecological stresses that urbanization places on a watershed, BMPs have been developed to reduce water quantity impacts and water quality constituents normally associated with stormwater runoff from urbanization. The "ultra-urban" environment (a term coined by the city of Alexandria, Virginia; see box below) has been used to describe metropolitan areas of the country where space for stormwater BMP implementation is limited. These heavily urbanized areas present special challenges to those responsible for stormwater management. Stormwater management in these ultra-urban areas may necessitate retrofits to existing stormwater control and conveyance systems.

### The Ultra-Urban Environment

Alexandria, Virginia, is one of the most densely populated cities in the U.S. Most of the land is already developed, in many cases with lot-line to lot-line structures. Property values are also extremely high (over $215 per square meter or $20 per square foot). For these conditions, which exist in the heavily urbanized portions of most metropolitan areas, the city staff coined the term, "ultra-urban environment." (Bell et al., 1998)

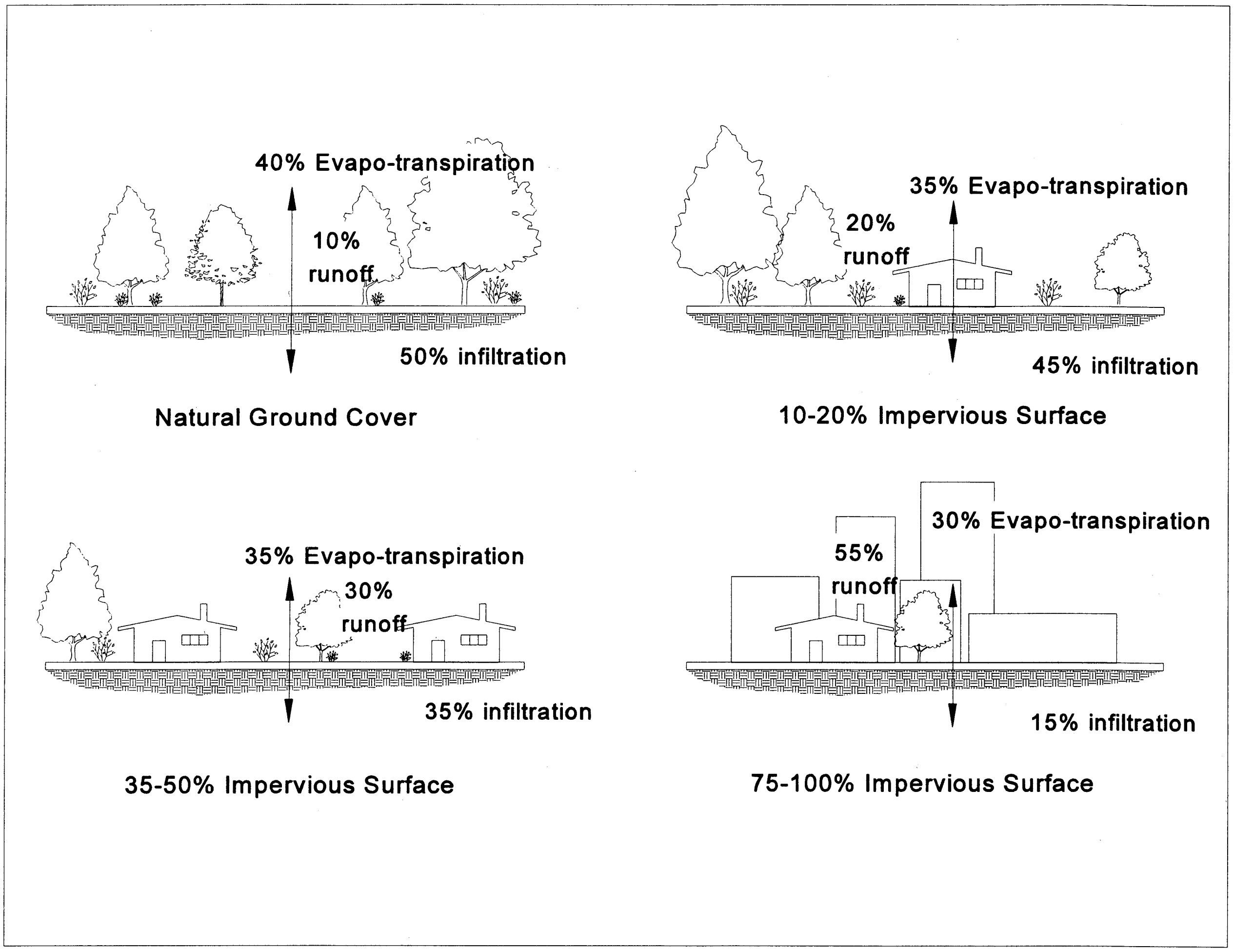


**Figure 1. Changes in runoff flow resulting from increased impervious area (adapted from North Carolina Department of Natural Resources and Community Development, as cited in Livingston and McCarron, 1992)**

## 2.2 THE ULTRA-URBAN ENVIRONMENT

Ultra-urban areas are characterized by high densities of paved surfaces or buildings that result in a high degree of imperviousness. Buildings, parking facilities, urban streets, highways, or walkways cover a majority of the land area, with imperviousness typically greater than 50 percent in ultra-urban areas, and up to 100 percent in some cases. These impervious surfaces can provide an effective environment to collect and accumulate constituents from atmospheric deposition, vehicular traffic, or other sources. Figure 1 illustrates these changes in runoff resulting from increased impervious area. High runoff conditions efficiently transport many water quality constituents. Several factors have been identified as major influences on the types of constituents and their concentrations in urban runoff. Among these are site-specific characteristics, such as land use practices. Ultra-urban areas typically contain higher population densities. These areas exhibit high levels of trash and debris, which tend to clog stormwater control structures and pollute receiving streams. In addition, the pets of the people living in ultra-urban areas are a potential concern since they deposit fecal matter in the urban environment. This fecal matter is washed off during storm events and contributes pathogenic bacteria to stormwater runoff.

Traffic characteristics are another major influence on constituent loadings in stormwater runoff. Though mass transit methods such as subways are frequently implemented in ultra-urban areas, automobile usage is typically very high. Traffic densities are highest in urban areas, due to commuter traffic and people traveling to commercial/business areas for personal business. Increased automobile usage contributes to the constituent loadings deposited in the urban environment.

Identifying these constituent sources aids in characterizing the runoff from ultra-urban areas. This information helps to determine the most effective technologies for removing constituents from stormwater runoff, one key element in determining the type of BMP necessary to achieve water quality benefits. Fish and aquatic life concerns may also be relevant to BMP selection in some areas. Lack of oxygen and high temperatures are inter-related and very important for aquatic life. For fish and other aquatic life, temperature can be one of the most significant pollutants and presents difficult challenges in ultra-urban areas.

### 2.2.1 Target Water Quality Parameters

The characteristics of highway runoff have been the focus of several studies (Barrett et al., 1995). Stormwater runoff from roadways and impervious surfaces in heavily developed areas has been shown to contain significant levels of constituents such as street litter, animal and bird waste, atmospheric deposition, and inputs from urban road runoff (Shaver, 1994). Among the constituents found in highway runoff are particulates, chromium, copper, cadmium, lead, nickel, nitrogen and phosphorus, zinc, manganese, petroleum hydrocarbons, and rubber. A list of these constituents and their primary sources is included in Table 1.

Major sources of constituents on highways are vehicles and atmospheric deposition. Vehicles generate water quality constituents on highways both directly and indirectly. Vehicles contribute constituents directly from normal operation and wear of frictional parts. Cars and other vehicles were suggested as the source of over 50 percent of the total load to the Lower San Francisco Bay of three metals—copper, cadmium, and zinc (Woodward Clyde, 1992). Reportedly, tire wear could account for at least half of the total cadmium and zinc loads deposited in the bay each year, with the copper load being linked to brake pad wear.

**Table 1. Constituents and sources in highway runoff**

| Constituent | Source |
|---|---|
| Particulates | Pavement wear, vehicles, atmospheric deposition, maintenance activities |
| Nitrogen, Phosphorus | Atmospheric deposition and fertilizer application |
| Lead | Leaded gasoline from auto exhausts and tire wear |
| Zinc | Tire wear, motor oil, and grease |
| Iron | Auto body rust, steel highway structures such as bridges and guardrails, and moving engine parts |
| Copper | Metal plating, bearing and brushing wear, moving engine parts, brake lining wear, fungicides and insecticides |
| Cadmium | Tire wear and insecticide application |
| Chromium | Metal plating, moving engine parts, and brake lining wear |
| Nickel | Diesel fuel and gasoline, lubricating oil, metal plating, bushing wear, brake lining wear, and asphalt paving |
| Manganese | Moving engine parts |
| Cyanide | Anti-caking compounds used to keep deicing salts granular |
| Sodium, Calcium, Chloride | Deicing salts |
| Sulphates | Roadway beds, fuel, and deicing salts |
| Petroleum | Spill, leaks, antifreeze and hydraulic fluids, and asphalt surface leachate |

Adapted from USEPA, 1993.

Metals that are strongly linked to cars, such as cadmium and copper, are found to have higher concentrations in runoff from streets and parking lots and minimal concentrations in roof and lawn runoff. Fish are very sensitive to metals such as copper. Vehicles can also pick up and carry solids from parking lots, urban roadways, construction sites, farms, and dirt roads and deposit them onto urban streets (Barrett et al., 1995). Through this indirect mechanism, vehicles can contribute solids and associated water quality constituents to highway surfaces. The results of several studies characterizing highway runoff constituent concentrations are presented in Table 2.

**Table 2. Constituents of highway runoff**

| Parameter | Concentration[1] |
|---|---|
| Total Suspended Solids (TSS) | 45-798 |
| Volatile Suspended Solids (VSS) | 4.3-79 |
| Total Organic Carbon (TOC) | 24-77 |
| Chemical Oxygen Demand (COD) | 14.7-272 |
| Biochemical Oxygen Demand (BOD) | 12.7-37 |
| Nitrate+Nitrite ($NO_3$+$NO_2$) | 0.15-1.636 |
| Total Kjeldahl Nitrogen (TKN) | 0.335-55.0 |
| Total Phosphorus as P | 0.113-0.998 |
| Copper (Cu) | 0.022-7.033 |
| Lead (Pb) | 0.073-1.78 |
| Zinc (Zn) | 0.056-0.929 |
| Fecal coliform (organisms/100 ml) | 50-590 |

Ranges of average values reported in the literature (Barrett et al., 1995).

[1] mg/L unless otherwise indicated.

Several factors affect overall constituent loadings in street runoff. Street runoff is strongly influenced by emissions and leaks from vehicular traffic. Streets are usually directly connected to stormwater drainage systems by curb and gutter. Curb and gutter systems are not very effective at trapping and retaining fine particles that are deposited in them. Often these particles are washed into storm drains.

Disconnecting impervious surfaces and directing runoff from impervious surfaces to pervious surfaces can provide the opportunity for infiltration of stormwater runoff, reducing both stormwater quantity and constituent loading to the receiving stream. Unfortunately, there are limited opportunities for directing stormwater runoff to pervious surfaces in the ultra-urban environment since most of the land area is already covered with impervious surfaces.

In one study, Bannerman et al. (1993), streets were identified as a significant source of urban constituents in residential, commercial, and industrial areas. The study collected over 300 runoff samples from 46 micro-sites in two watersheds, sampling runoff from lawns, driveways, rooftops (residential and flat industrial), commercial and industrial parking lots, and a series of street surfaces (feeder, collector, and arterial). Streets produced some of the highest concentrations of phosphorus, suspended solids, bacteria, and several metals. In addition, streets generated a disproportionate amount of the total runoff volume from the watershed. Parking lot areas had moderately high concentrations of all constituents.

Other studies have found the concentrations of some of the metals and nutrients significantly correlated with that of total suspended solids (TSS). These results suggest that controlling TSS may result in reducing other constituents with the same particle sizes. The City of Austin (1990) found the event mean concentration (EMC) values of total phosphorus (TP), total Kjeldahl nitrogen (TKN), total organic carbon (TOC), lead (Pb), and zinc (Zn) are related to the values of TSS EMC. This correlation indicates that these constituents may be removed along with the particulates by filtration technologies such as sand filters.

The impact on the environment from the use of road salt or other deicing agents is another issue to address when characterizing runoff from streets and highways. Although sodium chloride, typically used as the primary chemical deicer in northern states, is an inexpensive and effective choice, concerns have been raised about the potential negative impacts (from chloride) on the environment, human health, roadway infrastructure, and vehicles. The Michigan Department of Transportation identified some of

### Potential Impacts of Road Salt

- Contamination of drinking water supplies.
- Corrosion of automobiles.
- Corrosion of bridges and other infrastructure.
- Damage to vegetation within 15.2m (50 ft) of roadside.
- Temporary reduction in soil microbes, followed by summer recovery.
- Sensitivity of various deciduous trees.
- Attraction of deer to salts on roadways, increasing the risk of accidents.
- Stratification of small lakes, hindering seasonal turnover.
- Secondary components (3 to 5 percent of road salt composition) include nitrogen, phosphorus, and metals in concentrations exceeding those in natural waters. (Public Sector Consultants, 1993)

these impacts in a recent study (Public Sector Consultants, 1993), and those potential impacts of road salt are listed in the adjacent box.

Stormwater "hotspots" are another issue affecting ultra-urban runoff characterization. Land uses or activities that generate higher-than-normal concentrations of hydrocarbons, trace metals, or toxicants have been defined as "hotspot" areas. Increased constituent loadings from these areas may generate concerns about sediment toxicity, groundwater contamination, or toxicity in receiving surface waters. More effective stormwater treatment may be required in these areas. A preliminary list of potential stormwater hotspots is included below (Claytor and Schueler, 1996):

- Airport deicing facilities.
- Auto recycler facilities.
- Commercial nurseries.
- Commercial parking lots.
- Fueling stations.
- Fleet storage areas (bus, truck).
- Industrial rooftops (depending on the roof surface).
- Marinas.
- Outdoor container storage of liquids.
- Outdoor loading/unloading facilities.
- Public works storage areas.
- Vehicle service and maintenance areas.
- Vehicle and equipment washing/steam cleaning facilities.

Identifying "hotspot" areas will aid in determining the most effective BMP, in terms of constituent removal capability, in addition to determining the most appropriate location for the BMP. While the physical characteristics of ultra-urban areas help determine the water quality constituents contained in stormwater runoff, these physical characteristics may also limit the feasibility of various BMPs.

## 2.2.2 Urban Stormwater Management

The hydrologic effects of development can cause a multitude of problems, including significant flooding potentially endangering life and property. In the ultra-urban environment, stormwater runoff must be routed efficiently and effectively to minimize flooding. Therefore, when considering BMP alternatives for a specific site, both water quantity and water quality issues are taken into consideration.

Efficient collection and routing of stormwater runoff in ultra-urban areas are essential to minimize localized flooding and provide efficient drainage to properties. Increased impervious surfaces within ultra-urban areas can lead to increases in storm runoff volumes and higher runoff velocity due to increased imperviousness and reduced areas for infiltration of runoff. For example, approximately 55 percent of the rain that falls each year in forested basins in King County, Washington, eventually appears as streamflow; for an impervious basin, approximately 85 to 90 percent of annual rainfall eventually appears as streamflow (King County, Washington, 1996).

In some cases BMPs can be used to mitigate the downstream effects of increased peak flows in receiving waters. For example, detention facilities can help maintain the rate and/or duration of flows at predevelopment levels. The basic concept of a detention facility is to collect water from developed areas and release it at a slower rate than the rate at which it enters the system. The difference between the inflow and outflow is then temporarily stored in a pond or vault. Due to space limitations in the ultra-urban environment, BMPs are frequently designed to provide multiple benefits. Whenever possible, BMPs provide both water quantity and water quality benefits.

Several studies have documented the "first flush" phenomenon, indicating pollutant concentrations tend to be much higher at the beginning of a storm compared to the middle or the end (Barrett et al., 1995). This has led to requirements in some states to capture and treat the "first flush" or water quality volume (WQV) of a storm, typically the first 12.7 mm (0.5 in) of runoff from the impervious area in a drainage basin. Based on this definition of WQV, the WQV for each impervious hectare is just under 126 $m^3$ per impervious hectare (1,800 $ft^3$ per impervious acre). In other states, the WQV of a storm is defined as the first 25.4 mm (1 in) of runoff from the impervious area in a drainage basin. In ultra-urban areas stormwater quality requirements are frequently limited to treating only the WQV of a storm event.

Requirements for design of water quality BMPs vary around the country. For areas of existing development, requirements are not specifically identified because of the constraints of the ultra-urban environment. Local conditions, availability of funding, and problem pollutants vary widely in developed communities. Suitable areas for structural treatment systems are often unavailable in heavily urbanized areas. Retrofitting existing conveyance systems with new BMPs to provide water quality benefits may provide the only opportunity to improve the water quality of receiving streams.

Retrofitting is a process that involves the modification of existing control structures or conveyance systems, initially designed to safely convey or temporarily store stormwater runoff to minimize flooding. Retrofitting existing conveyance systems and installing a new BMP designed for water quantity control and/or water quality treatment is an option used in the ultra-urban environment. These BMPs must fit into the existing storm drain system, and match the existing hydraulic gradient. Ultra-urban BMPs are frequently configured off-line and designed to treat a certain portion (usually the "first flush") of a storm. The remainder of the runoff bypasses the water quality BMP. Where existing development or financial constraints limit the feasibility of locating different BMP options, it might be necessary to evaluate and prioritize various factors to determine the most appropriate retrofit for a particular site.

### 2.2.3 Ultra-Urban BMP Technologies

BMP technologies fall into two distinct categories, as illustrated in the box below. The first group of ultra-urban BMPs are control measures that are mainly associated with structural practices. These BMPs can be installed on-line, retaining and treating the entire storm event, or they can be configured off-line, treating only a portion of the storm event, with the rest of the runoff bypassing the BMP.

**Best Management Practices**

Structural:
- Infiltration technologies, including bioretention
- Ponds and pond/wetland combinations
- Filtering systems
- Vegetated swales and filter strips
- Water quality inlets
- Porous pavements

Nonstructural:
- Street sweeping
- Source controls

Ultra-urban stormwater BMPs focus on the collection, pretreatment, storage, and eventual treatment to remove constituents of a specific quantity, typically the WQV or first 12.7 mm (0.5 in) of runoff from impervious areas. Isolating the WQV of a storm requires the construction of an isolation/diversion weir, set to allow overflow when the BMP is completely full (Bell, 1996). Many BMPs designed to treat only the WQV portion of a storm can be more effective if designed off-line for this reason. These structural BMPs are generally implemented under conditions where land space requirements are considered to be a constraint. Such is the case in an ultra-urban setting, where retrofitting is a common practice.

Structural BMP technologies typically use one or more of the following treatment mechanisms to achieve water quality benefits:

- Detention (particle settling).
- Adsorption (chemical and physical processes).
- Biological removal mechanisms.
- Filtration (physical process).

*Infiltration technologies* include infiltration basins, trenches, and bioretention. Infiltration technologies use the interaction of the chemical, physical, and biological processes between soils and water to filter out sediments and other soluble constituents from urban runoff. As the stormwater percolates into the ground, fine material suspended in stormwater is captured within the soil. The resulting treated runoff percolates through to the groundwater. Infiltration trenches are well-suited to the ultra-urban environment since they can be located completely underground. However, they are limited to areas that have specific soil types and groundwater table characteristics and may have higher maintenance costs because they are completely underground. Bioretention is a relatively new type of infiltration technology potentially suited to ultra-urban areas. Bioretention areas manage stormwater runoff by using a conditioned soil layer that contains a mixture of detritus, humus, and mineral and biological complexes in a shallow depressed area. The soil layer and the microbes living in the soil enhance filtration, and the vegetation aids constituent removal. Since small bioretention areas can be located in medians, parking lot islands, or grassy areas along streets, they are ideal for the constricted ultra-urban environment.

*Detention and retention practices* temporarily store stormwater to control runoff, and settle and retain suspended solids and associated constituents. Stormwater ponds, including retention or wet ponds, dry detention ponds, and pond/wetland combinations, have been the traditional detention and retention practices used to provide both water quantity and water quality control. Generally, dry ponds are designed to provide stormwater hydrologic control through detention and retention or wet ponds are designed with a permanent pool to also provide for treatment of stormwater pollution. Wetlands and shallow marsh systems use the nutrient uptake of vegetation to enhance constituent removal. Ponds are effective technologies for reducing constituent loadings from stormwater runoff. They can be implemented in ultra-urban areas by siting a number of smaller ponds rather than one large pond system to provide some measure of water quality control. Opportunities exist, however, where sufficient land area is available to implement a pond BMP as part of an urban park setting, which provides both aesthetic and educational benefits. Ponds or pond/wetland combinations should be considered as a possibility where these opportunities exist.

*Stormwater filtering systems* have been developed and used successfully in ultra-urban areas due to their relatively small footprint and moderate physical requirements (modest head requirements and no soil restrictions). A number of filtering systems have been developed for use in heavily urbanized areas. These include the Delaware sand filter, Austin sand filter, packed bed filter, leaf compost filter, and vertical sand filter. Each of these filters provides the same basic components: (1) a sedimentation area to retain the largest particles, which may clog the filter medium, and (2) a filter chamber containing the filter medium, that filters and removes soluble constituents. Most stormwater filters are designed to treat only a portion of a storm event, usually the WQV, and therefore are configured off-line. The Delaware sand filter is an example of a stormwater BMP that has been modified to fit into the ultra-urban environment. Its shallow configuration, with the sedimentation and filtration chambers below ground but relatively accessible for periodic maintenance, fits in well with the limited space environment of ultra-urban areas.

*Vegetated practices* include technologies such as grassy swales and filter strips. Vegetated swales and filter strips are designed to capture and filter runoff, with a portion of the runoff infiltrating into the soil. Vegetation is used to enhance biological uptake of stormwater constituents. These BMPs can be easily used along roadway corridors and require minimal maintenance (mowing to maintain vegetation at a certain height). Buffer strips of only a few meters can remove a significant amount of suspended constituents from highway runoff (Yu et al., 1995).

*Manufactured/pretreatment technologies* include water quality inlet BMPs such as oil/grit separators, water quality access holes, and catch basin inserts. Water quality inlets typically use detention to enhance removal of both coarse and fine sediments, trap debris and trash, and separate oil and grease from the runoff. Though most of these technologies are well suited to the ultra-urban environment due to their minimal space requirements and physical restrictions, only limited independent evaluation of these technologies has been performed to date. To maintain their effectiveness, provisions must be made for frequent cleaning and inspection. FHWA has previously not recommended the use of water quality inlet BMPs such as oil/grit separators for highway applications, although they may perform adequately in maintenance yards with proper maintenance after installation. Finally, many states recommend they be considered only for pretreatment applications or as a last alternative.

*Porous pavements* are included in the category of infiltration technologies but are unique in their design. While conventional pavement results in increased runoff, porous pavements allow stormwater to percolate through the pavement and infiltrate into the soil below. Porous asphalt, concrete, and interlocking paving stones allow streets, parking lots, sidewalks and other impervious surfaces to retain their natural infiltrative capacity, while also providing the functional features necessary for automobile and pedestrian traffic. Porous pavements must be correctly sited, designed, and installed, as well as periodically maintained, for them to function properly over their life span. They continue to be studied and evaluated to determine whether any reduction in infiltrative capacity occurs over time due to an accumulation of sediments; the longevity of porous materials is part of this evaluation. Porous asphalt, concrete, and pavers have been used in urban and ultra-urban areas. In the highway setting, porous pavements could be used on shoulders and rest areas or parking areas for cars.

The second group of BMPs are viewed as preventive measures and are to a large extent associated with nonstructural practices. Nonstructural measures, such as streetsweeping, have been implemented in urban areas to reduce constituent loadings in stormwater runoff, thereby reducing the need for more expensive structural measures. In a study of stormwater characteristics for various land uses in the city of Austin (City of Austin, 1990), constituent median EMCs were reduced in areas where streetsweeping occurred at least once per week, versus those areas that did not receive maintenance. Street sweeping technologies, adapted from those used to remove spilled coal and coal dust from along railroad tracks, have recently been used in stormwater management applications and may reduce the need for more expensive structural controls.

The feasibility of various BMP technologies in the ultra-urban environment is limited by particular design considerations specific to each site. Conventional structural BMPs, such as extended detention dry ponds, wet ponds, and infiltration basins are often impractical to implement in ultra-urban environments. With older cities frequently located in river valleys, high water tables and the prevalence of marine clays may preclude the use of infiltration technologies (Bell, 1996). These limitations have generated modifications to existing structural BMPs, and in some cases have led to the design of new BMPs that can properly treat or dispose of urban stormwater constituents.

### 2.2.4 Ultra-Urban Design Considerations

Design considerations determined by the physical characteristics of ultra-urban areas fall into several categories. The considerations for a given ultra-urban site include:

- Space limitations.
- Economic considerations.
- Conflicts with existing utilities.
- Safety issues.
- Maintenance requirements for BMPs.

*Space Limitations:* The limited space available for BMPs can be a result of physical limitations, particularly in retrofit situations where no prior planning for BMP requirements has been performed. Build-out conditions usually exist in metropolitan areas, particularly in older business districts of the cities. Lot line-to-lot line structures are the norm, leaving limited space available for BMP implementation. BMPs are frequently located below ground, often the only appropriate and cost-effective location in ultra-urban areas.

Retrofitting an existing stormwater conveyance system with a water quality BMP involves designing the BMP to fit in with the existing storm drain system. Existing hydraulic gradients between source areas and final discharge to the receiving stream may limit the type of BMP feasible for a specific site. Some BMPs, such as filtering systems, have modest head requirements that can fit into the existing hydraulic gradient of the storm drain system. Head requirements for other BMPs might preclude their application in certain areas.

*Economic considerations* associated with BMP implementation often determine whether to locate installations below ground. Since there is less land available, property values are at a premium. The cost of real estate in areas of high land values and the lost opportunity costs of additional development that must be given up for conventional BMPs located at the surface frequently outweigh the cost of more expensive BMP options such as sand filters. Property values typically are over $215 per square meter ($20 per square foot) in ultra-urban areas (Bell, 1996). Right-of-way width for highways implemented in ultra-urban areas is usually minimized to reduce land requirements. This practice results in limited space available for stormwater BMP implementation. An example illustrating economic considerations in determining the feasibility of various BMP options is shown in the adjacent box.

#### Economic Considerations

A wet pond in Northern Virginia designed to treat 0.4 ha (1 ac) of impervious cover would be required to have a permanent pool volume of approximately 154 $m^3$ (5,500 $ft^3$). With an average depth of 1.5 m (5 ft), the pool would require approximately 102 $m^2$ (1,100 $ft^2$). Factoring in the need for side slopes, storm storage, buffer, access, etc., an area of approximately 232 $m^2$ (2,500 $ft^2$) would be necessary. With typical real estate values in the city of Alexandria of $430 per square meter ($40 per square foot), the real estate value alone of the site would be $100,000. A $25,000 underground sand filter (with no real estate cost since it can be located under a parking lot) appears a very attractive alternative in this situation (Bell, 1996). As a rule, maintenance requirements should also be factored into any evaluation of BMP options.

Locating BMPs below ground may require additional structural measures to ensure stormwater management structures can withstand vehicular traffic in areas where they are implemented. Delaware sand filters are typically designed to be located along the periphery of parking areas. Alaska Marine Lines located Delaware sand filters along the perimeter of a paved area used to ship,

## BMP Installation Costs

The installation of a full-scale multichambered treatment tank (MCTT) at a public works garage in Milwaukee, Wisconsin, was designed to withstand very heavy vehicles driving over the unit. Though construction estimates were $54,000, the actual cost of the unit was $72,000, due in part to the need for additional structural reinforcing and the uncertainties associated with construction of a new device by contractors (Pitt, 1996).

handle, and store cargo containers. Concrete lids (AASHTO H-20) are segmented for ease in removal and cover the complete trench area, with vertical scuppers for stormwater inflow. The lid material is designed to withstand loadings from pedestrians, bicycles, and occasional light vehicles (Spearman and Beard, 1995). An example illustrating the economic considerations resulting from additional structural measures is provided in the adjacent box.

*Conflicts with existing utilities* may also limit opportunities for BMP installation. Utilities are frequently located below ground, which may also be the only feasible location for stormwater BMPs. In ultra-urban environments, water and sewer piping, natural gas lines, and telephone and electrical conduits are frequently located in rights-of-way, also often the only available space for a BMP. The BMP might need to be modified to fit into the space available without disrupting existing utilities, incurring additional design costs. Or the utilities might need to be relocated in order to install the BMP, adding to the construction cost of the installation.

Two main factors concerning *safety issues* should be considered in evaluating the feasibility of various BMP options. First, ultra-urban areas are heavily populated, adding to safety concerns when considering potential BMPs such as ponds, wetlands, and surface sand filters. These open surface systems may require additional measures such as fencing to ensure the safety of the public. Second, locating BMPs underground, often the only feasible location in ultra-urban environments, presents additional maintenance requirements that trigger worker safety regulatory requirements. Depending on the type of BMP, these installations may be considered confined spaces. Confined spaces have specific requirements to ensure safe access to the unit, which must be followed each time the BMP is inspected or maintenance is performed.

*Maintenance requirements* must be carefully planned and implemented when BMPs are located completely below the surface and access is limited to access hole openings or the removal of concrete panels. As previously mentioned, underground BMPs may be considered confined spaces and require additional measures to ensure safe access for inspection or maintenance. Due to these potential restrictions or additional measures, BMP technologies that require periodic maintenance on an annual or semiannual basis are often preferred to those requiring more frequent maintenance efforts. Difficulty in performing the maintenance (increased level of effort) increases the cost of the required maintenance.

Stormwater management in the ultra-urban environment is determined by a number of different factors, including runoff characteristics, site design considerations, and the feasibility of implementing various BMP options based on these considerations. These factors are interdependent and may restrict the types of BMPs that can be implemented in a given location. The site design considerations and management issues related to each particular site must be analyzed and prioritized to provide sufficient information to evaluate the feasibility of various BMP options.

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# 3. BEST MANAGEMENT PRACTICES IN AN ULTRA-URBAN SETTING

Stormwater BMPs, both structural and nonstructural, have been used to mitigate the effects of stormwater runoff on receiving water bodies. Structural BMP techniques operate by trapping and detaining runoff so that stormwater constituents settle out or are filtered and trapped by the underlying soil or media. The basic mechanisms for removal of constituents are gravity settling, infiltration of soluble nutrients through the soil profile or filter media, or biological and chemical processes. Structural BMPs might use one or more of these mechanisms to achieve constituent removal from stormwater runoff. Nonstructural BMPs are typically "source control" measures, designed to reduce the level of contaminants and their concentrations in stormwater runoff.

## 3.1 OVERVIEW OF BMPs

This chapter presents design guidance to evaluate the different types of BMPs, both structural and nonstructural, and their applicability for a given ultra-urban site. The different BMP technologies have been grouped according to primary treatment mechanisms. The sections are outlined below:

***Structural BMPs***

3.2 - Infiltration Practices/Bioretention
3.3 - Detention and Retention/Wetland Practices
3.4 - Filtration Practices/Sand Filters
3.5 - Vegetated Swales/Filter Strips
3.6 - Water Quality Inlets
3.7 - Porous Pavements

***Nonstructural BMPs***

3.8 - Streetsweeping
3.9 - Other nonstructural BMPs (source control)

***New and Innovative Practices***

3.10 - New and Innovative Practices

Most of the sections contain summary "fact sheets" that give key information on specific BMP technologies and include carefully collected data on applicability, effectiveness, siting and design considerations, maintenance considerations, and cost considerations. The BMP technologies highlighted in the fact sheets are directly applicable to ultra-urban settings or areas directly connected to roadways.

These factors were used to distinguish BMPs applicable to ultra-urban settings and BMPs for urban areas that are applicable, under certain circumstances, to ultra-urban settings:

- Limited space available for BMP implementation (less than 0.5 ha [1 ac]).
- Drainage area imperviousness greater than 50 percent.
- Property value of land over $215 per square meter ($20 per square foot).
- Location of BMP in right-of-way (only available space).
- Existence of build-out conditions at the site (lot-line to lot-line development).

Table 3 provides a brief summary of each of the BMP technologies covered within each section of Chapter 3. The table indicates whether the information has been presented in a fact sheet format or is provided as part of the section, and whether case study evaluations are also presented. Citations are provided within each section for easy reference to detailed design procedures (if applicable), design detail specifications, and studies where technologies have been evaluated.

## Table 3. Overview of BMPs

| Section | | Treatment Mechanism | Common Characteristics | Technologies Addressed/ Fact Sheet (FS) or Case Study (CS) |
|---|---|---|---|---|
| **Structural BMPs** | | | | |
| 3.2 - | Infiltration Practices/Bioretention | adsorption, biodegradation, precipitation | adequate soil media critical | Infiltration Trenches (FS) (CS)<br>Infiltration Basins (FS)<br>Bioretention (FS) |
| 3.3 - | Detention and Retention/Wetland Practices | particulate settling and biological filtering (wetlands) | adequate hydrology and soils required for retention/wetland s | Detention Ponds (FS) (CS)<br>Wetlands/Shallow Marsh Systems (FS)<br>Detention Tanks and Vaults (FS) |
| 3.4 - | Filtration Practices/Sand Filters | straining, adsorption, chemical transformation, microbial decomposition | effective suspended solids removal | Underground Filters (FS) (CS)<br>Surface Filters (FS)<br>Organic Media Filters (FS) (CS) |
| 3.5 - | Vegetated Swales/Filter Strips | infiltration, filtration, adsorption | low cost, easy to install | Dry and Wet Swales (FS) (CS)<br>Vegetated Filter Strips (FS) (CS) |
| 3.6 - | Water Quality Inlets | settling | mainly pretreatment | Oil-Grit Separators (FS)<br>Catch Basin Inserts (FS)<br>Manufactured Systems (FS) |
| 3.7 - | Porous Pavements | infiltration | regular maintenance essential to prevent clogging | Porous Pavement (FS) |
| **Nonstructural BMPs** | | | | |
| 3.8 - | Streetsweeping | physical removal of surface build-up | can be implemented as part of a community-wide program | Street Sweepers (FS) (CS) |
| 3.9 - | Other Nonstructural BMPs | source control | | |
| **New and Innovative Practices** | | | | |
| 3.10 - | New and Innovative Practices | various | under development | Alum Injection Systems, Multi-Chamber Treatment Train (MCTT), Vegetated Rock Filters, Vertical Filter Systems |

Monitoring studies evaluating the effectiveness of various BMP technologies have been collected to provide original information on the effectiveness of the different BMPs. Figure 2 illustrates the location of the various ultra-urban monitoring studies collected during the literature search process. For illustrative purposes only, these BMPs have been grouped into general categories based on their treatment mechanisms. The categories are filtration systems (e.g., sand and organic media filters); infiltration practices (e.g., infiltration trenches and porous pavements); ponds and wetlands; swales and filter strips; and manufactured/pretreatment BMPs. These studies are in-depth reviews of specific BMPs or components of BMPs. Less than 10 percent of the BMP studies included an evaluation of the larger treatment system, where more than one BMP was used in series. Most of the monitoring studies have been concentrated in four areas of the country: Florida; City of Austin, Texas; Washington, D.C. metro area (including Maryland and northern Virginia); and the Puget Sound Region, Washington. Variations in geographic location, climatic conditions, and physical site constraints may have a significant impact on the results of the monitoring evaluations. When reviewing BMP information, it is advisable to consider the location and sites where they were designed and developed.

Nonstructural BMPs are presented in Section 3.9. These BMPs are typically "source control" measures and may include land use planning, materials management practices, infrastructure maintenance, and landscaping practices. Nonstructural BMPs may help to minimize the

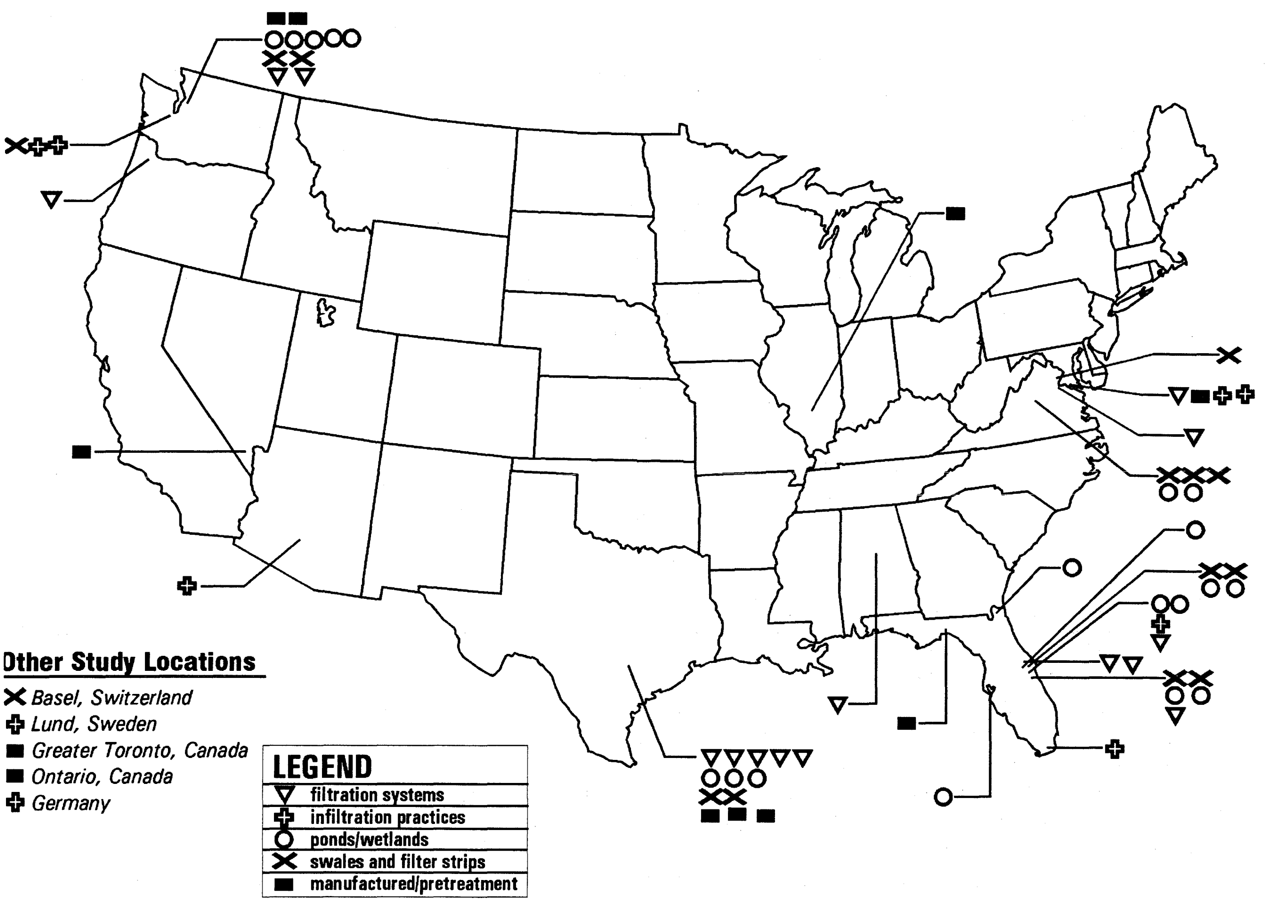


**Figure 2. Location of ultra-urban monitoring studies based on BMP type (number of symbols indicates the number of BMP evaluations)**

need for more expensive structural controls. They are often used together with structural controls to help improve effectiveness.

Section 3.10 addresses new and innovative practices for the ultra-urban environment.

These technologies have received some preliminary evaluation, but the data are insufficient at this time to provide the type of in-depth discussion that is included in the fact sheets presented in subsequent sections.

**Table 4. Site considerations**

| BMP | Area Typically Served (ha) | Area Required for BMP[7] | In Situ Soils | Minimum Head Requirement[1] (m) | Configuration | Climate a Significant Factor?[2] |
|---|---|---|---|---|---|---|
| **Structural BMPs** | | | | | | |
| Infiltration Trench | 0.8-1.6 | 2-4% | dependent | 0.9-2.4 | off-line/on-line | Yes |
| Infiltration Basin | 0.8-8.0 | 2-4% | dependent | 0.9-1.2 | off-line | Yes |
| Bioretention | 0.4-20.0 | 4-10% | independent[3] | 0.6-1.2 | off-line/on-line | Yes |
| Detention Ponds | 0.8 min | 10-20% | independent | 0.9-1.8 | on-line | No |
| Wetlands | 0.4 min | 10% | dependent | 0.3-2.4 | off-line/on-line | Yes |
| Detention Tanks[4] | 0.4-0.8 | 0.5-1% | independent | 1.5-2.4 | off-line | No |
| Underground Sand Filters | 0.8-2.0 | 2-3% | independent | 0.3-2.4 | off-line | No |
| Surface Sand Filters | 0.8-2.0 | 2-3% | independent | 1.5-2.4 | off-line | Yes |
| Organic Media Filters | 0.8-2.0 | 2-3% | independent | 1.5-2.4 | off-line | Yes |
| Vegetated Swales | 0.8-1.6 | 10-20% | dependent | 0.6-1.8 | on-line | Yes |
| Vegetated Filter Strips | <2 | 25%[5] | dependent | negligible | on-line | Yes |
| Oil-Grit Separators | 0.4-0.8 | <1% | independent | 0.9-1.8 | on-line | No |
| Catch Basin Inserts | < 0.4 | None | independent | 0.3-0.6 | on-line | None |
| Manufactured Systems | 0.4-4 | None | independent | 1.2 | on-line | None |
| Porous Pavements | 0.8-1.6 | NA | dependent | NA | NA | Yes |
| **Nonstructural BMPs** | | | | | | |
| Streetsweeping | NA | NA | independent | NA | NA | No |
| **New and Innovative Practices** | | | | | | |
| Alum Injection | 20-80 | <1% | independent | 0 | on-line | No |
| MCTT | 0.1-1.0 | 0.5-1.5 | independent | 1.2-1.8 | off-line | Yes |
| Biofilters (e.g., StormTreat System) | 0.8-2.0 | 2% | independent | 1.2-1.8 | off-line | Yes |
| Vegetated Rock Filters | 0.8-2.0 | 3-5%[6] | independent | 0.6-1.2 | off-line | Yes |

NA = Not Applicable or Not Available

Adapted from Claytor and Schueler, 1996; Young et al., 1996; and others.

[1] Either the depth of water in the typical design or the total drop in water level for flow-through designs.

[2] Climate issues to consider include prolonged drought and freeze periods.

[3] When equipped with an underdrain system.

[4] Based on storage of 12.7 mm (0.5 in) of runoff per acre of imperviousness.

[5] Minimum recommended for best treatment efficiency.

[6] Does not include pretreatment/equalization units required for the design.

[7] Expressed as a percent of the total drainage area, can be modified to accommodate ultra-urban conditions.

These technologies, for the most part, appear promising, and ongoing evaluations may provide confirmation of effective performance. For example, the multi-chamber treatment train (MCTT) has been piloted in a full-scale field setting, with promising results. The monitoring results from an installation at a public works garage in Milwaukee, Wisconsin, should provide additional verification of performance.

To help those involved in the BMP selection process, summary tables (Tables 4, 5, and 6) have been developed to assist in comparing and evaluating the various limitations, constituent removal capabilities, and site criteria associated with different BMP technologies. These tables will also be useful in applying the BMP selection process outlined in Chapter 6.

**Table 5. Management considerations**

| BMP | Capital Costs | O&M Costs | Maintenance | Training[1] | Effective Life[2] |
|---|---|---|---|---|---|
| **Structural BMPs** | | | | | |
| Infiltration Trench | Moderate to High | Moderate | Sediment/ debris removal | Moderate | 10-15 years |
| Infiltration Basin | Moderate | Moderate | Mowing | Low | 5-10 years before deep tilling required |
| Bioretention | Moderate | Low | Mowing/ plant replacement | Low | 5-20 years[3] |
| Detention Ponds | Moderate | Low | Annual inspection | Low | 20-50 years |
| Wetlands | Moderate to High | Moderate | Annual inspection/ plant replacement | Low | 20-50 years |
| Detention Tanks | Moderate to High | High | Frequent cleanout | Moderate | 50-100 |
| Underground Sand Filters | High | High | Annual media removal | Moderate | 5-20 years |
| Surface Sand Filters | Moderate | Moderate | Biannual media cleanout | Low | 5-20 years |
| Organic Media Filters | High | High | Annual media removal | Low | 5-20 years |
| Vegetated Swales | Low | Low | Mowing | Low | 5-20 years |
| Vegetated Filter Strips | Low | Low | Mowing | Low | 20-50 years |
| Oil-Grit Separators | Moderate | High | Frequent cleanout | Moderate | 50-100 years |
| Catch Basin Inserts | Low | Moderate to High | Frequent cleanout | Low | 10-20 years |
| Manufactured Systems | Moderate | Moderate | Periodic cleanout | Low | 50-100 years |

**Table 5. (Continued)**

| BMP | Capital Costs | O&M Costs | Maintenance | Training[1] | Effective Life[2] |
|---|---|---|---|---|---|
| **Structural BMPs (continued)** | | | | | |
| Porous Pavements | Low | Moderate | Semi-annual vacuum cleaning | Low | 15-20 years |
| **Nonstructural BMPs** | | | | | |
| Streetsweeping | Moderate | NA | NA | Low | 4-8 years |
| **New and Innovative Practices** | | | | | |
| Alum Injection | Moderate | Moderate | Periodic chemical resupply | Low | 5-20 years[4] |
| MCTT | High | High | Sand filter cleaning & replacement of oil absorbant material | Low | 5-20 years[4] |
| Biofilters (e.g., StormTreat System) | Moderate | Moderate | Regular cleanout of accumulated sediment/ floatables | Low | 5-20 years[4] |
| Vegetated Rock Filters | High | High | Regular inspection and cleanout | Low | 5-20 years |

NA = Not Applicable or Not Available
Adapted from Young et al., 1996; Claytor and Schueler, 1996; USEPA, 1993; and others.
[1] In confined space entry is required, then training is placed at a moderate level; otherwise, training requirements are low.
[2] Assumes regular maintenance, occasional removal of accumulated materials, and removal of any clogged media.
[3] As a relatively new BMP, the effective life is uncertain. It is reasonable to assume an effective life at least as long as a vegetated swale.
[4] Estimated based on best professional judgement.

**Table 6. Pollutant removal effectiveness (%)**

| BMP | TSS | TP | TN | $NO_3$ | Metals | Bacteria | Oil & Grease | TPH | References |
|---|---|---|---|---|---|---|---|---|---|
| **Structural BMPs** | | | | | | | | | |
| Infiltration Trench[1] | 75-99 | 50-75 | 45-70 | NA | 75-99 | 75-98 | NA | 75 | Young et al. (1996) |
| Infiltration Basin[1] | 75-99 | 50-70 | 45-70 | NA | 50-90 | 75-98 | NA | 75 | Young et al. (1996) |
| Bioretention[1] | 75 | 50 | 50 | NA | 75-80 | NA | NA | 75 | Prince George's County (1993) |
| Detention Ponds[4] | 46-98 | 20-94 | 28-50 | 24-60 | 24-89 | NA | NA | NA | City of Austin (1990); City of Austin (1995); Harper & Herr (1993); Gain (1996);Martin & Smoot (1986);Young et al. (1996); Yu & Benelmouffok (1988); Yu et al. (1993 & 1994) |
| Wetlands | 65 | 25 | 20 | NA | 35-65 | NA | NA | NA | USEPA (1993) |
| Detention Tanks | NA | NA | NA | NA | NA | NA | NA | NA | |
| Underground Sand Filters | 70-90 | 43-70 | 30-50 | NA | 22-91 | NA | NA | NA | Bell et al. (1995); Horner & Horner(1995); Young et al. (1996) |
| Surface Sand Filters | 75-92 | 27-80 | 27-71 | 0-23 | 33-91 | NA | NA | NA | City of Austin (1990); Welborn & Veenhuis (1987) |
| Organic Media Filters | 90-95 | 49 | 55 | NA | 48-90 | 90 | 90 | 90 | Claytor and Schueler (1996); Stewart (1992); Stormwater Management (1994) |
| Vegetated Swales | 30-90 | 20-85 | 0-50 | NA | 0-90 | NA | 75 | NA | City of Austin (1995); Claytor and Schueler (1996); Kahn et al. (1992); Yousef et al. (1985); Yu & Kaighn (1995); Yu et al. (1993 & 1994) |
| Vegetated Filter Strips | 27-70 | 20-40 | 20-40 | NA | 2-80 | NA | NA | NA | Yu and Kaighn (1992); Young et al. (1996) |
| Oil-Grit Separators | 20-40 | <10 | <10 | NA | <10 | NA | 50-80 | NA | Young et al. (1996) |
| Catch Basin Inserts | NA | NA | NA | NA | NA | NA | up to 90 | NA | King County (1995) |
| Manufactured Systems | NA | NA | NA | NA | NA | NA | up to 96 | NA | Bryant et al. (1995) |

**Table 6. (Continued)**

| BMP | TSS | TP | TN | $NO_3$ | Metals | Bacteria | Oil & Grease | TPH | References |
|---|---|---|---|---|---|---|---|---|---|
| **Structural BMPs (continued)** | | | | | | | | | |
| Porous Pavements | 82-95 | 60-71 | 80-85 | NA | 33-99 | NA | NA | NA | MWCOG (1983); Hogland et al. (1987); Young et al. (1996) |
| **Nonstructural BMPs** | | | | | | | | | |
| Streetsweeping[2] | 55-93 | 40-74 | 42-77 | NA | 35-85 | NA | NA | NA | NVPDC (1992) |
| **New and Innovative Practices** | | | | | | | | | |
| Alum Injection | NA | 89 | 78 | 14 | NA | NA | NA | NA | Harper (1990)[3] |
| MCTT | 83 | NA | NA | 14 | 95 | NA | NA | NA | Pitt (1996) |
| Biofilters (e.g., StormTreat System) | 95 | 89 | NA | NA | 65-98 | 83 | NA | NA | Allard et al. (1996) |
| Vegetated Rock Filters | 95 | 82 | 75 | NA | 21-80 | 78 | NA | NA | DRMP (1995) |

NA = Not Applicable or Not Available. Removal efficiencies may be based on either mass balance or average concentration calculations. The values may originate from evaluation of multiple events or from long-term monitoring. Ranges are provided wherever possible.

[1] Based on capture of 12.7 mm (0.5 in) of runoff volume. Effectiveness directly related to volume of captured runoff.

[2] Typical values; actual performance strongly related to the type of equipment, cleaning frequency, and number of passes.

[3] Study examined improvement in water quality within the lake receiving alum-treated stormwater runoff.

[4] Included are results for three different types of ponds: extended detention wet pond, wet pond, and extended detention dry pond.

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# 3.2 INFILTRATION PRACTICES/BIORETENTION

## 3.2.1 Description and Purpose

Bioretention areas, infiltration basins, and infiltration trenches can be classified as infiltration practices. Infiltration basins and trenches mainly use the interaction of the chemical, physical, and biological processes between soils and water to filter out sediments and constituents from stormwater. As an added dimension, bioretention areas use the interaction of plants to enhance the treatment process. Constituents are first absorbed, filtered and transformed by the soil and then taken up by the plant roots. In the ultra-urban environment facilities that incorporate infiltration may be off-line or on-line. Off-line facilities usually capture and treat the "first flush" of stormwater, which contains the highest concentration of pollutants. Larger storm events are diverted around the off-line infiltration facility, perhaps into another management system such as an extended detention pond. On-line facilities pass all of the stormwater through the system.

If the in situ soils in an ultra-urban area possess medium to high infiltration rates, infiltration practices can be extremely effective ultra-urban BMPs for the removal of pollutants, such as metals and nutrients from the stormwater. Bioretention areas and infiltration trenches can be used to serve small drainage areas, or they can be installed in larger drainage areas, such as roadway interchanges, to manage large quantities of runoff.

One of the issues encountered with using infiltration practices as ultra-urban BMPs is the potential for groundwater contamination. Recent research in Europe on a series of infiltration systems that had been installed for 12 to 45 years indicated roadway runoff can influence the concentration of heavy metals and polyaromatic hydrocarbons (PAHs) in the underlying soils. However, this study also found that pollution concentrations decline with depth in the soil column, reaching background levels at soil depths less than 1.5 m (4.9 ft). Furthermore, the pollutants captured in the soil tended not to repartition back into infiltrating stormwater (Mikkelsen et al., 1996). An earlier evaluation of infiltrating stormwater in sandy soil in Florida seems to confirm the capture of certain heavy metals, particularly lead and zinc (McKenzie, 1988). However, where systems infiltrate directly into highly permeable soil (gravelly) layers without passing through fine-grain soil layers, stormwater pollutants appear to have a greater influence on surficial groundwater aquifers (Adolfson Associates, 1995).

## 3.2.2 Design Alternatives

For each of the technologies discussed in the previous section, testing of in situ soils must be done to determine if the infiltration rates of the soils are acceptable. It is important that infiltration trenches and basins have sufficient clearance above the seasonal high groundwater level and any impermeable soil layers (e.g., fragipans). Captured stormwater must be able to infiltrate through all soil layers so that the system will drain before the next storm event. Bioretention area designs are also affected by groundwater levels and in situ soils. However, if there is insufficient clearance above the groundwater or an impermeable soil layer, underdrains can be installed to drain the area.

In an ultra-urban setting, bioretention areas are ideally suited to address water quality issues and can be used for a range of drainage areas. A bioretention area consists of a depressed planted area that retains and infiltrates stormwater through a carefully engineered soil that is typically 1.22 m (4 ft) deep. The depressed area is heavily planted with trees, shrubs, and groundcovers that can withstand urban conditions (e.g., heat, salt, drought conditions) and tolerate frequent inundation. The planted vegetation provides a number of benefits, including a habitat area for urban wildlife. Pretreatment of stormwater flowing into bioretention areas is recommended to remove large debris, trash, and sand.

Infiltration trenches are used primarily to provide water quality treatment for small drainage areas. They can be sited in roadway medians or adjacent to rights-of-way. The trench is filled with large stones, 25 to 75 mm (1 to 3 in) in diameter. The stormwater is stored in the pore space between the stones and then slowly infiltrates into the soils below. The depth of the stones is typically from 1.2 to 2.4 m (4 to 8 ft). Stormwater enters the trench either by sheet flow across the top of the stones or from the outfall of a storm drain system. It is recommended that some type of pretreatment of stormwater, such as a sand filter or oil grit separator, be used to remove sediments from the system. Sediments can reduce the storage capacity and clog the pore spaces of the subsoils, which reduces the infiltration rate into the trench.

Infiltration basins are typically used to manage large volumes of stormwater. Due to the amount of space required, particularly for excavation, infiltration basins typically are limited to roadway interchanges and large residual parcels of land in the right-of-way and may not be suitable for ultra-urban areas. It is recommended that some type of pretreatment, such as buffer strips or a dry, grassed swale, be used to remove sediments from the system.

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# FACT SHEET—INFILTRATION TRENCH

An infiltration trench is an excavated trench that has been lined and backfilled with stone to form a subsurface basin. Stormwater runoff is diverted into the trench and is stored until it can infiltrate into the soil, usually over a period of several days. Infiltration trenches are very adaptable BMPs, and the availability of many practical configurations make it ideal for small (less than 4 ha [10 ac]) urban drainage areas, such as ultra-urban sites. Infiltration trenches can be either on-line or off-line systems. They are most effective and have a longer life cycle when some type of pretreatment is included in their design. Pretreatment may include techniques such as vegetated filter strips or grassed swales.

Infiltration trenches provide the majority of treatment by processes related to soil infiltration, which include sorption, precipitation, trapping, filtering, and bacterial degradation. That the soils surrounding infiltration trenches are effective filters is best indicated by the tendency for these soils to clog if heavily loaded with oil, grease, and sediment. The extent of sorption and filtration is a function of the soil type; for example, highly permeable soils (i.e., sandy soils) usually have low cation exchange capacities (CECs, or the affinity for capturing positively charged pollutants). However, as an infiltration trench is used, fine material suspended in stormwater is captured within the natural soil, creating a more effective filtering matrix and increasing the pollutant removal. Based on the limited information available on chemical/biological changes in the soils surrounding infiltration trenches, the soil/stormwater interaction is complicated and site specific. It is difficult to generalize regarding the extent to which the soils operate aerobically or anaerobically.

## APPLICABILITY

Infiltration trenches are appropriate for ultra-urban applications, particularly subsurface designs that are covered with grating or pavement (Figure 3). Essentially all of the surface above a subsurface infiltration trench can be used as parking or public areas. Unfortunately, subsurface infiltration trenches are relatively expensive BMPs; the expense is due to construction of an underground vault, which must be placed among other subsurface utilities. Surface trench designs can be moderately expensive BMPs and can be easier to construct and operate, but they require greater space commitments because they are usually combined with area-intensive pretreatment such as grass filter strips (Figure 4). Surface infiltration trench designs are better suited to roadside application where space is at less of a premium.

Figures 3 and 4 indicate only two of many possible configurations. Both of these configurations illustrate the essential design features, which include pretreatment of runoff to minimize sediment loading, stormwater storage in a subsurface trench filled with stone, and discharge of all captured stormwater into underlying ground layers.

Both configurations shown in Figures 3 and 4 are *complete trench* designs or designs that discharge all treated stormwater into a highly permeable underlying soil trench. Where a complete trench design is undesirable or not feasible, a *partial trench* design can be employed to infiltrate only a portion of the stormwater runoff. Partial trench designs may incorporate an underdrain system placed several feet below the invert to intercept exfiltrating stormwater. This approach enables trench placement where there are relatively impermeable soils or there is a confining soil layer. As an alternative, a partial trench design can integrate a discharge pipe that limits the storage depth in the trench and routes all surplus stormwater to an outlet. The principal advantage of this design is it permits diversion of high flows and if the soils become clogged stormwater can still be discharged. Partial trenches can also be used as off-line facilities and can easily be retrofitted onto existing subsurface storm drains.

## EFFECTIVENESS

For infiltration trenches, effectiveness is solely a function of the amount of stormwater infiltrated; that is, the only pollutants not treated are those associated with the stormwater that bypasses the trench and are not infiltrated. The pollutants discharged to surficial groundwater aquifers are not generally accounted for in reported removal rates. Projected removal rates reported for two different designs are shown in Table 7.

In variable climates, harsh winter temperatures can freeze the water in infiltration trenches and eliminate the ability of the trench to store and infiltrate water. It is recommended that information on the soil freeze depth be obtained and the trench invert be located below this depth.

## SITING AND DESIGN CONSIDERATIONS

For most ultra-urban applications designers should look for soils with high percolation rates below the proposed trench invert, surficial groundwater aquifers that are not used for drinking purposes, and ample clearance over bedrock. A range of recommendations have been made regarding the minimum permeability of the soil surrounding the infiltration trench; some suggest a minimum infiltration rate of 12.7 mm/h (0.5 in/h) (Yu and Kaighn, 1992; Schueler et al., 1992), but some states accept minimum values of 6.9 mm/h (0.27 in/h) (MDE, 1986). Minimum infiltration rates between 6.9 and 12.7 mm/h (0.27 and 0.50 in/h) are usually associated with loamy sand, sandy loam, loam, and silt loam texture soils; however, site-specific infiltration rates are a function of more than the soil texture. It is recommended that site-specific infiltration be measured in soils located below the proposed invert of the infiltration trench. In addition, soils should be examined to a depth at least 1.52 m (5 ft) below the proposed invert to identify if there are any underlying impermeable soil layers (clay lenses, fragipans, or hardpans). It should be noted that ultra-urban developments are frequently placed on disturbed cut/fill soils. This greatly increases the importance of site-specific infiltration testing.

Designs can be sized to manage a range of runoff volumes to meet specific water quality and quantity objectives. Small-scale units can be designed just to manage the first flush runoff volume; these designs are sometimes referred to as water quality exfiltration systems. Conversely, the size of the trench can be increased to significantly decrease the postdevelopment runoff rates and limit flooding.

While placing infiltration trenches in low permeability soils is questionable, trench designs can be made to work in lower infiltrating soils, but the surface area or size of the trench may become prohibitively large. Designers should note that the invert of the infiltration trench should be at least 1.22 m (4 ft) above underlying bedrock and at least 1.22 to 2.44 m (4 to 8 ft) over the seasonal high groundwater elevation (Yu and Kaighn, 1992). The trench bottom should be rototilled after excavation. The addition of a sand filter layer at the trench bottom should be considered to facilitate movement of water between the stone storage area and the subgrade. Designers considering application of infiltration trenches can roughly estimate 121 $m^2$ (1300 $ft^2$) of trench bottom area (a 1.22 m [4 ft] deep trench) is needed to store 12.7 mm (0.5 in) of runoff from a 0.4 ha (1 ac) impervious service area. In addition, the minimum recommended drain time is 24 hours and the

**Table 7. Estimated pollutant removal effectiveness for water quality trenches (%)**

| TSS | TP | TN | Metals | BOD | Bacteria | Comments |
|---|---|---|---|---|---|---|
| 75 | 50-55 | 45-55 | 75-80 | 70 | 75 | Capture of 12.7 mm (0.5 in) of runoff (first flush) |
| 90 | 60-70 | 55-60 | 85-90 | 80 | 90 | Capture of 50.8 mm (2 in) of runoff |

Source: Schueler (1987).

maximum recommended drainage time is 72 hours. Finally, it is recommended that trenches should be located a minimum of 3.05 m (10 ft) downgradient and 30.5 m (100 ft) upgradient of any buildings and the ground slope should be less than 20 percent. There are several good sources available for detailed design and construction procedures and information, including *Urban Drainage Design Manual Hydraulic Engineering Circular 22* (Brown et al., 1996), *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996), and *Maintenance of Stormwater Management Structures* (MDE, 1986).

## MAINTENANCE CONSIDERATIONS

If appropriate sediment removal pretreatment is not provided, the life expectancy of an infiltration trench may be only five years (Schueler et al., 1992) due to the pore space and trench bottom becoming clogged. With proper regular maintenance, however, a trench may last as long as 10 or 15 years before major rehabilitation of the trench is required (Schueler, 1987). Following installation, frequent inspections are recommended at first, but these can be decreased to twice per year. These inspections should look into water levels in the infiltration trench, clogging of inlets or outlets, and accumulation of sediment in upstream pretreatment units. Immediate failure of the trench might occur if sediment is not directed away from the trench area during construction. Consequently, it is recommended that all upstream areas be stabilized before the trench is constructed.

Failure of an infiltration trench is determined by the continued presence of pooled water three days after rainfall has ended. A failure of this type leads to removal or replacement of part or all of the rock backfill. Surface infiltration trench rehabilitation can be estimated to cost approximately 20 percent of the initial construction costs, whereas rehabilitation of an underground trench can exceed the initial construction cost (Young et al., 1996). Clearly, proper, regular maintenance is essential to avoid costly trench rehabilitation.

Numerous design features can simplify maintenance. An example includes placing a filter fabric on top of the rock media, which can easily be stripped off when it is full of debris.

## COST CONSIDERATIONS

Infiltration trenches are most cost-effective for small drainage areas where space is at a premium and the water quality storage volume is less than 280 $m^3$ (10,000 $ft^3$ or approximately 12.7 mm [0.5 in] of runoff from 2 ha [5 ac]). Trench construction costs (1995 dollars) can be estimated using the following equation where V is the storage volume in cubic meters (Young et al., 1996):

$$C=1317.1\ V^{0.63}$$

This cost estimation is valid only for trenches that have storage volume on the order of 280 $m^3$ (10,000 $ft^3$). This formula does not include the cost of special inlets or grass filters for pretreatment of runoff but does include costs for excavation, backfill, filter cloth, inlet and outlet pipes, and fixtures.

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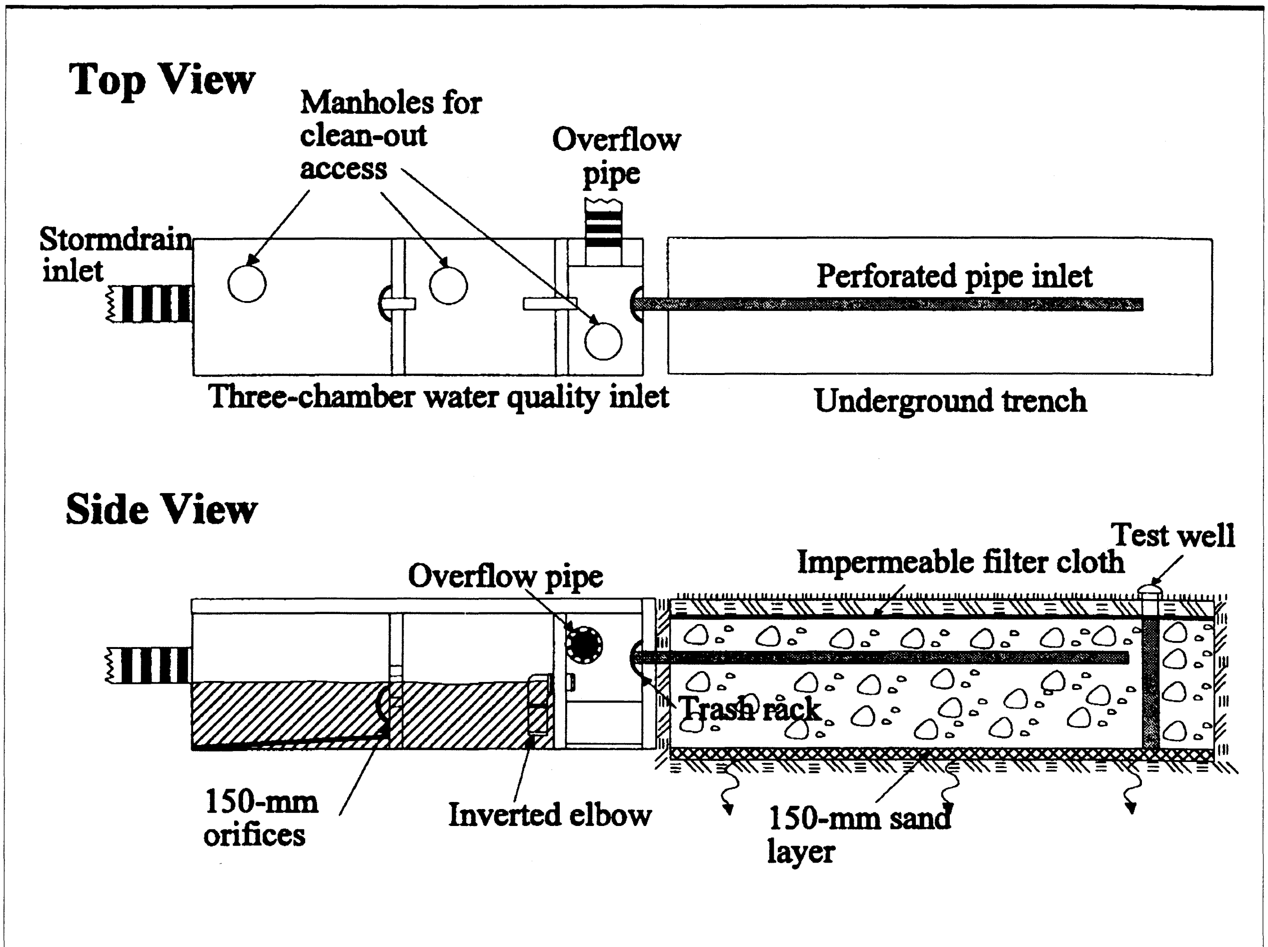


**Figure 3. Underground trench with oil/grit chamber (adapted from Schueler, 1987)**

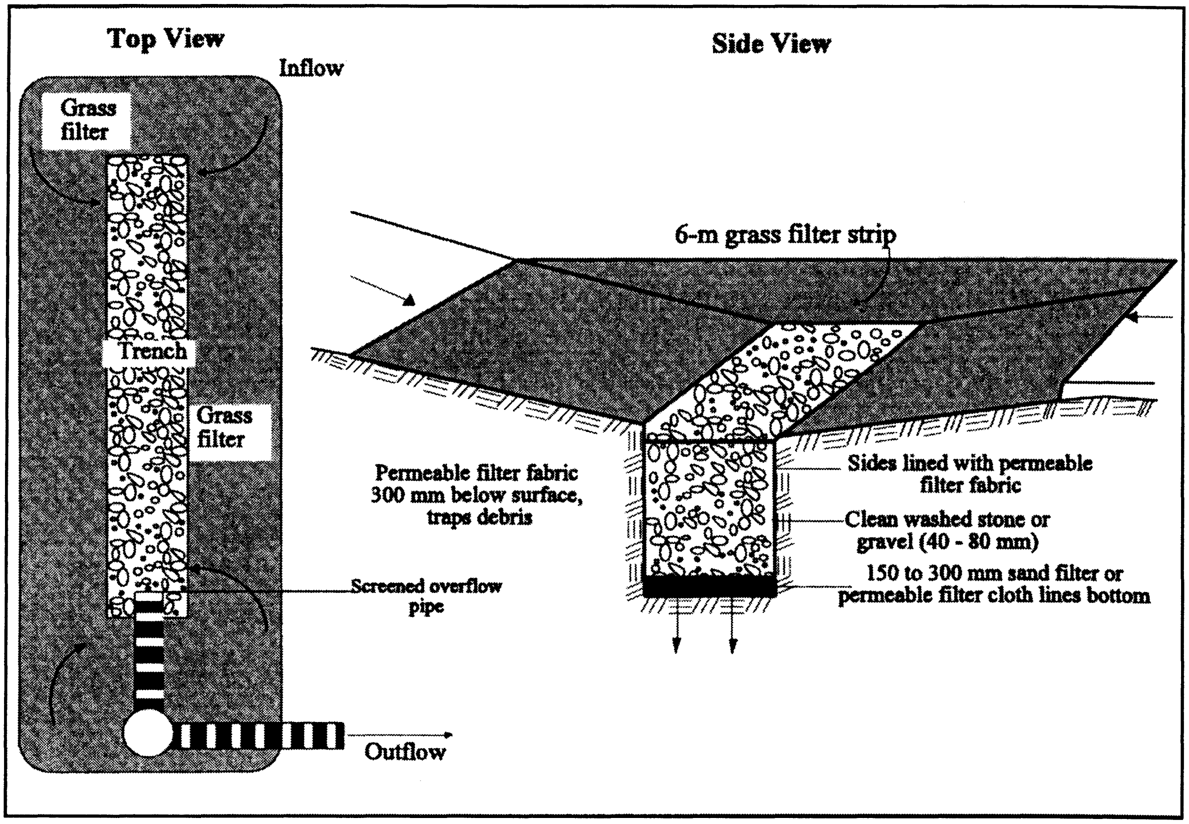


**Figure 4. Median strip trench design (adapted from Schueler, 1987)**

# FACT SHEET—INFILTRATION BASIN

An infiltration basin is a shallow depression created by excavation or berming that captures stormwater and stores it until it can infiltrate into the soil (Figure 5). Infiltration basins typically serve drainage areas from 2 to 20 ha (5 to 50 ac). In an ultra-urban setting it is strongly recommended that they be used in an off-line configuration because sediment accumulation and particulates from stormwater runoff can clog the system. The principal advantages of infiltration basins are that they help preserve the natural water balance of a site, they can serve large or small developments, and they can be integrated into a site's landscaping or open space. If the area served is less than 2 ha (5 ac), an infiltration trench is usually the preferred BMP.

Infiltration basins provide the majority of treatment by processes related to soil infiltration, which include absorption, precipitation, trapping, straining, and bacterial degradation. That the soils below infiltration basins are effective filters is best indicated by the tendency for these soils to clog if heavily loaded with oil, grease, and sediment. The extent of sorption and filtration is a function of the soil type; for example, highly permeable soils (i.e., sandy soils) usually have low cation exchange capacities (CECs, or the affinity for capturing positively charged pollutants). The majority of infiltration basins are placed in highly permeable soils. However, as the basin is used, fine material suspended in stormwater is captured within the natural soil, creating a more effective straining matrix and potentially increasing pollutant removal. There is limited information available on chemical/biological changes in the soils surrounding infiltration basins and the extent to which the soils operate aerobically and anaerobically.

## APPLICABILITY

Infiltration basins are appropriate only where there is ample room for installation. The basin can occupy an area between two and four percent of the upstream impervious area, but can be placed in confined spaces if necessary. These facilities are ideal for siting in interchanges and areas adjacent to roadways. The primary highway application for an infiltration basin is along roadways where runoff conveyed in a grassed swale can be diverted into the basin in areas where groundwater is not used for drinking purposes.

Infiltration basins are a relatively inflexible BMP primarily because a successful design requires soils with a reasonably high infiltration rate. If a high-infiltration-rate soil is not present, then the surface of the basin will become prohibitively large. If the proper soils are present, the designer is free to establish the basin width and length based on local constraints. Infiltration basins can be any shape; in fact, many review agencies are advocating nonrectangular shapes, which create aesthetically pleasing earth forms. Infiltration basins add an aesthetic value to roadside areas as long as they are maintained and litter and debris are regularly removed.

## EFFECTIVENESS

Effectiveness is a function of the fraction of stormwater infiltrated. The amount of stormwater that bypasses the system due to overflow during large storm events or that cannot be absorbed by the system determines infiltration effectiveness. To date, only limited data are available on the intensity and amount of pollutants discharged to surficial groundwater aquifers from infiltration basins. Removal rates (in percent) reported for three different design sizes are shown in Table 8.

In variable climates, harsh winter temperatures can freeze the infiltration basins and when frozen, infiltration basins will not provide pollutant removal. Local meteorologic records should be obtained to verify the mean monthly average low temperature remains above freezing.

**Table 8. Estimated pollutant removal effectiveness for infiltration basins (%)**

| TSS | TP | TN | Metals | BOD | Bacteria | Comments |
|---|---|---|---|---|---|---|
| 75 | 50-55 | 45-55 | 75-80 | 70 | 75 | Capture of 12.7 mm (0.5 in) of runoff (first flush) |
| 99 | 65-75 | 60-70 | 95-99 | 80 | 90 | Capture of 25.4 mm (1 in) of runoff |
| 90 | 60-70 | 55-60 | 85-90 | 80 | 90 | Capture of 50.8 mm (2 in) of runoff |

Source: Schueler (1987).

## SITING AND DESIGN CONSIDERATIONS

Infiltration basins can be installed where there is sufficient surface area and soil infiltration capacity. Given the general lack of open surface area in the ultra-urban setting, infiltration trenches are generally more applicable than infiltration basins. However, infiltration basins can be employed wherever large redevelopment efforts are planned or along roadways where there is sufficient right-of-way available.

Groundwater is one key issue in siting infiltration basins. For ultra-urban applications, the surface aquifer under many municipalities is not used as a drinking water source, however, in some areas it is the surface aquifer directly connected to a drinking water aquifer. Nevertheless, most states or municipalities have developed rules regarding the placement of any facilities that discharge to the groundwater, which must be researched by the designer. As a general rule a minimum buffer between the basin invert and the seasonal high groundwater level of 0.6 to 1.2 m (2 to 4 ft) is typically used in the eastern United States in areas where water table depths are relatively shallow, while 3 m (10 ft) is the buffer distance used in some western states (Dorman et al., 1996).

Infiltration basins can be designed in a number of ways. Often, infiltration basins are designed as stand-alone facilities to provide water quality management—a design that infiltrates the 2-year runoff event. As an alternative, infiltration basins are sometimes combined with detention ponds to provide both stormwater quality and quantity management. This arrangement yields multiple benefits: the detention pond provides pretreatment for the basin and provides flood protection, and the infiltration basin can be located off-line, where it is protected from high flows (Young et al., 1996).

Pretreatment is considered crucial to sustaining the performance of infiltration basins; infiltration basins are often preceded by detention ponds, grassed swales, and filter strips. Additional design examples and information can be found in *Urban Drainage Design Manual Hydraulic Engineering Circular* 22 (Brown et al., 1996), *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996), and *Design and Construction of Urban Stormwater Management Systems* (ASCE, 1992).

The performance of infiltration basins can be improved by keeping the infiltration area large, ensuring the bottom is flat, and vegetating with a dense turf of water-tolerant grass (Livingston, 1995). The actual size of the basin footprint is dependent on long-term meteorologic trends, the site's demonstrated minimum infiltration rate, and the dewatering time.

Construction activities will greatly affect the performance of infiltration basins and the potential for failure. It is critical to install the basin only after the construction site has been stabilized to minimize introduction of fine sediment into the basin. In one study, approximately 40 percent of the investigated basins had partially or totally clogged within their first few years of operation. Many of these systems failed almost immediately after construction (MDE, 1986). During excavation, compaction of the bottom and sides of the infiltration basin must be minimized by using vehicles equipped with oversized tires. The infiltration basin should be marked off or bermed prior to any construction activity to ensure vehicle entrance to the footprint area is not possible.

## MAINTENANCE CONSIDERATIONS

Routine and nonroutine maintenance is required to keep infiltration basins operating effectively. Infiltration basins should be inspected following major storms, especially in the first few months after construction. If stormwater remains in the system beyond the design drawdown time (typically 72 to 96 hours), either the infiltration capacity was overestimated or maintenance is needed.

Routine, periodic maintenance typically involves moderate costs. Periodic maintenance includes removing debris (litter, leaves, brush), mowing the sides and bottom once growth exceeds 0.3 m (12 in) in height, and revegetating eroded or barren areas. However, mowing is not necessary to maintain performance. If mowed, grass clippings should be removed to prevent clogging of the surface. It is recommended that the side wall slope be 3 (horizontal) to 1 (vertical) or flatter to help sustain vegetation, permit access for maintenance, and ensure public safety and ease of mowing. However, side slopes of 2:1 have been used successfully.

Occasionally, nonroutine maintenance or basin rehabilitation may be required, which can be costly, if clogging occurs. As a part of nonroutine maintenance, deep tilling every 5 to 10 years to break up the clogged surface layers followed by regrading and revegetating is recommended. This may include removing any accumulated sediment; sediment removal should be performed only when the soil surface is in a very dry condition to avoid compaction of the basin bottom (Livingston, 1995). For infiltration basins it is important to avoid the use of herbicides and fertilizers on grassed portions of the strip since these applications can directly contribute undesirable pollutants to waterways.

## COST CONSIDERATIONS

Infiltration basins are moderate-cost BMPs. The principal cost to install relates to earth moving and construction costs and installation of inlet systems. The construction cost can be estimated from the following equation, where V is the volume of stormwater managed in cubic meters (Schueler, 1987):

$$C = 13.9\left(\frac{V}{0.02832}\right)^{0.69}$$

Note that the cost estimate obtained should be used for conceptual cost estimating only and is in terms of 1995 dollars.

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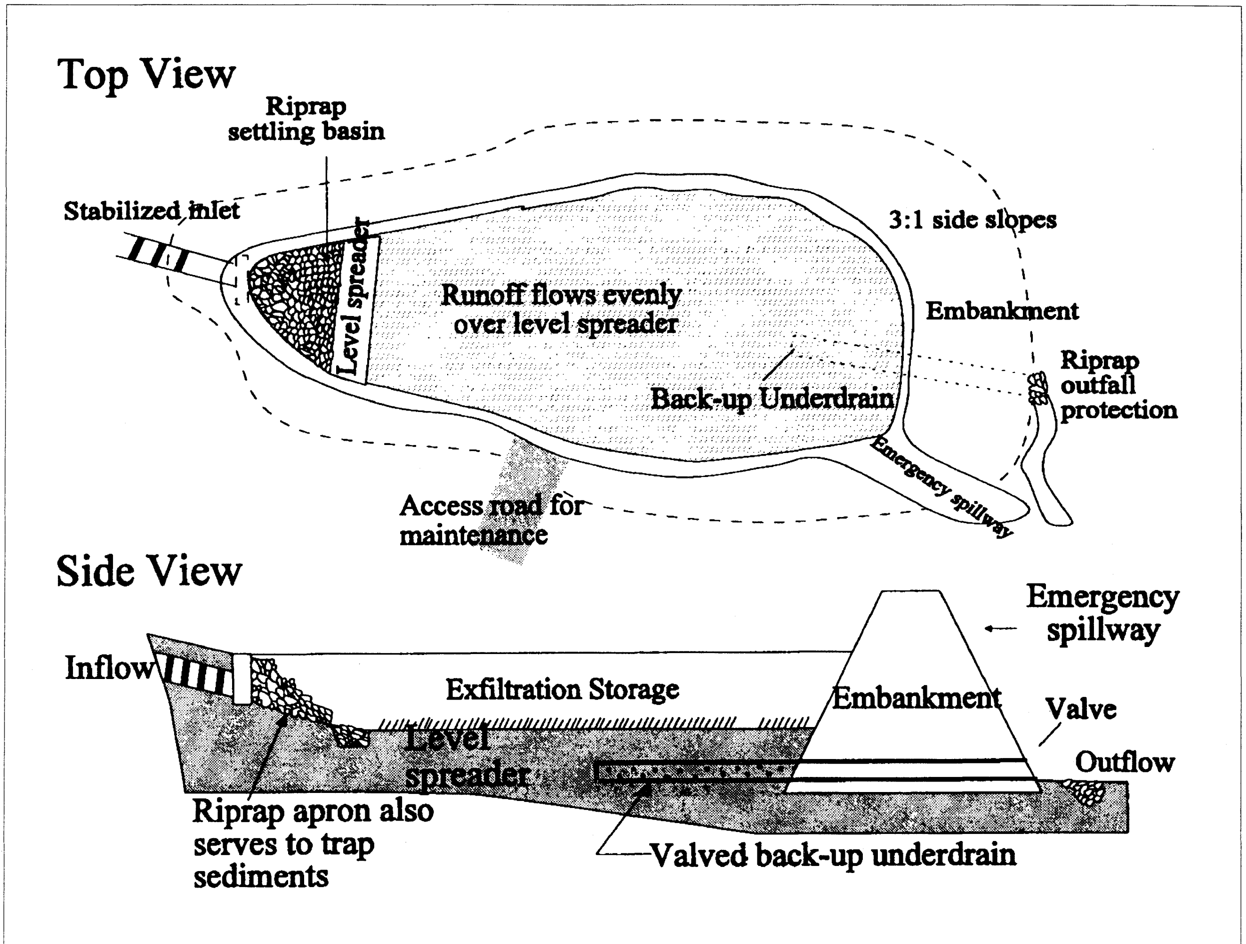


**Figure 5. Schematic of an infiltration basin design (Young et al., 1996)**

# FACT SHEET—BIORETENTION

Bioretention was developed as an innovative approach in the ultra-urban environment. Bioretention areas (BAs) are easy to construct and require less infrastructure maintenance than many other BMPs. In addition to their well-accepted aesthetic value, BAs can be tailored in design and location to fit into the ultra-urban landscape.

Water quality improvements result from sedimentation, filtration, soil adsorption, microbial decay processes, and the uptake of pollutants by plants. The use of vegetation in BAs is modeled from the properties of a terrestrial forest community—an ecosystem dominated by mature trees, subcanopy of understory trees, shrubs, and herbaceous plants. Plants are selected based on their tolerance to varying hydrologic conditions, soil and pH requirements, and general characteristics like aesthetics. An additional important feature of bioretention is the soil in the system, which contains a mixture of detritus, humus, and mineral and biological complexes. The soil layer and the microbes living in the soil enhance infiltration, groundwater recharge, and nitrogen and metals removal; provide valuable water and nutrients for plant growth; and provide oxygen for plant root metabolism and growth.

BAs consist of a flow-regulating structure that processes inflow passing through a shallow depressed planted area containing ground cover (low-lying plant growth or an organic mulch), a planting soil supporting a range of facultative plant types, and a bottom support soil layer. Each of these features has a specific role in stormwater pollutant removal (Figure 6).

## APPLICABILITY

BAs have unique features that make them attractive for use in the ultra-urban environment. They have the ability to fit in existing or proposed medians or grassy areas along streets and parking lots. In addition, by disposing of a significant volume of annual rainfall on-site, BAs may reduce the infrastructure costs required to collect and convey the runoff off-site. BAs can also provide benefits other than stormwater management, including creating green areas and natural habitat. For facilities placed in new developments, the land area requirement and cost can be minimized if the local jurisdiction considers BAs part of the required vegetated open space set-aside or if installed trees count against local landscaping and tree coverage requirements.

## EFFECTIVENESS

Limited monitoring of the effectiveness of BAs has been completed to date although there are ongoing monitoring efforts. Due to the similarity between bioretention technology and dry swales, however, the pollutant removal capability should be comparable (Claytor and Schueler, 1996). For planning purposes it is acceptable to anticipate BAs will remove 50 percent of total phosphorus (TP), 50 percent of total nitrogen (TN), between 75 and 80 percent of metals, and 75 percent of total suspended solids (TSS). Based on the nature of the planting soil and the facultative plants normally installed, BAs should be capable of managing some petroleum hydrocarbon concentrations commonly encountered in urban settings. Pretreatment is not considered crucial to the removal performance of BAs except where there is an atypically high level of pollutant loading, which can harm the planted growth (i.e., heavy commercial or industrial settings).

In variable climates, seasonal differences in removal performance should be anticipated for BAs, due to the growing and dormant periods of plants. Fall and winter temperatures force vegetation into dormancy, thereby reducing uptake of some runoff pollutants. However, carefully selected planting soil should provide significant storage capacity for many common urban pollutants during no/slow growth periods as long as soil infiltration can occur. Freezing temperatures greatly reduce infiltration in BAs and inactivate the most important pollutant removal mechanism.

BAs are intended to be water quality control practices, but they can be employed as either an on-line or off-line design. If BAs are employed as on-line facilities, design features must be incorporated to ensure nonerosive flow velocities exist within the BA. During these larger rainfall events, BAs should provide marginal treatment of the high flow volume (principally large-diameter suspended solids) even though the residence time in most facilities will be short.

## SITING AND DESIGN CONSIDERATIONS

Bioretention is a relatively new technology being refined to achieve maximum water quality benefits. The basic design elements and major components of BAs are discussed below. For design examples and additional information, several good sources are available, including *Design Manual for Use of Bioretention in Stormwater Management* (Prince George's County, 1993), *Design of Stormwater Filtering Systems* (Claytor and Schueler, 1996), and *Highway Runoff Manual* (WSDOT, 1995).

The basic design elements to be addressed are proper soils, vegetation, and drainage. For most ultra-urban applications designers should look for relatively flat areas where deep soils (1.68 m [6 ft] to bedrock) are present and where seasonal high groundwater elevations are at least 1.68 m (6 ft) below grade. Ideally, BAs will discharge collected stormwater into underlying in situ soils and then into the surficial groundwater aquifer. As an option, designers can employ an underdrain system to collect exfiltration from the BA wherever existing deep soil layers will prevent exfiltration. Underdrains are typically placed approximately 1.52 m (5 ft) below grade and must drain by gravity to either an outlet or a storm drain. Underdrain systems can also be used in BAs where they will be placed in close proximity of building foundations. A minimum 9.2 m (30 ft) offset is recommended for BAs without underdrains.

Bioretention facilities combine a number of physical, biological, and hydrologic components to provide complementary functions to improve water quality, control hydrology, and provide wildlife and aesthetic improvements. The major components of the BA are:

- Pretreatment area (optional).
- Ponding area.
- Ground cover layer.
- Planting soil.
- In-situ soil.
- Plant material.
- Inlet and outlet controls.

### Pretreatment Area

Some BA designs incorporate an upstream pretreatment area. Pretreatment is necessary where a significant volume of debris or suspended material will be conveyed by stormwater into the BA; for example, parking lots or commercial areas that are regularly sanded. In Figure 6, a grass buffer strip is used to reduce the runoff velocity and to filter large-diameter particulates from the runoff. Other pretreatment devices that can be employed are oil/grit separators, forebays, and stilling basins.

### Ponding Area

In BAs the ponding area is located over the planting soil and provides surface storage for stormwater runoff while it infiltrates and/or evaporates after the rainfall period. Major design parameters for the ponding area are the maximum ponding depth and the duration of ponding. In Prince George's County, Maryland, these parameters were established based on the type of planting soil used and the type of adjacent land use. The higher the infiltration rate of the planting soil, the greater the maximum ponding depth (up to 0.3 m [12 in]). Applications in residential areas are permitted ponding for less than 24 hours; all other applications are permitted 36 hours of ponding (Prince George's County, Maryland, 1993).

### Ground Cover Layer

The surface of the BA is covered with an organic ground cover layer. The organic layer provides a medium for biological growth and provides the carbon source needed for biological activities at the air/soil interface. It also helps to maintain a sufficient organic percentage in the surface soil horizon, in a sense simulating the leaf litter in forest communities. It is recommended that designers of BAs either use a mature mulch (maximum depth of 76.2 mm [3 in]) or establish permanent growth (e.g., grasses) within one growing season (Prince George's County, Maryland, 1993).

## Planting Soil

BAs contain a thick layer of planting soil, located below the ground cover layer and supported by the underlying in situ soils. This thickness also provides for deep root plant growth. Planting soil must have a high infiltration rate, support healthy plant growth, adsorb nutrients and pollutants, and provide additional storage capacity for stormwater. These objectives can be met by using a planting soil containing a clay content of 2.5 to 10 percent and an organic content between 1.5 and 3 percent.

Prince George's County permits BAs with higher infiltration soils to have a greater ponding depth, which resulted in a smaller surface area of the BA. Based on this approach, designers might have to choose between using less expensive existing onsite soils or replacing existing soils with imported highly permeable soils to permit a smaller BA. To provide the infiltration necessary to remove ponded stormwater it is recommended that the soil texture be sand, loamy sand, sandy loam, loam, or silt loam. In addition it is recommended that the planting soil thickness be 1.22 m (4 ft) to ensure significant contact time between infiltrating stormwater and the soil. This soil depth will also help deeply rooted plant growth become well established (Prince George's County, Maryland, 1993).

## In Situ Soil

As shown in Figure 6, the in situ soil layer provides a foundation for planting soils and drains the infiltrated stormwater from BAs. Experimental BAs have shown that in situ soils are crucial to the success of the facility; if a location drains in a poor manner, the BA will fail unless another means of drainage is established. Prince George's County, Maryland, recommended percolation tests be performed to demonstrate that in situ soils possess at least 12.7 mm/h (0.5 in/h) infiltration capacity. Where poorly drained in situ soils are encountered, it is still feasible to install bioretention but only with the aid of an underdrain system. Additional information on investigating in situ soils and designing underdrain systems is provided in the Prince George's County *Design Manual for Use of Bioretention in Stormwater Management* (Prince George's County, Maryland, 1993).

## Plant Material

The role of plant species is to use nutrients and other pollutants and remove water from the planting soil through evapotranspiration. Plants must be a low-maintenance, aesthetically pleasing variety that is tolerant of urban stormwater pollutants. They must have the ability to adapt to conditions of drought and inundation. Key design parameters for optimum plant material function include species diversity, density, and morphology, and the use of native plants. Ideally, the community structure will be similar to that of a forest community, providing diversity to reduce susceptibility to insect and disease infestation. The intention is to create a microclimate that is resistant to urban stresses. The plants selected must be able to prosper even when flooded to a depth of 0.15 m (0.5 ft) or more at frequent intervals.

## Inlet and Outlet Controls

The specifics of inlets and outlets of BAs are highly dependent on whether the BA is an on-line or off-line design. An on-line facility is one that does *not* have a bypass that diverts excess stormwater around the BA once it becomes full.

Because all stormwater will pass through an on-line bioretention facility, both inlets and outlets must be designed to ensure that the runoff rate does not damage the BA. Prince George's County states that designers must ensure nonerosive flow velocities exist within the BA for the 10-year postdevelopment event (Prince George's County, Maryland, 1993). On-line facility designs usually include protection such as riprapped inlets and outlets, which are designed through an in-depth hydraulic evaluation. Possible outlets for on-line areas include drop inlets or overflow weirs that feed downstream swales or pipe systems.

Off-line BAs generally require smaller inlets than on-line facilities because inlets are usually designed to convey the runoff from the first 12.7 mm (0.5 in) of runoff from the site. All other runoff must be diverted around the BA and downstream to subsequent swales or pipe systems without passing through the BA. This diversion can be established by creating a ponding area in the BA, which causes backwater conditions and a resulting shift in discharge direction.

Designers must be careful not to undersize entrances into BAs and to keep entrance velocities in excess of 0.15 m/s (0.5 ft/s) to help prevent clogging of the inlet area. Debris (e.g., sand) on the parking area can be washed toward the bioretention inlet and form a small dike, blocking the inlet.

## MAINTENANCE CONSIDERATIONS

BAs require routine, low-cost maintenance, similar to conventional landscaping maintenance, to ensure the system functions well as a stormwater BMP and remains aesthetically pleasing. Routine inspections of the bioretention facility, semiannually for the first year and annually thereafter, along with spot inspections after major storms the first year to verify the BA has not been significantly disturbed, aid in ensuring the performance of the BA. Other maintenance considerations include:

- Planting soil bed - check the pH of the soils, correct erosion, cultivate unvegetated areas to reduce clogging from fine sediments over time.
- Ground cover layer - mulch or replant bare spots annually.
- Planting materials - replace dead or severely distressed vegetation, perform periodic pruning, etc.
- Inflow/outflow - inspect for clogging, remove sediment build-up, repair eroded pretreatment areas, remove accumulated trash and debris.

## COST CONSIDERATIONS

Initial estimates from engineers designing BAs suggest project costs will be approximately $24,700 per impervious hectare ($10,000 per impervious acre), exclusive of real estate costs (Bell, 1996).

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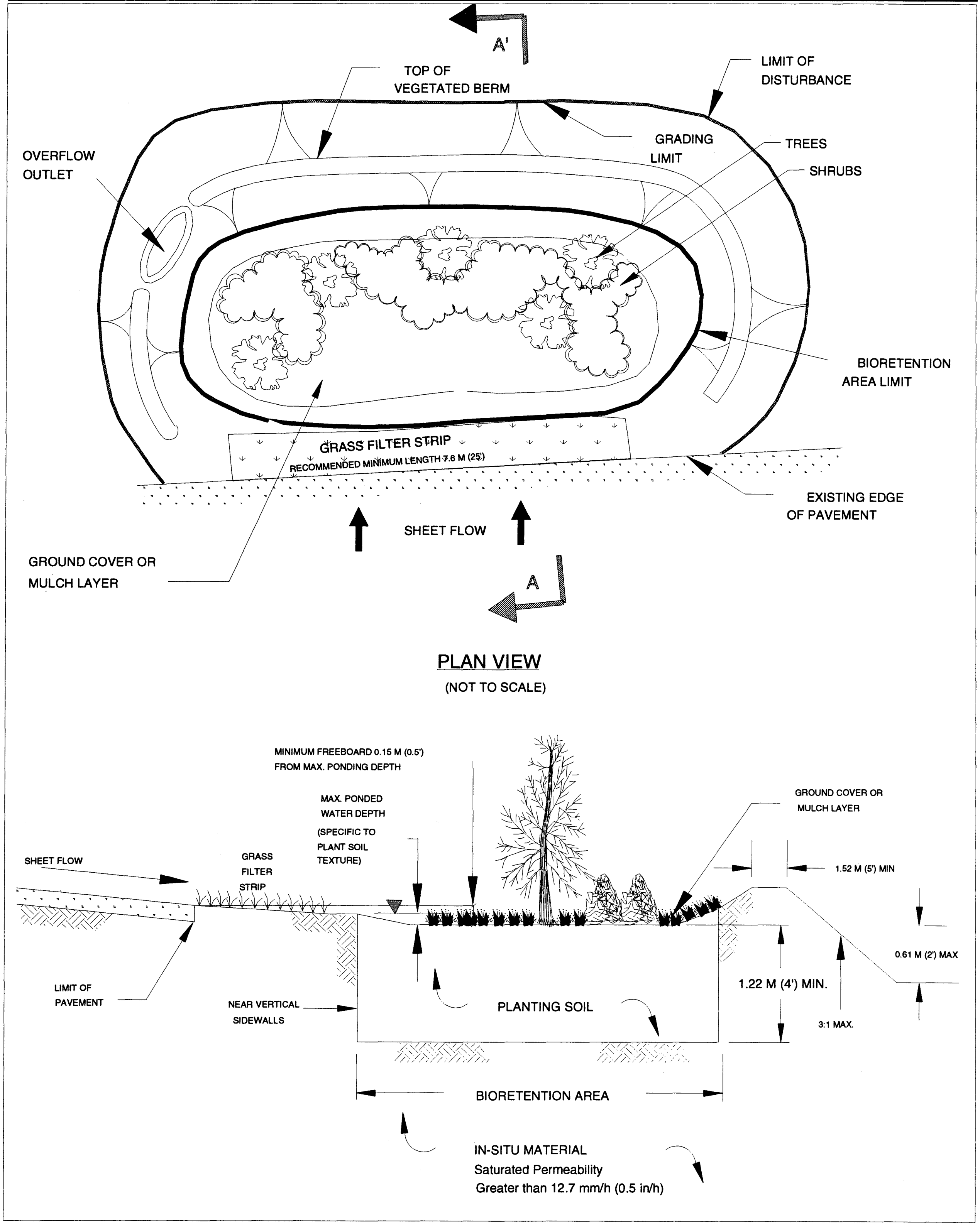


**Figure 6. Parking edge and perimeter without curb (Prince George's County, Maryland, 1993)**

# 3.3 DETENTION AND RETENTION/WETLAND PRACTICES

## 3.3.1 Description and Purpose

Stormwater management ponds are designed to mitigate the hydrologic and water quality impacts of stormwater runoff by providing stormwater quantity management and/or quality control. The increased volume of runoff, due to increases in impervious area, is stored and then released at a controlled rate through an outfall structure. Controlling the rate at which flow is released from the facility can help to reduce downstream channel erosion and prevent downstream flood damage. Improvements in stormwater runoff quality can also be achieved through settling, infiltration, nutrient uptake, adsorption, and physical filtration. Ponds that incorporate permanent pools of water are designed to use the biological action of plants and organisms to trap and then treat pollutants.

The distinction between the various types of stormwater management ponds is based on the type of hydrologic control provided due to the design of the outlet control structure. Stormwater management ponds can be designed to provide for both control of increases in stormwater volumes and peak flow rates, as well as for treatment of stormwater pollution. In many cases, depending on the design of the pond, multiple functions are provided resulting in a hybrid system. The pond design features that determine its function, and thus provide the basis for categorization include: depth of permanent pool, storm event discharge volume/storage volume, storm event peak discharge rate, and detention time.

The most basic categorization of pond types is between wet and dry facilities. When designing for water quality treatment, this is one of the most important features to determine pollutant removal efficiency. For these facilities, detention time, generally a function of the travel distance or height of the outflow weir, is an important design feature for efficient pollutant removal. Generally, dry ponds are designed to provide stormwater hydrologic control. In most cases, this means providing enough volume to store the stormwater runoff from a site for a particular storm event, and release this volume at a predetermined rate (usually that of predevelopment conditions). The pond volume, coupled with the design of the outflow control structure, determines the extent of stormwater detention management provided. Outflow control structures can take various forms and shapes. Their most important features for ensuring adequate quantity control include height and area of outflow opening. Wet ponds generally are designed with a permanent pool to provide for greater treatment of stormwater pollution than by dry ponds.

A variety of forms of detention and retention practices exist. Detention ponds, extended detention ponds, and retention (or wet) ponds are common. Design of these facilities can take the form of a shallow marsh or constructed wetland when hydric conditions are available and facultative plant species are abundant, with outlet controls determining the extent of detention or retention provided. In addition, these practices can be designed as surface or underground facilities, depending on available funding, soils and groundwater conditions, and space limitations.

Where insufficient land area is available, as is the case in many ultra-urban environments, underground storage structures may be required. Underground storage areas are usually constructed of concrete vaults or corrugated metal pipe (CMP). Pretreatment for water quality can help reduce clogging.

## 3.3.2 Design Alternatives

Attenuation and treatment of stormwater runoff are the primary objectives for designing detention and retention/wetland practices. Design features can be added to provide wildlife habitat, aesthetics, recreation and educational opportunities and to improve property values (USEPA, 1995).

The *attenuation and storage* features of detention and retention practices reduce the volume and rates of discharge of stormwater runoff generated from a site. In an ultra-urban setting, design control volumes can vary depending on the available space for the facility. Following storage, volume reduction occurs through infiltration, evaporation, and evapotranspiration—key design features of infiltration basins, retention/wet ponds, and wetlands. Reduction in the rate of discharge of stormwater runoff occurs by constricting the outflow from these facilities, generally through an outlet control structure. In an ultra-urban setting, facilities should be designed to reduce the peak discharge rates, as well as their frequency of occurrence, to as close to predevelopment conditions as possible, while working within available space constraints.

*Treatment* of stormwater runoff is designed to reduce concentrations of suspended sediment, dissolved and particulate nutrients, trace metals, trash and debris, oil and grease, and toxins such as trace organics. An effective detention, retention, or wetland facility will reduce most or all of these pollutants to levels below predevelopment levels. Parameters of facility design that affect the pollutant removal performance of these facilities include the residence time (length-to-width ratio); the depth of the permanent pool; the total depth; the existence of a plunge pool; the presence, density, and type of vegetation; and the presence and length-to-width ratio of a forebay.

Table 9 provides a brief description of the alternative detention and retention facilities and their respective design goals, as well as important design features.

**Table 9. Detention and retention BMP options**

| BMP Type | Design Goals: Water Quality Treatment | Design Goals: Water Quantity Attenuation | Primary Internal Design Processes | Important Features to Meet Design Goals |
|---|---|---|---|---|
| Detention Facility | ✔ | ✔✔✔ | settling<br>adsorption | outlet control structure<br>length/width ratio<br>storage volume provided<br>depth |
| Retention Facility (Wet Pond) | ✔✔✔ | ✔ | evaporation<br>settling<br>adsorption<br>nutrient uptake<br>evapotranspiration | soils<br>hydrology<br>vegetated bench<br>depth of perm. pool<br>length/width ratio<br>forebay design |
| Extended Detention Dry Facility | ✔ | ✔✔ | settling<br>adsorption | detention time<br>outlet control structure<br>length/width ratio<br>storage volume provided<br>depth |
| Extended Detention Wet Facility | ✔✔✔ | ✔✔ | evaporation<br>settling<br>adsorption | detention time<br>soils<br>hydrology<br>vegetated bench<br>depth of perm. pool<br>length/width ratio<br>forebay design |
| Shallow Marsh/ Constructed Wetland | ✔✔✔ | ✔ | evaporation<br>evapotranspiration<br>nutrient uptake<br>physical filtration<br>settling<br>adsorption | soils<br>hydrology<br>vegetation density and type<br>depth of perm. pool<br>length/width ratio<br>forebay design |

✔ - low effectiveness, ✔✔ - moderately effective, ✔✔✔ - highly effective.

Generally, stormwater management ponds can be categorized into five basic types (Figure 7). Each type is described briefly below.

### Stormwater Detention Ponds

Stormwater detention ponds are usually dry ponds that provide hydrologic controls for increased runoff discharge flowrates. However, detention control volumes can be provided in wet ponds, above the retention volume. These ponds temporarily detain stormwater, releasing it at a predetermined design flow rate, generally that of predevelopment conditions. They are intended to remain dry between storm events. Unless significant infiltration occurs, the post development increases in total stormwater runoff volume are not significantly changed by detention ponds (Schueler, 1987).

### Stormwater Retention (Wet) Ponds

Stormwater retention ponds are often referred to as "wet" ponds because they are designed to have a permanent pool of water. This permanent pool enhances particulate settling by increasing residence time, and also provides conditions for growth of aquatic vegetation, thereby enhancing filtration, and metals and nutrient uptake (transpiration). The permanent pool volume is often defined as the volume equivalent to three times the water quality volume or 12.7 mm (0.5 in) of runoff from the contributing drainage area (Yu and Kaighn, 1992). Pollutant removal efficiency is a function of pond depth, residence time, drainage area-to-pool volume ratio, and existence of aquatic vegetation. The post development increases in total stormwater runoff volume may not be significantly changed by retention ponds.

### Stormwater Extended Detention Ponds

Stormwater extended detention ponds are designed to temporarily detain stormwater runoff for an extended period of time, generally 12 to 24 hours. Longer detention times have been found to provide optimal pollutant removal (Schueler, 1987). The detention time is a function of the size of the outflow opening with respect to the storm event runoff volume. These facilities are usually designed for the purposes of providing water quality treatment for the first flush of stormwater runoff, and may also provide quantity control for small storm events (1-2 year) necessary to minimize downstream bank erosion. Pollutant removal of particulates is primarily accomplished by gravitational settling (Schueler et al., 1992).

*Extended Detention Dry Ponds*: Dry extended detention ponds are normally "dry" between storm events, and therefore, do not have a permanent pool of water (Schueler et al., 1992).

*Extended Detention Wet Ponds*: Wet extended detention ponds improve the water quality treatment efficiency of their dry counterparts by providing additional settling and particulate removal. The extended detention volume is computed as the volume above the normal (permanent) pool elevation.

### Wetlands/Shallow Marsh Systems

Stormwater wetlands are typically hybrids of either detention, retention or extended detention ponds, that temporarily store stormwater runoff in shallow pools throughout the facility. Design conditions are such that emergent and riparian wetland plants thrive within these facilities, adding to their pollutant removal and wildlife habitat benefits. These facilities require adequate baseflow conditions to maintain their permanent pool to support vegetation.

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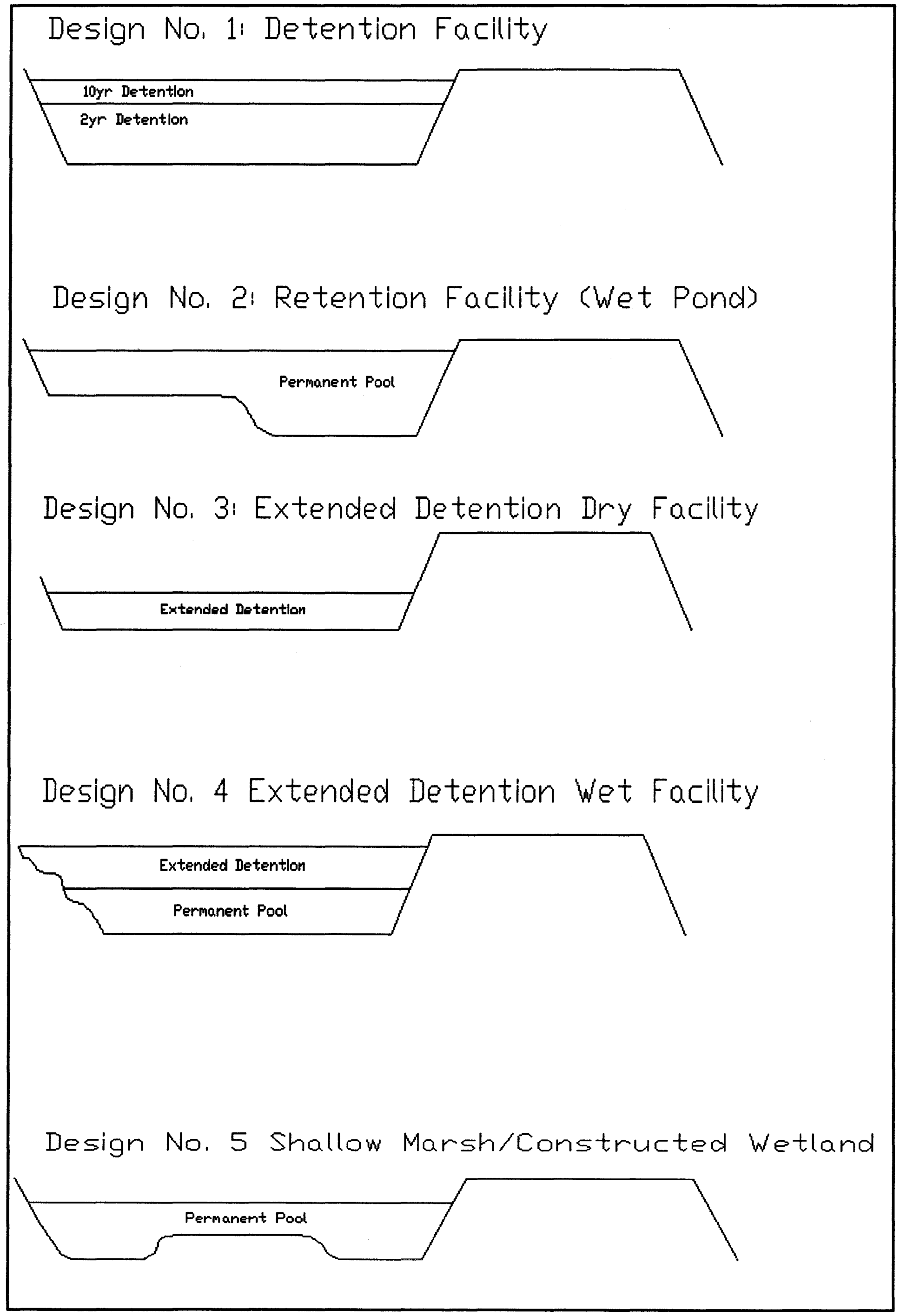


**Figure 7. Design Variations**

# FACT SHEET—DETENTION PONDS

Extended detention ponds have been used for a number of years in urban applications, and are designed to mitigate highway runoff stormwater quality and/or quantity impacts. These systems function by storing the increased runoff volume that results from development, then slowly releasing it at predevelopment runoff rates. The controlled release rate is designed to maintain the existing hydraulic conditions in the downstream watercourse (ASCE, 1992). The most commonly built facilities are dry extended detention (ED) ponds and wet ponds with extended detention. Figure 8 illustrates a cross-sectional view of a standard ED pond system design.

Water quality benefits are achieved by treating the "first flush" of runoff from impervious areas. The "first flush" of runoff often contains the most pollutants. When extended detention is the method used for water quality treatment, the required volume is released over a long period of time, allowing sufficient time for particulates to settle out. Nutrients, heavy metals, and other pollutants associated with these particulates can also be removed.

## APPLICABILITY

In an ultra-urban application, detention ponds are generally applicable as an end-of-pipe treatment facility. The pond design will be site-specific and extremely dependent on the site soils, existing utility conflicts, property ownership, and drainage area to be routed through the pond. Additional space constraints may reduce the applicability of some pond enhancement features such as a forebay, micropool, and safety bench. For example, the additional area needed to provide a safety bench (0.3 m [1 ft] wide strip around facility) may not exist in an ultra-urban setting. A safety alternative such as a chain-link fence, although not as aesthetically pleasing, may be required.

Another problem that may occur in siting detention ponds in ultra-urban environments is finding an adequate 100-year storm overflow path. Unfortunately, in the ultra-urban environment, space is usually limited at the end of storm drain systems. Additional opportunities for siting extended detention facilities are in medians, interchanges, adjacent to ramps, and along rights-of-way adjacent to roads.

## EFFECTIVENESS

Properly designed detention ponds can greatly reduce the stormwater runoff impacts of highway development. When coordinated with other BMPs in the watershed, they can effectively reduce stormwater peak flows. Dry detention ponds can also remove up to 90 percent of particulates (Kehoe, 1993). Dry detention ponds, however, are not as effective at removing soluble pollutants. Other design approaches such as wet ponds and wetlands may be used in conjunction with extended detention for more efficient water quality control. Additional data on pollutant removal effectiveness of detention ponds is shown in Table 10.

## SITING AND DESIGN CONSIDERATIONS

The success of a stormwater management pond design is very dependent on site-specific conditions. The major components common to each system are the water storage area for quantity and/or quality control and some type of outlet structure. The outlet structure can be a concrete or corrugated metal pipe (CMP) riser with openings to release the stormwater at the predevelopment runoff rates for specific storm events. The calculations and routings may be accomplished with very simple techniques, such as the Rational and Storage-Indication methods, or more complex models, such as HEC-22 or the Storm Water Management Model (SWMM), may be used.

A number of physical conditions are critical to siting and designing a pond. The side slopes of the pond and embankment may be steep. To protect both pedestrians and passengers, sufficient barriers, such as fences, guardrails, and safety zones, must be incorporated into the design. The saturated soils found below a wet pond can affect the structural stability of adjacent road embankments. The rate and timing of the peak discharge of the pond may be critical to preventing or increasing downstream flooding.

Although ponds are classified into the major categories of detention and retention facilities, there are also hybrid facilities that contain features found in both systems. The most common of such facilities, which are described below, are extended detention dry ponds and wet ponds with extended detention. Additional design examples and information can be found in *Urban Drainage Design Manual Hydraulic Engineering Circular 22* (Brown et al., 1996), *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996), and *Design and Construction of Urban Stormwater Management Systems* (ASCE, 1992).

## Extended Detention Dry Ponds

Extended detention dry ponds can be designed as two-stage, or water surface elevation, facilities. In these cases, the upper stage stores and reduces flood peaks and the lower stage is designed for water quality control. The lower stage volume may be able to treat a certain depth of water over the impervious area, such as 12.7 mm (0.5 in) or a design storm frequency, such as the 1-year 24-hour storm event. The water is drawn down over a period of time, normally between 24 and 48 hours, through an orifice in the riser of the principal spillway. This residence time may allow for as much as 90 percent removal of particulates through settling (Young et al., 1996). Residence times that are too long may allow the water to become heated, resulting in a potential thermal impact to receiving waters. Removal of soluble compounds is limited in dry ponds. A shallow marsh or wetland may be incorporated into the design to facilitate removal of nitrogen and phosphorus. The incorporation of a forebay, energy dissipator, or pretreatment facility before flow enters the pond from a channel or pipe is important to lessen the impact of sediment and grit on the pond and to facilitate pond maintenance.

**Table 10. Pollutant removal effectiveness of detention ponds (%)**

| Study | TSS | TP | TKN | $NO_3$ | Metals | Comments |
|---|---|---|---|---|---|---|
| City of Austin (1990)[1] | 46 | 37 | 14 | 36 | 40-60 | On-line wet pond |
| City of Austin (1995)[1] | 94 | 81 | 44 | 64 | - | Wet retention pond |
| Yu & Benelmouffok (1988)[2] | 76 | 70 | 65 | 75 | 50-57 | Extended detention wet pond |
| Martin & Smoot (1986)[2] | 78 | 20 | -- | -- | 63 | In-line wet detention pond as pretreatment to wetland system. Efficiencies are for pond only |
| Gain (1996)[1] | 54 | 30 | 16 | 24 | 24-73 | Evaluates modification by flow barrier in wet pond; pond is pretreatment to wetland |
| Harper & Herr (1993)[1] | 85 | 54 | 26 | 92 | 37-75 | Based on water column sampling from various sites in the wet detention pond |
| Yu et al. (1993)[2] | 67-93 | 75-94 | - | - | - | Dry detention pond |
| Yu et al. (1994) [2] | 96 | 81 | 44 | 64 | - | Dry detention pond, study evaluated modifications to outlet |

[1] Removal efficiencies based on concentrations.
[2] Removal efficiencies based on mass loading.

### Extended Detention Wet Ponds

Wet ponds use a permanent pool of water to aid in achieving water quality control. The pool may cover the entire pond bottom or may be located in only a portion of the pond. Sufficient drainage area, fairly impermeable soils, and an adequate base flow to the pond are important to maintain a permanent pool. Sizing of the wet pool should consider the "first flush" runoff volume.

Consideration must also be given to water depth and pond length for settling. The pond depth must be deep enough, usually 0.9 m (3 ft) or more, so that wind-generated disturbance of bottom sediments does not cause the resuspension of sediments. Also, the pond depth should be shallow enough, usually 2.4 m (8 ft) or less, so that mixing occurs and the pond does not become anoxic. Pond depths in excess of 2.4 m (8 ft) should be avoided to prevent thermal stratification (Schueler, 1987). Alternating areas of shallow and deep pools in wet ponds can also be used to increase the sediment trapping efficiency and habitat diversity. Forebays are usually included to reduce sediment deposition throughout the system and facilitate maintenance. Incorporation of wetland plants along the fringe of the pond helps reduce erosion on the banks, provides some habitat, and may provide opportunities for nutrient removal.

The extended detention volume for a wet pond occurs above the water quality volume and below the crest of the pond. The water is released through openings in the outlet structure. An emergency spillway should be required to allow water to discharge safely in the event of a large-scale storm event.

## MAINTENANCE CONSIDERATIONS

Many detention facilities are embankment ponds. Regular inspections are required to check for seepage through the embankment, burrowing animals, deep-rooted vegetation, and erosion along the embankment and sides of the pond. Other routine maintenance includes reseeding of the pond banks and bottom and removal of debris from the spillway. Over time, sediment accumulation may significantly reduce the capacity of the pond. Studies have shown that every year up to 1 percent of the storage of the 2-year 24-hour storm event can be lost to sediment deposition (siltation) (Yousef et al., 1986). Sediment can reduce the quantity storage in a pond up to 20 percent over a 10-year period. Dredging of the material may be required every 5 to 10 years to restore the capacity of the pond. The sediment should be tested to determine if it is a hazardous material. Other considerations critical to the efficiency of the pond include maintenance of outlet structures, flow splitters, and clean-out gates (Koon, 1995).

## COST CONSIDERATIONS

Cost factors for stormwater management ponds are extremely sensitive to site conditions. Availability of in situ materials for embankment construction, outlet protection, cost of excavation, liner materials, and land costs are significant factors. Maintenance and inspection costs for mowing and periodic dredging are postdevelopment factors. Other technologies such as infiltration trenches may be more cost-effective in smaller drainage areas due to construction and long-term maintenance costs (Young et al., 1996). Studies have suggested that preliminary costs can be estimated by the following equation (adapted from Wiegand et al., 1986):

$$C = 168.39 \times V^{0.69}$$

where:

C = construction cost estimate (1995 dollars) and

V = volume of storage of the pond (cubic meters) up to the crest of the emergency spillway.

This cost should be increased by 25 percent for construction contingencies.

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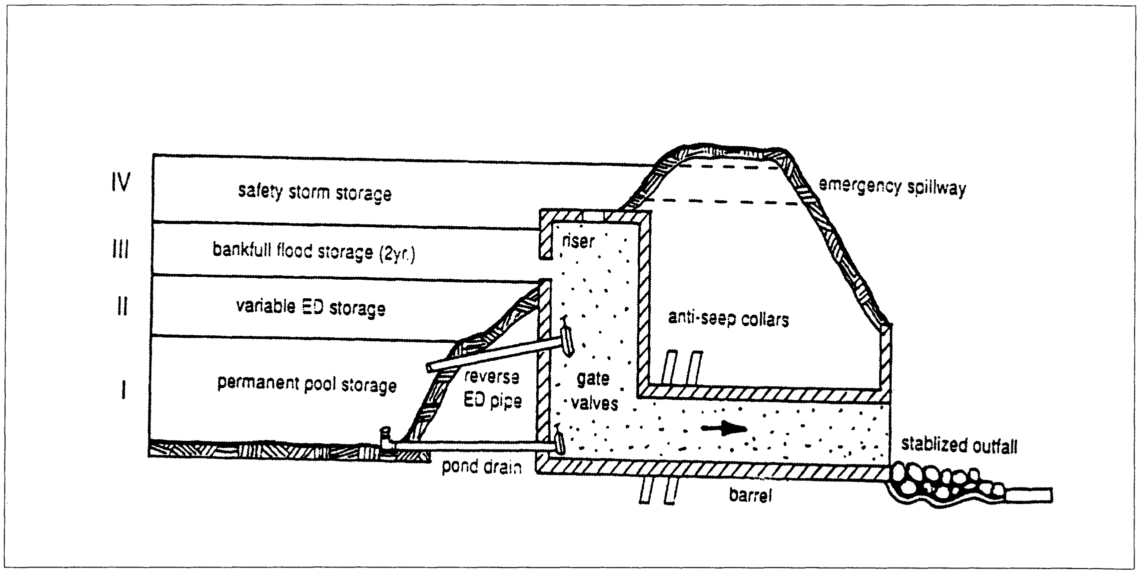


**Figure 8. Cross-section view of a standard extended detention pond system (Schueler, 1992)**

# FACT SHEET—WETLANDS AND SHALLOW MARSH SYSTEMS

Wetlands and shallow marsh systems use the biological and naturally occurring chemical processes in water and plants to remove pollutants (ASCE, 1992). Oils, particulates, suspended sediment, and soluble nutrients are removed or settled out due to their residence time in the wetland system and before they enter the downstream receiving waters. Wetland and marsh systems can have additional stormwater features that help to attenuate peak storm flows. Figure 9 is an example of a shallow marsh system.

These systems can often have great habitat value. The fringe wetlands and deep water habitats provide shelter and breeding places for many species. Properly sited wetland systems can also be scenic assets along a highway corridor.

## APPLICABILITY

Wetland and shallow marsh systems must be carefully sited to ensure that the desired functions for the system are established and maintained. In the ultra-urban environment the feasibility of wetland establishment may be limited due to factors such as drainage area or the absence of high groundwater tables. Due to these considerations, potential sites are most likely at low-lying interchanges or medians where runoff can be directed to them, or existing open areas such as parks, which provide additional aesthetic and educational benefits.Wetland and shallow marsh systems have habitat value and can be efficient at removing pollutants. Since these systems are frequently inundated, adequate safety measures such as safety benches, fences, guardrails, and safety zones must be provided.

## EFFECTIVENESS

Properly designed wetland systems are extremely effective at removing soluble pollutants and particulates from ultra-urban stormwater runoff. Biological oxygen demand (BOD), chemical oxygen demand (COD), and metals are also significantly reduced. As the system ages and more algae and detritus are generated in the pond, the efficiency increases. When combined with extended detention, wetland BMPs may be one of the most effective systems to mitigate stormwater runoff impacts. Figure 10 illustrates the use of an extended detention pond as a pretreatment for a wetland system. Table 11 provides data from a study that monitored the pond and wetland system at the inlet and outlet to the wetland. Many of the suspended solids and some of the solubles were removed by the pretreatment in the detention facility (OWML, 1990). Average removal rates that can be expected from a stormwater wetland are 65 percent for total suspended solids (TSS), 25 percent for total phosphorus (TP), 20 percent for

**Table 11. Pollutant removal effectiveness for wetlands (%)**

| Study | TSS | TP | TN | $NO_3$ | Lead | Zinc | Comments |
|---|---|---|---|---|---|---|---|
| Martin & Smoot (1986) | 95 | 53 | 42 | 47 | 90 | 92 | Pretreatment by in-line detention pond. Results are maximum removals for shallow wetland system only. |
| OWML, 1990 | 96 | 69 | 73 | 53 | 94 | 90 | Results are maximum removals for pond and wetland system. |

total nitrogen (TN), and 35 to 65 percent for metals (USEPA, 1993).

## SITING AND DESIGN CONSIDERATIONS

Hydrology is likely to be the most important limiting factor in the feasibility of a wetland or marsh system for an ultra-urban area. Such facilities may be on-line or off-line. On-line facilities allow all stormwater flows to pass through the system. Off-line facilities divert higher flows, which may have erosive velocities or which would inundate the system. There must be a sufficient drainage area to maintain base flow in the system. Water budgets should be performed to determine the ability of the pond to maintain vegetation in dry months. Adequate water will help prevent the die-off of planted vegetation, which can prevent invasive species from taking hold. The groundwater elevation is also important since it helps maintain the hydrology. A ratio of watershed area to wetlands area of at least two percent is recommended to have efficient removal capabilities (Schueler, 1992). However, smaller systems could be used in ultra-urban settings.

The wetland system should be designed to have pockets of deeper water to help trap sediments and to provide a diverse habitat. The length of the wetland system and ratio of surface area to width are important pollutant removal factors. The flow length must be long enough to provide adequate residence time to remove soluble pollutants and sufficient settling time for particulates. A length-to-width ratio of 2:1 is recommended to achieve an adequate residence time.

Proper soil conditions are necessary for wetland success. The wetland site must have existing natural soil conditions that facilitate ponding, or these conditions must be created using clay, PVC, or other types of liners. In addition, wetland pollutant removal functions are mediated in part by the supply of organic material in the site. Organic matter also affects the success of wetland plant establishment. Consequently, organic material must be incorporated into project soils if construction requirements necessitate removal of topsoil from the site.

Native plant species that are present in the area should be retained whenever possible. When planting a site is necessary, a diverse plant community of species native to the project area should be established to maximize wildlife and water quality benefits. Planting a variety of species increases the probability of establishing a vigorous plant community and reduces the chance of exotic species invasion into the site. A vegetative buffer strip included around the marsh or pond will reduce sediment inflow and provide additional pollutant filtration. Irregular shorelines, incorporation of nesting boxes, use of plants with habitat characteristics of cover or food, islands for nesting of waterfowl, and sufficient mudflat and deepwater areas will also greatly enhance wildlife habitat. For a thorough discussion of design considerations, refer to *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996). Designers are generally cautioned to avoid species known to be aggressive colonizers, noxious weeds, or ones not recognized by state regulatory agencies.

## MAINTENANCE CONSIDERATIONS

Frequent maintenance and inspection, which usually involves moderate costs, are critical during the establishment of vegetation in the marsh or wetland. Invasive and undesirable plants must be culled from the planting area. The outfall structure might also have to be adjusted to maintain the proper hydrology for introduced plant species. Though sediment rates may initially be high from construction activity, it is important that sediment be removed so that the plants can become established and the pond capacity is maintained. Once established, the wetland vegetation should be periodically harvested so that the stand can regenerate and the pond is not choked off by vegetation. Systems that do not have consistent and steady base flow may become eutrophic. The outlet structure should incorporate features that protect it from blockage by debris and that allow adjustments to be made to the water surface.

## COST CONSIDERATIONS

Costs for ponds typically include costs for embankment, riser and spillway structures, outfall protection, vegetative stabilization, excavation, and grading. Additional costs for site preparation can include soil amendments, precision grading, plant materials and creation of occluding layers in coarse-textured soil types if wetlands systems must be created on upland sites due to project constraints. Project costs can be lowered if existing pre-construction site conditions are carefully considered and isolated areas with hydric soils contained within the footprint of the project are utilized as stormwater management facilities.

Additional maintenance costs will be incurred until the establishment of the wetland ecosystem. Invasive plants must be culled and dead plants replaced. The outlet structure may have to be adjusted, based on seasonal observations, to achieve the proper water surface in the pond.

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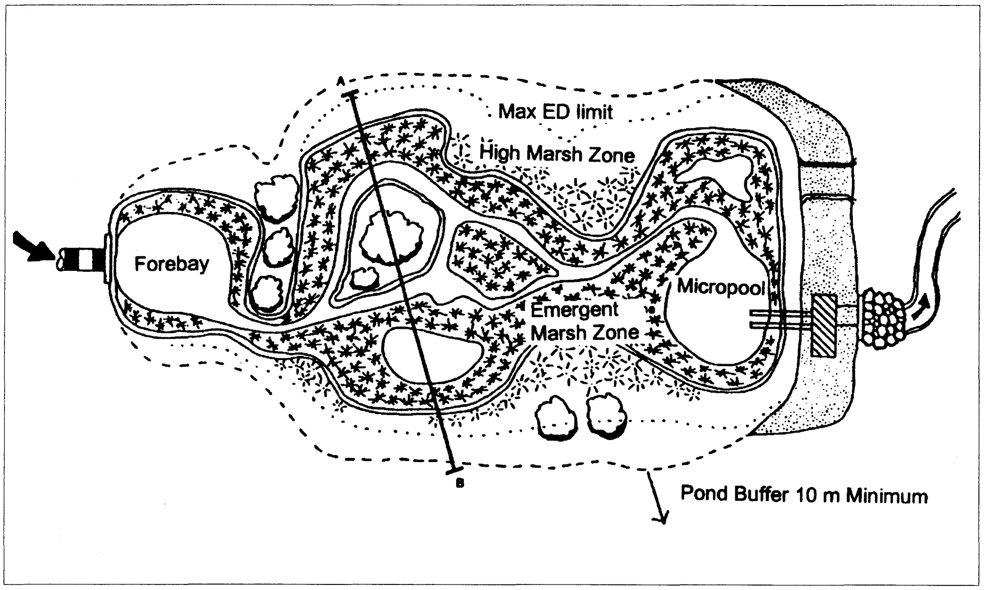


**Figure 9. Schematic design of a shallow ED marsh system (adapted from Schueler, 1992)**

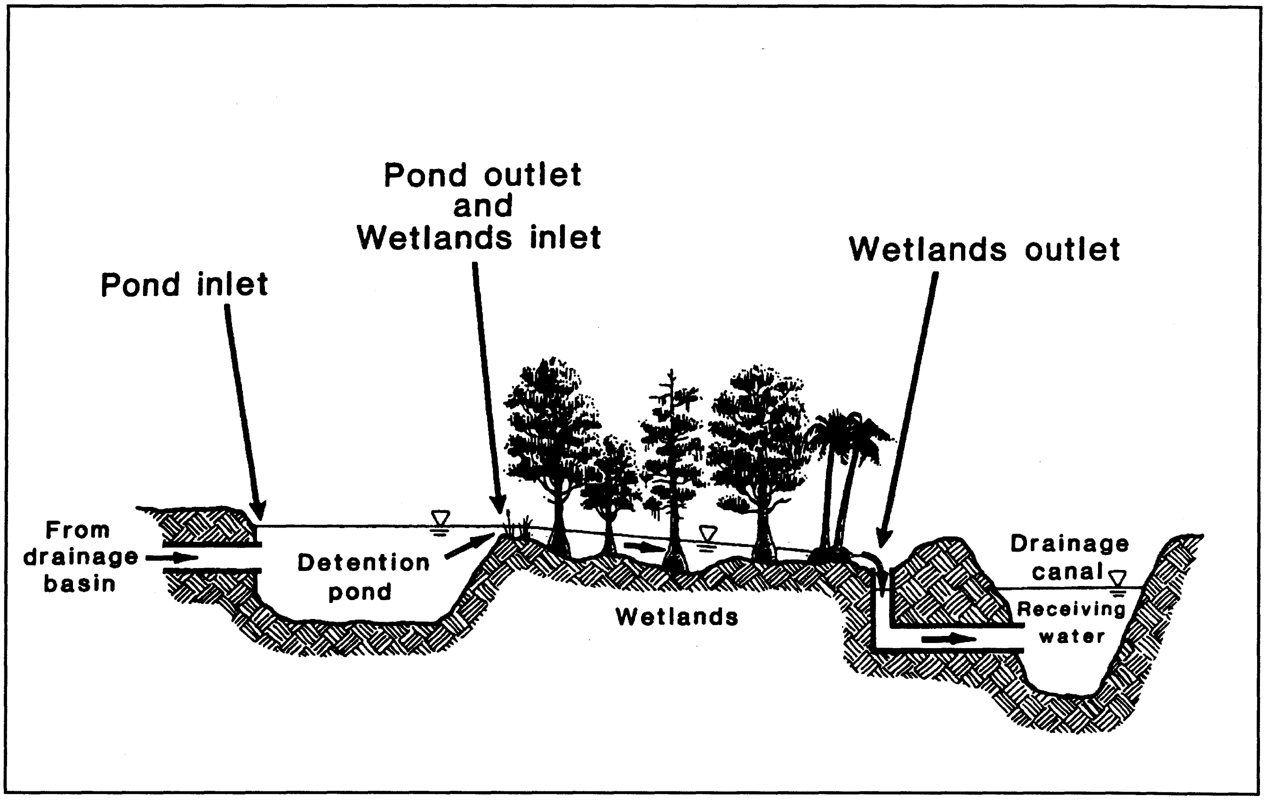


**Figure 10. Movement of water through a detention pond-wetlands system (Martin and Smoot, 1986)**

# FACT SHEET—DETENTION TANKS AND VAULTS

Detention tanks and vaults are underground structures used to attenuate peak stormwater flows. They are usually constructed out of either concrete or corrugated metal pipe (CMP) and must consider the potential loading from vehicles on the vault or pipe (Figure 11). Pretreatment structures can be used at the inlet to treat stormwater runoff and remove trash and debris. In addition, flow splitters can be used to direct only a portion of the stormwater runoff to an underdrain detention.

## APPLICABILITY

Due to the costs associated with underground detention systems for construction and maintenance, these systems are primarily used when space is limited and there are no other practical alternatives. In the ultra-urban environment, costs for developable land may be high enough that these systems become a feasible alternative. Relatively expensive to construct, concrete vaults are used primarily to control small flows in areas where system replacement costs are high. Less expensive, CMP systems are typically used to control significant volumes of runoff in parking lots, adjacent to rights-of-way, and in medians, where they can be replaced or maintained if necessary.

In the ultra-urban environment, underground detention tanks have been used to decrease flows in combined sewer systems. The stormwater is stored in the tank and then can be released by a remotely controlled valve to the wastewater treatment plant after the peak flows have passed through the plant.

## EFFECTIVENESS

Underground detention structures are effective measures for stormwater runoff quantity control; however, these facilities do not provide significant water quality control or primary stormwater treatment, without extensive modifications. Consequently, they are more frequently used to attenuate and store peak flows. In addition to providing insignificant stormwater treatment without modifications, receiving waters can be very sensitive to releases of the stored volume from these underground detention systems.

Preliminary results of water quality monitoring of modified underground detention structures have demonstrated a total suspended solids (TSS) removal rate of between 60 to 80 percent; a total phosphorous (TP) reduction of between 20 and 40 percent; and a total lead reduction of between 40 and 70 percent. This facility, however, required weekly maintenance and cleaning out of the structure to maintain this efficiency (Northern Virginia District Planning Commission, 1992). In reality, few detention tanks and vaults receive weekly maintenance.

## SITING AND DESIGN CONSIDERATIONS

The CMP systems used for large storage volumes are usually a series of pipes interconnected by a junction box or main pipe with an outfall structure. There should be a sufficient number of access holes and access points in the system to efficiently inspect and maintain both the outfall structure and the storage area. Whenever possible, the system should be located in an area where maintenance and potential repairs can be conducted with minimal disturbance to surrounding uses. Some design information on CMP systems is available in *Design and Construction of Urban Stormwater Management Systems* (ASCE, 1992).

Water quality controls, such as water quality inlets and sand filters, are often used to pretreat the stormwater before it enters the system. This is done to remove sediment and pollutants, which might clog the system. CMP systems can work in conjunction with infiltration to provide additional stormwater treatment.

When infiltration is used, perforations may be added to the pipe to allow the pipe to store the water until it can be exfiltrated into the soils below the pipe. In critical areas, such as under roads and parking lots, pipe joints may require gaskets and water-tight seals to protect the integrity of the pipe. Most systems have pipes or vaults inverts that are 1.8 to 3 m (6 to 10 ft) underground. Therefore, it may be difficult to obtain an adequate outfall for the system.

Another type of underground detention is the retrofitting of overcapacity storm drain pipes with baffles. The baffles cause the water to be stored in the pipes and to be released to the outfall at a slower rate (ASCE, 1992).

## MAINTENANCE CONSIDERATIONS

The cost and maintenance of these systems are major considerations. The systems must be designed so that they can have easy access for inspection and maintenance. Maintenance is usually conducted by periodically pumping out sediments and debris. In areas of high sediment flows, pretreatment is required to minimize the inflow of particulates so that the need to clean the system is reduced. An analysis of other management measures in the watershed is required to ensure that peak release rates are coordinated so that peak flows are reduced to predevelopment rates.

With the facilities located underground, inspection and maintenance are important issues because of the relatively high costs. In the ultra-urban environment, the facilities may require location under structures, such as buildings, parking lots, and roadways. Frequent maintenance is required to remove sediment and debris and to ensure that the outlet structure is functioning properly. Large-scale removal of accumulated sediment in the system may be difficult due to limited access. In addition, underground systems will be considered confined spaces that require additional safety requirements for inspection and maintenance.

## COST CONSIDERATIONS

Due to the high costs associated with concrete structure construction, the use of vaults is limited to small drainage areas. A preliminary cost estimate for the more expensive concrete vaults can be provided by the following equation (Wiegand et al., 1986):

$$C = 38.1\left(\frac{V}{0.02832}\right)^{0.816}$$

where:

C = construction cost estimate (1995 dollars) and

V = volume of storage (cubic meters) for the maximum design event frequency.

Corrugated metal pipes have been used extensively in urban areas and are significantly less expensive than vaults for storing large amounts of water. Both concrete and CMP systems have long life cycles.

## REFERENCES

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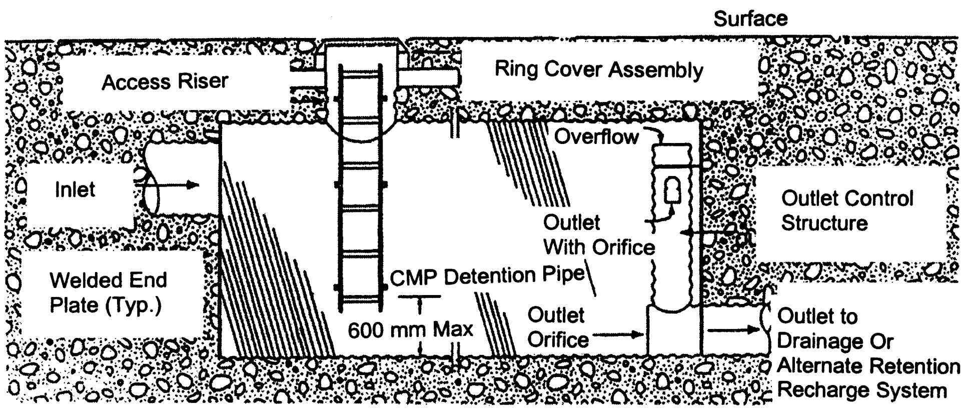


**Figure 11. Basic CMP stormwater detention system (adapted from Pacific Corrugated Pipe, 1995)**

## 3.4 FILTRATION PRACTICES

### 3.4.1 Description and Purpose

Surface or underground filters that use sand, peat/sand, or compost filter media can be classified as filtration practices. Noted for their ability to consistently remove fine-grain suspended solids, filters are not usually employed alone. Typically, filters are combined with pretreatment measures that remove large-grain sediments and other constituents from stormwater prior to filtration.

Ultra-urban BMPs that use filters can be designed for placement above or below ground level and can operate as either off-line or on-line facilities. Off-line facilities can capture and treat the water quality volume (WQV) or the "first flush" of stormwater, which often contains the highest concentration of pollutants. Larger storm events are diverted around an off-line filtration facility, sometimes into another management system such as an extended detention pond. On-line facilities pass all of the stormwater through the system and, as a result, are generally larger structures.

Filtration practices are usually designed to provide only stormwater quality management due to the relatively high cost of both installation and subsequent maintenance, especially for underground filters. Filtration BMPs have, however, been installed and maintained at some sites for many years and have been found to provide consistent performance. Best of all, filtration practices provide turnkey performance that is independent of local conditions (e.g., soil infiltration, seasonal groundwater levels).

Due to a wide range of available designs, a practical filtration design can be found for roadside applications (e.g., a ground-level design set in a open space) and for congested ultra-urban applications (e.g., an underground design set below a parking area). In terms of its surface area requirements, the footprint of a filtration practice typically occupies between two and three percent of the drainage area it serves. Consequently, most applications of filtration practices are for small to medium drainage areas.

### 3.4.2 Design Alternatives

Often the commitment of land area for surface filters is too large for most ultra-urban applications. However, surface filters have been extensively employed by several urban municipalities, including Austin, Texas. Filter designs consisting of a settling area and a filter (most often with sand medium) have applicability to highway settings, particularly at cloverleaf interchanges. Pretreatment measures are not usually incorporated into their design since the settling area is designed with sufficient residence time to remove the large-diameter material that would accelerate clogging of the filter medium. The settling area is typically a sediment chamber with a permanent pool that provides for pretreatment by storing the WQV to allow settling of these larger diameter suspended solids.

An underground filter design is well adapted for applications with limited land area and can also be retrofitted into existing storm drain systems. Of all filter practices, the underground system is the most expensive, primarily due to the construction costs of subgrade vaults. However, it may be the only pragmatic option where multiple use of land area is required (i.e., where the committed land area must also be used for automobile parking or for public parks). There are a number of design configurations for underground filters, with operating installations in a number of locations including Washington, D.C., and Alexandria, Virginia (Claytor and Schueler, 1996).

A variety of media can be employed as filter media, including sand (only), peat/sand combinations, and compost. Each of these media has advantages and disadvantages. The longest performance record exists for the sand medium, which is used in the majority of existing facilities. However, more recent designs have employed peat/sand or compost in an effort to improve the removal of metals and oil and grease from stormwater. Some designs have resulted in proprietary systems that attempt to standardize and modularize the application of compost media.

# REFERENCES

Claytor, R.A., and T.R. Schueler. 1996. *Design of Stormwater Filtering Systems.* The Center for Watershed Protection, Silver Spring, MD.

# FACT SHEET—UNDERGROUND SAND FILTERS

The underground sand filter typically consists of a multi-chamber underground vault accessible by access holes or grate openings. Multiple configurations have been developed for underground sand filters including the D.C. filter design (Figure 12) and the Delaware filter design (Figure 13). The D.C. design is intended to treat flow conveyed by a storm drain, and can be retrofitted within existing systems. The Delaware filter design is intended to collect flow directly from an impervious area and is well suited to placement along parking areas. While their deployments may differ, both of these designs operate in basically the same manner.

During a storm, the water quality volume is temporarily stored in an underground chamber(s) that provides for pretreatment by settling. Over time the stored volume flows by gravity into a filter chamber where it moves through the sand filter. Filtered runoff is collected in underdrains and is then discharged into an adjacent storm drain or natural channel. During large rainfall events any flow in excess of the filter's capacity is diverted around the sand filter by means of an overflow weir.

The underground sand filter works by a combination of sedimentation and filtration. The sedimentation section serves as a pretreatment measure by removing larger diameter suspended solids and capturing floating hydrocarbons. If the filter consists of a 45.7 cm (18 in) layer of sand the filter will trap up to 90 percent of the small particles in stormwater runoff (diameters between 6 to 41 microns). A lower level of removal will occur for any dissolved pollutants because the sand medium adsorbs relatively small amounts of positively charged dissolved materials. For example, sand has a cation exchange capacity that is 13 percent that of soil and 0.002 percent that of peat. This means it is less effective in filtering and removing dissolved metals and hydrocarbons.

Often the intended use of sand filter BMPs is to manage the first flush, which typically contains the highest concentration of pollutants. If designed as an off-line facility, however, it can provide true capture and treatment of any water quality volume. However, designers should note that it is relatively expensive to install large structures (e.g., concrete vaults) below grade and between any existing subsurface utilities.

In summary, the underground sand filter is well adapted for applications with limited land area and provides turnkey performance that is independent of local soil conditions, groundwater levels, and other factors. It is most useful where multiple uses of land area are required (i.e., where committed land area is to be used for automobile parking or for public parks).

## APPLICABILITY

The underground sand filter is considered to be highly applicable to the ultra-urban setting. It requires a small commitment of land area, provides dependable service, and is relatively effective at urban pollutant removal. Its design is inherently flexible; the size and shape of the unit can be set based on local constraints. Because the unit is below grade, it is safe for application in public areas and is relatively vandal-proof. For roadside applications, it can be placed adjacent to roadways without imposing a safety hazard and can function satisfactorily in the area below elevated roadways or ramps. The effective life of a typical, maintained underground sand filter is 5 to 20 years.

If there is a disadvantage associated with underground sand filters, it is the relative expense of construction compared to surface BMPs like detention ponds. However, recognizing the premium for space in the ultra-urban environment, the underground filter is actually cost-effective and sometimes may be the only feasible alternative.

## EFFECTIVENESS

Underground sand filters can be designed to effectively treat a range of target water quality volumes (e.g., the first 12.7 mm [0.5 in] runoff of a storm). The design water quality volume may be established by available space constraints, hydraulic conditions, or by local stormwater ordinances. Performance of this BMP is not greatly affected by climate since its subsurface placement will be below the frost line in most locations, limiting freezing of the filter. In addition, the level of treatment is generally independent of placement and on-site soil conditions do not affect performance. For larger-than-design events, underground sand filters (on-line and off-line) will only provide partial treatment. Pretreatment options such as street sweeping or catch basins remove trash and accumulated sand from roadway sanding, both of which diminish a filter's operational performance and increase maintenance requirements.

The underground sand filter has demonstrated good total suspended solids (TSS) removals, typically providing 85 percent treatment. Effectiveness for nutrient removal is low, and in fact the sand filter may be a source of nitrate ($NO_3$) since ammonia in stormwater will undergo nitrification in an aerobic filter environment. Trace metal removal rates range from between 65 and 95 percent. Removal of oil and grease averages about 80 percent with influent concentrations of 20 ppm and below. Reductions in fecal coliform bacteria range from between 40 and 80 percent. See Table 12 for additional information on the effectiveness of underground sand filters.

The sand filter is most effective in managing suspended solids but has questionable benefit where downstream conditions are sensitive to loadings of nitrogen or where high loadings of hydrocarbon pollutants are expected. Anions such as chloride from salted roadways are not removed during sand filtration.

## SITING AND DESIGN CONSIDERATIONS

The flexible design of an underground sand filter permits a variety of applications. A first test of the feasibility of an application can be based on the space requirements for 12.7 mm (0.5 in) of runoff from an impervious area of 0.4 ha (1 ac). Using an assumed storage depth of 0.9 m (3 ft), the surface area requirement for a sand filter is approximately 14 $m^2$ (150 $ft^2$) for the sediment chamber and 18.6 $m^2$ (200 $ft^2$) for the sand filter area. More detailed design information can be found in *Design of Stormwater Filtering Systems* (Claytor and Schueler, 1996) and *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996).

In the final design the key components are the sedimentation chamber that is usually a 0.92 m (3 ft) permanent pool depth and the filter bed that is typically 45.7 to 61 cm (18 to 24 in) deep. A maximum residence time of 40 hours is generally applied to ensure the sand filter drains prior to subsequent rainfall events. The total hydraulic drop from inlet to outlet should be between 1.5 and 2.4 m (5 and 8 ft) to reduce the potential for backwater

**Table 12. Pollutant removal effectiveness for underground sand filters (%)**

| Study | TSS | TP | TKN | NO3 | Metals | Bacteria | Comments |
|---|---|---|---|---|---|---|---|
| Bell et al., 1995 | 79 | 65 | NA | (-53) | 25-91 | NA | Delaware sand filter |
| Horner and Horner, 1995 | >81 | 43-60 | NA | NA | 22-66 | NA | Delaware sand filter; oil and grease removal at >80% |

flow into the sand filter from the downstream outlet. If the filter discharges to an existing storm drain, it is recommended that the underdrain outlet pipe drain into the top half of the downstream storm drain. The main collector pipe should be constructed with a minimum slope of 0.5 percent, and observation/inspection ports and cleanouts must be incorporated for all pipes. Access must be provided to all chambers in the design, and the design must conform to standards established by OSHA for worker safety.

Underground sand filters consist of precast or cast-in-place concrete vaults and can be installed as on-line or off-line facilities. Off-line applications are generally simpler to design because a high-flow bypass is not required and there is less potential for backwater flow entering the facility. During construction no runoff should enter the sand filter bed until the upstream drainage area is completely stabilized and site construction is completed. If practical, a sedimentation basin may serve as a temporary sediment control basin during site construction with the provision that overflows will bypass the filter bed. It is recommended that underground sand filters located in areas with sensitive groundwater aquifers be tested for water tightness prior to placement of the filter layers.

## MAINTENANCE CONSIDERATIONS

The recommended frequency for performance monitoring is four times per year. Each inspection should log information on the depth of ponding and oil and grease in the first chamber, the depth of water over the sand medium, and the accumulation of material over the sand medium. Any standing water over the sand medium 40 hours after the cessation of rainfall is indicative of clogging. Silt accumulation of more than 12.7 mm (0.5 in) indicates the need for replacement of the top layer or all of the sand medium. Typical sand media replacement intervals are from one to three years (Claytor and Schueler, 1996).

The sand filter design can be modified to minimize the effort associated with maintenance. For example, incorporating a plastic filter cloth covered with a gravel layer (ballast) on top of the sand medium creates a sacrificial layer that can be easily replaced when clogging occurs.

Currently, there are limited data on the expected maintenance costs associated with subsurface sand filters. A Washington, D.C., underground sand filter serving a 0.4 ha (1 ac) area was serviced by removal and replacement of a gravel ballast and filter cloth, for $1300 in 1994 (Bell, 1996). Note that repair of subsurface sand filters requires confined space entry, which requires larger management crews, leading to higher repair costs.

Preparations must be made for disposing of fluids and sediment removed from underground sand filters. Captured fluids may have a high hydrocarbon fraction and require special handling, and if the sand filter medium is not regularly replaced pollutants such as metals may accumulate in the sediment to the point where their level is considered hazardous.

## COST CONSIDERATIONS

Underground sand filters are generally considered to be a high-cost BMP option for water quality management. In 1994, the construction cost per impervious hectare served was $24,700 to $34,600 (or $10,000 to $14,000 per impervious acre served), excluding real estate, design, and contingency costs (Schueler, 1994). (Note that this unit cost value should be used for conceptual cost estimating purposes only.) In ultra-urban areas where land costs are high, however, underground sand filters can represent significant cost savings in reduced land consumption. For small ultra-urban areas with no land available, they may be the only practical option for stormwater quality treatment as they can be placed under roads or parking lots.

At this time manufacturers are beginning to make available prefabricated units that include precast vaults and inlets delivered to the site either partially or fully assembled. These units will eventually result in a decrease in construction costs. Typical significant cost variables include the location of subsurface utilities; type of lids and doors; customizing casting of weirs, sections, or holes; and depth of the vault.

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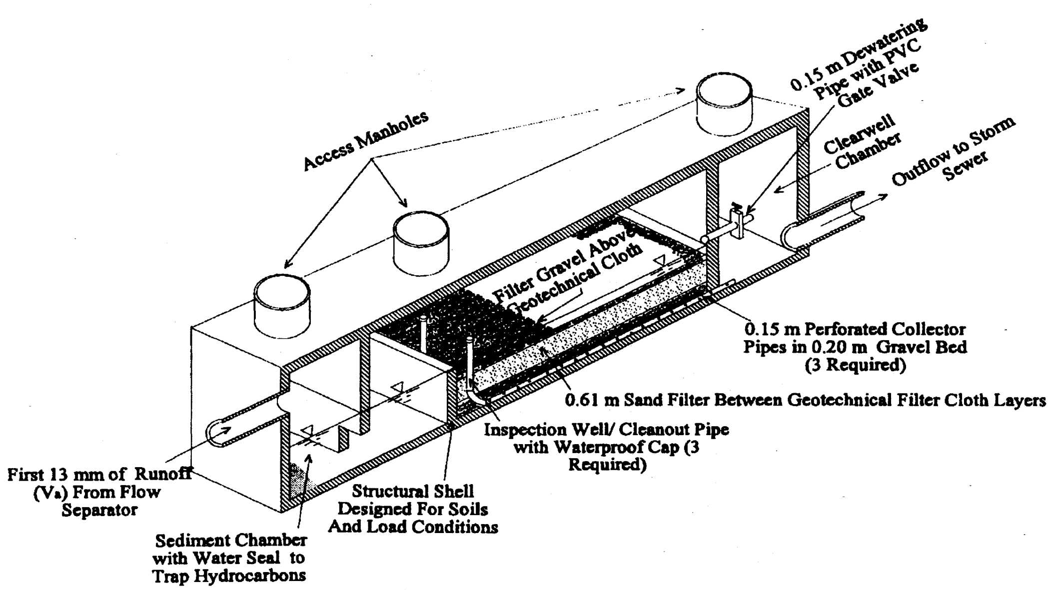


**Figure 12. Original D.C. underground sand filter system (Young et al., 1996)**

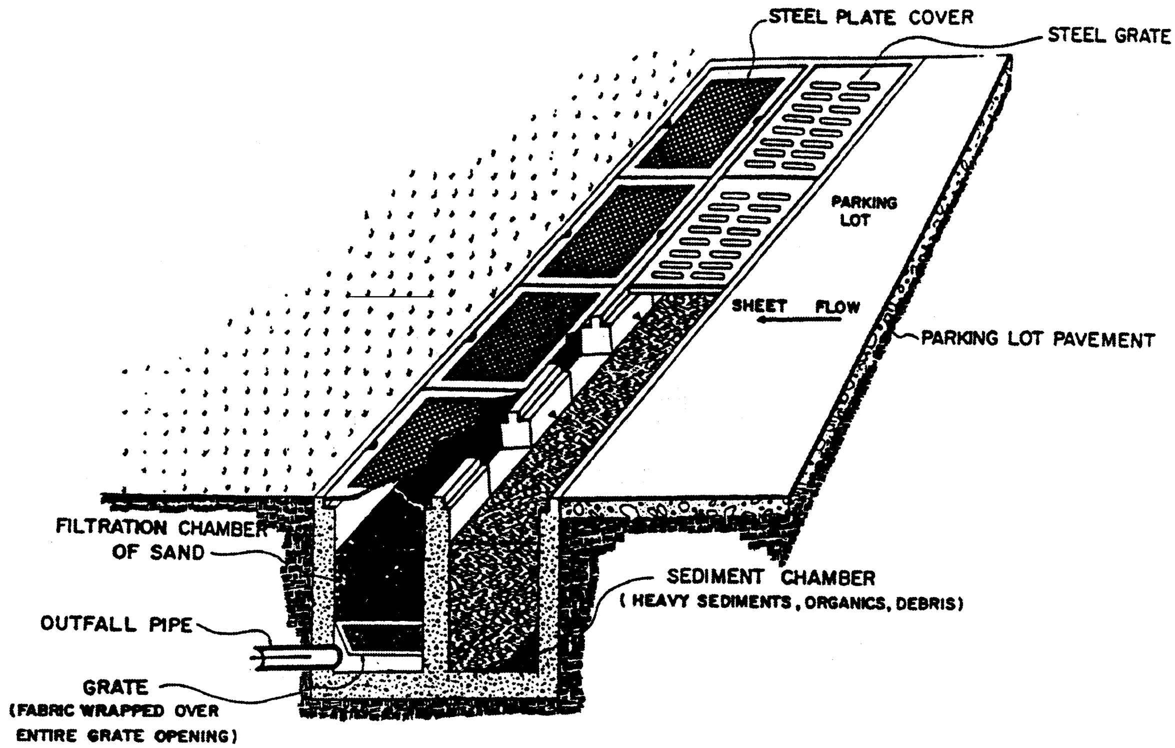


**Figure 13. Delaware sand filter with grated inlets (Bell et al., 1995)**

# FACT SHEET—SURFACE SAND FILTERS

The surface sand filter has been employed since the early 1980s to provide stormwater quality management. One of the forerunners in developing the surface sand filter design has been the City of Austin, Texas. As shown in Figure 14, the Austin design consists of a bypass chamber, a sedimentation chamber that provides pretreatment, a flow distribution cell, and a sand filter bed. The design illustrated shows many of the features common to surface sand filters. Typically, the filter bed has a 450 to 600 mm (18 to 24 in) deep sand layer that traps or strains pollutants before runoff is collected in an underdrain system (gravel and perforated pipe) and conveyed to a discharge point.

A bypass chamber is used to protect the BMP from high inflows, diverting any flow in excess of the capacity of the structure. This works with the sedimentation cell(s) to prevent high loads of coarse sediment from entering the filter bed. While the design illustrated in Figure 14 consists of concrete structures/walls, earthen walls backed with geomembranes and riprap sections can be substituted in the basic design. In terms of drainage area, the Austin design has been successfully employed for drainage areas ranging from 0.4 to 40.5 ha (1 to 100 ac).

Surface sand filters are very well suited to managing the first flush volume, which typically contains the highest concentration of pollutants. However, the design is poorly suited to providing stormwater quantity management to prevent flooding because high flows can easily damage the filter bed. As a result, it is strongly recommended that the design be installed in an off-line configuration.

The Austin filter works by a combination of sedimentation, filtration, and adsorption. The sedimentation section located just upstream of the filter section serves as pretreatment, removing larger-diameter suspended solids. Partially treated stormwater then flows slowly into the filter section, where fine-grain material is strained from the stormwater as it passes through the filter medium. The sand medium filter traps up to 90 percent of the small particles in stormwater runoff (6 to 41 microns) if a 460 mm (18 in) layer of sand is used. However, the extent of adsorption by sand of some dissolved pollutants is relatively small when compared to other filter media. For example, sand medium adsorbs much less positively charged dissolved metals and hydrocarbons than either soil or peat medium primarily due to its relatively low cation exchange capacity (CEC); sand has a CEC that is 13 percent that of the soil medium and 0.002 percent of the peat medium.

## APPLICABILITY

Although it has been applied within an urban setting, the Austin sand filter may require a significant commitment of land area (generally between two and seven percent of the drainage area). Consequently, many of the installations within the City of Austin are in newer, less densely developed portions of the municipality. Within an ultra-urban setting this design might be restrictive requiring a completely subsurface BMP (see underground sand filter design in the Underground Sand Filters Fact Sheet).

The applicability of surface sand filters to roadway projects has been demonstrated. For example, the Texas Department of Transportation has designed and/or installed Austin sand filters to provide stormwater management for several large highway projects. Overall, the design provides dependable performance and can be designed so it does not pose an additional safety hazard for automotive traffic.

## EFFECTIVENESS

The Austin sand filter design has demonstrated good total suspended solids (TSS) removals, typically providing 85 percent treatment. Performance for nutrients is less significant, and in fact the sand filter may be a source of nitrate (NQ) since ammonia in stormwater will undergo nitrification in the aerobic filter. However, sand filters are reported to decrease the total nitrogen (TN) load by approximately 35 percent. Total phosphorus (TP) removals range up to 55 percent, and there is a wide variation in metal removal rates (ranging between 35 and 90 percent). Removal of oil and grease by sand filters has been reported to average between 55 and 84 percent (Horner and Horner, 1995). Reduction in fecal coliform bacteria ranges between 40 and 80 percent.

The bulk of Austin sand filter designs have been in a warmer climate (central Texas) and reported removal rates probably reflect this influence (see Table 13). The filter performance would probably decrease if exposed to prolonged cold periods, which freeze the filter media. However, in a recent application of a sand filter in Alexandria, Virginia, it was reported that the filter operated effectively immediately after an arctic freeze even with several inches of frozen runoff in the settling area (Bell et al., 1995).

With the integration of a sedimentation chamber, the design provides pretreatment for the filter. However, where high loadings of oil or grease are encountered, additional pretreatment measures, such as grassed swales or vegetated filter strips are advisable.

## SITING AND DESIGN CONSIDERATIONS

Various design approaches can be taken in designing surface sand filters, including those developed in Austin. Design differences tend to be found in the size of the sedimentation area, the duration of sedimentation, and the loading rate of the filter media. For practicality, most designs limit the maximum water depth in the facility to less than 2.4 m (8 ft) and drain the system by gravity.

There are two basic designs for the Austin surface sand filter that manage the first 12.7 mm (0.5 in) of runoff, a partial sedimentation design and a full sedimentation design. The designs differ in terms of the volume of the sedimentation chamber and the size of the filter area. A partial sedimentation design creates a smaller footprint than a full sedimentation design but typically requires more maintenance. The partial sedimentation design is intended for areas that are relatively flat sloped and requires sufficient sedimentation area to store 20 percent of the water quality volume. The partial sedimentation design requires 16.7 $m^2$ (180 $ft^2$) of filter area per impervious acre. The full sedimentation design provides sufficient sedimentation area to store the entire water quality volume (100 percent), a volume that is subsequently released to the filter bed over a 24-hour period. The full sedimentation design requires 9.3 $m^2$ (100 $ft^2$) of area per impervious acre (assuming a permeability of the sand medium of 1 m/day [3.5 ft/day]). More extensive information regarding the design process used for the Austin sand filter should be acquired directly from the City of Austin's *Environmental Criteria Manual* (City of Austin, 1991).

There are also other approaches to surface sand filter designs that can be considered. One general rule of thumb is the required sedimentation area in square meters should be equal to 0.020 times the

**Table 13. Pollutant removal effectiveness for surface sand filters (%)**

| Study | TSS | TP | TN | $NO_3$ | Metals | Comments |
|---|---|---|---|---|---|---|
| City of Austin (1990) | 75 | 59 | 44 | -13 | 34-82 | Lead and zinc removal high; copper removal low |
| City of Austin (1990) | 92 | 80 | 71 | 23 | 84-91 | |
| City of Austin (1990) | 87 | 61 | 32 | -79 | 60-81 | |
| Welborn & Veenhuis (1987) | 78 | 27 | 27 | -111 | 33-60 | |

water quality volume in cubic meters (0.066 for area in square feet and volume in cubic feet) for drainage areas with an imperviousness of less than 75 percent (Claytor and Schueler, 1996). For areas with imperviousness greater than 75 percent, the sedimentation area commitment is 0.0024 times the water quality volume (0.0081 for area in square feet and volume in cubic feet). These recommendations recognize that ultra-urban runoff typically contains a high percentage of large-diameter sediment particles and therefore the settling area can be decreased (Shaver, 1994). When using this design approach, the recommended length-to-width ratio of the settling chamber is 2:1 or greater to limit short-circuiting, and the minimum recommended water depth in the settling chamber is 0.92 m (3 ft). This design approach also calls for the total storage volume in the sedimentation chamber and filter chamber to be equal to 75 percent of the water quality volume. At least half of the total storage volume should be located in the sedimentation chamber. The facility storage volume calculation should include void storage in the sand medium (typical porosity between 30 and 40 percent). In sizing the filter area it is recommended that a drawdown time of 40 hours be used and that the total depth of sand medium not exceed 0.61 m (2 ft). More information regarding this design approach can be found in *Design of Stormwater Filtering Systems* (Claytor and Schueler, 1996).

It should be noted that for any of the surface filter designs it is possible to substitute filter media other than sand. Refer to the Organic Media Filters Fact Sheet for additional information on organic media filters (peat/sand and compost media) and their advantages and disadvantages. Although over 500 Austin sand filters are currently operating, it is not known how long the basic design will last. Given the relatively low level technology typically employed, it seems reasonable to assume an effective life between 25 and 50 years with regular maintenance.

## MAINTENANCE CONSIDERATIONS

In general, the recommended frequency for performance monitoring is at least once per year. Each inspection should log information on the depth and location of any ponding, the depth of discoloration in the filter bed, and the depth of accumulated material over the sand media.

Most filters exhibit diminished capacity after a few years due to surface clogging by organic matter, fine silts, and hydrocarbons. Restoration of the original filtration capacity includes manual removal of any accumulated material and the first several inches of discolored sand. New sand is placed to reestablish the design grade of the filter medium. From a review of numerous references, it appears the material (sand/silt) accumulates in most sand filters at a rate between 13 to 25 mm/yr (0.5 to 1 in/yr). Maintenance can be reduced by employing surface sand filters only in drainage areas with 100 percent imperviousness. This significantly reduces the fine-grain material reaching the filter (silt and clay) which can clog the filter bed (Schueler, 1995). In areas with high trash loading, a wide-mesh geotextile screen can be placed over portions of the filter surface to simplify removal of the debris.

Regarding specific maintenance issues for the Austin sand filter design, the partial sedimentation design requires more frequent maintenance of the filter bed because there is less settling of solids in the sedimentation chamber. This tends to lead to greater sediment loads entering the filter bed than is experienced for full sedimentation designs (Young et al., 1996). Greater sediment loads translate into higher maintenance costs because more frequent replacement of the sand media will be required.

## COST CONSIDERATIONS

The surface sand filter design is a moderately expensive BMP to employ (Claytor and Schueler, 1996). However, the cost of installation is strongly correlated with the nature of the construction employed. If the filter is installed within an ultra-urban setting, it is likely that relatively expensive concrete walls will be used to create the various chambers. This type of installation will be significantly more expensive than an earthen-walled design, where relatively inexpensive excavation and compaction construction techniques lower the installation cost. However, earthen-wall designs require a greater land area commitment, which can offset the reduction in construction costs.

The construction cost of surface sand filters is also related to economies of scale—the cost per impervious hectare or acre served decreases with an increase in the service area. In 1994, the construction costs for Austin sand filters were \$39,500 per impervious hectare (or \$16,000 per impervious acre) for facilities serving less than two acres and \$8,400 per impervious hectare (or \$3,400 per impervious acre) for facilities serving greater than five acres (Schueler, 1994). These construction cost estimates exclude real estate, design, and contingency costs. (Note that these unit cost values should be used for conceptual cost estimating purposes only.)

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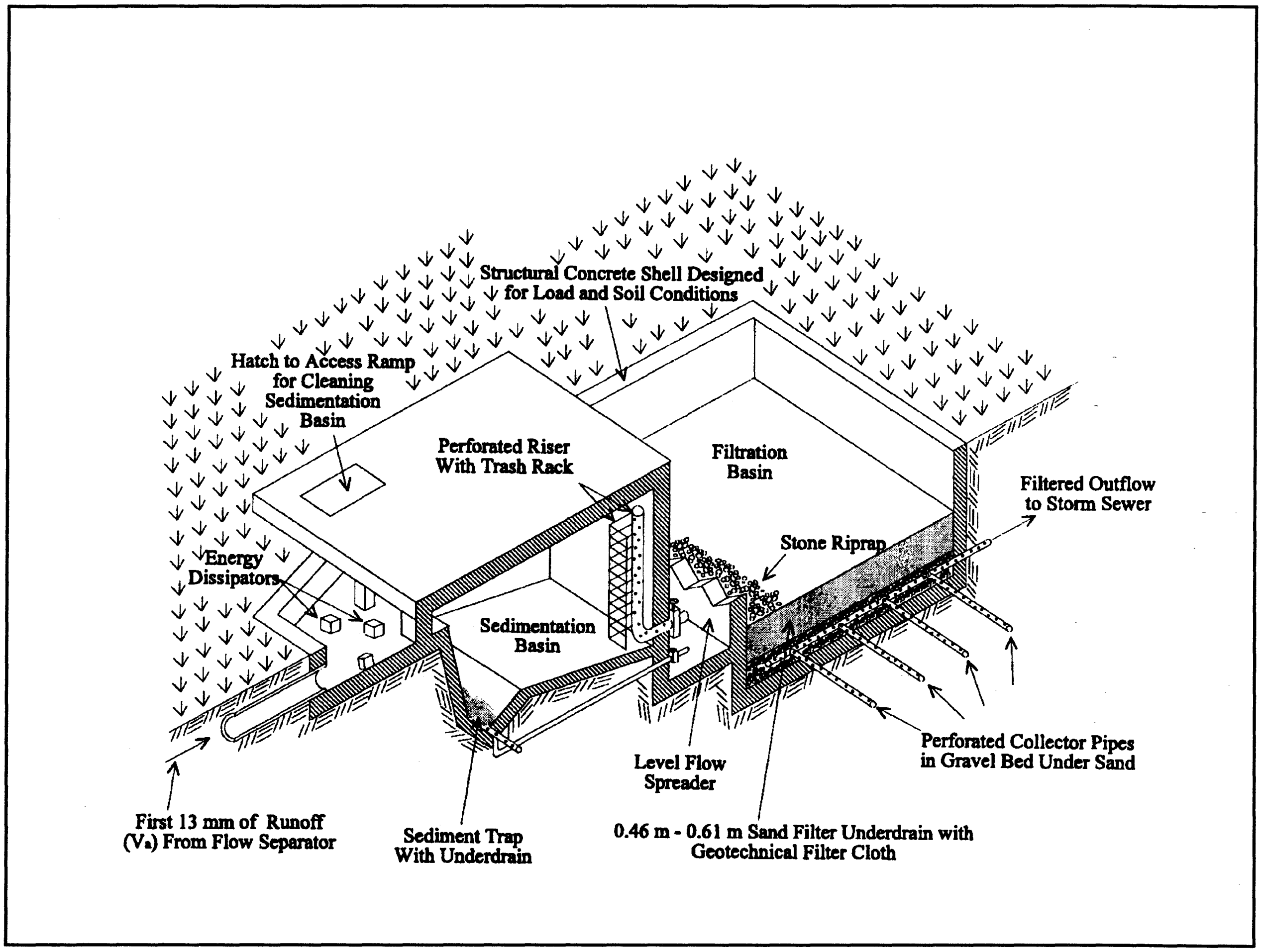


**Figure 14. Austin sand filter with full sedimentation protection (Young et al., 1996)**

# FACT SHEET—ORGANIC MEDIA FILTERS

There are two types of organic filter media typically used for stormwater management—peat/sand and compost. The use of organic media in surface or subsurface filter designs is intended to provide a higher level of stormwater treatment than a sand-only filter. Both of these organic media are typically installed in filters to depths between 460 to 600 mm (18 to 24 in), and are drained by piped underdrain systems. (Figures 15 and 16 illustrate typical filter cross sections.)

The organic media filters improve water quality through a combination of sedimentation, filtration, and adsorption processes. The sedimentation section located just upstream of the filter section serves as pretreatment, removing larger diameter suspended solids and capturing floating hydrocarbons. Partially treated stormwater then flows slowly into the filter section where fine-grain material is strained from stormwater as it passes through the filter media.

The subsurface or underground filter design is well adapted for applications with limited land area and provides turnkey performance that is independent of local soil conditions, groundwater levels, and other factors. The underground filter design typically consists of a multi-chamber vault that is completely below grade and is covered with a grating or structural concrete. It is most useful for multipurpose land uses, that is, where committed land area will also be used for automobile parking or for public parks. The surface filter design, sometimes called the Austin filter, also consists of a multichambered facility. While most of the filter is located at or slightly below grade the filter is not covered and so requires a commitment of land area (refer to the Fact Sheets on Underground Sand Filters and Surface Sand Filters for additional information).

As with other stormwater filters, the purpose of organic media filters is to manage the first flush, which typically contains the highest concentration of pollutants. If designed as an off-line facility, however, such filters can provide true capture and treatment of any water quality volume.

A number of design variations or proprietary systems featuring organic media are currently available (e.g., CSF® Stormwater Treatment System, now Storm*Filter*™). While these systems basically use the same treatment mechanisms, there are differences in the size of settling areas or chambers, loading rates, and media configuration.

## APPLICABILITY

Organic media filters can be used in underground and surface filter designs. Of these, the underground sand filter is considered to be more applicable to the ultra-urban setting. It requires a small commitment of land area, provides dependable service, and is relatively effective in removing urban pollutants. Furthermore, its design is inherently flexible, and the size and shape of the unit can be set based on local requirements.

Surface filter designs can also utilize organic media and are typically less expensive to construct and maintain than underground filter designs. Unfortunately, surface designs typically prevent multipurpose land uses and therefore are limited in their application to ultra-urban settings. In roadside settings where there is sufficient space (typically two to three percent of the drainage area served), a surface filter design may be preferred.

If they are placed below the frost line, the performance of organic media filters is relatively independent of season. In addition, the level of treatment is generally independent of placement and in situ soil conditions do not affect performance. For most designs pretreatment is integrated into the filter facility in the form of a settling chamber. Additional pretreatment may be provided by street sweeping to remove accumulated sand and trash, which can diminish the useful life of the filter.

## EFFECTIVENESS

Organic media filters are highly efficient in removing fine-grain material (small particles in stormwater runoff between 6 and 41 microns). As an additional benefit, organic media are capable of removing a portion of dissolved material found in stormwater. For example, the peat medium has a cation exchange capacity (CEC) 500 times that of sand. This greatly increases its ability to adsorb or capture positively charged dissolved metals and hydrocarbons, increasing the removal performance.

Organic media filters have demonstrated good total suspended solids (TSS) removals, typically providing 90 to 95 percent removal (Claytor and Schueler, 1996; Stewart, 1992). Performance for nutrients is less significant; in fact, the organic media may be a source of soluble phosphorus and nitrate ($NO_3$). Total phosphorus (TP) removals range up to 49 percent, while variable removal of metals is typically between 48 and 90 percent (Figure 14). Removal of oil and gasoline averages about 90 percent (Claytor and Schueler, 1996).

## SITING AND DESIGN CONSIDERATIONS

Two broad categories of organic media designs exist: (1) variations on existing sand medium filter designs and (2) proprietary designs that are optimized for organic media. For the first design category, organic media are simply substituted for sand, affecting the size of the filter portion of the facility. Information on existing sand filter designs is provided in the Surface Sand Filters and Underground Sand Filters Fact Sheets. These sand medium designs should be varied to reflect the permeability of the substituted organic media. It has been recommended in a recent evaluation that combination peat/sand filters be designed based on a permeability of 0.8 m/day (2.75 ft/day), or a value approximately 79 percent of that recommended for sand-only filters (City of Austin, 1991). On the other hand, compost medium filters have a wide range of permeability values depending on their age and degree of clogging. Designers should be aware that initial permeability can be very high (in the range of 122 m/day [400 ft/day], a value much higher than that used to specify the filter area); Claytor and Schueler (1996) recommend a design permeability value of 2.7 m/day (8.7 ft/day). Several good sources are available for detailed design procedures and information on underground and surface filter designs, including *Design of Stormwater Filtering Systems* (Claytor and Schueler, 1996) and *Evaluation and Management of*

**Table 14. Pollutant removal effectiveness of organic filters (%)**

| Study | TSS | TP | TKN | $NO_3$ | Metals | Comments |
|---|---|---|---|---|---|---|
| Stewart, 1992 | 95 | 41 | 56 | -34 | 50 - 90 | CSF® Type I system |
| Stormwater Management, 1994 | 92 | 49 | 57 | -145 | 48 - 81 | 3-year results for CSF® Type I system |

*Highway Runoff Water Quality* (Young et al., 1996).

One proprietary underground design that features organic media is the CSF® Type II system, which uses cylindrical filter cartridges filled with a granular organic medium consisting of composted leaves. (Figure 16 illustrates a recent advancement in Storm*Filter*™ technology, formerly the CSF® system.) The filter works by percolating stormwater through the cylindrical cartridges containing certified CSF® compost media. Because of the highly porous nature of the granular media, the flow through a newly installed cartridge is restricted by a valve to 57 L/min (15 gal/min). This allows more time for sediment to settle and ensures adequate contact time for pollutant removal. The CSF® system is equipped with scum baffles that trap floating debris and surface films; even during overflow conditions. A typical unit requires 0.67 m (2.2 ft) of drop from the inlet invert to the outlet invert. A portion of the sediment settles out in the area around the cylinders; more sediment, including particulate forms of nutrients and heavy metals, are trapped by the porous structure of the compost. Sizes range from 1.83 m X 2.44 m (6 ft X 8 ft) (treating about 284 L/min [75 gal/min] peak flow) to 2.44 m X 5.49 m (8 ft X 18 ft) vaults (which treat about 1360 L/min [360 gal/min], or 0.023 $m^3/s$ [0.8 $ft^3/s$]). Housed in standard size precast or cast in place concrete vaults, the filter systems are installed in-line with storm drains.

## MAINTENANCE CONSIDERATIONS

Annual maintenance costs for organic filters vary as a function of the design used. Surface filter designs using a peat/sand medium require periodic mowing and removal of the grass cuttings to avoid unwanted plant growth. In addition, at least an annual inspection is required for this design and reseeding of the grass cover crop may be required.

Filter designs that feature horizontal compost bed filters will likely be replaced every three to four years to prevent heavy metal concentrations from reaching levels that exceed the "clean sludge" definition under 40 CFR Part 503 (USEPA, 1994). These designs also require removal of accumulated material and rototilling of the compost to reestablish the required permeability.

Maintenance for underground designs that use organic media can be inferred from information given for sand-only medium filters given in the Fact Sheets for Underground Sand Filters and Surface Sand Filters. A D.C. underground sand filter serving a 0.4 ha (1 ac) area was serviced by removal and replacement of a gravel ballast and filter cloth, for $1300 in 1994 (Bell, 1996). It is reasonable to assume organic media filters would require comparable service. It should be noted that repair of subsurface filters requires confined space entry, which dictates larger management crews and a higher cost to repair than surface filters.

The maintenance of proprietary organic media filters varies with the manufacturer; it is likely that maintenance will include removing accumulated material that has settled in the facility and periodic replacement of organic media cartridges on an annual or biennial basis. For example, manufacturers of the CSF® system indicate annual maintenance costs will range from $500 to $1200 (for 280 and 1360 L/min [75 and 360 gal/min] systems, respectively).

## COST CONSIDERATIONS

The cost of surface facilities using organic media filters is comparable to the cost of filtration facilities that use sand medium (with the exception of proprietary systems). For conceptual costing a price of $8,400 to $39,500 per impervious hectare served (or

$3,400 to $16,000 per impervious acre served) can be used to estimate the construction cost of a proposed facility, excluding real estate, design, and contingency costs (Schueler, 1994).

Underground filters are generally considered to be a high-cost BMP option for water quality management. The construction cost per hectare served is typically around $34,600 and the cost per acre served is typically around $14,000, excluding real estate, design, and contingency costs (Schueler, 1994).

Drop-in CSF® vertical organic media units are typically precast vaults delivered to the site either partially or fully assembled. Typical cost variables include the need for ballast, type of lids and doors, customized casting of sections or holes, and depth of the vault. Systems treating peak flows of 280 and 1360 L/min (75 and 360 gal/min) have an estimated installed cost of $10,000 and $25,000, respectively (Stormwater Management, 1996).

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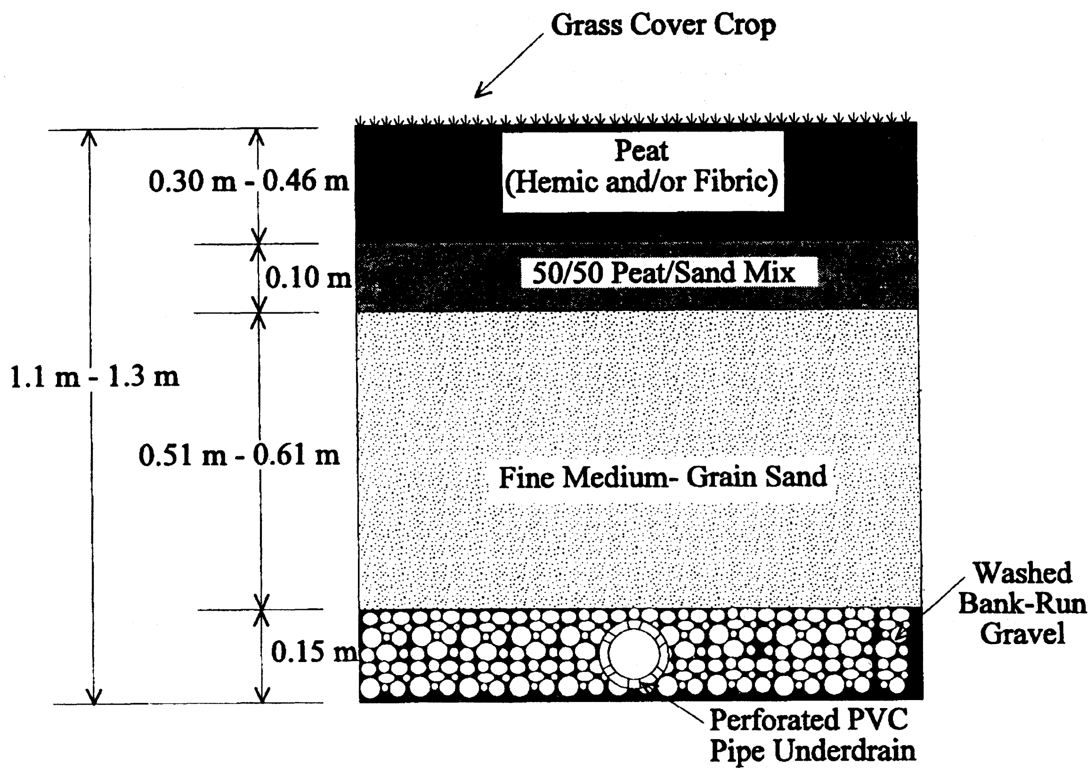


**Figure 15. Typical peat-sand filter cross section (Young et al., 1996)**

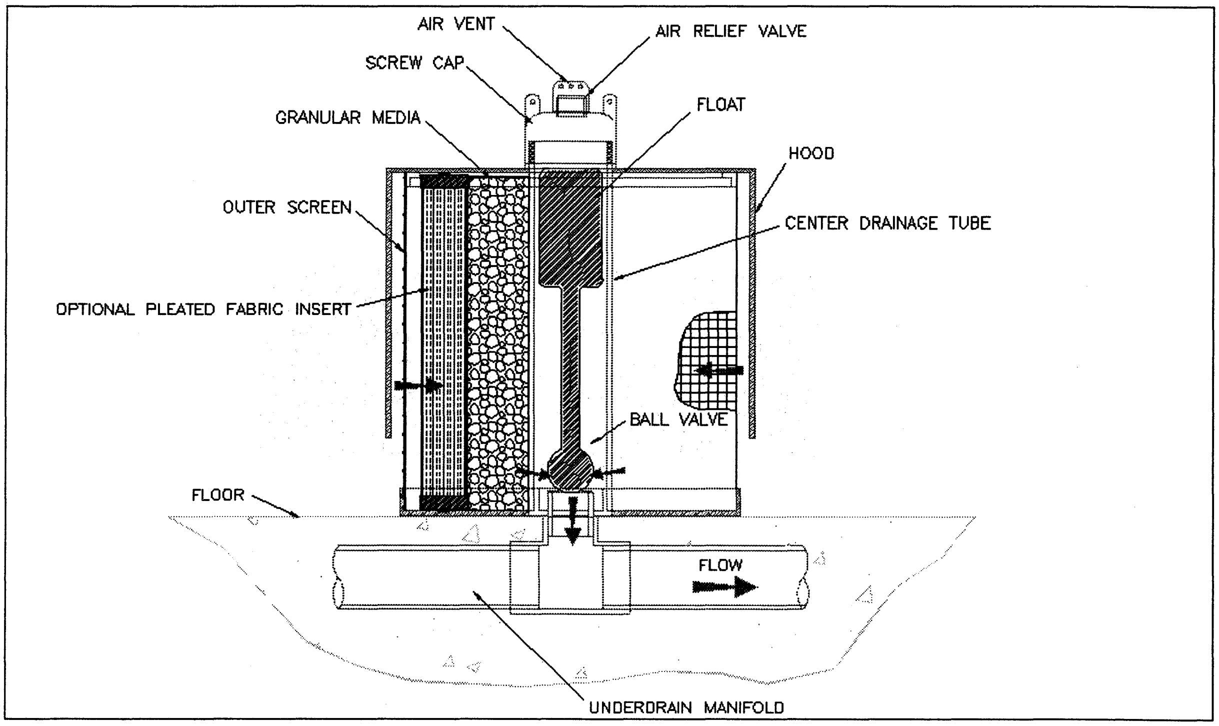


**Figure 16. Cross-section of a StormFilter siphon-actuated cartridge (Stormwater Management, 1998)**

# 3.5 VEGETATED SWALES/FILTER STRIPS

## 3.5.1 Description and Purpose

Grassed swales and filter strips are moderate to low-cost BMPs designed to improve the quality of stormwater runoff by using biological and chemical processes in soils and vegetation to filter out constituents. Both BMPs are well suited to the ultra-urban environment and can be located in medians or along the shoulders of roads.

Grassed swales are carefully engineered grassed channels that not only safely convey stormwater from a roadway but also provide water quality benefits. Grassed swales can also be sized to detain stormwater and address water quantity management needs. The swale designs can be adapted to accommodate in situ soils with differing percolation rates by varying the method of detaining the stormwater within the channel.

Filter strips are evenly sloped vegetated areas that treat stormwater by filtering it through vegetation (grass or wooded growth). Filter strips located on soils with high percolation rates can efficiently address water quality issues over a short horizontal length. This feature makes it feasible to use filter strips as roadway shoulders or safety zones.

## 3.5.2 Design Alternatives

Grassed swale designs are categorized as either wet or dry designs. Wet grassed swales maintain a volume of water in the bottom of the trench by having the invert located below the groundwater table or by the use of baffles in the trench to detain water. This system is designed to emulate a natural wetland. Water quality improvement is achieved by the settling out of particulates in the water column and by the biological and chemical action of the water. Dry grassed swales are designed so that runoff infiltrates through the bottom of the swale into the ground below. The subsoils must be permeable and possess a high infiltration rate. The treatment efficiency of both grassed swale designs is dependent on the gradient of the swale, the swale size, and the infiltration rate of the subsoils.

As a design option, stormwater quantity management can be achieved in larger swales by the use of check dams to pond the water within the channel. The stormwater is slowly dewatered by a notch in the check dam and released downstream or infiltrated into the subsoils. Pretreatment by a vegetated filter strip or other acceptable method to reduce sediment loads in the system is important so that the capacity of the channel can be maintained and the soil pores are not clogged.

Vegetated filter strips are designed as a water quality measure. As water flows in a sheet across the area, particulates and constituents in the first flush of stormwater are filtered out by the vegetation. They are then infiltrated into the soils or taken up as nutrients by the plants. Removal efficiencies are dependent on the slope length, gradient, and condition of the vegetation. A long slope length and mild gradient provide the most efficient removal rates. A berm is often included at the downstream end to temporarily detain the runoff. If necessary, energy dissipators, such as gravel strips, are used to reduce the velocity of the stormwater from the pavement areas before it enters the filter strip. This helps to spread the water out so that channels and rills, which can cause the runoff to bypass the system, do not develop.

# FACT SHEET—DRY AND WET VEGETATED SWALES

Traditionally, swale designs were simple drainage and grassed channels (Figure 17) that primarily served to transport stormwater runoff away from roadways and rights-of-way and provided inconsistent water quality treatment (Claytor and Schueler, 1996). Today, designers emphasizing water quality management are shifting from the drainage/grassed channel design concepts to carefully engineered dry/wet vegetated swale designs (Figure 17). Two general types of grassed swales are discussed in detail here—a dry swale, which provides water quality benefits by facilitating stormwater infiltration, and a wet swale, which uses residence time and natural growth to treat stormwater prior to discharge to a downstream surface water body.

Dry swales are distinguished from a simple drainage/grassed channel by the addition of carefully selected, highly permeable soil (usually sandy loam), check dams, and an underdrain system (Figure 18). These design features ensure that infiltration of stormwater will not depend only on the infiltration rate of the existing natural soils. Only in special circumstances where natural soil and groundwater conditions consistently provide high infiltration will a traditional drainage/grassed channel design provide the same water quality benefits as a dry swale design.

Wet swales are distinguished from the simple drainage/grassed channel by design features that maintain a saturated condition in soils at the bottom of the swale (Figure 19). The goal of a wet swale is to create an elongated wetland treatment system that treats stormwater through physical and biological action. Unlike dry swales, infiltration of stormwater is an undesirable condition in a wet swale because it would likely result in conditions detrimental to maintaining saturated soils to support wetland vegetation.

## APPLICABILITY

Dry and wet swales are appropriate for use in narrow areas along roads and medians where sufficient space exists to accommodate the additional storage depth and width. These swales are relatively inexpensive BMPs, and the total cost is principally related to earth moving construction costs. Because drainage/grassed channels are commonly installed in roadway right-of-way areas to provide essential drainage, implementing a more complex dry or wet swale design usually results in a relatively small additional cost and provides significantly better water quality management. Where sufficient space is available in ultra-urban areas, either dry or wet swales may be appropriate BMPs.

The design requirements of swales are relatively flexible; the gradient, size, and shape are typically based on local regulations that ensure adequate conveyance of the stormwater. In most applications, swales are placed parallel to roadways and care must be taken to ensure they do not impose an unacceptable safety hazard to any vehicles that might leave the roadway. Swales are practically vandal-proof and add an aesthetic value to roadside areas as long as they are maintained and litter and debris are regularly removed. However, wet swales can create ideal breeding habitat areas for nuisance insects such as mosquitoes.

## EFFECTIVENESS

Both dry and wet swales demonstrate good pollutant removal, with dry swales providing significantly better performance for metals and nitrate. Dry swales typically remove 65 percent of total phosphorus (TP), 50 percent of total nitrogen (TN), and between 80 and 90 percent of metals. Wet swale removal rates are closer to 20 percent of TP, 40 percent of TN, and between 40 and 70 percent of metals. The total suspended solids (TSS) removal for both swale types is typically between 80 and 90 percent. In addition, both swale designs should effectively remove petroleum hydrocarbons based on the performance reported for grass channels. See Table 15 for additional removal effectiveness rates for swales. Seasonal differences in dry/wet swale performance have been reported; pollutant removal efficiencies for many constituents can be markedly different during the growing and dormant periods (Driscoll and Mangarella, 1990). In seasonal climates, fall and winter temperatures force vegetation into dormancy, thereby reducing uptake of runoff pollutants and removing an important mechanism for flow rate reduction. Furthermore, decomposition of accumulated organic matter can lead to production of nutrients in a soluble form, making them free to be transported downstream. Freezing temperatures greatly reduce infiltration in dry swales, removing an important pollutant removal mechanism.

There are limited data currently available on wet swale treatment processes and it can only be assumed that the treatment processes are similar to those of a wetland. In the absence of infiltration, biological activity and limited sedimentation are probably important treatment mechanisms. The data available at this time suggest wet swales provide less pollutant removal than dry swales, which might be due to the absence of infiltration.

## SITING AND DESIGN CONSIDERATIONS

Designers of grassed swales must have site-specific data on topography, depth to seasonal high groundwater, and soil type prior to designing dry or wet swales. Existing topography will establish the general bottom slope of the swale (recommended between one and two percent) and dictate whether check dams will be required. The depth to groundwater is needed to determine if the swale will be of a dry or a wet design. In dry swales the surficial groundwater table should be more than 0.92 m (3 ft) below the proposed invert; wet swales require that the surficial groundwater table is close to the proposed invert. If the depth to the surficial groundwater table and fluctuations in this depth are not considered, it may result in an unacceptable design. Evaluating in situ soil characteristics such as color and structure is helpful in identifying whether excavated soil can be used for the highly permeable soil medium placed below the invert of a dry swale (e.g., a well-drained silty sand).

Dry or wet swales can be designed to treat the first flush of stormwater runoff (frequently taken as the first 12.7 mm [0.5 in] of runoff from the impervious area). In sizing dry or wet swales it is important to define what depth of runoff is associated with the first flush or water quality

**Table 15. Pollutant removal effectiveness for swales (%)**

| Study | TSS | TP | TN | $NO_3$ | Metals | Comments |
|---|---|---|---|---|---|---|
| City of Austin (1995)[1] | 68 | 43 | 23 | -2 | | Grassed channel |
| Yu et al. (1993)[2] | 21-95 | 32-85 | - | - | - | Vegetated swale |
| Yu et al. (1994) [2] | 49 | 33 | - | - | 13 | Length of swale evaluated reduced to 100 ft |
| Yu and Kaighn (1995)[1] | 30 | negligible | - | - | 11 | Grassed swale |
| Yousef et al. (1985)[1] | - | (-48)-48 | (-14)-25 | - | (-25)-92 | Grassed Swale |
| Kahn et al. (1992)[2] | 83 | 29 | - | - | 30-72 | 200 foot swale |

[1] Removal efficiencies based on concentrations.
[2] Removal efficiencies based on mass loading.

volume (WQV), as this runoff depth varies from state to state. Swales are configured as on-line facilities; while providing treatment of the WQV for small, frequent storms, swales must still retain the ability to convey high runoff rates from the roadway when high-intensity storms occur. During these larger rainfall events, swales provide marginal treatment of the high flow rates; however, because the flow velocity in the swale is nonerosive, resuspension or transport of accumulated pollutants is minimized.

Pretreatment is not considered crucial to the removal performance of dry/wet swales unless there is sufficient loading of pollutants (e.g., oil and grease) to harm the grassed surface. However, pretreatment (e.g., street sweeping or forebays) can provide a benefit by reducing and simplifying operation and maintenance of dry/wet swales.

Dry swales provide the majority of treatment by the process of soil infiltration, which filters suspended pollutants and facilitates adsorption of dissolved pollutants. It has been found that the mass removal of pollutants in dry swales is roughly proportional to the mass runoff that infiltrates through the bottom of the channel (Yousef et al., 1985). Even though the residence time in swales can be relatively long (on the order of a day), a review of water monitoring results suggests sedimentation plays a very small role in treatment in dry swales (Claytor and Schueler, 1996).

A dry swale is designed to capture and filter runoff from a water quality rainfall event. In designing a dry swale it is important to first determine the volume of water to be stored. This establishes the basic swale dimensions of width, length, and side slopes. Of equal importance in the design is to select a soil that permits infiltration of the stored stormwater within a reasonable period of time (typically on the order of one day). Infiltration rates for soils are quite variable, even within a single textural class. For example, soils classified as "Loam" may have infiltration rates ranging from 1.5 mm/h to 86 mm/h (0.06 in/h to 3.4 in/h). Computer programs, such as Soil Conservation Service Technical Release 20 Project Formulation Hydrology, can be used to evaluate how effective the storage capacity and infiltration rates of the swales are at attenuating peak stormwater runoff. Additional design procedures and information can be found in *Urban Drainage Design Manual Hydraulic Engineering Circular 22* (Brown et al., 1996), *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996), *Design of Stormwater Filtering Systems* (Claytor and Schueler, 1996), and *Highway Runoff Manual* (WSDOT, 1995).

In establishing the grassed swale, it is important to check that the swale has sufficient conveyance to drain large rainfall event. Depending on the applicable state or local ordinance this might be as large as the 25-year event. This requirement will establish the minimum size of any culverts and maximum size of any low-flow weirs placed in the swale.

## MAINTENANCE CONSIDERATIONS

Maintenance efforts and costs for swales are minimal (Schueler, 1992). Periodic maintenance for dry/wet swales should primarily focus on removing accumulated materials (e.g., sediment and trash or debris). Sediment build-up within the bottom of the swale should be removed when it has accumulated to the point where it occupies approximately 25 percent of the original design volume (Claytor and Schueler, 1996) or when the depth of sediment exceeds 101.6 mm (4 in) (Young et al., 1996). For publicly maintained swales, planners should anticipate removing sediment from 3 to 10 percent of the total swale length for each year of operation (Urbonas et al., 1992).

Maintenance of dry swales includes steps to ensure a vigorous and healthy grass growth. This includes periodic mowing to keep grasses at acceptable levels and minimize the growth of successional vegetation. The frequency of mowing varies with location, but it is recommended that the maximum height of the grass be between 7.62 and 10.2 cm (3 and 4 in) (Claytor and Schueler, 1996). Growth established above the sustained waterline in wet swales must also be maintained; wetland growth will colonize those areas below the waterline. Unfortunately, there is no firm rule for establishing when and where vegetation must be managed so it does not interfere with the basic function of the wet swale. For both dry and wet swales, it is important to avoid the use of herbicides and fertilizers. Particularly in urban areas, the low-lying nature of swales makes them a likely collector of unsightly litter, which must be removed by hand. It is recommended that twice-a-year inspection be performed for litter (Urbonas et al., 1992). One source gives the annual cost of maintaining a grassed swale (in Wisconsin) at between $1.90 and $4.10 (1995 dollars) per linear meter ($0.58 and $1.25 per linear ft) (SWRPC, 1991).

## COST CONSIDERATIONS

Dry and wet swales are considered moderate and low-cost BMPs, respectively. The principal cost difference between the two swale designs arises from the cost of installing highly permeable soils and underdrain systems in a dry swale. The construction cost per hectare served is typically around $3,700 ($1,500 per acre served) based on a nearly flat dry swale with a 3.05 m (10 ft) bottom width, 3:1 side slopes, and a ponding depth of 0.31 m (1 ft). This cost estimate excludes real estate, design, and contingency costs. This unit cost value should be used for conceptual cost estimating only. The cost of a dry/wet swale can also be inferred from the cost of a traditional grass swale, which typically ranges between $16 and $49 per linear meter ($5 and $15 per linear foot) depending on local conditions, swale dimensions, and the degree of internal storage (i.e., check dams) provided (Schueler, 1992).

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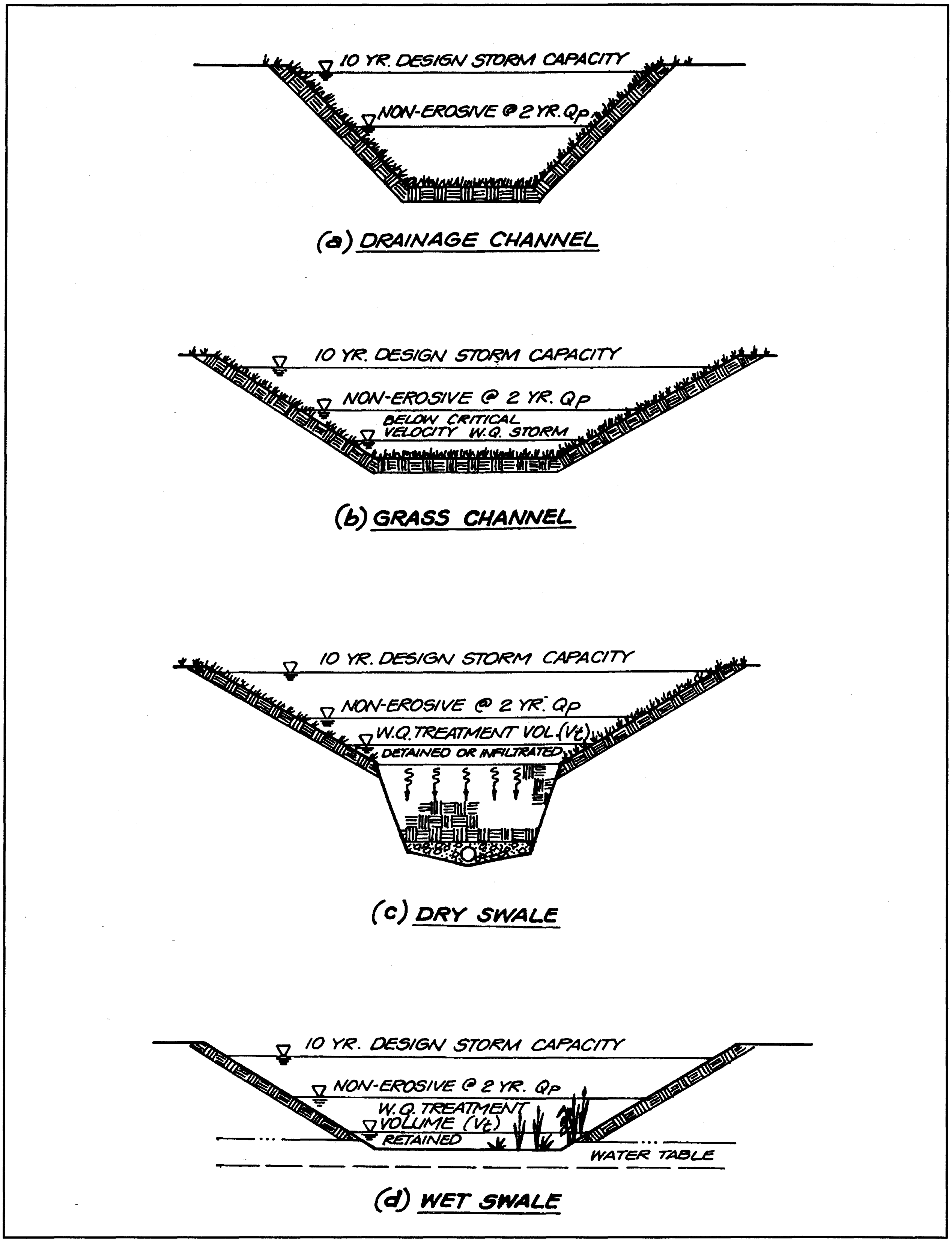


**Figure 17. Channels and swales (Claytor & Schueler, 1996)**

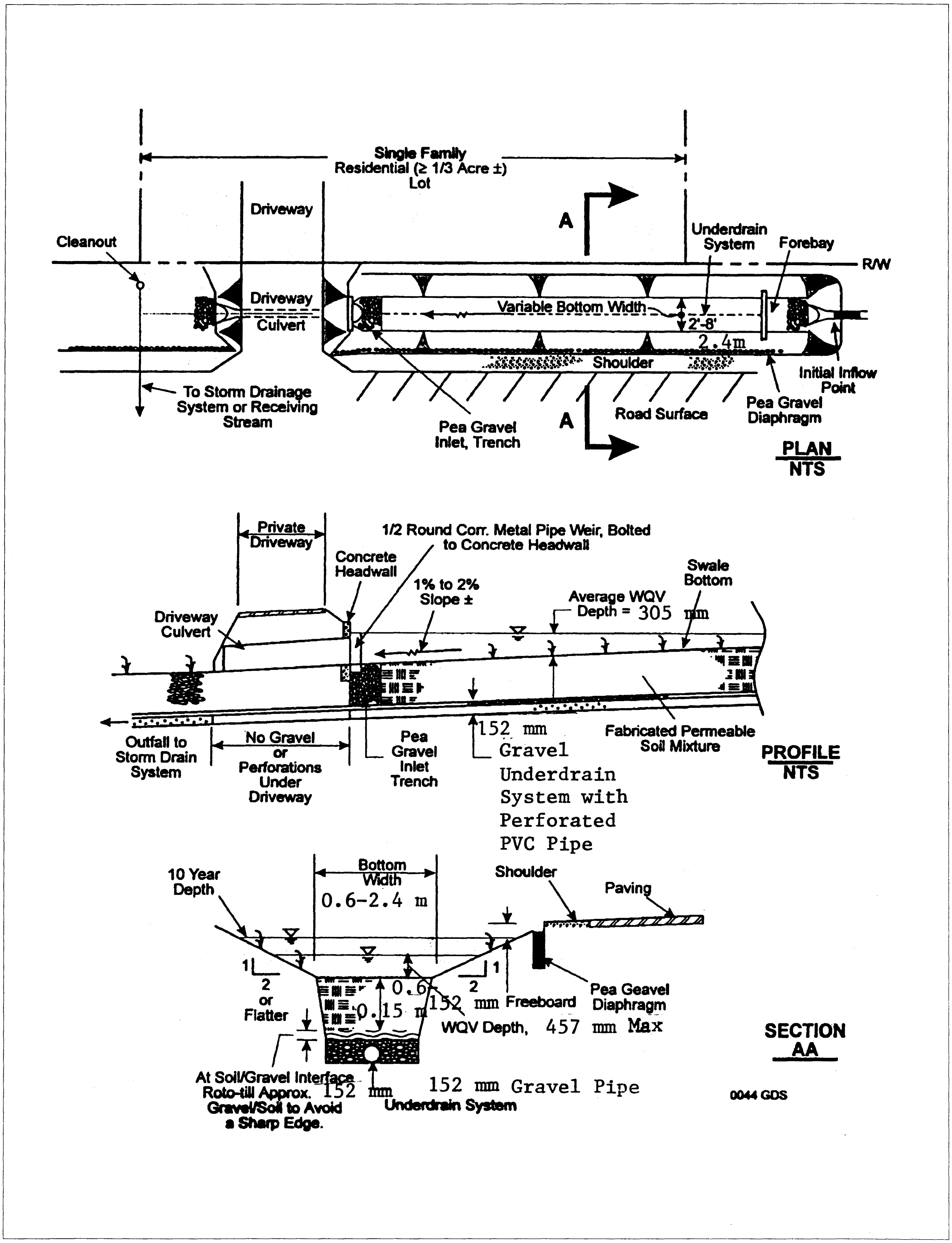


**Figure 18. Dry swale (adapted from Claytor & Schueler, 1996)**

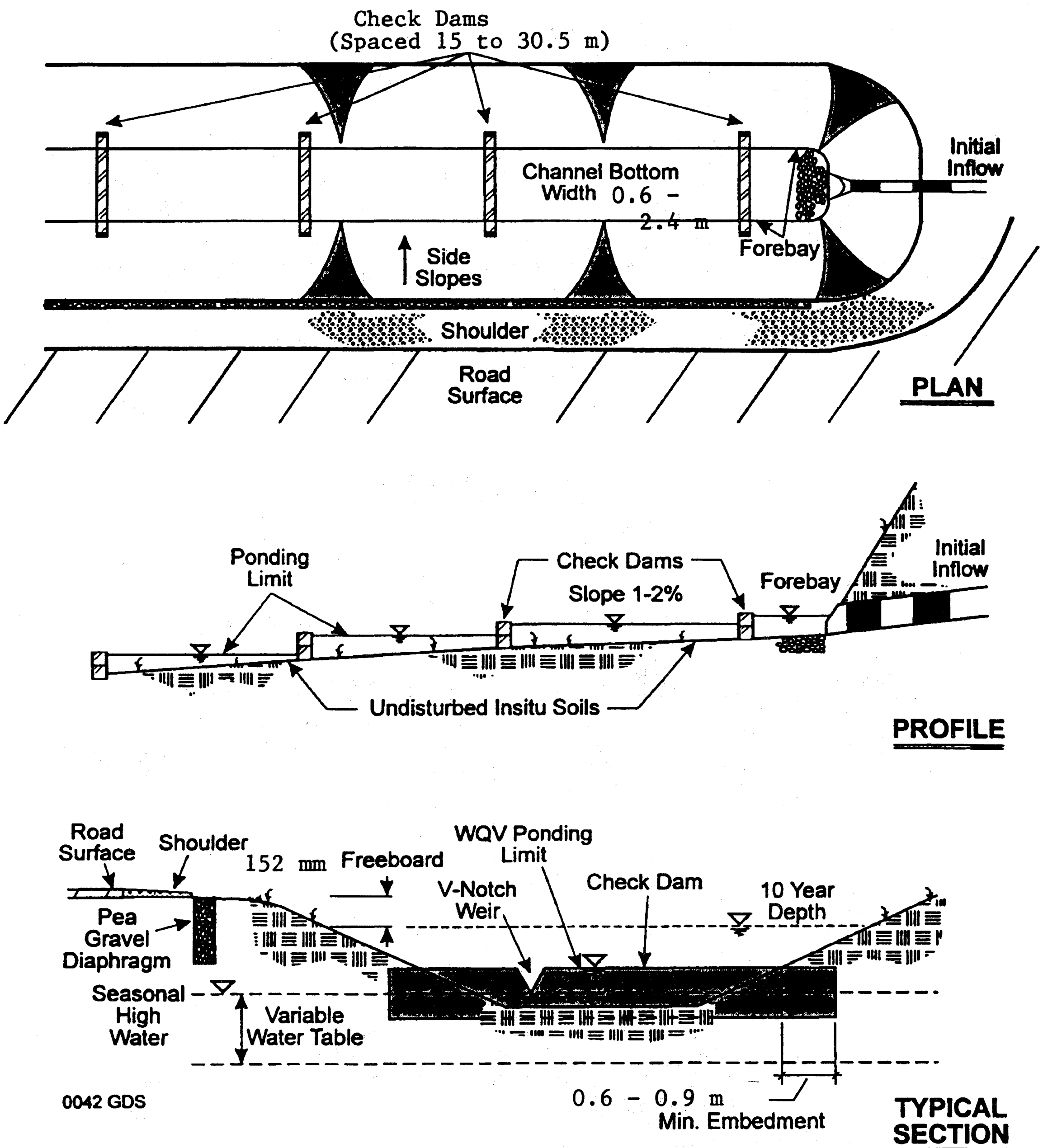


**Figure 19. Wet swale (adapted from Claytor & Schueler, 1996)**

# FACT SHEET—FILTER STRIPS

Filter strips, also known as vegetated buffer strips, use biological and chemical processes to filter stormwater runoff. Water flows in a sheet across the vegetated area, and is treated by infiltration into the soil and uptake by plants (Figure 20). Small berms may be installed at the downslope edge of the filter strip so that the water can be detained and infiltrated into the underlying soils.

Filter strips are not designed to attenuate peak stormwater flows, but can be an effective water quality measure. A dense vegetative cover, long flow length, and low gradient provide the most efficient removal rates.

## APPLICABILITY

Filter strips are appropriate only where ample room exists for installation. There must be sufficient flow length and gradient to adequately treat the stormwater. In the ultra-urban environment, they have limited application due to the required flow length. The primary highway application for vegetative filter strips is along rural roadways where runoff that would otherwise discharge directly to a receiving water first passes through a filter strip before entering a conveyance system (WSDOT, 1995).

A filter strip is commonly operated as a pre-treatment BMP located upstream of other BMPs capable of greater pollutant removal rates. As a stand-alone BMP, filter strips can only treat the lowest intensity rainfall events. While providing water quality treatment for small frequent storms, filter strips operating as on-line facilities must still retain the ability to convey high runoff rates from the roadway when high-intensity storms occur.

Filter strips cannot treat high-velocity flows and do not provide enough storage or infiltration to effectively reduce peak discharges to predevelopment levels (Schueler, 1992).

By design, filter strips are relatively flexible BMPs; the gradient, width, and length can be set based on local constraints. In most applications, filter strips are placed perpendicular to roadways and, therefore, may make highways safer by providing stopping distance for any vehicles that may leave the roadway. Filter strips are practically vandal-proof and add an aesthetic value to roadside areas as long as they are maintained and litter and debris are regularly removed. In most cases, however, site constraints will restrict their use in ultra-urban areas.

## EFFECTIVENESS

There is relatively little data on the effectiveness of filter strips on urban stormwater runoff. In one study, moderate to high removal rates were found for a 45.7-m-long (150-ft-long) grass filter strip treating urban runoff, but only mediocre pollutant removal occurred with a 22.9-m-long (75-ft-long) grass filter strip (Yu et al., 1993). Slope length and slope are also related to sediment removal efficiency (Wong and McCuen, 1982). These results are different from applications in agriculture, where much shorter grass strips have been found to work acceptably for agricultural runoff. Additional data on pollutant removal effectiveness is shown in Table 16.

Pretreatment is not considered crucial to the removal performance of filter strips unless there is sufficient loading of pollutants (e.g., sand, oil and grease) to harm the vegetated surface. Designers

**Table 16. Pollutant removal effectiveness for filter strips (%)**

| Study | TSS | TP | $NO_3$ | Lead | Zinc | Comments |
|---|---|---|---|---|---|---|
| Yu and Kaighn (1992) | 27 | 22 | 6 | 2 | 17 | 18-foot flow length[1] |
| | 67 | 22 | 8 | 18 | 46 | 50-foot flow length |
| | 68 | 33 | 9 | 20 | 50 | 150-foot flow length |

[1] Flow length is distance traveled uphill to downhill on surface of the filter strip.

should note that field surveys indicate many filter strips lack good vegetative cover, are subject to excessive sediment deposition, or are short-circuited by channels formed by concentrated flow (i.e., rill development). This is particularly true for filter strips employed in urban areas, where runoff concentrates very quickly (Claytor and Schueler, 1996). Furthermore, it is expected that there will be seasonal differences in filter strip performance in seasonal climates, where plant growth will be dormant and thinned. Cold winter temperatures will freeze the soil surface and prevent runoff infiltration into soils. Filter strips are not recommended for arid areas where sustaining growth is difficult.

Filter strips provide relatively low rates of pollutant removal and are most effective for total suspended solids (TSS), with approximately 70 percent removal. It has been estimated that filter strips can remove approximately 10 percent of total phosphorus (TP), 30 percent of total nitrogen (TN), and between 40 and 50 percent of suspended metals. During large rainfall events, filter strips provide marginal treatment and may in fact become sources of erosion.

## SITING AND DESIGN CONSIDERATIONS

The most important features of the filter strip that dictate effectiveness are the slope of the vegetated surface, the length of the vegetated surface, the uniformity of the surface, and the density of plant growth.

First, slope constraints exist for filter strips; most sources recommend that the surface slope be between two and six percent (Claytor and Schueler, 1996). Designers should note that with steeper slopes it becomes difficult to meet other design recommendations such as having a peak flow velocity of 0.27 m/s (0.9 ft/s) and a desired hydraulic residence time of nine minutes (Young et al., 1996). In addition, there are suggested flow length limits for filter strips, such as a minimum flow length (uphill to downhill) of 7.6 m (25 ft) (Claytor and Schueler, 1996). Field monitoring found that limited pollutant removal occurred in an urban application when the flow length was 23 m (75 ft); moderate to high removal of pollutants was found to occur for a filter strip with twice the flow length (45.7 m [150 ft]).

There are also recommended limits on the size of the service area served by the filter strip. The maximum recommended overland flow distance starting at the uphill edge of the filter strip and going uphill in the service area should not be more than 23 m (75 ft) for an impervious service area or 45.7 m (150 ft) for a pervious service area. However, various states have developed local limits or design requirements for filter strips. The Washington State Department of Transportation suggests that filter strips be used to treat runoff from roadways with a maximum of two lanes, and for a roadway with average daily traffic of less than 30,000 vehicles (WSDOT, 1995). The Colorado Department of Transportation sets the maximum flow depth on the filter strip at 0.64 cm (0.25 in) (CDOT, 1992).

To be effective, filter strips require sheet flow across the entire strip. Once flow concentrates to form a channel, it effectively short-circuits the filter strip. Unfortunately, this usually occurs within a short distance for filter strips in urban areas. It is difficult to maintain sheet flow over a distance of 45.7 m (150 ft) for pervious areas and 23 m (75 ft) for impervious areas. This may be due in part to the inability to obtain evenly compacted and level soil surfaces using common construction methodology. For some applications, a level spreader can be used to help ensure even distribution of stormwater onto the filter strip. To help maintain a uniform soil surface, some designs divert runoff from storms greater than the 2-year rainfall around the filter strip to avoid erosion and rill development.

During the construction phase, the topsoil should be of good quality and the subsoil should be tilled to reduce erosion and promote establishment of vegetation. Soil amendments such as lime, fertilizer, and organic material may be required.

Designers considering the application of filter strips can roughly estimate they need a filter strip 177 m (580 ft) wide by 23 m (75 ft) long (uphill to downhill) to manage a 0.4 ha (1 ac) service area (100 percent imperviousness). For those seeking design examples and additional information, several good sources are available, including *Design of Stormwater Filtering Systems* (Claytor and Schueler, 1996), *Urban Drainage Design Manual Hydraulic Engineering Circular 22* (Brown et al., 1996), *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996), and *Highway Runoff Manual* (WSDOT, 1995).

## MAINTENANCE CONSIDERATIONS

In general, maintenance efforts and costs for filter strips are small. Periodic maintenance for filter strips is primarily focused on ensuring a vigorous and healthy plant growth, preventing the formation of rills and gullies, and removing debris and litter. Of these items the most significant, costwise, is periodic mowing to keep grasses at acceptable levels and to minimize the growth of successional vegetation. It is recommended that mowing be performed perpendicular to the slope to help minimize the development of rills. For filter strips, it is important to avoid the use of herbicides and fertilizers on grassed portions of the strip, since these applications can directly contribute undesirable pollutants to waterways.

Filter strips can last for 10 to 20 years with proper conditions and regular maintenance. Proper maintenance is defined as those operations needed to ensure that uniform sheet flow and dense vegetation are maintained. For example, in locations where sanding of roadways or parking lot areas occur, it may be necessary to scrape away sediment build-up at the edge of the pavement to maintain even inflow to the filter strip. It is also recommended that maintenance of the filter strip be performed twice a year to patch any bare spots and fill and replant any rills that are forming.

## COST CONSIDERATIONS

Filter strips are low-cost BMPs. The principal cost to install is related to earth moving construction costs and planting costs. The cost for vegetative establishment, in 1995 dollars, is approximately $5,000 per ha ($2,000 per ac) for establishing an area by hydroseeding (Schueler, 1987). This does not include real estate, design, and contingency costs. Costs for sodding and planting of woody vegetation are significantly higher. (Note, that this unit cost value should be used for conceptual cost estimating only.)

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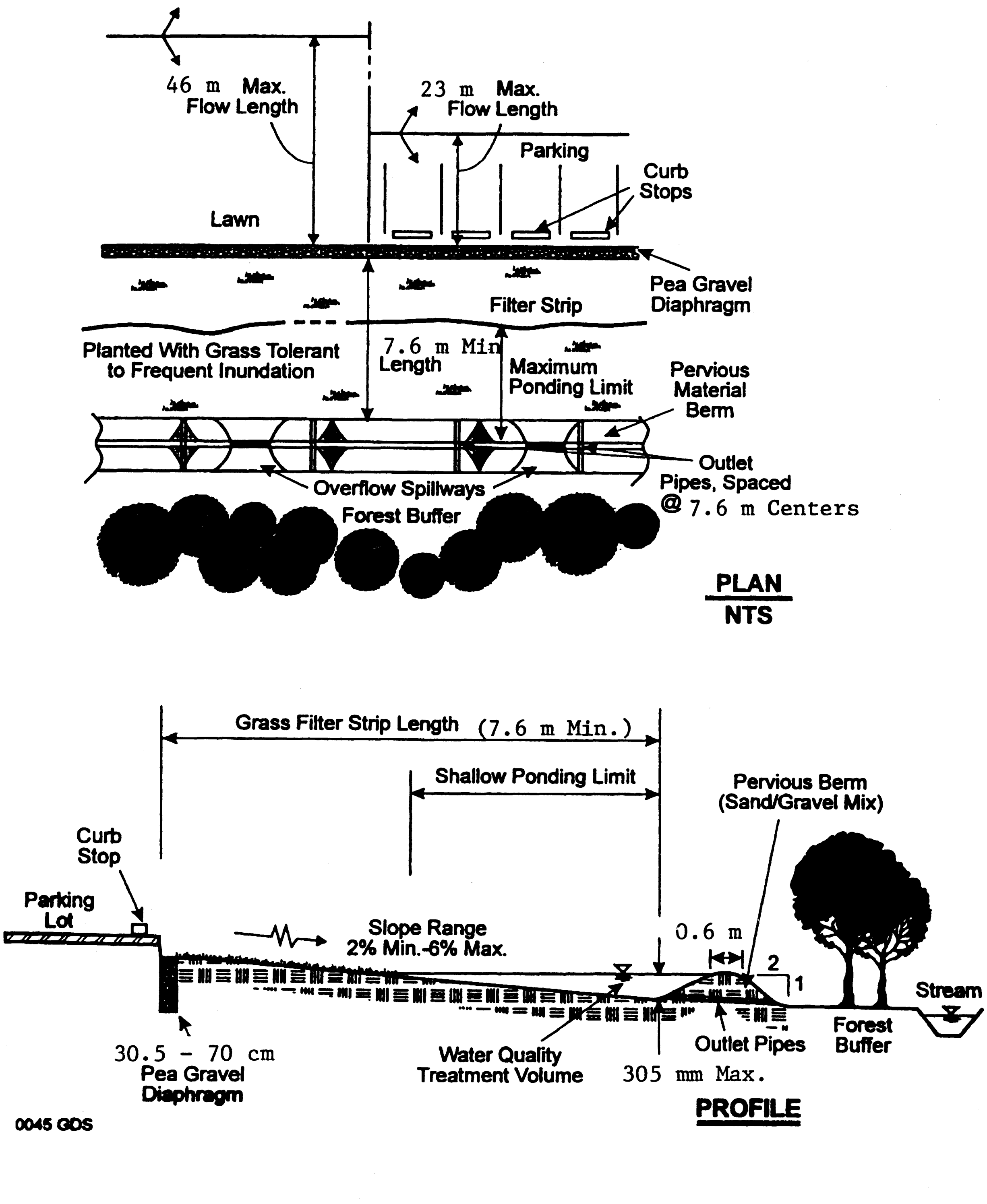


**Figure 20. Typical filter strip (adapted from Claytor & Schueler, 1996)**

# 3.6 WATER QUALITY INLETS

## 3.6.1 Description and Purpose

Due to their subsurface application, water quality inlets are particularly suitable for the ultra-urban environment. Prefabricated water quality treatment devices have evolved considerably since the oil/grit separator was first introduced into the marketplace; however, the basic design objectives remain the same. The main purpose of a water quality device is to improve the quality of stormwater runoff by settling out fine and coarse sediment, trapping debris and trash, and separating oil and grease. In general, water quality devices contain mechanisms to enhance both particle settling and oil and water separation. Some devices use settling and surface oil separation mechanisms, whereas others use filtration or vortex motion settling and separating mechanisms.

Most prefabricated water quality treatment systems come in a range of sizes. The size of the unit depends to a great extent on the quantity of stormwater runoff that needs to be treated. Additional stormwater can be bypassed into the existing storm drain system. Water quality treatment devices can be either on-line or off-line depending on the design of the treatment mechanism.

Although well suited for the ultra-urban environment, water quality inlets must receive frequent cleaning and inspection to maintain their effectiveness. FHWA has previously not recommended the use of water quality inlet BMPs such as oil/grit separators for highway applications, although they may perform adequately in maintenance yards with proper maintenance after installation. Finally, many states recommend they be considered only for pretreatment applications or as a last alternative.

## 3.6.2 Design Alternatives

The conventional oil/grit separator (OGS) is a three-chambered concrete gravity separation system. Typically, OGSs are installed in highly impervious areas that generate sediment, debris, and petroleum hydrocarbons in the stormwater runoff. OGSs are ideal for an ultra-urban environment because they are installed below the ground and can be retrofitted to an existing storm drain system. Because of resuspension problems associated with this device, OGSs typically are designed off-line, and clean-out should be conducted after each storm. In reality, OGSs are rarely cleaned out after every storm.

The catch basin insert (CBI) unit is a gravity filtering system designed to trap coarse sediments (gravel-size), debris, and oil and grease from stormwater runoff. The basic design consists of some type of screening mechanism for debris and trash, and a filter medium for particle settling and oil absorption. CBIs can be either mounted beneath the catch basin grate or placed within the sump area. CBIs typically are installed in small unpaved land use areas that generate coarse sediments and debris in the stormwater runoff. These devices are not meant as stand-alone systems, but rather they are designed to supplement other BMPs such as OGSs, sand filter systems, ponds, and infiltration trenches. Clean-out frequency depends largely on the land use and size of the basin that drains to the insert.

Prefabricated access hole and multichamber water quality devices are designed to trap sediment and oil within a storage chamber area and release the treated stormwater through an outlet pipe back into the storm drain system. Sediment separation results from a vortex motion that is created within the storage chamber area. As stormwater runoff is diverted into the storage chamber, the velocity of the flow is decreased and sediment particles are encouraged to settle out. These devices are ideal for ultra-urban areas since they are installed underground. They can either be retrofitted to an existing storm drain system or used in the design of a new system. These devices typically are installed in areas of high impervious land use where sediment and petroleum hydrocarbons are found in the stormwater. The size of the unit is a function of the quantity of stormwater to be treated. These devices can be on-line or off-line. Clean-out generally occurs when 85 percent of the sediment and oil storage chamber is filled. Both the access hole and concrete chamber devices are equipped with bypasses for large storms.

# FACT SHEET—OIL/GRIT SEPARATOR UNITS

The typical oil/grit separator (OGS) unit operates by settling sediment and particulate matter, screening debris, and separating free surface oils from stormwater runoff. The unit typically consists of three or four chambers. Figure 21 is a schematic of a typical water quality oil/grit separator unit. In the case of a conventional OGS unit, the first chamber, termed the grit chamber, is designed to settle sediment and large particulate matter; the access from the first chamber to the second chamber is covered with a trash rack, which operates as a screen to prevent debris from passing through to the second chamber. The second chamber, termed the oil chamber, is designed to trap and separate free surface oils and grease from the stormwater runoff. The third chamber houses the stormwater outlet pipe that discharges the overflow to the storm drain system.

Most OGS units are designed to be placed in highly impervious parking areas that drain about 0.4 ha (1 ac). Results from one OGS study conducted in the State of Maryland showed that the treatment capacity of most conventional OGS units inventoried was less than 5.1 mm (0.2 in) of runoff for the service area (Schueler and Shepp, 1993). Because of the limited retention capacity, conventional OGSs are not capable of removing large quantities of stormwater constituents. Instead, they are designed and implemented to control hydrocarbons, debris, large organic matter, and coarse sediments that are commonly associated with heavily traveled parking areas.

## APPLICABILITY

The OGS unit is designed to trap and settle large sediments and particulate matter, debris, and hydrocarbons from highly impervious areas such as parking lots, gas stations, loading docks, and roadside rest areas. The OGS unit is constructed beneath the surface of the impervious area, and as such does not require additional space. Because of this, it can be easily retrofitted into existing impervious land use conditions, which makes it suitable for ultra-urban environments. Results from an OGS study in the State of Maryland have shown that detention times for conventional OGS units are generally less than 30 minutes during storm events (Schueler and Shepp, 1993). Trapped sediments and particles tend to resuspend during subsequent storms and exit the chambers. Because settling and trapping are temporary, actual pollutant removal occurs only when the units are cleaned out. Therefore, these devices are best suited for an off-line configuration where only a portion of the first flush is treated by the unit and clean out occurs after every major storm event. A study produced by the Metropolitan Washington Council of Governments showed that particulate matter within conventional OGS units remained the same or decreased over a 20-month period (Shepp et al., 1992).

## EFFECTIVENESS

Conventional OGS units have demonstrated poor pollutant removal capabilities. The primary removal mechanism of the OGS is settling; with short detention times, and resuspension occurring after every storm event, removal effectiveness is limited to what is physically cleaned out after every storm. If the unit is not cleaned after each storm, resuspended trace metals, nutrients, organic matter, and sediments will eventually pass through each chamber and into the storm drain system.

A study performed on OGS units in the State of Maryland showed that negative sediment deposition from storm to storm indicated that re-suspension and washout were a common problem (Schueler and Shepp, 1993). The only constituent that was trapped with some efficiency in the second chamber was total hydrocarbons. This was probably due to the inverted siphon, which is designed to retain free surface oils and grease (Schueler et al., 1992; Schueler and Shepp, 1993).

## SITING AND DESIGN CONSIDERATIONS

The OGS unit is a structural BMP that is easily installed in areas of high imperviousness such as parking lots, gas stations, commercial and industrial sites, and shopping centers, and even along roadways. The OGS unit would be well suited for ultra-urban environments where available land area is a major constraint. OGS units typically are sized for highly impervious drainage areas of less than 0.4 ha (1 ac), though up to 0.61 ha (1.5 ac) is feasible. Locating the units off-line would alleviate some of the problems associated with the retention and re-suspension of pollutants.

The OGS units are designed using a three- or four-chamber configuration. Settling of larger sediments, trash, and debris takes place in the first chamber. The primary function of the second chamber is to separate oils and grease from the stormwater runoff; some absorption of oils and grease to smaller sediments, and settling will also occur in the first chamber. The third chamber houses the overflow pipe. The OGS unit typically is sized based on the drainage area, which often includes rooftops, and the percent imperviousness of the basin. One common practice is to size the unit based on a design storm to provide some amount of storage. In general, OGS units are rectangular in shape, with the largest chamber being the initial settling chamber. Approximate dimensions for an OGS unit located in a parking area that drains 0.4 ha (1 ac) would be 1.82 m deep by 1.22 m wide by 4.23 long (6 ft deep by 4 ft wide by 14 ft long) (inside dimensions). The length of the first chamber would be 1.82 m (6 ft) with 1.22 m (4 ft) for each of the other two chambers.

Specific dimensions for each OGS design are dependent on site characteristics and local design storm requirements. Improvement in OGS performance can be achieved by extending the interior chamber walls to the top of the chamber, thereby eliminating recirculation and overflow from one chamber to another. In addition, placing the OGS off-line from the main stormwater system helps to reduce resuspension of oil and grit.

Additional design examples and information can be found in *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs* (Schueler, 1987), and *Northern Virginia BMP Handbook: A Guide to Planning and Designing Best Management Practices in Northern Virginia* (NVPDC, 1992). Because studies have shown that water quality inlets are a marginal method for removing particulate matter (Schueler and Shepp, 1993), other design references (Claytor and Schueler, 1996) do not recommend them for sand filter pretreatment.

## MAINTENANCE CONSIDERATIONS

Very few structural or clogging problems have been reported during the first five years of OGS operation (Schueler and Shepp, 1993). The OGS unit should be inspected after each major storm event. Clean-out would require the removal of sediments, trash, and debris. In reality, OGSs are rarely cleaned out after every storm because such intensive maintenance is beyond most budgets.

The removal of oily debris, sediments, and trash might require disposal as a hazardous waste. However, some local landfills may accept the sediment and trash if it is properly dewatered.

## COST CONSIDERATIONS

OGS units can be either cast-in-place or precast. Precast concrete chambers are usually delivered to the site partially assembled and tend to cost slightly less than the cast-in-place option. The cost associated with a cast-in-place concrete OGS unit is a function of several parameters. Excavation, gravel bedding, amount and size of rebar, amount of concrete and form work, and grate and clean-out access holes all contribute to the total cost of the OGS unit. In 1992, OGS units were reported to cost between $5,000 and $15,000 fully installed.

On average, costs per inlet ranged from $7,000 to $8,000 (Schueler et al., 1992).

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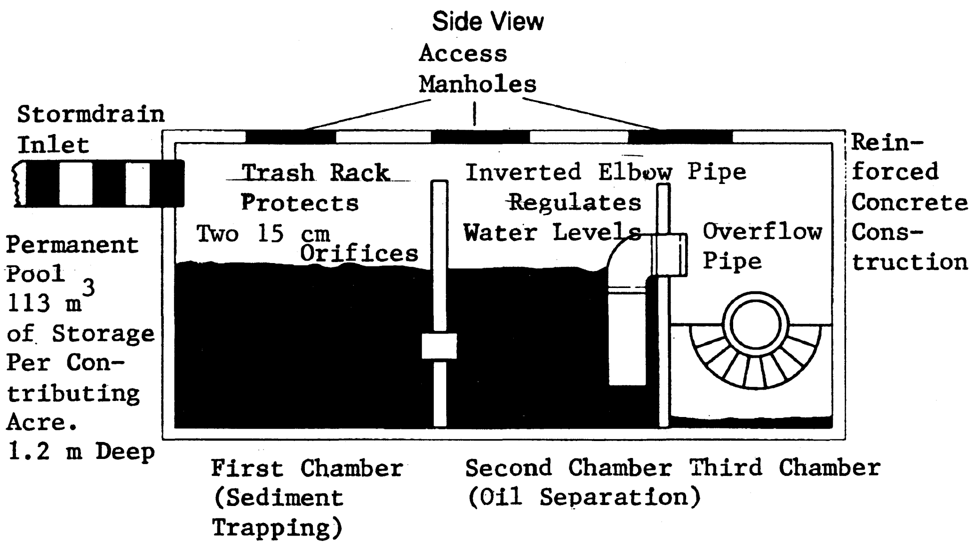


**Figure 21. Schematic of an oil/grit separator (OGS) (adapted from Schueler, 1987)**

# FACT SHEET—CATCH BASIN INSERTS

Catch basin inserts (CBIs) are designed either to hang from a drain-inlet frame or to be inserted well below the drain inlet in the sump area, taking advantage of additional space in the lower part of the catch basin. The information provided here refers to drain-inlet inserts that are mounted directly beneath the frame. Figure 22 shows a typical frame-mounted CBI. CBIs work by gravitational filtering to remove debris and large (gravel-sized) sediment particles entering the catch basin. Some of the insert models also are designed with an inner component that contains an oil-absorbent material to facilitate in the removal process.

CBI devices are designed to be suspended from the storm drain inlet structure. Hydraulically, they are designed with a high-flow bypass to prevent resuspension and washout. Only the designed flow rate should pass through treatment surfaces. The insert can contain one or more treatment mechanisms, which include filtration, sedimentation, or gravitational absorption of oils. Two outlets also are designed into the devices. The first outlet is for treated stormwater, and the second is for stormwater that exceeds the capacity of the device. In some manufactured CBIs, the overflow outlet is not a true bypass because excess water still contacts the treatment area prior to overflow. For such CBIs, due to the very short contact time and potential for flushing previously trapped materials, treatment may be compromised at higher flow rates (King County, 1996).

## APPLICABILITY

CBIs are not suitable for removal of fine particulate stormwater pollutants such as metals, nutrients, silts, or clays; however, inserts can be used in unpaved areas where the sediment concentration in the stormwater is expected to contain coarse material. In addition, CBIs are suited for sites where a substantial amount of debris is found in stormwater runoff. Areas where CBIs would be appropriate include unpaved roads or parking areas, construction sites, or unpaved industrial sites and lumber yards. Because oil/grit separators are not recommended for unpaved areas, CBIs could be used in lieu of them.

## EFFECTIVENESS

In a recent study by King County, Washington, and others (King County et al., 1995), six different CBIs were evaluated. The inserts tested did not remove significant amounts of pollutants associated with silt- or clay-sized particles; however, the inserts were capable of trapping and removing the coarser materials and debris that are typically found in unpaved areas. New inserts that were designed to remove petroleum hydrocarbons were found to reduce oil and grease concentrations by 30 to 90 percent; after some use, the sustained removal rates were reduced to 30 percent or less. While the inserts varied in their ability to remove oil and grease, most units exhibited some level of treatment if maintained on a regular basis. Inserts did not exhibit any ability to remove metals such as total copper, lead, or zinc. Tests on new and used insert units showed that the CBIs were not effective at removing total phosphorus associated with very fine sediment.

## SITING AND DESIGN CONSIDERATIONS

Because of their limited ability to remove stormwater runoff pollutants, CBIs should not be used as a stand-alone BMP, but rather installed in conjunction with other BMPs. CBIs are best suited for installation as pretreatment for other BMPs to remove large sediment or debris from unpaved or pervious areas. It should be noted that there are different types of CBI designs and media and one type might not cover all possible pollutants. It is important, therefore, to specify which pollutant is of primary importance because systems optimized for large sediment or debris might not provide acceptable long-term removal of oils and grease, and vice versa. Because catch basin inserts are commercially available, design and installation information can be obtained from their manufacturers or distributors. Catch basin inserts developed by three vendors were evaluated by the

Interagency Catch Basin Insert Committee in the Seattle, Washington, area (King County et al., 1995). General design criteria and siting recommendations can be found in the King County, Washington, *Surface Water Design Manual* (King County, 1996).

CBIs should be designed to perform acceptably for a reasonable design storm (e.g., 2-yr rainfall event) based on hydrologic characteristics and the percent of imperviousness of the site. At the same time, they should not interfere with the drainage for larger rainfall events (e.g., the 10-year rainfall event).

## MAINTENANCE CONSIDERATIONS

One of the major concerns with CBIs is the need to regularly clean the filter system or medium. Units designed for coarse sediment or debris removal tend to have more holding capacity and, depending on their location, will operate correctly if cleaned after every two or three major storms. Maintenance for CBIs configured for oil and grease removal is also a function of specific site conditions but in general is more intensive. In the majority of the cases, this maintenance focuses on removing accumulated fine-grain sediment from the filter surface or screens. The filter or medium has to be replaced less frequently because of saturation by oil and grease. Street sweeping could potentially reduce the maintenance frequency for inserts that have this problem.

There is currently an effort to improve the design of CBIs to manage oil and grease and sediment. CBIs currently under development would separate sediment holding areas from the filter media. Captured sediment collected from several storm events would be stored in a dead-storage area at the base of the catch basin, thereby, preventing clogging of the filter media.

Most of the inserts are made of lightweight material and can be removed by one person; however, filter inserts allowed to fill up with sediment or debris may require two-person crews to lift.

## COST CONSIDERATIONS

Depending on the complexity of the unit, the CBI grate-mounted units can range in cost from as little as $100 up to $1,500. Variables affecting cost include the size of the insert, the type of filter medium, the filtering system, and the material used to construct the insert. Another consideration is the clean-out and maintenance requirements of a sump with an insert versus a sump without the insert. Costs for maintaining CBIs range from $10 to $100 per unit per month, assuming monthly replacement of filter media (King County, 1996). In a study conducted by the Port of Seattle, it took one person 90 minutes to clean 18 inserts. In contrast, it took two vacuum truck operators about three hours to clean 18 sumps (King County et al., 1995).

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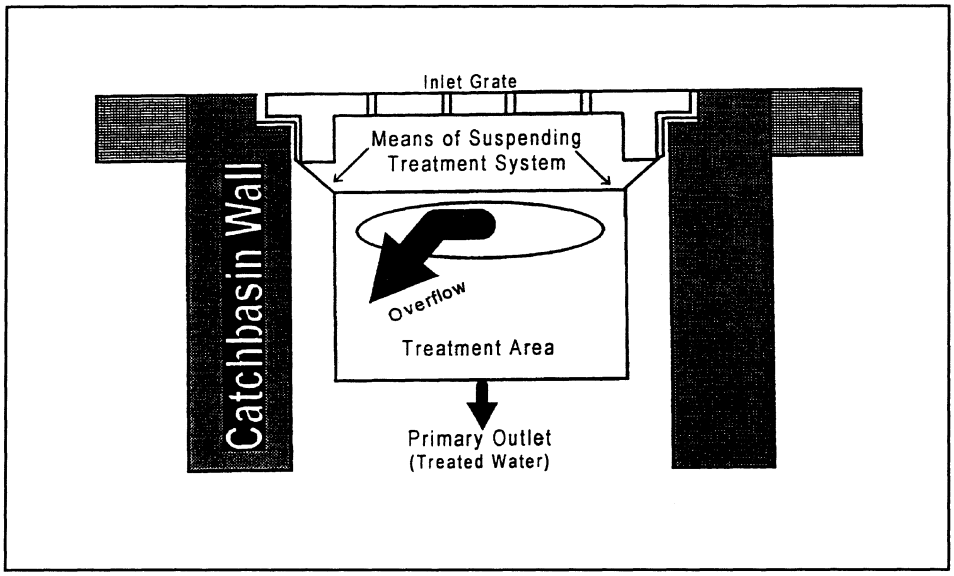


**Figure 22. Typical features of a catch basin insert (King County, Washington, 1995)**

# FACT SHEET—MANUFACTURED SYSTEMS

Cylindrical access hole and box structure stormwater treatment devices have become increasingly popular for the removal of particulate matter normally found in stormwater runoff. The two main treatment mechanisms are vortex motion particle and particulate settling and oil-water separation. The devices operate by intercepting a portion of the flow traveling through the storm drain system and using a vortex motion and/or conventional settling chamber to separate out large sediments and oils. Two common types of access hole treatment devices include the Storm*ceptor*® and the Downstream Defender™. An example of a box-type treatment unit is the Vortechs™ Stormwater Treatment System. Figures 23, 24, and 25 show the Storm*ceptor*®, Downstream Defender™, and Vortechs™ treatment devices, respectively.

The Storm*ceptor*® and Downstream Defender™ can be designed to retrofit an existing stormwater access hole structure or be designed as a new storm drain system. Each of the devices is designed to treat low to moderate storm flows. The incoming stormwater and pollutants enter a diversion chamber and are diverted into the lower chamber for treatment. While oils and floatable particulate matter rise to the surface, sediments settle out to the bottom. During peak or high flows, the excess stormwater bypasses the lower treatment chamber and flows directly to the downstream storm drain system.

The Storm*ceptor*® is divided into two water quality chambers designed for removal of the oil and sediment normally found in urban stormwater runoff. Stormwater flows into the upper chamber and is diverted by a V-shaped weir down a drop pipe and into the lower chamber. The flow is then redirected horizontally around the circular walls of the lower chamber and through an outlet pipe. The inlet drop pipe and outlet riser pipe are set at the same elevation to provide storage for oil and sediment within the lower chamber.

The Downstream Defender™ operates by introducing stormwater into its cylindrical base, where the runoff spirals down the perimeter, allowing the larger sediments to settle out. The internal components of the Downstream Defender™ allow oils, grease, and floatables to be trapped. Unlike the conventional oil/grit separator unit, the Storm*ceptor*® and Downstream Defender™ are designed to prevent the resuspension of sediment, thereby providing actual removal during every storm event.

The Vortechs™ system consists of four chambers. The first chamber is termed the grit or swirl chamber. Settleable particles are swept to the center of this chamber, where they are induced to settle out. The higher the flow rate through the system, the greater the strength of the vortex settling motion. Particles eventually migrate toward the center of the cylindrical chamber, where velocities are low and conditions are tranquil. The particles remain trapped until the system is cleaned. The first chamber is designed to prevent wash-outs that occur in conventional water quality inlet devices. The second chamber is the oil chamber. The oil barrier traps floatables, oils, and grease. Unlike conventional oil traps that lack flow controls and extra tank capacity, the Vortechs™ system is designed to handle most flow surges. The third chamber is the flow control chamber, which is designed to reduce forces that encourage resuspension and wash-out. During conditions of intense storm surge through the unit, the low-flow control within the Vortechs™ system causes the inlet pipe to become submerged. This process floats oily constituents up above the inlet pipe and out of the influent stream; thus, oils and grease are kept within the trap. The fourth chamber is the outlet chamber.

## APPLICABILITY

The Storm*ceptor*® and Downstream Defender™ treatment systems are used primarily for treatment of stormwater runoff from impervious surfaces. The devices are ideal for use in ultra-urban settings since each is composed of a precast structure that is installed beneath the ground and can either be retrofitted to an existing storm drain system or replace a proposed access hole in a storm drain system. The structures are designed to capture and treat a portion of the flow that enters into the storm drain system; however, the volume of runoff treated is limited to the available volume in the lower chamber structure. Because of this, Storm*ceptor*® and Downstream Defender™ might treat less than a typical water quality treatment volume and should be placed at the beginning of the storm drain line for maximum treatment efficiency. The Storm*ceptor*® and Downstream Defender™ treatment devices do not significantly reduce either biological or nutrient pollutants that are not sorbed to particles (Weatherbe, et al., 1995; Bryant, et al., 1995; H.I.L. Technology, 1996).

The Vortechs™ system is designed to counter the resuspension problem associated with conventional oil/grit separator water quality inlets. Data for a Vortechs™ system obtained through in-field monitoring of an actual installation in Freeport, Maine, showed that particulate matter within the unit increased over a 20-month period (Vortechnics, 1996).

## EFFECTIVENESS

There are only a few independently verified studies of the effectiveness of manufactured systems. Field testing at over 21 installed and operating Storm*ceptor*® units in the Toronto, Canada, area has shown that 86 percent of the trapped sediments were in the clay and silt particle size range (Weatherbe, et al., 1995). The average annual accumulation rate was determined to be about 0.70 $m^3$/ha (0.37 $yd^3$/ac) of land. Unlike conventional oil/grit separators, the study showed that the accumulation was increasing over time. This was important because it showed captured sediments (both fine and coarse) were not being resuspended by subsequent storms. On average, monitoring studies have reported a 96 percent removal of oil, 83 percent removal of sand, and 72 percent removal of peat. Depending on the size of the unit, treatment rates range between 7,079 and 4,201 L/min (285 and 1,110 gal/min); all flow greater than the treatment rate is bypassed.

Preliminary results for the Downstream Defender™ show overall removal efficiencies in excess of 90 percent of particles greater than 150 microns (sand-sized particles). The device intercepts the first flush and retains floatables, oils, and grease. Head loss across the Downstream Defender™ is typically less than 30.5 cm (12 in); thus backwater effects are generally not a problem.

Bench-scale testing performed on the Vortechs™ system showed that for silt-sized sediments, the average removal efficiency was in excess of 80 percent. The removal efficiency is greater for larger-sized particles. For example, for a single 2-month storm event in Portland, Maine, the same bench-scale test showed that the Vortechs™ unit exhibited a removal efficiency of approximately 89 percent for sand-sized particles (Vortechnics, 1996).

## SITING AND DESIGN CONSIDERATIONS

Vendors of manufactured systems are often willing to provide services to build, install, and maintain manufactured systems. These services frequently include technical support to design a system for a customer in the process of making a sale. If not carefully evaluated by the customer, however, these systems may become a problem, especially with respect to maintenance considerations (see below). The Storm*ceptor*®, Downstream Defender™, and Vortechs™ units are structural precast BMP water quality devices that can be installed on-line in new storm drain systems. The structures come in various sizes and are best suited for land uses with drainage areas of 4 ha (10 ac) or less. The Storm*ceptor*®, Downstream Defender™, and Vortechs™ systems are stand-alone BMPs and do not require any pretreatment; however, they can be used to pretreat stormwater runoff to other

BMPs such as ponds, sand filters, or infiltration/exfiltration trenches. On the other hand, some BMPs, such as water quality inlets (see Section 3.6), should be used only for pretreatment and never as a stand-alone BMP.

The Storm*ceptor*® comes in eight different precast sizes and can treat 0.018 to 0.07 $m^3/s$ (0.64 to 2.5 $ft^3/s$, respectively) of stormwater runoff prior to bypass. The individual size of the Storm*ceptor*® would depend on the amount of stormwater runoff expected to drain to the device. The Downstream Defender™ comes in four different precast sizes and can treat 0.021 to 0.37 $m^3/s$ (0.75 to 13 $ft^3/s$) of stormwater runoff prior to bypass. Vortechs™ systems are sized based on required design flow rate. The precast units come in nine different sizes that handle flow rates between 0.04 and 0.7 $m^3/s$ (1.6 and 25 $ft^3/s$).

Design specifications for these manufactured systems can be obtained from their manufacturers or distributors. Current information is readily available on the web sites for each manufacturer. Web site addresses are:

- Storm*ceptor*®: http://www.stormceptor.com.
- Downstream Defender™: http://www.hil-tech.com.
- Vortechs™: http://www.vortechnics.com.

## MAINTENANCE CONSIDERATIONS

The Storm*ceptor*® and Downstream Defender™ systems are access hole structures that are engineered to be installed within roadways in residential, commercial, industrial, or institutional areas. The access hole includes a built-in internal device that diverts stormwater runoff to the lower treatment chamber. Normal installations take only a few hours once the excavation is complete. The general maintenance procedure for the Storm*ceptor*® is to clean out the unit once a year, or when 15 percent of the operating storage volume is filled with solids, or when oil levels reach 25 mm (1.0 in) or greater (Storm*ceptor*®, 1996). The sediment holding capacity of the Storm*ceptor*® units range from 2.12 to 20.56 $m^3$ (2.77 to 26.87 $yd^3$). The manufacturer of the Downstream Defender™ recommends cleaning out the units at least twice a year using a conventional vacuum truck (H.I.L. Technology, 1996).

The Vortechs™ system sediment storage capacity ranges from 0.57 to 5.4 $m^3$ (0.75 to 7 $yd^3$), depending on the size of the unit. Routine inspections are necessary to schedule cleaning. The Vortechs™ system can be cleaned by a conventional vacuum truck (Vortechnics, 1996).

If not properly maintained, manufactured systems can become exporters of oil and grease and other constituents. Generally, however, manufactured systems are designed to counter the resuspension problem associated with conventional oil/grit separators.

## COST CONSIDERATIONS

Storm*ceptor*® and Downstream Defender™ units are precast manhole structures that contain a built-in diversion device. The structures are delivered to the site partially assembled. Contractors need only set the grade and alignment to properly install the units. The Storm*ceptor*® comes in eight standard sizes, with the cost of the units ranging from $7,600 to $33,560. Based on the maximum impervious drainage area in hectares treated for the 60 percent TSS removal rate, the cost per impervious hectare ranges from $9,900 to $26,800. On average, the cost of maintaining the system is about $300 to $500 per cleaning (pumping, dewatering, and disposing of solids). The expected life of the Storm*ceptor*® is 50 to 100 years (Storm*ceptor*®, 1996).

Downstream Defender™ devices are available in four standard sizes. An average cost at capacity is $44,100 per $m^3/s$ ($1,250 per $ft^3/s$) (H.I.L. Technology, 1996).

The Vortechs™ unit comes in nine different sizes depending on the quantity of stormwater for treatment. The average cost is $52,900 to $123,500 per $m^3/s$ of capacity ($1,500 to $3,500 per $ft^3/s$) (Vortechnics, 1997).

Installation costs for all of the structures are site-dependent but generally run about 25 to 35 percent of the unit cost of the structures.

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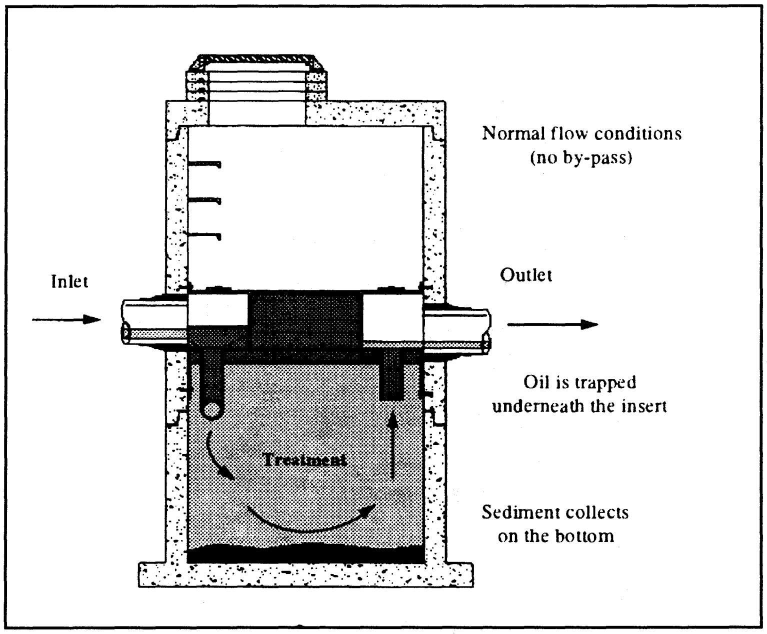


**Figure 23. Storm*ceptor*® operation during average flow conditions (Storm*ceptor*®, 1995)**

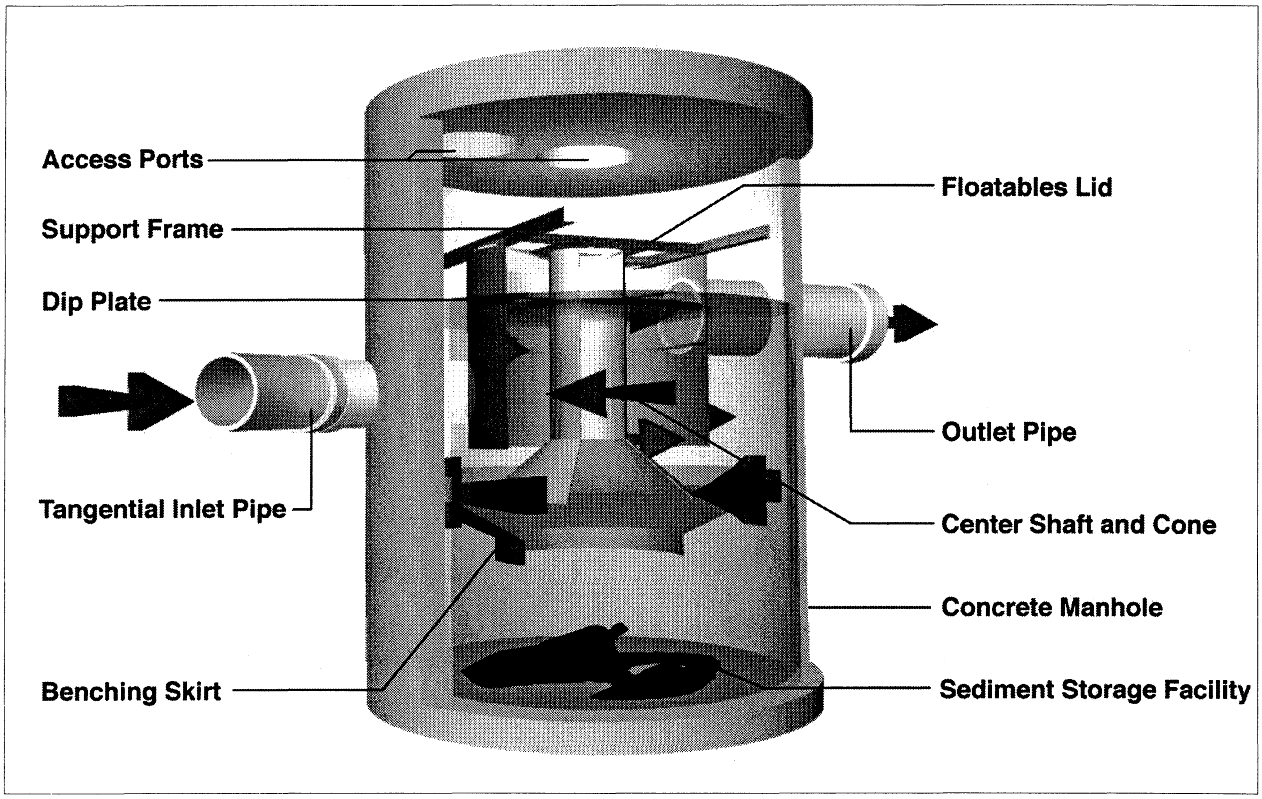


**Figure 24. Downstream Defender™ (H.I.L. Technology, 1996)**

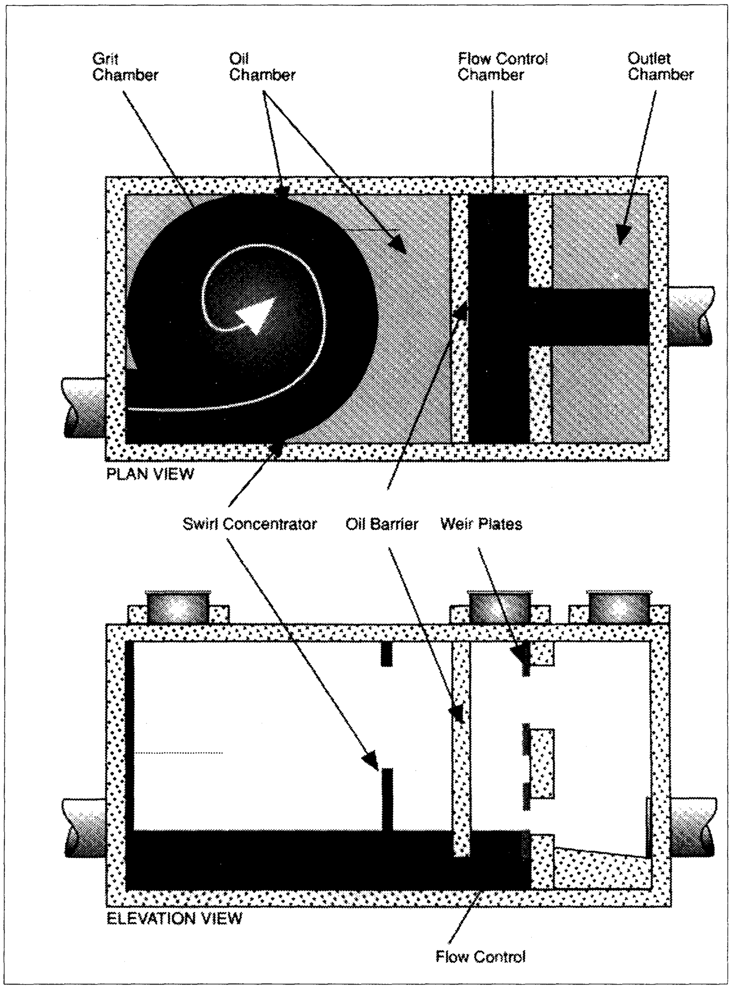


**Figure 25. Vortechs™ Stormwater Treatment System (Vortechnics, 1996)**

# 3.7 POROUS PAVEMENTS

## 3.7.1 Description and Purpose

Porous pavements have the potential to be an effective ultra-urban BMP. Different types of porous pavements commercially available include porous asphalt and concrete surfaces, as well as several types of lattice-type pavers (hollow concrete blocks and paving stones).

While conventional pavement results in increased rates and volumes of surface runoff, porous pavements, when properly constructed and maintained, allow some of the stormwater to percolate naturally through the pavement and enter the soil below. This helps to retain the natural infiltration rate facilitating groundwater recharge and maintaining base flows in urbanized streams while providing the structural and functional features needed for the roadway, parking lot, or sidewalk.

The paving surface, subgrade, and installation requirements of porous pavements are more complex than those for conventional asphalt or concrete surfaces. For porous pavements to function properly over an expected life span of 15 to 20 years, they must be properly sited and carefully designed and installed, as well as periodically maintained. A failure to properly test for soil drainage capacity and water table height, and a failure to protect paved areas from construction-related sediment losses, can result in their premature clogging and failure. The proper operation of porous pavements may also be a problem in regions that apply large amounts of road salt and where heavy truck loads are a problem.

## 3.7.2 Design Alternatives

Porous pavement systems generally consist of at least four different layers of material. The top or wearing layer consists of either asphalt or concrete with a greater than normal percentage of voids (typically 12-20 percent in the case of asphalt). The wearing layer may also be comprised of lattice-type pavers (either hollow concrete blocks or paving stones made from solid conventional concrete or stone) that are set in a bedding material (sand, pea-sized gravel or turf grass).

Below the wearing layer, a stone reservoir layer or a thick layer of aggregate (e.g., 50 mm [2 in] stone) provides the bulk of the water storage capacity for a porous pavement system. In the pavement design, it is important to ensure that this reservoir layer retains its load bearing capacity under saturated conditions because it may take several days for complete drainage to occur.

Typically, porous pavement designs include two (or more) transition layers that can be constructed from 25 to 50 mm diameter stone. One transition layer separates the top wearing layer from the underlying stone reservoir layer. Another transition layer is used to separate the stone reservoir from the undisturbed subgrade soil. Some designs also add a geotextile layer to this bottom layer or some combination of stones and geotextile.

Porous asphalt pavement, for example, consists of open grade asphalt mixture ranging in depth from 50 to 100 mm with 16 percent voids. The thickness selected depends on bearing strength and pavement design requirements. This layer sits on a 25 to 50 mm transition layer located over a stone reservoir. The bottom layer completes the transition to the underlying undisturbed soil using a combination transition/filter fabric layer.

Modular paving stones are also used to create porous pavements. These pavements can be constructed insitu by pouring concrete into special frames or by using preformed blocks. The top layer for these porous pavements consists of conventional concrete, with the intervening void areas filled with either turf or sand. A transition or bedding layer is used to make the transition to the reservoir layer. These lattice-type pavers or hollow concrete blocks are often used in conjunction with turf grasses and are used in low-traffic parking lots, lanes, or driveways. Porous pavements using paving stones have similar construction, but can be designed to have a much higher load bearing capacity, and therefore have more widespread applicability. Construction guidelines and design specifications are available from the manufacturers of these products.

# FACT SHEET—POROUS PAVEMENTS

Porous pavements have the potential to be an effective ultra-urban BMP. While conventional pavement results in increased rates and volumes of surface runoff, porous pavements allow some of the stormwater to percolate through the pavement and enter the soil below.

The types of porous pavements used include porous asphalt and concrete surfaces, as well as several types of lattice pavers, which are hollow concrete blocks or stones (Figure 26). Porous pavements work by allowing streets, parking lots, sidewalks, and other impervious covers to retain their natural infiltration capacity while maintaining the structural and functional features of the materials they replace.

## APPLICABILITY

In many instances porous pavements can be used in place of conventional asphalt or concrete in an ultra-urban environment. They are generally not suited for areas with high traffic volumes or loads. Composite designs that use conventional asphalt or concrete in high-traffic areas adjacent to porous pavements along shoulders or in parking areas have, however, been designed (Figure 27). Generally, porous pavements are most often used in the construction of parking areas for office buildings, recreational facilities, and shopping centers. Other uses include emergency stopping areas, traffic islands, sidewalks, road shoulders, vehicle cross-overs on divided highways, and low-traffic roads. Some porous pavements such as porous asphalt have also been tested for use in highway projects (Hossain and Scofield, 1991). Their use at gas stations, truck stops, and industrial sites is not recommended due to the high risk of groundwater contamination from trace organic compounds (Cahill, undated). As a BMP retrofit option, porous pavement might have limited application because prior disturbance or modification of in situ soil often significantly reduces its infiltration capacity (Schueler et al., 1992).

Porous pavements such as porous asphalt are also effective at reducing hydroplaning, as well as improving wet weather visibility (Stotz and Krauth, 1994). The use of interlocking concrete paving stones on walks and crosswalks can also make them more visible and safer for both drivers and pedestrians, thereby reducing the need for repainting.

## EFFECTIVENESS

When operating properly, porous pavements are as effective at removing pollutants from stormwater as other infiltration devices. Also like other infiltration BMPs, porous pavements are not designed to sustain a high removal rate for suspended sediment. While initial removal rates for suspended sediment are very high, the removal process causes clogging of the pavement and subsequently reduces its infiltration capacity. As the infiltration capacity decreases, so does the capture and treatment of runoff pollutants. Careful attention to maintenance is necessary to reduce the potential for clogging. In addition, all adjacent areas should be stabilized to prevent sediment from washing onto the pavement surface to prevent premature clogging.

**Table 17. Pollutant removal effectiveness for porous pavement (%)**

| Study | TSS[2] | TP | TN | $NO_3$ | Metals | Comments |
|---|---|---|---|---|---|---|
| MWCOG (1983) | 95 | 60 | 88 | - | 99 | Rainfall |
| Hogland et al. (1987) | 95 | 71 | -305[1] | -1607[1] | 33-96 | Snowmelt |

[1] Prior agricultural land use in the area.

Hossain and Scofield (1991) found that a test section of porous pavement performed satisfactorily over five years. Although a slight decrease in the infiltration rate occurred, both the infiltration rate and storage capacity were above design values. Typical removal rates based on load reductions observed are summarized in Table 17.

## SITING AND DESIGN CONSIDERATIONS

Suitable sites for porous pavements are generally limited to low-traffic areas with a minimum soil infiltration capacity of 7 mm/h (0.27 in/h) (greater than 13 mm/h (0.5 in/h) is preferred). Geotechnical testing of potential installation locations is needed to quantify the infiltration capacity. In siting porous pavement, groundwater contamination can be minimized by ensuring that the depth to the seasonally high water tables is at least 1.2 m (4 ft) below the reservoir layer and that installations are no closer to drinking water wells than 30 m (100 ft). Sites that are probable sources of high contaminant loads, such as gas stations, should be avoided.

Porous pavement installations should also be 30 m (100 ft) upgradient and 3 m (10 ft) downgradient of building foundations. More detailed guidelines for the siting of porous pavements and related design specifications can be found in *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996), and *A Current Assessment of Urban Best Management Practices - Techniques for Reducing Non-Point Source Pollution in the Coastal Zone* (Schueler et al., 1992). Additional information on existing designs and their effectiveness is available in *Stormwater Infiltration* (Furgerson, 1994).

The design considerations for porous pavement should be consistent with the concepts of flexible pavement design. These requirements, summarized by Rollings and Rollings (1993), include:

- The use of sufficient pavement thickness to protect the subgrade from being overstressed.
- The use of quality base and subbase materials that can support the applied loads.
- A stable surface that serves as the wearing course for traffic.
- The compaction of all materials to provide strength and to resist densification under traffic.

Standard cross section designs typical of those for porous asphalt and modular paving stones are shown in Figures 28 and 29, respectively.

Porous pavements using lattice-type pavers or hollow concrete blocks and paving stones have similar construction details. Paving stones, however, can generally be designed to have a much higher load-bearing capacity and therefore have more widespread applicability. Detailed construction information and specifications are generally available from the manufacturers of these products (Florida Concrete and Products Association, 1989; Rollings and Rollings, 1993).

Based on construction experience, Cahill (undated) recommends the inclusion of a perimeter stone filter inlet around the edges of porous pavement installations as a reliable means of ensuring that runoff enters the stone filter reservoir if surface clogging of the pavement occurs. In addition, when specifying the pavement or paver stones it is important to ensure the surface infiltration rate is greater than the peak design rainfall intensity. One source gives this peak design rainfall intensity as the 1-h, 2-year rainfall (Young et al., 1996).

## MAINTENANCE CONSIDERATIONS

To maintain the infiltrative capacity of porous pavements such as asphalt, quarterly vacuum sweeping in conjunction with jet hosing or jet hosing alone is recommended (Schueler et al., 1992). Therefore, the installation of porous pavement BMPs in regions that lack the equipment or resources for routine maintenance is not recommended; a high failure rate for porous asphalt installations in Maryland is attributed in part to a lack of routine maintenance (Lindsey et al., 1991). Failures at sites in the Middle Atlantic states have also been attributed to poor site conditions and installation practices (Cahill, undated). In contrast, unmaintained parking areas constructed in 1985 with concrete block pavers had retained an infiltration capacity in excess of 100 mm/h (4 in/h) when inspected in 1994 (Pratt et al., 1995). Pratt et al. (1995) estimated the useful life of these types of permeable surfaces to be between 15 and 20 years. Since paving stones can be lifted and reused, the repair or reconstruction of these surfaces is also expected to be less than that associated with porous asphalt or concrete.

When modular pavements incorporate turf into their void area, normal turf maintenance practices, including watering, fertilization, and mowing might be required (WDOE, 1992). Mowing is not usually necessary in high-traffic areas. In regions were rainfall is infrequent, provisions for watering are required.

## COST CONSIDERATIONS

Costs for porous asphalt are approximately 10 to 15 percent higher than those for regular asphalt; porous concrete is about 25 percent more expensive than regular concrete. Requirements for site preparation or the use of specialized equipment may also increase these costs. The use of modular paving stones can be up to four times as expensive as either regular asphalt or concrete. The higher costs of installation of porous pavements can be offset to some extent by the elimination of curbs, gutters, and storm drains. In some cases this may lower the overall cost for a project (Field et al., 1982). The final economics associated with a particular site are also affected by site-specific conditions, such in situ permeability, and the cost and proximity of gravel supplies.

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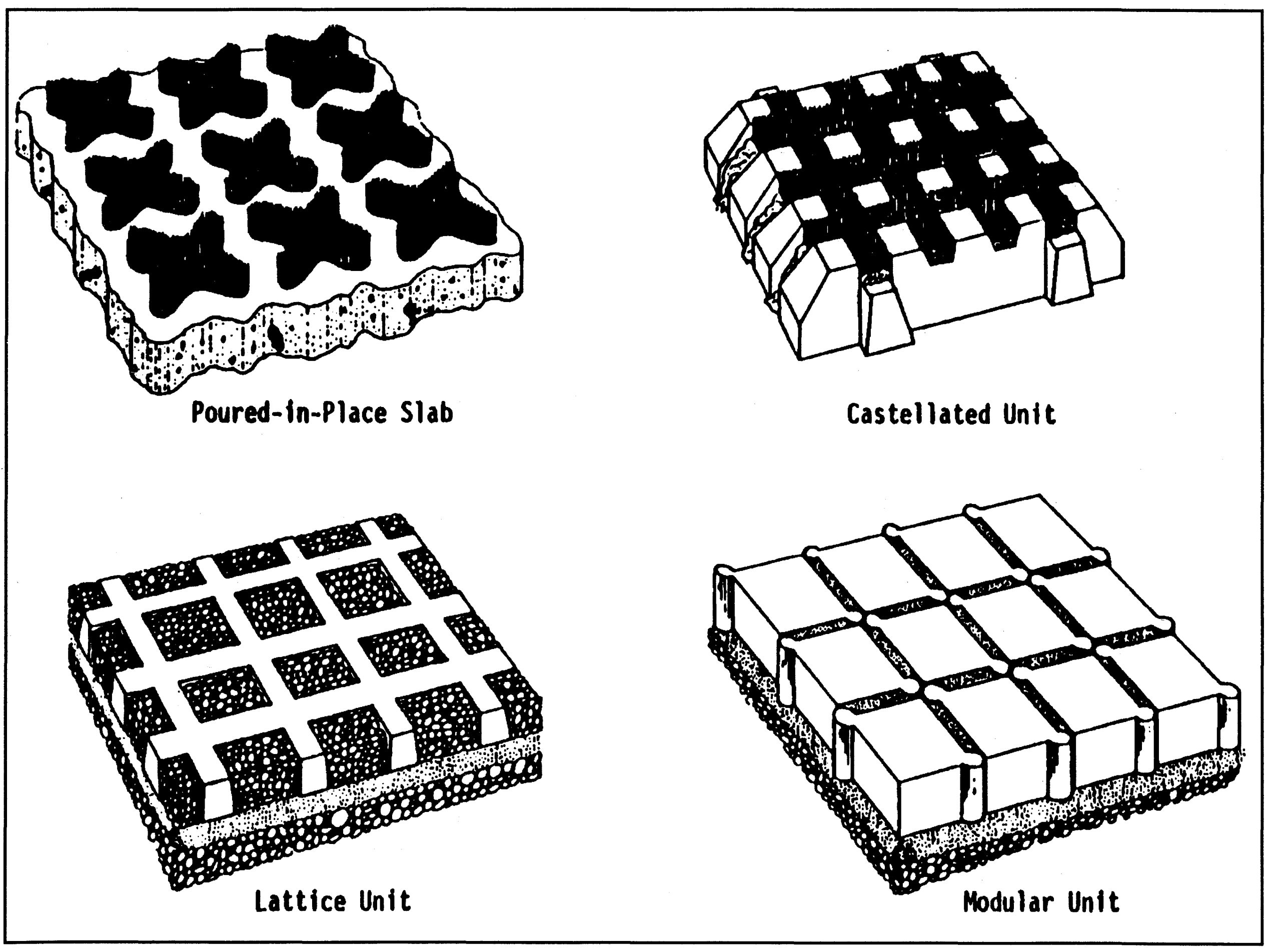



**Figure 26. Types of grid and modular pavements (Virginia Soil and Water Commission, 1990)**

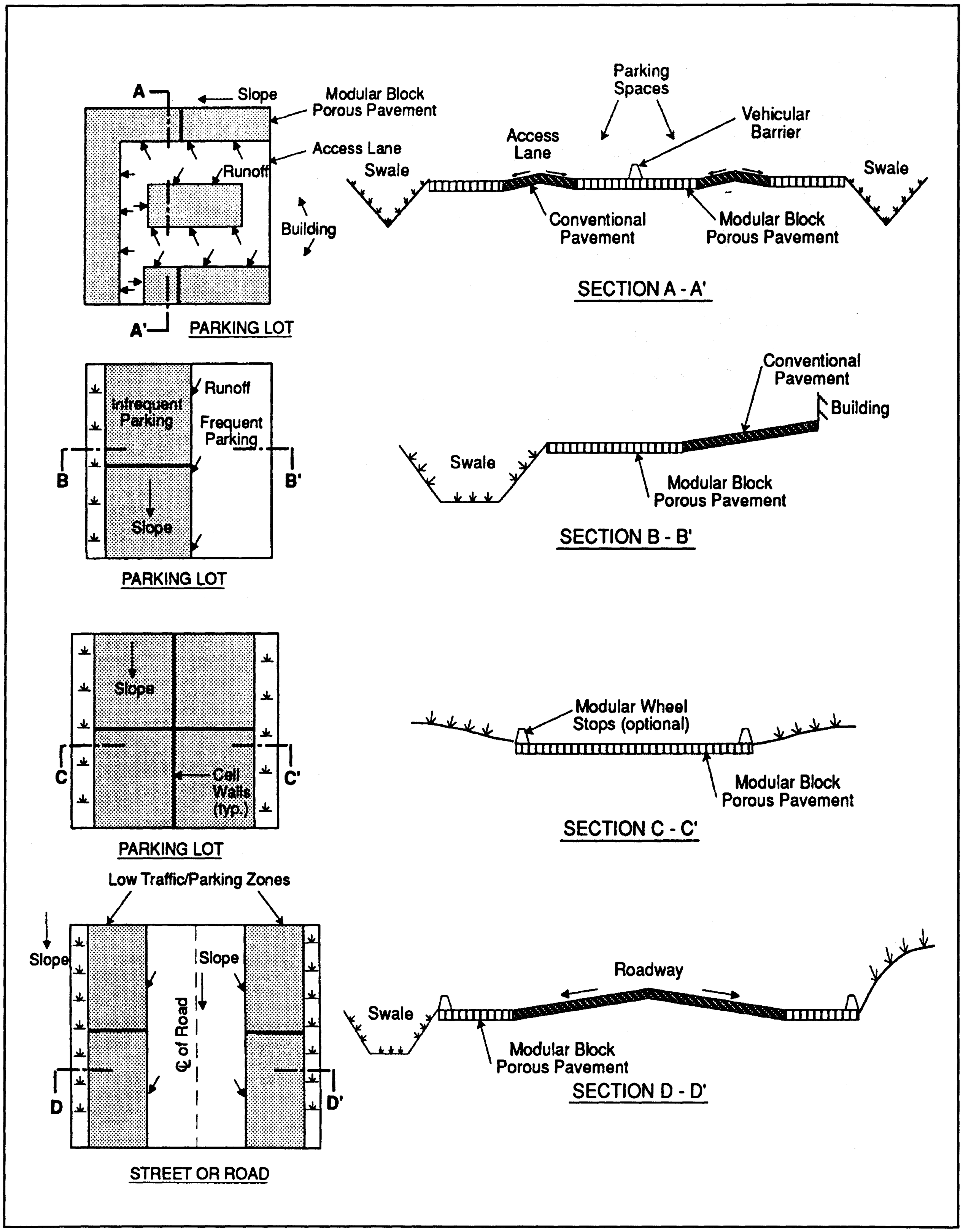



**Figure 27. Typical applications of modular block porous pavement (not to scale) (Urban Drainage and Flood Control District, 1992)**

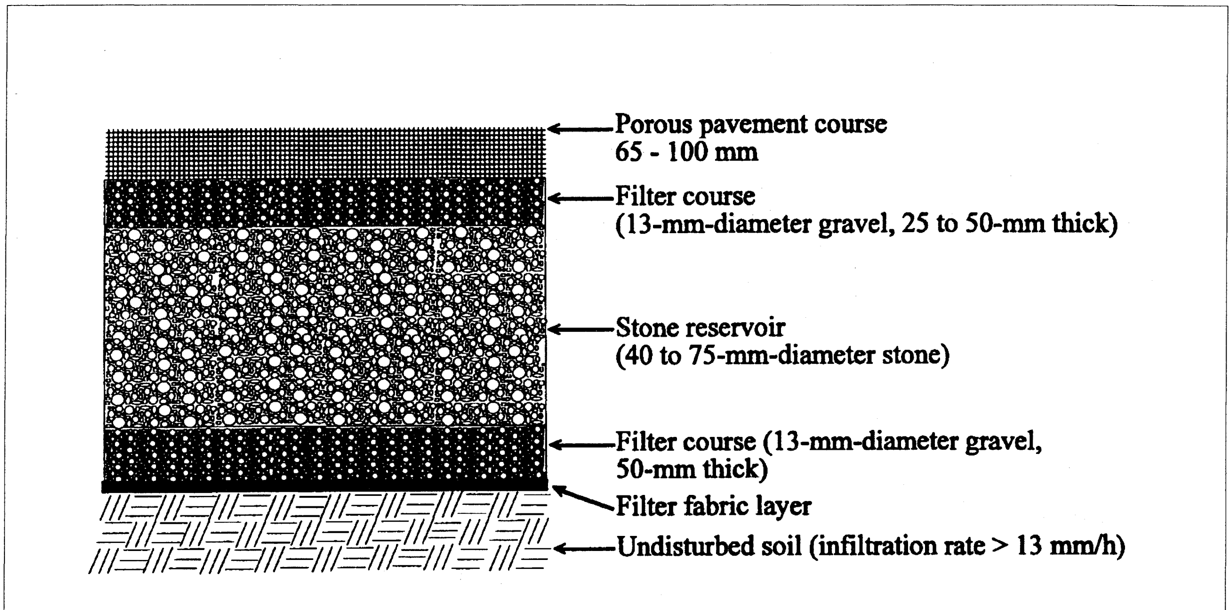
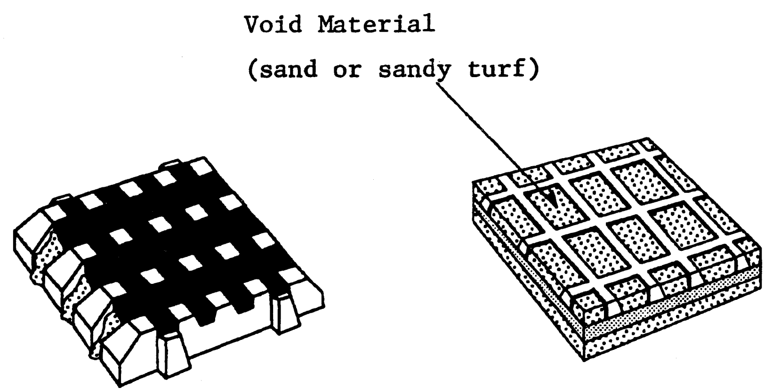
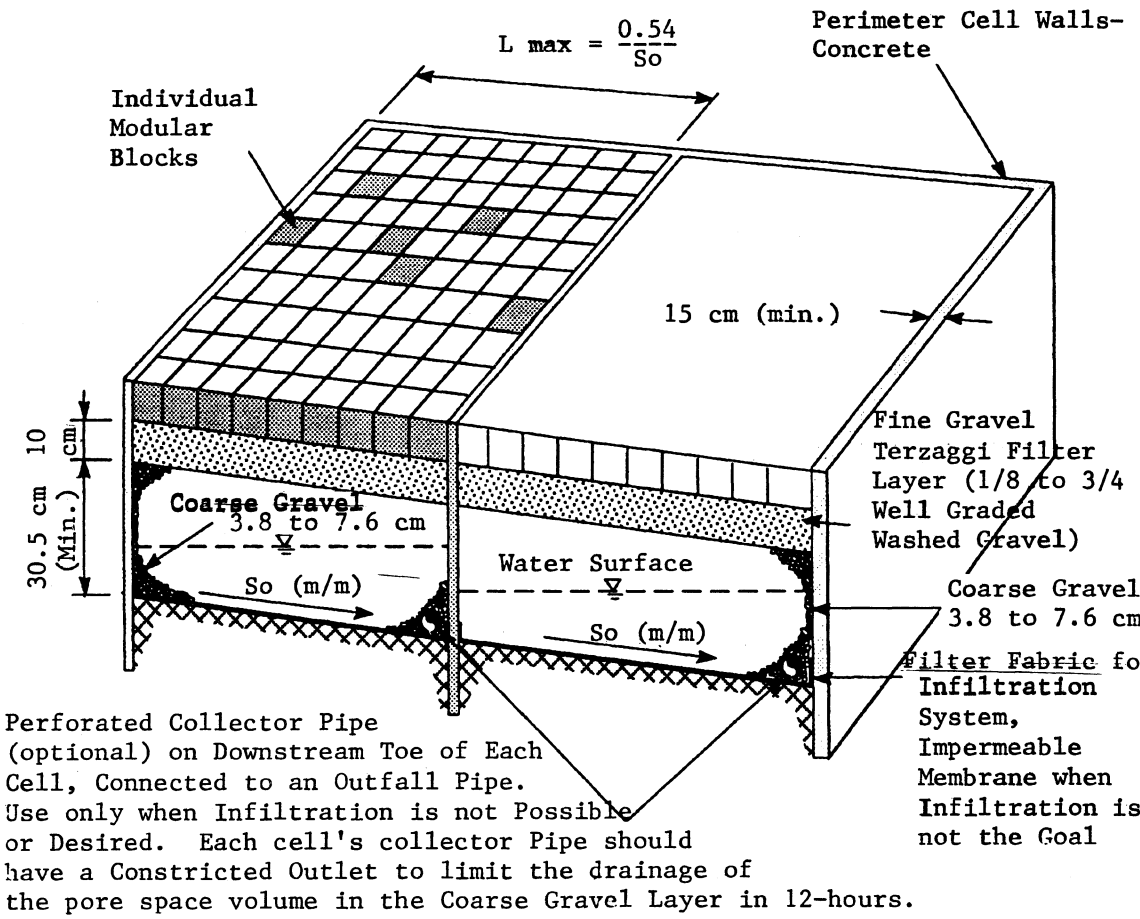



**Figure 28. Schematic of typical porous pavement section (Young et al., 1996)**




TWO EXAMPLES OF INDIVIDUAL CONCRETE MODULAR PAVING BLOCK




PERSPECTIVE OF SIDE-BY-SIDE MODULAR BLOCK CELLS

**Figure 29. Modular block porous pavement**
**(adapted from Urban Drainage and Flood Control District, 1992)**

# 3.8 STREET SWEEPING

## 3.8.1 Description and Purpose

Street sweeping entails regular street cleaning using mechanical vehicles to reduce pollutants in stormwater runoff from street surfaces. Street sweeping vehicles physically remove solids from impervious surfaces, by mechanical means (which can be vacuum-assisted), thus reducing the availability of solids and associated pollutants for pickup by subsequent runoff-generating rainfall.

Under certain circumstances street cleaning may include "street flushing," in which water transported by tanker trucks is used to wash accumulated solids from the street into gutters and stormwater inlets. The primary utility of street flushing is in areas served by combined sewers, where runoff generated by flushing would be conveyed to a municipal wastewater treatment plant. Most NPDES permits for separate storm drains do not allow street flushing.

While earlier results of the Nationwide Urban Runoff Program (USEPA, 1983) suggested that conventional street sweeping had a relatively low impact on the improvement of water quality in the Midwest and eastern United States, more recent studies have found vacuum-assisted street sweeping to be more effective. Street sweeping using equipment based on new vacuum-assisted technologies can significantly reduce pollutant washoff from urban streets. Weekly to bimonthly sweeping programs can achieve reductions of up to 80 percent in annual total suspended solids and associated pollutants (Sutherland and Jelen, 1996).

## 3.8.2 Design Alternatives

There are three basic types of conventional street sweepers—mechanical, vacuum-assisted, and regenerative. Mechanical and vacuum-assisted sweepers use gutter brooms to loosen particles and remove them from the street. For both types, a fine water spray is used to limit dust generation. Mechanical sweepers carry the particles removed to a storage hopper using a conveyor belt, whereas the vacuum-assisted sweepers place the particles in the path of a vacuum intake leading to a hopper. Sweeping operations may be performed in tandem, with a first pass conducted by a mechanical sweeper followed immediately by a vacuum-assisted sweeper. Regenerative air sweepers alternately blast air onto the pavement and vacuum it back to entrain and capture accumulated sediment.

A new type of vacuum-assisted dry sweeper has been developed, an example is that produced by Enviro Whirl Technologies, Inc. The sweeper provides the important components of tandem sweeping in a single unit, with a specialized, water-free rotating brush used for the mechanical sweeping component. Tests indicate that the vacuum-assisted dry sweeper has greatly enhanced capabilities for fine sediment pickup and containment compared to conventional street sweepers.

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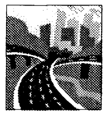

# FACT SHEET—STREET SWEEPERS

Street sweeping is an effective ultra-urban best management practice for reducing total suspended solids and associated pollutant washoff from urban streets. Recent studies have found that street sweeping programs using equipment based on new technologies can significantly reduce pollutant washoff from urban streets, with potential reductions of up to 80 percent in annual total suspended solids and associated pollutants (Sutherland and Jelen, 1996).

## APPLICABILITY

Street sweeping is well suited to ultra-urban environments where little land is available for installation of structural controls. It should be considered in commercial business districts, industrial sites, and intensely developed areas in close proximity to receiving waters. For highway applications, street sweeping may be considered for road shoulders, where safety permits, rest stop parking areas, or maintenance yards. The benefits of street sweeping will be best realized by using the most sophisticated sweepers at a weekly to bimonthly frequency depending on local conditions, with a careful assessment of whether certain rules such as restricted street parking prior to and during sweeping can be enforced. Street sweeping is not effective in removing oil and grease, and older conventional mechanical sweepers are limited in their ability to remove fine sediment.

## TYPES OF STREET SWEEPERS

*Mechanical sweepers* employ a rotating gutter broom to remove particles from the street gutter area, with a water spray used to control dust. The particles removed are placed in the path of a cylindrical broom that rotates to carry the material onto a conveyor belt and into a storage hopper. This is the most widely used equipment for street cleaning in the United States.

*Vacuum-assisted sweepers* also use gutter brooms to remove particles from the street. However, the refuse is then placed in the path of a vacuum intake that transports the dirt to the hopper. The transported dirt is usually saturated with water. The overall efficiency of vacuum-assisted cleaners is generally higher than that of mechanical cleaners, especially for particles larger than the dust and dirt range (larger than about 3 mm).

*Tandem sweeping* operations involve two successive cleaning passes, first by a mechanical (broom and conveyor belt) sweeper, followed immediately by a vacuum-assisted sweeper.

*Regenerative air sweepers* blow air onto the pavement and immediately vacuum it back to entrain and capture accumulated sediments. Air is regenerated for blowing through a dust separation system. If the accumulated loading is not too great, regenerative air sweepers are generally considered effective for removing fine sediment (Sutherland and Jelen, 1996).

*Vacuum-assisted dry sweepers* combine the important elements of tandem sweeping into a single unit. These sweepers apply technology originally developed to remove spilled coal and coal dust from railroad tracks. The technology has also been applied to industrial sites where complete removal without leakage of particulate matter is important. The mechanical sweeping component in these sweepers is completely dry. A specialized rotating brush is used to scratch and loosen dirt and dust from impervious surfaces, allowing the vacuum system to recover practically all particulate matter. A continuous filtration system prevents very fine particulate matter from leaving the hopper, which prevents the formation of the dust trails typically seen with conventional mechanical sweepers.

## EFFECTIVENESS

The effectiveness of street sweeping programs depends on several factors, including:

*Type and operation of equipment used*: Vacuum-assisted and regenerative air sweepers are generally more efficient than mechanical sweepers at removing finer sediments, which often bind a higher proportion of heavy metals (Table 18). The performance of sweepers can be enhanced by operating them at optimal speeds (6 to 8 mi/h), ensuring that brushes are properly adjusted, and ensuring that appropriate rotation rates and sweeping patterns are used. Tests conducted on the newer vacuum-assisted dry sweepers have shown they have significantly enhanced capabilities to remove sediment compared to conventional sweepers, with projected reductions of up to 79 percent in total suspended solids loadings from urban streets. In addition, these sweepers are extremely effective at removing respirable (PM-10) particulate matter (particles with an aerodynamic diameter less than or equal to 10 microns) compared to conventional sweepers (Table 19) and are designed to help meet National Ambient Air Quality standards.

*Sweeping frequency and number of passes:* To achieve a 30 percent removal of street dirt, the sweeping interval should be less than two times the average interval between storms. To achieve 50 percent removal, sweeping must occur at least at least once between storms. Generally two passes per run should be conducted, which will result in the removal of up to 75 percent of total solids present before sweeping. Certain conditions may warrant increased sweeping frequencies. These include streets with high traffic volumes in industrial areas and streets with high litter or erosion zones. In addition, the sweeping frequency should be increased just before the wet season to remove sediments accumulated during the summer.

**Table 18. Efficiencies of mechanical (broom) and vacuum-assisted sweepers**

| Constituent | Mechanical sweeper efficiency (%) | Vacuum-assisted sweeper efficiency (%) |
|---|---|---|
| Total Solids | 55 | 93 |
| Total Phosphorus | 40 | 74 |
| Total Nitrogen | 42 | 77 |
| COD | 31 | 63 |
| BOD | 43 | 77 |
| Lead | 35 | 76 |
| Zinc | 47 | 85 |

**Table 19. PM-10 Particulate removal efficiencies for various sweepers**

| Sweeper type | Removal Efficiency (%) |
|---|---|
| Mechanical - Model 1 | -6.7 |
| Mechanical - Model 2 | 8.6 |
| Regenerative Air | 31.4 |
| Vacuum-assisted wet - Model 1 | 40.0 |
| Vacuum-assisted wet - Model 2 | 82.0 |
| Vacuum-assisted dry | 99.6 |

Source: Satterfield (1996).

*Climate*: Sweeping appears most effective in areas with distinct wet and dry seasons (CDM et al., 1993).

Factors that limit the overall effectiveness of street sweeping programs include:

- Presence of parked cars and traffic congestion during sweeping.
- Poor road surface and curb conditions.
- Presence of construction projects nearby.

## CONSIDERATIONS FOR EQUIPMENT SELECTION

The selection of the type of sweeper will depend on specific conditions prevailing at sites targeted for sweeping. In general, mechanical sweepers are more effective at picking up large debris and cleaning wet streets and have lower capital and operating costs. However, mechanical sweepers can create large amounts of airborne dust. Vacuum-assisted and regenerative air sweepers are more effective at removing fine particles and associated heavy metals but tend to be ineffective at cleaning wet streets. They may also be noisier than mechanical sweepers, which can restrict the hours of operation in some areas. It may also be necessary to deploy a mechanical sweeper ahead of vacuum-assisted sweepers to remove large debris.

The somewhat larger capital costs associated with the newer vacuum-assisted dry sweepers may be warranted for areas where worker and public safety from respirable particulate matter is of concern. Vacuum-assisted sweepers are capable of providing close to 100 percent removal of PM-10 particulates and also provide better overall removal of sediment.

## MAINTENANCE AND OPERATIONAL REQUIREMENTS

The overall maintenance requirements for mechanical sweepers are greater than those for vacuum-assisted and regenerative air sweepers since mechanical sweepers contain more moving parts that require periodic replacement. Vacuum-assisted dry sweepers have significantly less down time than water-based sweepers (less than 10 percent of total operating time compared to about 50 percent for water-based sweepers) because they require no water loading. In addition, clean-up and dumping times are shorter.

For an effective street sweeping program, consideration should be given to the following operational requirements:

- Ensure there are adequately trained sweeper operators and maintenance personnel.
- Provide traffic control officers to enforce parking restrictions.
- Choose sweeping frequencies and cleaning routes to optimize overall sweeping efficiencies.
- Make appropriate arrangements for disposal of collected waste.
- Reduce source loadings through various measures such as public awareness of proper disposal procedures for used oil and yard waste, and enforcement of erosion control and stormwater pollution prevention practices at urban construction sites.

## COST CONSIDERATIONS

Conventional sweeper costs range from $69,000 to $127,000 (1995 dollars), with the higher end of this range associated with vacuum-assisted and regenerative air sweepers (CDM, 1993). The useful life span of these sweepers is generally four to seven years, and the operating cost associated with these sweepers about $70 per hour (1996 dollars; Finley, 1996). The capital cost of vacuum-assisted dry sweepers is on the order of $170,000 (1996 dollars; Enviro Whirl Technologies, personal communication, 1996) with a projected useful life span of about eight years and operating costs of approximately $35 per hour (Satterfield, 1996 dollars).

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# 3.9 OTHER NONSTRUCTURAL BMPs

## 3.9.1 Introduction

Nonstructural BMPs focus on prevention and removal of stormwater volumes and constituent loads at their source. While little data is available on the effectiveness of nonstructural BMPs their implementation is based on good common sense (Roesner, 1995). When space is too limited for the use of structural BMPs, such as in ultra-urban areas, nonstructural BMPs may be among the most cost-effective options available for reducing water quality constituents in stormwater runoff. When used in conjunction with structural BMPs, they may improve BMP efficiency and help to reduce maintenance requirements by reducing the accumulation of trash and sediment.

Examples of nonstructural BMPs range from activities such as land use planning and infrastructure maintenance to more site-specific activities. Examples of site-specific nonstructural BMPs applicable to ultra-urban areas include, but are not limited to:

- Materials management practices that prevent either rainfall or stormwater from collecting and transporting water quality pollutants.
- Road and storm drain maintenance practices such as street sweeping and catch basin cleaning.
- Controls on illegal dumping.
- Landscaping practices that reduce or eliminate the use of fertilizers and pesticides.

Many of these practices can be implemented at different levels of involvement ranging from individual action to municipal, state, or business initiatives (Figure 30). For individuals, this can mean changing the products they use, how they use them, or how they eventually dispose of them. Even changes in behavior such as joining a car pool can be considered effective nonstructural BMPs (CDM, 1993). Highway agencies or departments of public works can change many of their practices, including how they store materials like road salt and sand, complete road repairs, or maintain their vehicles. Commercial businesses and industrial facilities may also implement a variety of generally site-specific nonstructural BMPs voluntarily or as a result of ordinances or regulations. Road and highway bridge cleaning, deck drainage, and painting activities may also require special nonstructural measures to mitigate effects on the atmosphere and receiving waters.

A comprehensive implementation of nonstructural BMPs, including an education and participation component, is best achieved through the implementation of stormwater pollution prevention plans. This is particularly true for municipalities, government departments, and businesses whose diverse activities can affect both stormwater quantity and quality. A key element of these plans is an active education and participation program to inform the public, municipal employees, or businesses of particular programs and their various options.

These stormwater pollution prevention plans and nonstructural BMPs can play an important role in watershed planning for stormwater management. Highway agencies and departments of public works may consider participating as a stakeholder in these comprehensive programs, which can be very effective at preventing or reducing water quality constituents in stormwater runoff from ultra-urban areas.

## 3.9.2 Options and Strategies for Implementation

Options for implementing nonstructural BMPs focus on identifying activities that have the potential to negatively impact stormwater. These activities may result in changes in the water quality of stormwater, primarily through the input of new materials such as toxic chemicals, nutrients, or salts. Using these materials on impervious surfaces facilitates their direct input into stormwater drainage systems. In many cases, stormwater quantity or hydrologic changes also contribute to the impacts on water quality and aquatic biota. Once a problem has been identified, there is a need to develop alternatives for both individuals and groups to minimize their effects on both stormwater quality and quantity.

Individuals

Nonstructural BMPs that can be implemented by individuals include:

- The use of safer or alternative products for lawn care.
- The proper disposal of hazardous wastes.
- The proper maintenance and care of vehicles.

The use of fertilizers can be minimized by establishing grasses and other ground covers recommended for the local climate region by the local municipality or the local Cooperative Extension Service of the U.S. Department of Agriculture. Using grasses that have been found to grow best in an area and are the least susceptible to diseases generally reduces the need to use fertilizers and pesticides. Proper watering and mowing also reduce the need for fertilizers and pesticides by encouraging the growth of a thick lawn (CES, 1993). Homeowners who use lawn care companies to maintain their lawn can, in many cases, switch to lawn care programs that are less reliant on chemicals. The use of low-maintenance alternative ground covers or reducing the size of a lawn also reduces the need to use fertilizers and pesticides (Bormann et al., 1993).

Cars and car care practices also contribute to stormwater pollutants. These constituents come from the phosphates found in soaps used to wash cars, leaks and spills of oil and antifreeze, and toxins found in the paints, polishes, and cleaners used to care for cars. To reduce and prevent these potential sources, car owners should avoid the use of phosphate-based soaps for car cleaning (or use a commercial car wash), repair leaks from their cars, recycle used oil and antifreezes, keep their car properly tuned, and be careful in their use of car paint, polishes, and cleaners. To prevent the inadvertent entry into storm drains of materials such as used motor oil, antifreeze, and paints and pesticides, these products should be taken to a hazardous waste site for disposal. Small amounts of these compounds can have toxic effects on downstream aquatic biota or may contaminate drinking water supplies.

## Stream Team Program

The Stream Team program developed in Prince George's County, Maryland (Prince George's County, 1993) has four different projects that interested groups can agree to perform to benefit their adopted stream or stream watershed. These include stream cleanups to remove trash from the streambed and stream banks, storm drain stenciling to educate the public that storm drains lead to the local stream, tree planting to create or increase forested buffers along the adopted stream, and an education and action plan for individuals to learn about a wide variety of environmental issues and to make personal changes in their own daily activities.

More detailed information on nonstructural BMPs can be obtained from municipal, state, and federal agencies and environmental organizations that deal with stormwater management issues (CDM,1993; Greenfield and LeCouteur, 1994; Mills and Eckert, 1996; USEPA, 1993).

Municipal

Municipalities can not only adopt the use of alternative products and practices in their own everyday activities, but can also assist individuals in their efforts by providing advice and information on nonstructural BMPs and by implementing hazardous waste collection and disposal sites or systems. A number of municipal activities, such as maintaining vehicle maintenance and storage yards, implementing roadside and park landscape practices, optimizing road sand and salt application, and properly storing and using hazardous materials, can reduce the impact of these practices on water quality (Figure 31). Nonstructural measures include methods that cover material storage piles and hauling equipment to prevent rainfall from washing constituents into stormwater, prevent or reduce stormwater runoff from vehicle maintenance and parking areas, or reduce the need and use of potential stormwater contaminants such as salt and pesticides (Figure 32).

The municipality may also use ordinances to require commercial and industrial businesses to develop and implement specific nonstructural BMPs, such as requiring a dike around garbage disposal bins to contain spills and runoff from the immediate area. Many municipalities have also developed programs to identify and disconnect illicit connections to their storm drain system. In a Wisconsin community, a water quality protection manual has been developed to inform businesses of the importance of using BMPs and the options available for their participation (WC and UWIN, 1996). High-visibility, low-cost programs such as the Adopt-a-Road and Adopt-a-Stream programs are also effective in raising environmental awareness and helping to reduce trash problems in ultra-urban areas. These programs generally require minimal organization and advertising, and the provision of collection bags and pick-up sites for the clean-up program.

Ordinances can also be extended to require specific types of businesses or industries to develop and implement a pollution prevention plan. The key elements of the plan, in some cases already required by state or federal regulation, include a process with five main phases (USEPA, 1992).

- Planning and organization.
- Site assessment.
- BMP selection and plan design.
- Implementation of plan.
- Evaluation and monitoring.

The first phase requires the planning and organization of staff and review of existing environmental facility plans. This includes identifying the persons who will develop, implement, maintain, and update the plan—usually those most familiar with the facility and how it operates. The site assessment or second phase of the plan requires the development of a site map showing features relevant to stormwater management, including drainage paths and discharge points, surface water bodies, stormwater drainage system and outfalls, an inventory and the location of significant materials exposed to stormwater or rainfall, the identification and location of past spills and leaks, and the identification and location of non-stormwater-related discharges to storm drains.

BMP selection and plan design is the third phase of a pollution prevention plan. This phase focuses on good housekeeping, preventive maintenance, visual inspections, spill prevention and response, sediment and erosion control, stormwater management, and employee training. The fourth and fifth phases of the plan are implementation and evaluation and monitoring. Implementation requires the development of a schedule for activities, the delegation of responsibilities, and the organization of employee training. Evaluation and monitoring requires that an annual site compliance evaluation take place and that procedures for record keeping, internal reporting, plan revisions, and updates be formalized.

<u>Commercial and Industrial</u>

Commercial areas such as retail and service-related businesses can ensure that their properties are properly maintained, that garbage bins are used and not overflowing, that parking lots are cleaned with sweeping equipment, and that road surfaces are maintained. The use of low-maintenance ground covers to meet landscaping needs can reduce the need for watering and for the use of pesticides. Specific businesses, such as service stations, can also be encouraged to improve their stormwater management by voluntarily developing and implementing pollution prevention plans. Industrial activities are likely to require a pollution prevention plan for their particular site as a result

## Commercial Application

Best management practices can also be incorporated into new construction. A car dealership in Wisconsin has used a mix of structural and nonstructural stormwater management practices to help protect a nearby trout stream. The car lot design demonstrates the use of a number of practices, including clean water diversion, stormwater infiltration beds for roofs and paved areas, grassy swales, and zinc-free roofing (Struss, 1993).

of state or federal regulation. This plan should deal with the issues outlined earlier, including activities such as the handling, storage, use and disposal of hazardous materials; maintenance; and recycling programs. Industries should investigate all non-stormwater discharges to storm drains and identify and remove illicit storm drain connections. In particular, vehicle washing, fueling, and maintenance areas often need measures to prevent the contamination of stormwater.

Highway and Road

Highway and road maintenance and repair programs need to establish and use procedures that reduce or prevent stormwater pollution. Nonstructural BMPs recommended include provisions for landscaping and vegetative practices, pesticide and fertilizer management, litter and debris controls, illicit discharge controls, bridge cleaning and deck drainage, bridge painting, and chemical storage. These BMP options range from innovative programs to conventional good common sense. For example, in a town in Vermont the use of infrared sensors mounted on salt trucks to measure pavement temperatures (as the basis for salt application rates) has reduced the use of salt by 15 percent (Lawson, 1993). This "smart salting" program reduces pollution and also saves money. A more conventional approach to salt management and use is illustrated below.

In addition to general nonstructural BMPs, highway and road departments can prevent the contamination of water bodies by restricting equipment from entry into water and by requiring equipment refueling and stockpile setbacks from water bodies. Examples of many nonstructural BMPs and how they can be implemented, along with their associated cost, can be found in the *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996).

### Road Salt

The use of road salt can be optimized in a number of ways:

*Storage*

- Salt storage piles need to be completely covered.
- Storage and handling operations should be done on impervious surfaces.
- Stormwater runoff from areas were salt is stored should be contained in a suitable area.

*Application*

- Trucks can be equipped with ground-speed sensors that can accurately control the rate of spreading.
- Training programs for drivers and handlers should be implemented to improve the efficiency of application and to reduce losses.
- Snow plow operators need to avoid piling snow on or near frozen ponds, lakes, or wetlands.

*Road Departments and Municipalities*

- Can identify ecosystems, particularly wetlands, that are sensitive to salt.
- The use of alternatives to salt such as calcium chloride and calcium magnesium acetate may be less environmentally harmful to sensitive ecosystems. These alternatives are more expensive than regular salt, but are also less corrosive to bridges and overpasses.
- In some instances, sanding may be used in place of salt to improve traction (Lawson, 1993). However, in other instances, sanding may not be appropriate where sedimentation has adverse environmental impacts.

## 3.9.3 Effectiveness

The effectiveness of nonstructural BMPs relies heavily on educational and participation programs that target schools, public service organizations, municipal employees, businesses, and the general public. It also relies on the leadership of government departments— particularly highway and road departments, which are an important and very visible component of every community. The leadership shown by both adopting and facilitating educational programs for nonstructural BMPs improves the community-wide acceptance of such practices.

Educational programs work best when they increase the level of environmental awareness in the target audience and convey a clear link between people's everyday activities and stormwater quality impacts. The stenciling of storm drain systems with educational language or graphic icons, for example, helps discourage the dumping of hazardous materials such as used motor oil and paint into storm drains. Probably just as importantly, it raises the environmental awareness and knowledge level of program participants with respect to stormwater management issues. Education programs can also increase the public scrutiny of industrial and municipal practices, with a resulting increase in the reporting of incidents such as spills or illegal discharges to storm drains.

### 3.9.4 Cost Considerations

Costs of nonstructural BMPs are primarily incurred in proportion to the level of effort and the methods used in an education and public relations program. These efforts can range from the use of display booths, posters, decals, school packets, and public service announcements to developing awareness using local news programs and other media. Efforts can also involve the development of alliances with neighborhood groups, civic organizations, and business associations (Watson, 1994).

Capital costs may be incurred for the purchase of street sweeping equipment and spill cleanup and prevention equipment, material storage, or implementation of pollution prevention plans. The installation of roadside barriers to prevent illegal dumping in stream valleys and the removal of illicit connections to storm drains also require capital expenditures and in many cases the cooperation of individuals and government agencies.

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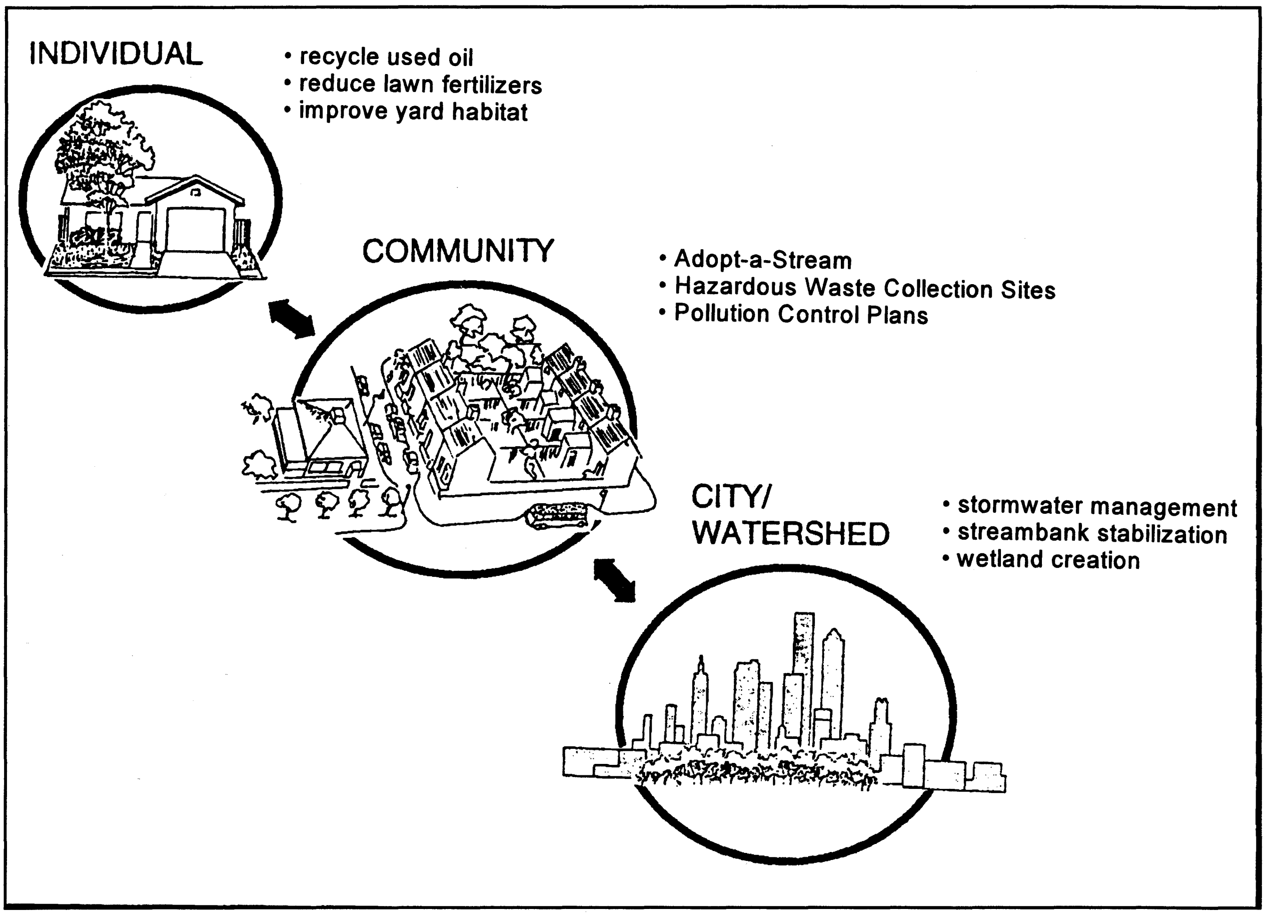


**Figure 30. Levels of involvement in nonstructural BMP programs that may be part of watershed planning for stormwater management (adapted from Greenfield & LeCouteur, 1994)**

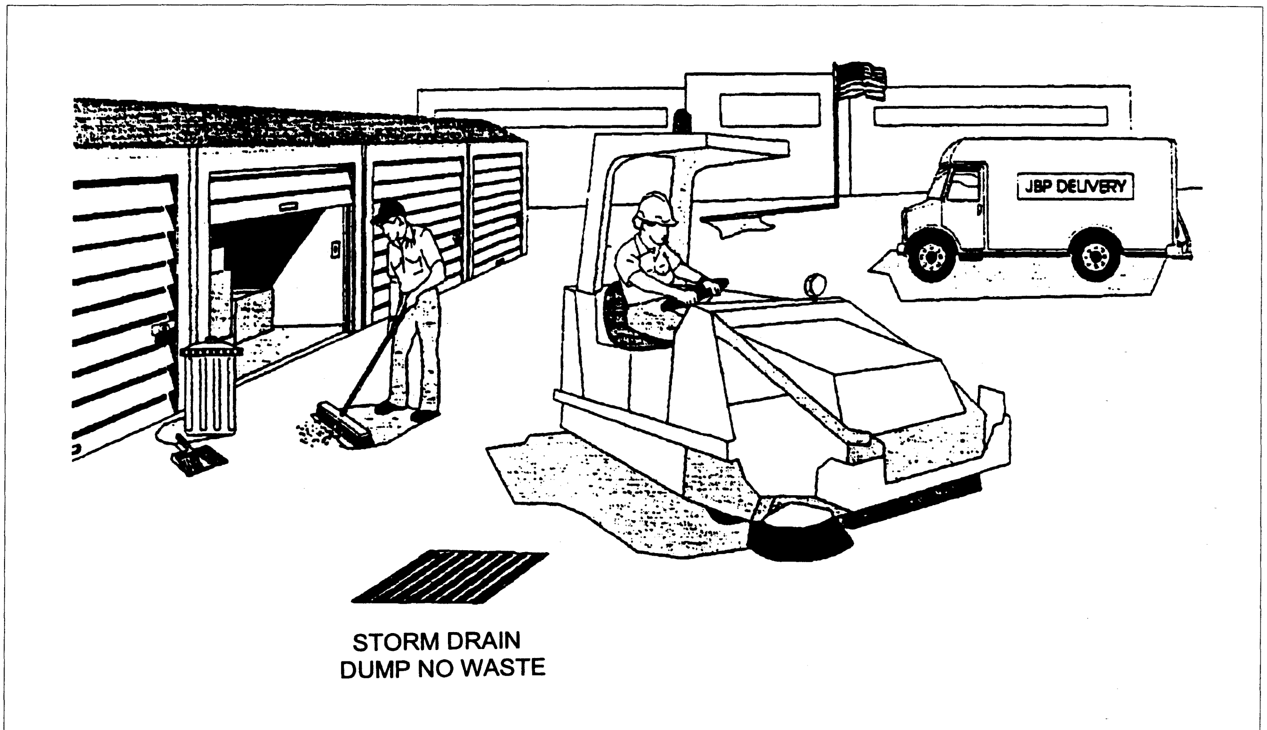


**Figure 31. Maintenance yard nonstructural BMPs (adapted from CDM, 1993)**

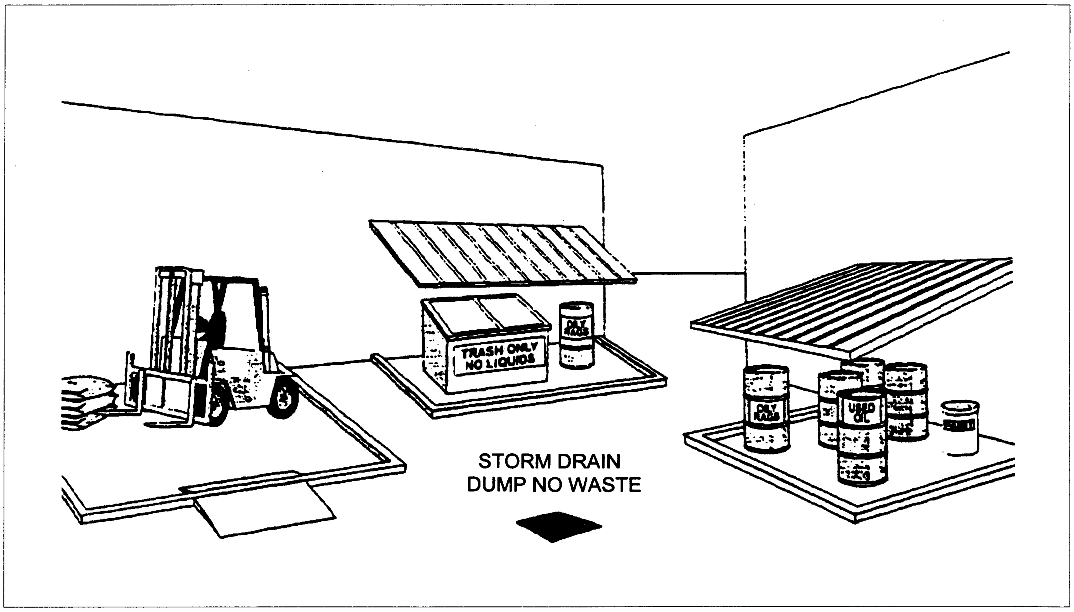


**Figure 32. Materials handling measures (adapted from CDM, 1993)**

# 3.10 NEW AND INNOVATIVE PRACTICES

## 3.10.1 Description and Purpose

A number of new BMP designs and design concepts are of potential interest to those managing ultra-urban runoff. Although these designs have been installed and operated at relatively few locations, the field trials clearly indicate noteworthy performance.

Each of the following sections gives a brief synopsis of an innovative practice, which may be sufficient for the reader to determine its applicability. In some cases, additional (more current) information can only be obtained directly from the proprietor of the equipment used in the design.

The practices described are alum injection systems, MCTT system, biofilters (e.g., StormTreat™ System), vegetated rock filters, and vertical filter systems.

## 3.10.2 Alum Injection Systems

Alum injection systems (AISs) have been used successfully in treating urban stormwater runoff that was significantly impairing several lakes in the state of Florida. Their small footprint, relatively dependable components, and effectiveness on a wide range of pollutants make AISs worth considering for ultra-urban applications. Furthermore, AISs have been applied to treat entire watersheds, with drainage areas between 36 and 65 ha (90 and 160 ac).

Unlike other BMPs, an AIS treats common pollutants by chemically fixing them into an inert floc, which settles from the water column. The floc binds common stormwater pollutants into a nontoxic aluminum salt that is stable as long as the pH remains between 6 and 7. Alum is an acid salt of aluminum that has been extensively used for drinking water treatment, removal of phosphorus in wastewater treatment, and lake restoration projects.

Most AIS applications to date permit the floc to settle within the receiving water body, where it augments existing natural sediment. Given the relatively low concentration of alum addition (on the order of 10 mg/L) the aggregation of aluminum salt sediment in receiving water bodies is small. Furthermore, dissolved aluminum concentrations in water bodies receiving AIS-treated stormwater have been found to remain below levels judged to be toxic by USEPA.

Alum and any other additives needed to establish the proper pH are injected into the storm drain upstream of the receiving water body. If the floc is permitted to settle within the receiving water body, there is no need for costly settling chambers or for sludge removal and disposal. AIS typically consists of an alum storage tank storing liquid alum, pumps and piping to convey the alum to injection points, and flow rate monitoring equipment for controlling the injection feed rate. As a result, the capital cost of the system is relatively independent of the size of the system. The principal cost variation between different size systems stems from the variation in the amount of alum needed annually.

In an evaluation of the improvement in water quality due to alum treatment of stormwater inputs to Lake Ella, Florida, total nitrogen decreased by 78 percent ($NH_3$ by 95 percent and $NO_2$+$NO_3$ by 14 percent), total phosphorus by 89 percent, and turbidity reduced by 89 percent (Harper, 1990).

## 3.10.3 MCTT System

The multi-chamber treatment train (MCTT) consists of a series of treatment units that mimic those found in a conventional wastewater treatment plant (Figure 33). The first chamber aerates the stormwater as it enters the treatment train and permits preliminary settling of larger diameter sediment. Stormwater is then conveyed to an inclined tray settler, where the majority of the settleable particulates are captured. Dissolved air flotation is then provided to help lift floatables and oil to absorbent media. The last step entails passing stormwater through a sand/peat filter.

The MCTT is applicable to small and isolated paved critical source areas from about 0.1 to 1 ha (0.25 to 2.5 ac). Gas stations, high traffic areas, and car washes are examples of land uses that could warrant this practice. As a relatively expensive BMP, the MCTT is reserved for those locations equipped with electric power and where regular maintenance is feasible. A recent retrofit installation cost $95,000 to tie an MCTT into an existing storm drain system for a 1 ha (2.5 ac) drainage area (Pitt, 1996). The cost to install would be lower if the installations were in new, developing areas and if prefabricated units became available.

During 13 storms monitored at a parking lot, the MCTT was found to remove 83 percent of total suspended solids, 100 percent of lead, and 91 percent of zinc (Pitt, 1996). In addition, the MCTT was found to be effective at removing toxicants: a 96 percent reduction was found in total toxicity as measured by the Microtox™ screening test. As a result of its processes, ammonia nitrogen was found to increase by several times and the water gained a color due to staining from the peat medium.

In another study, 15 storms were monitored at a municipal maintenance yard where an MCTT had been installed to measure the pollutant reduction achieved by this device. The actual quantity of water passing through the MCTT consistently was found to be approximately 87 percent of rainfall volume. High pollutant reduction efficiencies were found for all particle-associated constituents, such as total suspended solids (98 percent) and total phosphorus (88 percent), and some dissolved constituents, such as dissolved zinc (68 percent). This municipal maintenance garage and parking facility is used primarily by garbage trucks, plows, and other heavy equipment (Greb et al., 1998).

The design of the MCTT is very site-specific and depends highly on local meteorology (e.g., mean inter-event periods, local rainfall intensity/duration relationships). The design challenge is to provide sufficient equalization capacity to ensure even inflow into the filter bed. As a result, there can be a 300 percent difference in the size of the MCTT depending on the facility location. The size of components is dependent on the depth of the facility and whether the facility will drain by gravity or be pumped dry. For most applications, the commitment of surface area will probably fall between 0.5 percent and 1.5 percent of land area (Pitt, 1996).

### 3.10.4 Biofilters

A recent design innovation, developed in the mid-1990s, uses biofilters for stormwater treatment. An example, in Figure 34, is the StormTreat™ System (STS), which consists of a circular treatment tank (2.9 m dia. by 1.2 m tall) surrounded by wetland vegetation (Allard et al., 1996). First developed in 1994, STS uses sedimentation, filtration, and biological action to manage the common stormwater pollutants. Stormwater pretreated to remove large-diameter sediment is piped into the STS tank, where the captured runoff, is treated over the course of a 5- to 10-day period. Unlike most constructed wetlands, stormwater is conveyed into the subsurface of the wetland and through the root zone (Figure 34).

Based on manufacturer's literature, four standard-size STS tanks are required to manage the 12.7 mm (0.5 in) of stormwater generated by 0.4 impervious ha (1 ac) if pretreatment by preliminary detention is provided. In the absence of preliminary detention, 10 tanks are needed to manage the same volume of stormwater. Based on a footprint area of 3 $m^2$ per tank (includes wetland vegetation area), the total commitment of land for this BMP is approximately two percent of the drainage area.

As expected, the removal efficiency of STS is high. The STS system has demonstrated total suspended solids removals of 95 percent and removal of metals ranging from 65 to 98 percent (Allard et al., 1996). Nutrients are also significantly reduced (total phosphorus by 89 percent, orthophosphate by 32 percent, and total dissolved nitrogen by 44 percent). Finally, STS has demonstrated a removal of fecal coliform of 83 percent, which is why it has been used to protect shellfish beds closed by high coliform levels.

Based on product literature, the costto purchase STS and install a single tank is between $3,600 and $4,000 (1996 dollars). The maintenance costs have been estimated at $100 to $150 per tank cleaning, which is typically required every two to three years. This maintenance cost does not include the cost to remove sediment from any upstream pretreatment (e.g., catch basins).

Current design information can be obtained from the manufacturers web site: http://www.stormtreat.com.

### 3.10.5 Vegetated Rock Filters

Another recent design innovation for stormwater is the vegetated rock filter (VRF). Although wetland treatment systems similar to the VRF have long been used to treat wastewater, only since the mid-1990s has the design concept been applied to stormwater. A number of design variants exist for VRF; the basic design concept is also found in designs called the packed bed filter, rock-reed filter, vegetated submerged bed wetland, and shallow horizonal flow wetland.

Typically, the VRF design consists of a series of connected tanks filled with several feet of aggregate that are planted with wetland species (Figure 35). Stormwater flows pretreated to remove most suspended solids are introduced below grade into the aggregate, which is maintained in a saturated condition by carefully placed standpipes.

Stormwater treatment is provided primarily by biological action and root uptake. Anaerobic conditions, which help with denitrification, are generated in the lower depths within the rock filter (Kadlec and Knight, 1996). Under simulated rainfall conditions removal efficiencies of VRF systems have been found to be high: total suspended solids (95 percent), metals (21 to 80 percent), total phosphorus (82 percent), orthophosphate (14 percent), nitrate-nitrogen (75 percent), and fecal coliform (78 percent) (DRMP, 1995). These removal rates do not include any pollutant removed by pretreatment sedimentation.

Although VRF systems show promise for the removal of nutrients missed by other BMPs, the major drawback of this design is its space requirements. Test designs employed an off-line storage unit to capture the first flush and provide a steady inflow into the VRF (Eagan et al., 1995). It has been estimated the area needed for VRF is between three and five percent of the drainage area (Claytor and Schueler, 1996). This commitment of area may be too high for the typical ultra-urban application. Typical loading rates for the VRF are around 0.05 to 0.19 L (0.0125 to 0.05 gal) per minute per square foot of bed (DRMP, 1995).

Although specific information is not available, it is easy to state that the cost of a VRF is high when compared to other BMPs. In fact, some designs employ expensive pump systems to control dosing of multiple VRF units. However, the additional expense of VRF systems can result in consistent removal of nutrients (principally nitrogen) that might not be sufficiently removed by other less expensive BMPs.

### 3.10.6 Vertical Filter Systems

Stormwater BMPs that use vertically mounted filters are being developed at this time. Typically, vertical filter systems (VFSs) consist of a single large, concrete-lined chamber that serves as a combination storage and settling area. To one side of the chamber is a permeable wall, frequently constructed of sand layered between filter fabric and then sandwiched between sets of gabions (Figure 36).

The VFS concept has attracted interest because the design could provide filtration of stormwater in a facility that is smaller than the typical horizontal bed sand filter. The smaller facility footprint is obtained because the vertical filter can serve as one of the vertical walls of the chamber that stores captured stormwater.

Although laboratory, pilot, and field tests of the vertical filter design have been performed (Tenney et al., 1995), as of this time the design parameters have not been fully developed. Some of the design problems encountered relate to clogging of the geotextile fabric incorporated into the filter, loss of the sand medium due to high hydraulic pressures, and piping flow at the interface of the vertical filter and adjacent walls. In addition, designs are being augmented to minimize any resuspension of settled material that is slowly moved through the settling chamber and onto the vertical filter, accelerating clogging of the filter. These problems make it difficult to provide specific pollutant reduction rates for VFSs at this time.

Some design modifications under evaluation include installation of baffles within the storage chamber to minimize sediment transport and layered multi-media filters (compost, zeolites, sand) that are resistant to clogging and effective on a wide range of pollutants.

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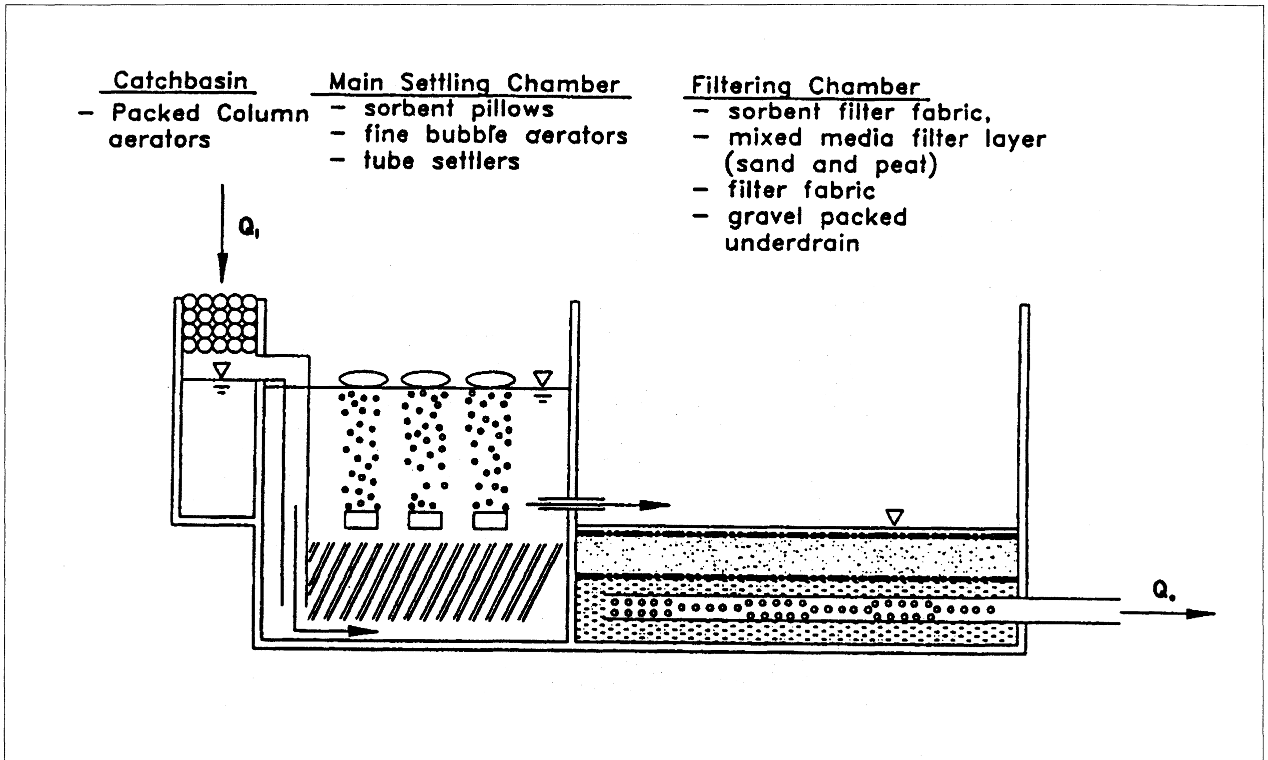


**Figure 33. General schematic of MCTT (Pitt, 1996)**

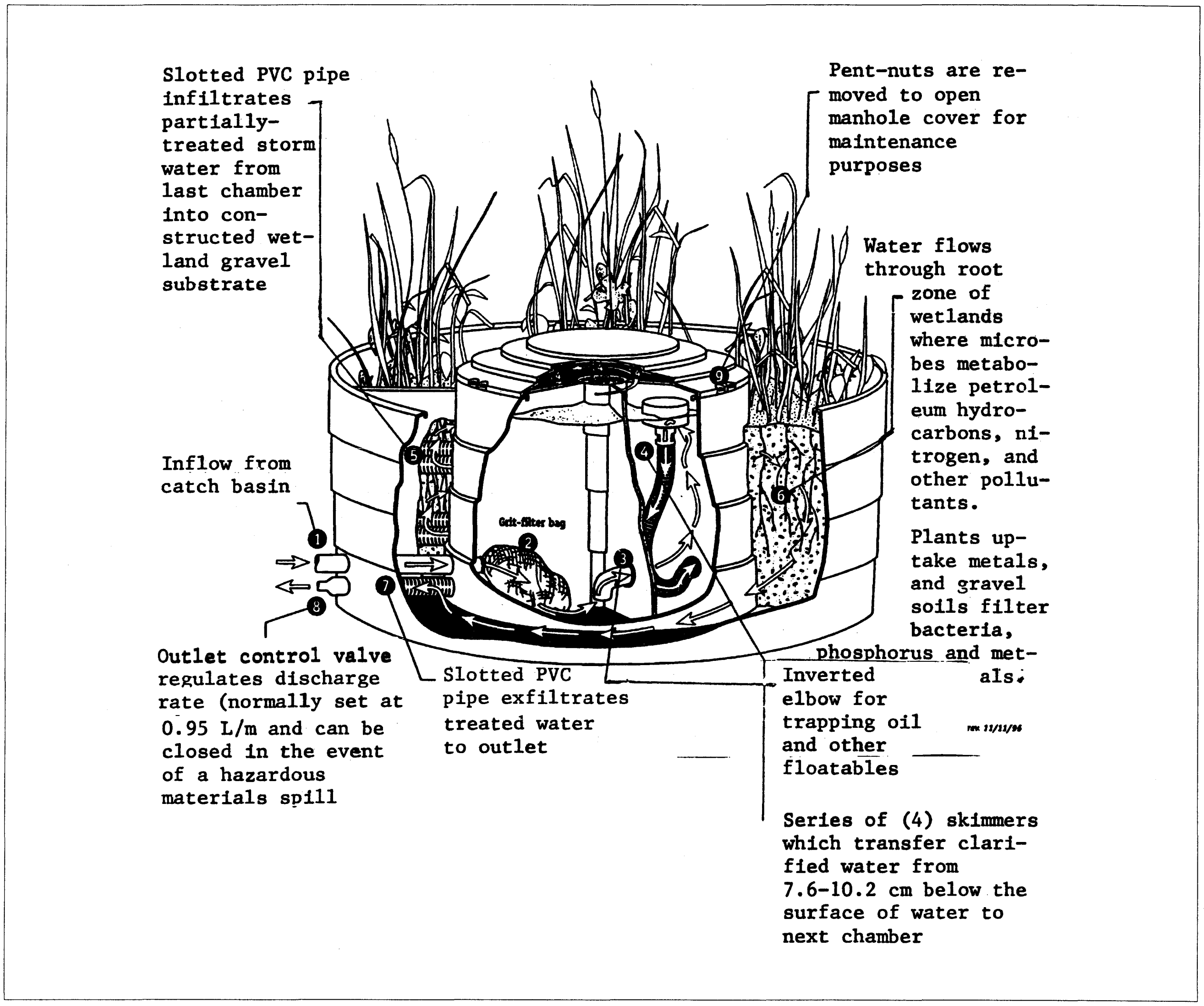


**Figure 34. StormTreat®System Tank (adapted from StormTreat Systems, 1996)**

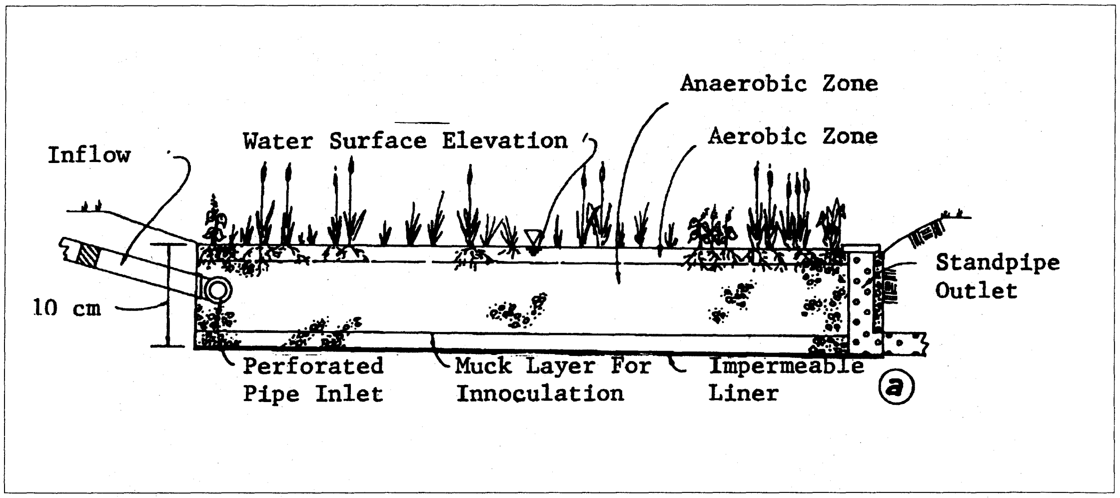


**Figure 35. Vegetated rock filter (adapted from Claytor and Schueler, 1996)**

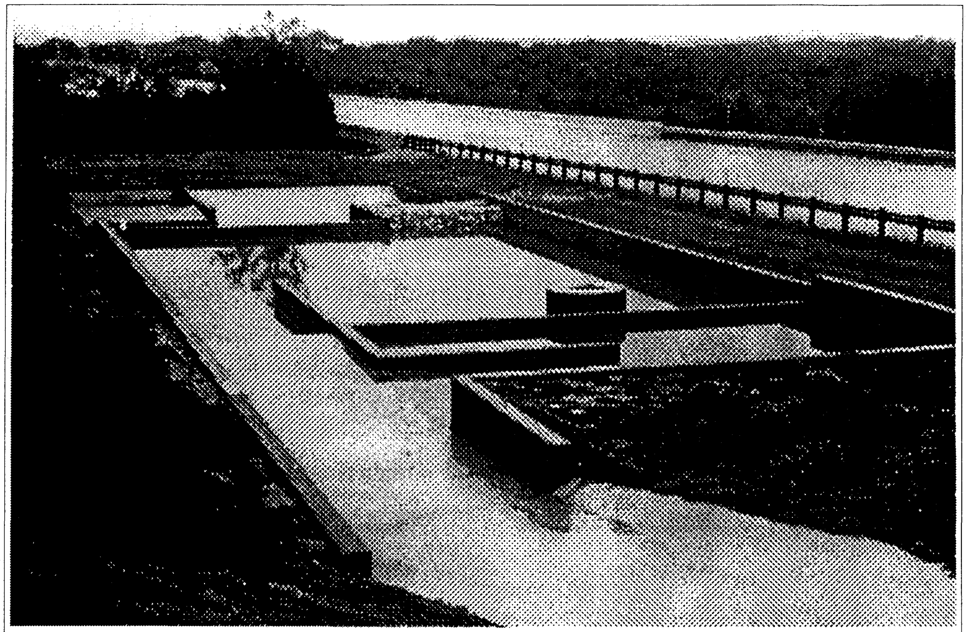

**Figure 36. Typical vertical filtration system (Tenney et al., 1995)**

# 4. MONITORING PROGRAM DEVELOPMENT

## 4.1 INTRODUCTION

Monitoring is a direct and effective method of evaluating water quality and its response to various land treatment activities. Monitoring best management practices (BMPs) provides valuable information on their performance in controlling stormwater runoff and associated pollutants, and supports both management and engineering decisions regarding BMP use, design, operation, and maintenance. This chapter presents a structured approach to developing a well-designed monitoring program. Key steps of the approach are illustrated using actual case studies conducted on a variety of different types of BMPs and settings around the country.

## 4.2 PHASES OF A MONITORING PROGRAM

The development of a BMP monitoring program can be divided into four distinct phases as shown in Figure 37. These phases are:

- The *program planning phase* identifies key management questions to be answered by the monitoring program and defines the anticipated data quality requirements.
- The *program design phase* details the technical aspects of field sampling and associated operating procedures, methods for laboratory analysis and quality control, and chain of custody, and develops a data management plan.
- The *program implementation phase* consists of field measurements and data collection, laboratory analysis, and processing and storage of program data. Program implementation is performed according to standard operating procedures and a quality assurance plan developed during the design phase.
- The *program evaluation phase* analyzes data collected from the monitoring program for adequacy and sufficiency and formulates answers to the management questions defined during the planning phase.

Each phase consists of a set of elements that provide a structured approach for ensuring that all monitoring considerations are addressed and coordinated in an effective manner. Brief descriptions of the phases and corresponding elements are provided in the following sections.

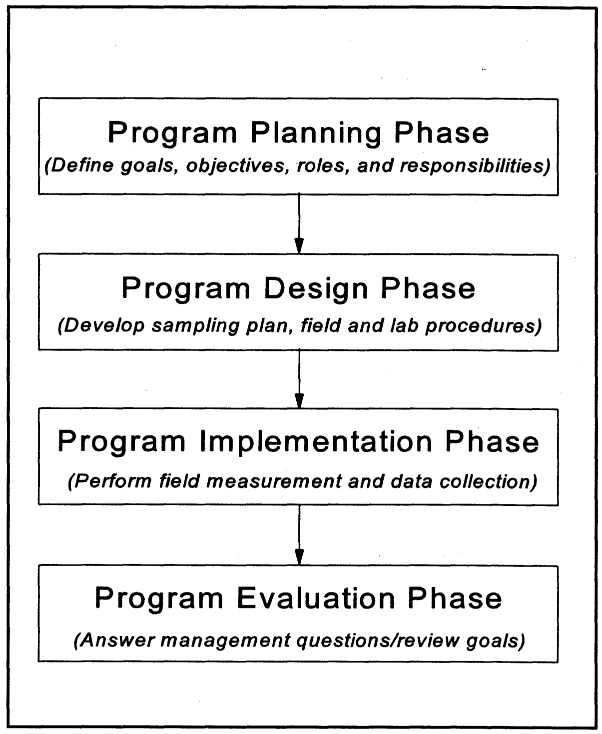


**Figure 37. Key phases for development of a monitoring program**

## 4.3 MONITORING PROGRAM PLANNING PHASE

Program planning represents a critical phase of monitoring program development and implementation. It establishes the overall framework with well-defined criteria and the specifications required for designing an effective sampling plan and associated laboratory analyses and data quality control procedures. Figure 38 summarizes the components evaluated during the program planning phase and provides a set of key considerations and monitoring planning decisions. These key components include:

- Well-defined *management goals* and a description of technical questions to be answered by the program.
- Understanding of the *physical characteristics of the site*, as well as the *function and design considerations of the targeted BMP*.
- Identification of the *available resources and constraints*, including staff and funding availability and constraints such as time frame, access and permits, and staff allocation and expertise. Under this component, staff roles and responsibilities in the program are defined.

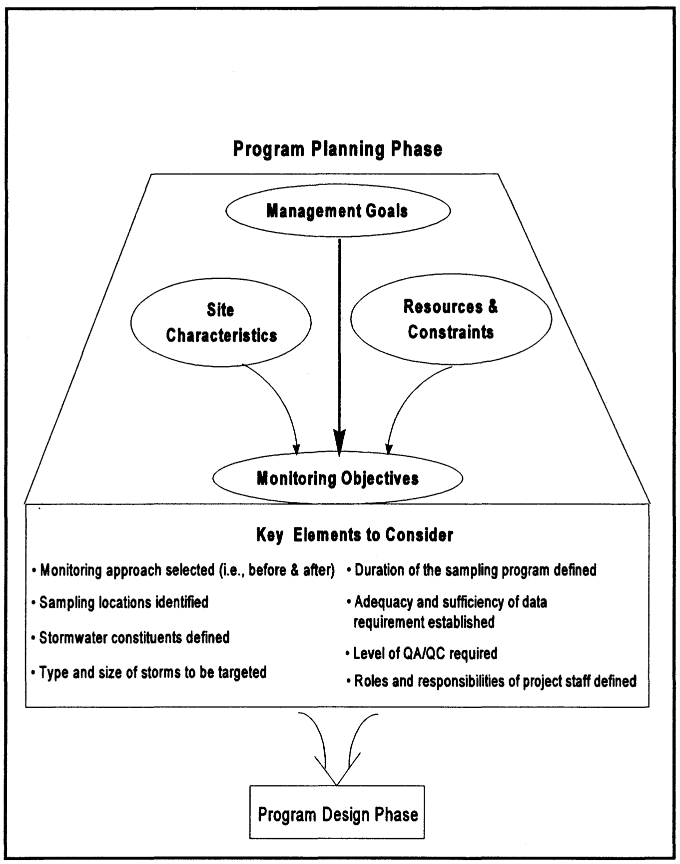


**Figure 38. Components of the program planning phase**

- Development of clear *monitoring objectives* based on the results of previous components, including guidelines for selecting the constituents to monitor, number of monitoring locations, and data quality objectives.

A successful program planning phase relies on (1) collecting and properly processing all programmatic and technical information relevant to characterizing the intended use of the data; (2) defining the interrelationships between the various planning components, including management questions to be answered, available resources, and site conditions; and (3) deriving a set of monitoring objectives and guidelines for final design of the program. The interrelationships between the various planning components can be developed through a dynamic and iterative process to optimize the available resources while providing monitoring data to answer multiple questions.

### 4.3.1 Management Goals

Stormwater management goals are generally broad statements or questions concerning a water quantity or quality issue. Water quality issues related to stormwater runoff can be associated with implementation of BMPs as a means of mitigating potential impacts. Management goals can thus be viewed as questions concerning implementation of the selected BMPs. The goals can be confined to addressing a specific site condition, or a specific type of pollution source, or they can be broad enough to encompass application of BMPs to an entire watershed or region. An adequately designed BMP monitoring program should generate sufficient information to support a variety of management, programmatic, and technical goals. Examples of typical management goals related to monitoring of BMPs, or combinations of BMPs, include:

- Evaluate the ability of a BMP to provide water quality benefits to receiving waters when applied watershed-wide.

- Support integration of a BMP technology or approach into a large-scale program of watershed or stormwater management.
- Determine the ability of a BMP to target and treat specific stormwater constituents in a new setting or as compared to other BMPs.
- Evaluate the feasibility of, or enhanced function of, alternative or innovative BMP designs.
- Demonstrate the ability of a BMP to perform under site-specific land use, physiographic, and climatic conditions.
- Evaluate the ability of a BMP to address specific pollution sources.
- Define the longevity of a BMP and evaluate maintenance requirements.

### Example of Management Goals

In 1991, a two-phase field study was initiated by the Virginia Department of Transportation to test the pollutant removal efficiency of selected BMPs (Yu et al., 1993, 1994). The Virginia Department of Transportation defined the major goal of the monitoring program as the development of design guidelines for the stormwater best management practices section in its Stormwater Management Manual. Additional goals of the program were to:

- Evaluate the pollutant removal efficiency of a dry pond detention facility.
- Evaluate the pollutant removal efficiency of a grass-lined swale that collects runoff from an urban highway.

Although management goals can be stated in the broad perspective of overall stormwater or watershed management, during the planning phase they should be redefined to reflect specific monitoring requirements. Examples of management goals related to monitoring formulated by the Virginia Department of Transportation are shown in the following box.

## 4.3.2 Physical Site and BMP Characterization

Characterization is a review and interpretation of the condition of the area draining or hydrologically connected to the monitoring location, the key design features of the BMP to be monitored, and the constituents that may be associated with the upstream land use activities. Characterization develops the information base that supports understanding the BMP systems and setting and ultimately the formulation of specific monitoring objectives. The results of the characterization can be used to help define objectives that target the water quality constituents of concern and their expected concentrations in runoff under various hydrologic (wet-weather) conditions. Checklists of site characteristics that are typically used in supporting the design of a sampling plan or have a significant influence on the site's response to water quantity and quality controls are presented below. These include the following categories of factors influencing or assisting in understanding the site hydrology, site water quality condition, and type and design characteristics of the BMP to be monitored.

### Hydrologic Characterization

The purpose of hydrologic characterization of a monitoring site is to (1) review the distribution of storm size and storm frequency on a seasonal and annual basis to help define a hydrologically representative set of storm types and sizes to be sampled, (2) evaluate the local rainfall-runoff relationship to assist in defining the number of samples per storm and the sampling interval, and (3) determine the primary flow and transport mechanisms to better understand the behavior of flow routing within the drainage area and associated flow controls (e.g., swales, pollution prevention, connected imperviousness, slopes). Flow routing can have a significant impact on the fate of water quality constituents, and an understanding of localized flow routing processes can support locating key sampling stations. In addition, hydrologic assessment at the site contributes to identification of potential problems associated with increased stormwater runoff from impervious surfaces and a targeted assessment of the benefits of the BMP.

In an ultra-urban environment, a high percentage of the infiltratible land has been replaced with structures and paved surfaces. The runoff that was naturally retained and infiltrated is now routed directly to downstream water bodies (Brookes, 1988). Some of the direct effects are an increase in the flow volume, higher frequency of medium to high flows, and reduced base flow and groundwater recharge (Nunnally and Keller, 1979). These impacts can tend to increase erosion within stream channels to unacceptable levels. The eroding streams drain wetlands and can destroy both wetland and aquatic habitat, as well as diminish the aesthetic value of the stream and wetland system (Brookes, 1988). Changes in hydrologic regime due to increased imperviousness can be manifested by flooding of roads or structures in the immediate vicinity of the BMP, downstream flooding in areas adjacent to receiving streams, or degradation of stream channels downstream of outfalls. The adjacent box presents a checklist of site characteristics that can influence the hydrologic conditions and provide information to support design of the sampling plan. Analyses that can be used to investigate the hydrology of the site and any potential or existing impacts to downstream water bodies include:

**Checklist of Site Characteristics**
**Site Hydrology**

- ✓ Drainage area
- ✓ Rainfall records and statistical analysis of storm characteristics and frequency
- ✓ Gaging station records and statistical analysis (for closest downstream gaging station)
- ✓ Parameters that influence hydrology:
  - percent imperviousness
  - percent imperviousness hydrologically connected to storm drainage system
  - storm drainage systems, location of outfalls
  - soil characteristics
  - depth to water table
  - topography
  - land cover
  - land use (existing and future)
  - development history
  - projected roadway alignment modifications, roadway expansion

- *Rainfall data from a nearby rain gauge* can be used to calculate a storm return interval, or the frequency of specific storm sizes, at the site. Evaluation of the rainfall frequency spectrum can be used to identify criteria for selection of storms for sampling and can be used to determine whether the sampled events are representative of the rainfall regime that normally occurs within the watershed.
- *Downstream gaging station information* can be used to produce stage-discharge rating curves as well as a frequency analysis of flow conditions. The rating curves can be used to determine the short-term or long-term shifts normally associated with urbanization. Frequency analysis can be used to determine the peak design storm associated with a specific return interval. This information can be used for evaluation of design storms in critical conditions for evaluation of BMP function.
- *Field reconnaissance* can provide qualitative assessment of downstream water bodies for signs of urbanizing effects, such as bank widening, channel down-cutting, or drained wetlands. Review of field data and information gathering supports the identification of specific impacts prior to initiation of monitoring efforts. This baseline evaluation can be used to support a "before and after" assessment of site conditions. Evaluation of site conditions is used in targeting sampling locations and identifying potential problem locations for sampling. For example, sampling sites should not be located in areas where backwater conditions may occur.
- *Drainage area characteristics,* such as imperviousness of the site, drainage system design, land use activities, soils, and slopes, can provide valuable insights into the

hydrologic response of the system to rainfall events. This information can be used to estimate the quantity of stormwater runoff for various size storms and antecedent conditions (i.e., number of days since previous rainfall or soil moisture conditions). A basic understanding of the runoff characteristics is used to size sampling equipment and select sampling periods (i.e., storm sizes). Direct measurement of runoff at gaging stations or localized sampling points can be used to support monitoring design. In the absence of local data, estimates can be made based on site characteristics. A typical technique for runoff estimation is the Soil Conservation Service TR-20, which estimates runoff based on site imperviousness and use. More sophisticated estimation of runoff characteristics based on drainage area features and storm drainage systems can be performed using computer simulation models. For additional discussion of runoff estimation methods, see *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996).

- *Local studies* relevant to the site or data that have been collected nearby should be reviewed if available. In some areas extensive floodplain analyses have been performed, or studies on roadway design might have included runoff estimation for the purpose of culvert and bridge design.
- *Future conditions* should also be considered in the hydrologic characterization phase. If drainage area characteristics or land use activities change significantly during the sampling period, the monitoring results may be skewed. Evaluation of future conditions includes consideration of land use zoning and build-out conditions, population or development projections, and roadway alignment or expansion plans.

This investigation will determine the hydrologic condition of the sites, the potential sampling locations, and the potential timing of monitoring efforts based on hydrologic conditions.

## Characterization of Site Water Quality

Water quality conditions at the site can be characterized through (1) delineation of built-up areas and their connectivity to the transport network; (2) identification of land uses, including industrial and commercial facilities and specialized uses that may be hot spots such as gas stations and vehicle storage areas; (3) documenting and characterization of land use activities such as chemical applications of nutrients or pesticides on grassed areas, and their rate and timing; and (4) identification of any constituent sink areas such as floodplain/wetland areas upstream of the BMP monitoring locations. The site characterization process is used to define the most likely constituents of concern, their potential magnitude in stormwater runoff, and their most likely removal processes (e.g., settling, biological decay). The following box presents a set of site characteristics that influence land deposition of stormwater quality constituents and washoff, and provides information for the design of monitoring requirements and a sampling plan.

The most direct method of investigating water quality characteristics at a site is to conduct a preliminary site screening through an analysis of a limited set of samples. Short of such screening activity, the review of available information on water quality conditions at the site or at sites with similar characteristics can be accomplished through a combination of site environmental assessment and review of available literature and case studies.

## Site Water Quality Characteristics

Parameters that influence water quality:
- percent imperviousness
- percent of imperviousness hydrologically connected
- storm drainage systems
- soil characteristics
- depth to water table
- slopes
- land cover
- land use (existing and future)
- specialized land uses ("hot spots" such as gas stations)
- land use activities (i.e., fertilizer application, deicing materials).

Evaluation of water quality conditions in surface water or groundwater (depending on availability):
- monitoring or screening samples collected in the immediate vicinity of the site during site characterization phase
- monitoring in nearby drainage areas
- monitoring in locations in similar regions or settings
- literature values for similar land use conditions
- visible impacts (qualitative) observed during field reconnaissance.

**Table 20. Constituents and sources in highway runoff**

| Constituent | Source |
|---|---|
| Particulate | Pavement wear, vehicles, atmospheric deposition, maintenance activities |
| Nitrogen, Phosphorus | Atmospheric deposition and fertilizer application |
| Lead | Leaded gasoline from auto exhausts and tire wear |
| Zinc | Tire wear, motor oil, and grease |
| Iron | Auto body rust, steel highway structures such as bridges and guardrails, and moving engine parts |
| Copper | Metal plating, bearing and brushing wear, moving engine parts, brake lining wear, fungicides and insecticides |
| Cadmium | Tire wear and insecticide application |
| Chromium | Metal plating, moving engine parts, and brake lining wear |
| Nickel | Diesel fuel and gasoline, lubricating oil, metal plating, bushing wear, brake lining wear, and asphalt paving |
| Manganese | Moving engine parts |
| Cyanide | Anti-caking compounds used to keep deicing salts granular |
| Sodium, Calcium, Chloride | Deicing salts |
| Sulphates | Roadway beds, fuel, and deicing salts |
| Petroleum | Spill, leaks, antifreeze and hydraulic fluids, and asphalt surface leachate |

Source: Adapted from USEPA, 1993.

Table 20 presents a summary of potential sources of chemical constituents generally found in highway runoff. Suspended sediment concentrations typically are the highest of any stormwater runoff parameters associated with ultra-urban stormwater runoff (Driscoll and Mangarella, 1990). Sediments having high organic or clay content typically act as a carrier of bacteria, trace metals, and toxicants. Heavy metal concentrations within stormwater runoff are of concern because of their potentially toxic effects on aquatic habitat and drinking water sources.

Typically, the three heavy metals with the highest concentrations in ultra-urban stormwater runoff are copper, lead, and zinc (Driscoll and Mangarella, 1990). Oil and grease includes a wide variety of different hydrocarbons, including trace organics such as polynuclear aromatic hydrocarbons (PAHs). In general, hydrocarbons tend to adsorb readily to sediments and settle out in the bottoms of rivers, lakes, and estuaries, where they accumulate. In the majority of the monitoring case studies that were evaluated for use in this document, the constituents sampled for were similar to those sampled during NURP (USEPA, 1983). In many cases, the list of NURP constituents, although comprehensive, was not targeted to the local conditions or to typical constituent concentrations.

Examples of information and analysis to consider during the site characterization process include:

- In the absence of localized sampling, *downstream water quality monitoring data* or data from nearby drainage areas with similar use characteristics can provide a general overview of water quality conditions.
- *Field reconnaissance* can provide a qualitative assessment at the site and at downstream water bodies that can support estimation of water quality conditions and potential constituents of concern. Observations of land use activities (i.e., gas stations, parking lots, park areas) can provide indicators of potential constituents available during runoff events.
- *Local studies,* reports, or data documenting existing or potential problems related to water quality, biological integrity, or stream stability can provide background information on the water quality conditions.
- *Literature values* that characterize constituent loadings by source under similar climatic conditions and land use distribution can be used in the absence of (or as a supplement to) localized monitoring information. An example of typical constituent concentration values in highway runoff reported in the literature is shown in Table 21. The nationally derived literature values shown in Table 21 may vary widely depending on the local climate and soil/slope conditions.
- *Drainage area characteristics and land use activities* such as imperviousness of the site, drainage system design, land use activities, soils, and slopes can provide valuable insights

**Table 21. Constituents of highway runoff, ranges of average values reported in the literature**

| Constituent | Concentration (mg/L unless indicated) | Load (kg/ha/year) | Load (kg/ha/event) |
|---|---|---|---|
| Solids | | | |
| Total | 437 - 1147 | | 58.2 |
| Dissolved | 356 | 148 | |
| Suspended | 45 - 798 | 314 - 11,862 | 1.84 - 107.6 |
| Volatile, dissolved | 131 | | |
| Volatile, suspended | 4.3 - 79 | 45 - 961 | .89 - 28.4 |
| Volatile, total | 57 - 242 | 179 - 2518 | 10.5 |
| Metals (totals) | | | |
| Zinc | .056 - .929 | .22 - 10.40 | .004 - .025 |
| Cadmium | ND - .04 | .0072 - .037 | .002 |
| Arsenic | .058 | | |
| Nickel | .053 | .07 | |
| Copper | .022 - 7.033 | .030 - 4.67 | .0063 |
| Iron | 2.429 - 10.3 | 4.37 - 28.81 | .56 |
| Lead | .073 - 1.78 | .08 - 21.2 | .008 - .22 |
| Chromium | ND - .04 | .012 - 0.10 | .0031 |
| Magnesium | 1.062 | | |
| Mercury, x $10^{-3}$ | 3.22 | .007 | .0007 |
| Nutrients | | | |
| Ammonia, total as N | .07 - .22 | 1.03 - 4.60 | |
| Nitrite, total as N | .013 - 2.5 | | |
| Nitrate, total as N | .306 - 1.4 | | |
| Nitrite + nitrate | 0.15 - 1.636 | .8 - 8.00 | .078 |
| Organic, total as N | .965 - 2.3 | | |
| TKN | 0.335 - 55.0 | 1.66 - 31.95 | .17 |
| Nitrogen, total as N | 4.1 | 9.80 | .02 - .32 |
| Phosphorus, total as P | .113 - 0.998 | .6 - 8.23 | |
| Miscellaneous | | | |
| Total coliforms organisms/100 mL | 570 - 6200 | | |
| Fecal coliforms organisms/100 mL | 50 - 590 | | |
| Sodium | | 1.95 | |
| Chloride | | 4.63 - 1344 | |
| Total organic carbon | 24 - 77 | 31.3 - 342.1 | .88 - 2.35 |
| Chemical oxygen demand | 14.7 - 272 | 128 - 3868 | 2.90 - 66.9 |
| Biological oxygen demand (5 day) | 12.7 - 37 | 30.60 - 164 | 0.98 |
| Polyaromatic hydrocarbons (PAHs) | | .005 - .018 | |
| Oil and grease | 2.7 - 27 | 4.85 - 767 | .09 - .16 |

Source: Barrett, et. al., 1995.

into the availability of constituents for washoff during rainfall events or leaching to groundwater systems. This information can be used to estimate the quality of stormwater runoff during various time periods and conditions. Prediction of constituent concentrations or loads can be used to guide in the selection of constituents, type of sample (e.g., dissolved, particulate), and frequency of sampling for the program. Water quality concentration and loadings can be estimated using computer simulation models (e.g., SWMM). Although water quality modeling is not typically performed solely for the purpose of monitoring design, models developed as part of broader objectives can be used to supplement, test, and evaluate monitoring designs. For additional discussion of stormwater quality estimation methods, see USEPA (1992) and Young et al. (1996).

- *Future conditions* should also be considered in the water quality characterization phase. If the drainage area characteristics or land use activities change significantly during the sampling period, the monitoring results may be skewed. Evaluation of future conditions includes consideration of land use zoning and build-out conditions, population or development projections, and roadway alignment or expansion plans.
- *Historical land use* changes within the watershed or at the site can provide insights into current conditions and form a baseline for future evaluations.

## BMP Characterization

The purpose of the BMP characterization is to provide an understanding of the setting of the BMP, the BMP features, and the processes governing the fate and transport of constituents within the BMP that result in an overall removal rate under various hydraulic loading conditions. During the BMP characterization, design criteria influencing the primary removal processes should be reviewed and preliminary assessment of each removal process (i.e., settling, adsorption/ filtration, biological decay) should be performed, considering the set of targeted constituents. The adjacent box provides a list of key characteristics to be considered when assessing the BMP to be monitored. BMP characterization focuses on gathering relevant information to support development of general guidelines to be used in final design of the monitoring program. An example of BMP characteristics and their relevance to the design of a monitoring program is presented in Table 22. It should be noted, however, that additional site and BMP characteristics are needed to assist in the later data analysis and interpretation phase. An understanding of the primary treatment processes employed by BMPs supports the design of an effective monitoring program. BMP monitoring is an examination of the effectiveness either as a "black box" measuring in and out, a collection of processes within a BMP, or components in a train

### BMP Characterization

- Type of BMP (off-line or on-line)
- BMP surface area (detention/retention type)
- Design storm/storage capacity
- Inlet features
- Presence of overflow structures and characteristics
- Description of the types and designs of outlets
- Primary water quality treatment process
- Localized (in immediate vicinity of BMP) channel type and geomorphology, soils, slopes, depth to water table, proximity to stream system
- Hydraulic response of BMP to hydrologic inputs
- Location of separate inflow/outflow points
- Date installed or retrofitted, planned installation date
- Type and frequency of maintenance activities
- Upstream and downstream site characteristics
- Right-of-way, easements, and required permits

of BMPs. Monitoring objectives may be defined to include the examination of particular dissolved or adsorbed constituents and selected processes in the system or BMP. The principal fate processes of constituents in stormwater runoff are:

- Adsorption.
- Volatilization.
- Biodegradation.
- Filtration.
- Settling.
- Bioassimilation.

Table 23 summarizes the constituent removal processes employed by the various types of BMP categories. For additional discussion of BMP categories and specific design features, refer to Chapter 3. Review of the primary constituent removal mechanisms for the BMP to be monitored can guide selection of the constituents to be monitored in inflow and outflows (i.e., dissolved, adsorbed, transformation products), the

**Table 22. Example of BMP characteristics relevant to developing a monitoring program**

| BMP Characteristics | Relevance to Monitoring | Examples/Definitions |
|---|---|---|
| BMP type | Type of monitoring | Surface water, groundwater, sediment |
| | Sample media | Filter media |
| Hydraulic response | Define frequency and extent of flow bypassing | Overflow, diversion structures |
| | Sediment resuspension due to high velocities | Unconsolidated depositional areas |
| BMP size (ratio of BMP surface area to drainage area) | Understanding the flow routing through BMP | |
| | Assist in defining sampling intervals and duration during storm events | |
| Design storm and storage capacity | Assist in defining sampling intervals and duration during storm events | Wet pond and wetland systems |
| Outlet control and flow restrictions/diversions | Define the number and location of sampling stations | Single/multiple outlets (overflows, direct sheet flow) |
| | Define flow monitoring techniques (weir, theoretical rating curves, direct measurements) | Backwater problems<br>Outlet blockages |
| Inlet features | Number and location of inflow inlets | Ratio of base flow to mean storm flow |
| Primary treatment processes | Refine sampling constituent list | Sedimentation ponds |
| | Define detection limits and QA/QC requirements | |
| Channel type and geomorphology | Locating station and sampling points | Natural channel/concrete pipe |
| | Secure water sampling intakes and stage sensors | Rapid changes in velocity/channel geometry (unstable stream sections (scouring, deposition) |
| | | Backwater problem |
| Upstream pretreatment devices | Refine sampling constituent list | Sediment forebay |
| | Define detection limits and QA/QC requirements | Flow spreaders |

type of supplementary monitoring (i.e., filter media, depositional materials), and the timing of the monitoring (i.e., settling, infiltration timing).

### 4.3.3 Project Resources and Physical Site Constraints

A review of resources and constraints is needed to define the scope and timing of implementation of the monitoring program. In this component, the availability of resources, resource distribution options, and constraints in staff time, laboratory resources, or contract funding are defined. The box below presents examples of project resources and constraints.

The definition of funding options and constraints will support definition of specific monitoring objectives and ultimately design of appropriate and cost-effective monitoring techniques. Funding for BMP monitoring should consider the cost for design and installation of the monitoring system, implementation of the monitoring program (sample collection, data analysis and processing, laboratory costs), and evaluation of the monitoring results. The funding evaluation should also consider the time frame and level of staff time required to support monitoring activities throughout the life cycle of the monitoring program. These activities can be supported by combinations of in-house staff, program resources, grants, cooperative funding, or other external funding. Funding can be evaluated in terms of resource options to allow optimizing monitoring design specifications in later phases. Flexibility in resource options may allow trade-offs between various funding sources and use of staff, cooperative agreements, and external contracting. Typical costs associated with establishment of a BMP monitoring station are shown in Table 24.

Review of in-house staff capabilities and skills to support monitoring tasks should consider the following:

- Identify capabilities, staff time available, and options for the monitoring program implementation phase in terms of hours/month.
- Identify roles of key staff members based on skills such as design, monitoring implementation, QA/QC officer, data analysis and statistics, and data interpretation.
- Clearly identify constraints in terms of time

**Table 23. Primary constituent removal mechanisms in selected BMP categories**

| Constituent | Infiltration/ Bioretention | Detention/ Retention/ Wetlands | Sand Filters | Vegetated Swales/ Filter Strips | Water Quality Inlets | Porous Pavement | Street Sweeping | Other Nonstruct. BMPs |
|---|---|---|---|---|---|---|---|---|
| Heavy Metals | Adsorption Filtration | Adsorp. Settling | Settling Filtration | Settling Filtration | Adsorp. Settling | Filtration Adsorption | Physical Removal | Source Control |
| Organics | Adsorption Biodeg. | Adsorp. Settling Biodeg. Volatil. | Filtration Settling | Adsorp. | Settling | Filtration Adsorption | Physical Removal | Source Control |
| Nutrients | Adsorption Bioassim. | Bioassim. | Settling | Bioassim. | Settling | Filtration Adsorption | None | Source Control |
| Solids | Adsorption | Adsorp. Settling | Settling Filtration | Setting Filtration | Settling | Filtration Adsorption | Physical Removal | Source Control |
| Oil & Grease | Adsorption | Adsorp. Settling | Filtration | Adsorp. | Adsorp. Settling | Filtration Adsorption | None | Source Control |

Source: Adapted from Maestri et al., 1988; Scholze et al., 1993.

## Project Resources and Constraints

Monitoring cost
- design
- installation
- implementation

Funding sources
- staff time
- grants
- cooperative agreements

Constraints
- staff time
- logistics/climate
- access/transport
- equipment availability
- laboratory receiving times and processing

period, funding or staff time available per period (annual or monthly), staff laboratory costs or capacity including logistical issues (e.g., days lab will receive samples), transportation logistics (distance to sampling location from offices and laboratory), and access permission.

### Constraints Related to Site-Specific Conditions

These constraints are identified based on the site characterization process. Review of site constraints should consider:

- Size of the site for installation of monitoring equipment.
- Access, rights-of-way, easements for access or permission to access site for monitoring.
- Permitting requirements for monitoring installation.
- Access to electrical power if automated equipment is needed.
- Site safety for sample collection and processing.
- Access to sampling locations or other special logistical constraints due to climate.

The vegetated buffer case study presented in the adjacent box shows how resources such as time and money and constraints associated with physical site conditions can affect the monitoring design and the results of the monitoring program.

## 4.3.4 Monitoring Objectives

The final element of the planning phase is specification of monitoring objectives. Monitoring objectives are formulated from the results of the interaction between management goals, site characterization, and identification of resources and constraints. Within the framework of the monitoring program design process, objectives also serve as the link between the planning phase and the design phase, as shown in Figure 39.

**Table 24. Typical costs associated with establishment of an automated BMP monitoring station**

| Equipment | Range in Cost ($) |
|---|---|
| Stage (flow) Monitoring | 2,500 - 3,500 |
| Water Sampler | 2,500 - 4,000 |
| Sensors (e.g., rainfall, temp, pH, dissolved oxygen, conductivity) | 300 - 1,500 per sensor |
| Instrument Shelter and Platform | 2,000 - 3,000 |
| **Installation and Testing of Equipment** | 3,000 - 6,000 |
| **Total Costs** | 10,300 - 18,000 |

Source: TetraTech, Inc. (1995 dollars).

## Vegetated Buffer Study

A field study to determine the influence of vegetation composition, buffer width, and infiltration rate on the effectiveness of native vegetation buffer zones for treatment of urban runoff was carried out in Austin, Texas (Glick et al., 1993). The field study was developed to monitor pollutant removal efficiency of different water quality buffer zones established adjacent to an existing parking lot. Test plots were established to monitor the runoff quality through the buffer. Water sampling devices were constructed using a series of overland flow collection flumes, which were placed at four locations in each of the eight test plots. However, due to parkland restrictions on the amount of clearing to place flumes, only three locations were in the wooded areas. The goal of the monitoring program was to collect as many samples as possible between July 1990 and October 1991, which was the time allotted for the monitoring program. Twelve stormwater runoff constituents—both dissolved and particulate—were sampled. Because dissolved samples were not collected in the wooded areas due to space limitations, only seven runoff constituents were measured in the areas. Because of these constraints, the results of the wooded areas were biased.

Various kinds of data can be collected and analyzed to determine whether a particular BMP is achieving the desired goal of stormwater management at a site, as well as to evaluate differences in treatment efficiencies of BMP designs or factors affecting the operating of BMPs at different sites. The definition of objectives takes the broad goals formulated in the management goals component ("What questions will the monitoring program answer?") and interprets them as specific objectives ("What data will need to be collected to answer the questions addressed by the monitoring program?"). The objectives are formulated to give specific direction for the constituent to be monitored, the accuracy required, and the quality of data and level of QA/QC required.

The specific elements of the monitoring objectives can include:

- Monitoring approach (i.e., inflow-outflow).
- Sampling equipment (i.e., manual, automated).
- Sampling method (i.e., discrete, composite).
- Identify number and location of sampling stations.
- Field sampling duration.
- List of constituents selected for monitoring.
- Any additional physical or biological monitoring upstream or downstream of core BMP site.
- Special considerations.

The case study on the City of Mountlake Terrace, Washington (see box below) illustrates how management goals, site characterization, and costs and sampling difficulty can be used to formulate monitoring objectives. In addition, physical constraints at one of the sites prevented one of the objectives from being implemented.

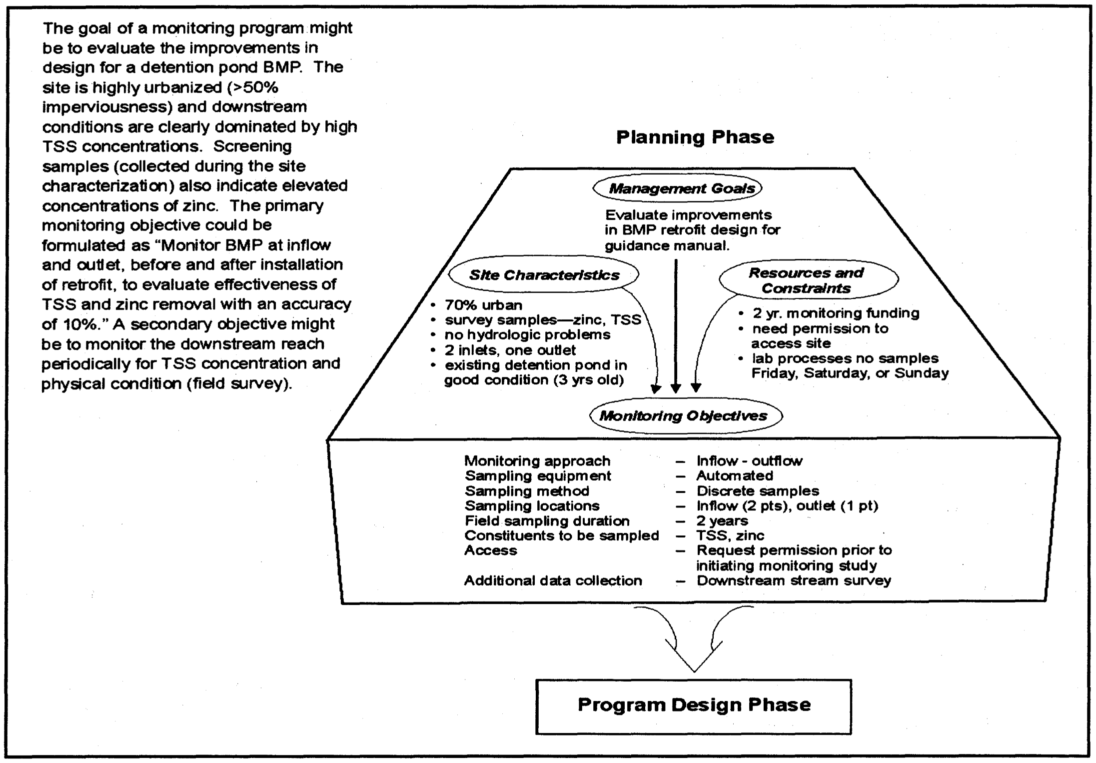


**Figure 39. Development of monitoring objectives**

## Formulating Monitoring Objectives

A swale located in the city of Mountlake Terrace, Washington, was monitored in an attempt to determine if a 70 m (200 ft) swale length could be replaced by a shorter, 30.5 m (100 ft) swale without loss of treatment performance, provided a proportionate increase in width was provided (Khan et al., 1992). The swale was constructed in the summer of 1989 and seeded the following fall. Sample collection began in the spring of 1990. The grass in the swale was mowed twice during the growing season, in June and October. The management goal of the project was to assemble as much information as possible to aid in choosing ranges of the crucial variables that would produce effectively operating biofiltration swales. The project team recognized that a good monitoring design was predicated on proper planning and followed by effective implementation. Although a number of questions were of interest to the management, the three objectives that were identified as the most valuable for investigation, considering cost, sampling difficulty, and the overall state of knowledge about the stormwater treatment ability of grassy swales, included:

- Determine the types and amounts of pollutants that are removed from stormwater, during typical storm events, by a grassy swale BMP.
- Determine whether equivalent pollutant removal performance could be achieved in a grassy swale with length less than 70 m (200 ft) if a proportionate increase in width was provided.
- Measure Manning's *n*, the coefficient of roughness in the Manning's equation, in a functioning grassy swale.

Unfortunately the 70 m (200 ft) swale was confined on both sides by a highway and a hillside and could not be widened. The project team attempted without success to find another 30.5 m (100 ft) swale that could accommodate a larger width. Due to the inability of the project team to physically modify the width of the 30.5 m (100 ft) swale, the second objective was revised to explore the question of performance under two different residence times.

## 4.4 MONITORING PROGRAM DESIGN PHASE

The design phase of a monitoring program for BMP evaluation is initiated following the identification of program objectives in the planning phase of the program. Components of the program design phase involve development of (1) data quality and monitoring objectives; (2) a sampling design plan, including detailed specifications for standard operating procedures, and a logistical and training program; (3) a data management plan; and (4) a Quality Assurance Project Plan (QAPP). Figure 40 illustrates the components of monitoring design and outlines the key elements to consider prior to the implementation of data collection. These components and their elements define the type and quality of data needed for a BMP performance and evaluation assessment. The design phase provides complete documentation of the data collection procedures and the rationale or justification supporting the various planning and design decisions.

### 4.4.1 Data Quality Objectives

Data quality objectives (DQOs) are developed and used to support preparation of a scientific and resource-effective sampling design plan (USEPA, 1994b). DQOs are qualitative or quantitative statements that clarify the monitoring program objectives, define the most appropriate type of data to collect, determine the most appropriate conditions under which to collect the data (temporal and spatial), and specify limits on decision errors that will be used to establish the quantity and quality of data needed to support the decision.

The purpose of collecting data is to answer specific management questions regarding whether

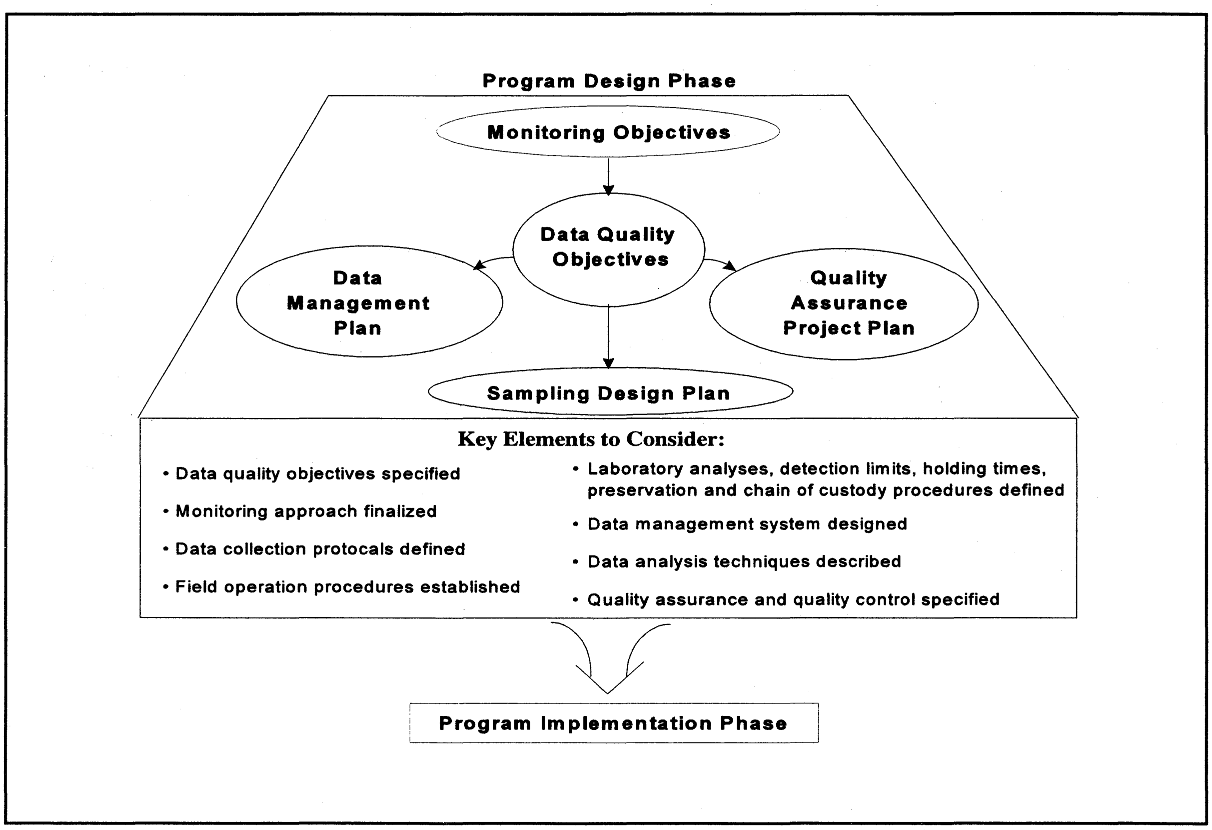


**Figure 40. Components of the monitoring program design phase**

a particular BMP provides a desired level of stormwater management, to evaluate differences in the constituent removal efficiencies of BMP design alternatives, or to assess the factors affecting the operation and maintenance requirements of BMPs. Specific hypotheses to be tested are usually identified during the development of monitoring objectives in the planning phase of the project. Examples of such hypotheses might include the following:

- Comparing BMP alternative designs to address specific site conditions.

*No significant difference between BMP (grassed swale) design A and design B, or can BMP design A, given specific site conditions, achieve a higher constituent removal than design B?*

- Comparing BMP alternative designs to address a specific constituent type.

*No significant difference between the influent/effluent concentration of a given constituent for BMP design A, or can a modification or retrofit to BMP design A effectively remove a given constituent ?*

- Comparing various BMP types to address specific constituent loadings.

*No significant differences in constituent loading reductions measured between BMP types A, B, and C (Which BMP type is most effective at reducing the loadings of a constituent?).*

*No significant difference in constituent removal efficiency of BMP design A with increased hydraulic/constituent loading conditions (Does BMP design A work the same under all combinations of stormwater flows and constituent loads?).*

- Comparing effectiveness of BMP types or BMP designs based on downstream impacts.

*No significant differences in the ability of BMP design A, B, or C to protect downstream aquatic or riparian resources (Can BMP design A, B, or C prevent downstream impacts on aquatic or riparian communities and streambank stability due to hydrologic alterations/changes?).*

Illustrations of the first two hypotheses are provided in the boxes below.

The design phase of the monitoring program includes the refinement of the type, quantity, and quality of the data required to support stormwater management decisions. Examples of these are:

- BMP design A needs to be structurally modified to improve its removal efficiency for a given constituent.
- The BMP design is reducing the loadings of constituent and can be used at other similar sites.
- BMP design B can be used only at sites with a limited range of flows.
- Structural modification B cannot be used to improve the removal efficiency at a retrofit site with BMP design A.

Common management questions regarding ultra-urban stormwater management with respect to BMP monitoring may include a combination of the above hypotheses with emphasis on whether a particular BMP can reduce the loadings of constituents to water bodies. Measurement of constituents such as TSS, BOD, COD, nutrients (particulate and soluble fractions of nitrogen and phosphorus), and pH, as well as oil and grease, and when desired, specific chemical constituents such as the heavy metals lead, copper, zinc, and cadmium, will provide information that can be used to judge the effectiveness of the BMP design or implementation.

When multiple objectives for evaluating a BMP are considered, they may consist of establishing various constraints and an optimization scheme to assess design alternatives that will best meet management goals. An illustrative example might include control of all flows exceeding stream bankfull flow rates that have a detention of more than X hours, while preserving water temperature at lower than 18.3 °C (65 °F).

## Comparison of Grassed Swales

A grassed swale on U.S. Route 29 south of Charlottesville, Virginia (29S) was monitored for its ability to remove constituents from highway runoff (Yu and Kaighn, 1995). This site was chosen because its characteristics contrasted with a swale on U.S. Route 29 north of Charlottesville (29N), which had been the subject of previous evaluations. The 29N swale had a slope of approximately 5 percent, whereas the 29S swale had a slope closer to 2 percent. The average daily traffic (ADT) of the 29N site was approximately 50,000, with the ADT at the 29S site approximately 30,000. Mowing was much more frequent at the 29N swale, occurring about once every 2 weeks during the growing season, while the 29S swale was mowed only four times during the same period. According to the literature, these differences should have led to higher removal efficiencies for the 29S swale.

The results of the monitoring program for the 29S swale found significantly lower constituent removals. Though lateral barriers had been installed to eliminate lateral inflow to the swale, the measured flow increased from the inflow point to the outflow point for two of the storms, resulting in negative mass balance removal results. Even if these two storms were omitted, constituent removal percentages were all less than 30 percent (significantly less than the 80-90 percent removal observed at the 29N site).

The only advantage the 29N site had over the 29S site was the downstream weir, which acted as a check dam. A significant amount of water ponded behind the weir, creating a small detention pond where constituents were allowed to settle and stormwater runoff could infiltrate into the soil. The 29N site had significant decreases in flow; it can only be assumed that this flow loss was a direct consequence of the downstream weir.

## Modified Detention Pond

A dry detention pond was the focus of a recent study in Charlottesville, Virginia, (Yu et al., 1993, 1994). The immediate drainage basin for the pond is a parking facility for daily commuters and athletic event traffic. The entire watershed contributing to the detention pond is approximately 3.2 ha (7.9 ac) in size, with 60 percent of the drainage area consisting of the paved parking facility. The detention pond was initially designed and constructed solely to attenuate the post development peak runoff flow rate to the predevelopment flow rate for 2- and 10-year storms. No provisions were made for water quality improvements. To create an extended detention dry pond for water quality improvement, the outlet structure was modified to provide a slow release of the runoff from a designated storm (i.e., 2-year frequency or less). For this study, the outlet was restricted to a 7.6 cm (3 in) diameter orifice.

The first two storms where both flow and concomitant pollutant concentrations were monitored provided a baseline study of the efficiency of the existing pond, since the orifice was not in place; however, the last two storms of Phase I were monitored with the extended detention orifice in place. In Phase II, four storms were monitored for both flow and pollutant concentration. Detention time is usually considered to be one of the most important factors affecting pollutant removal; however, it appears that it is not the only determinant of pond efficiency. The two storms with paired inflow/outflow data that occurred prior to the modification of the outlet orifice had unusually high removal efficiencies. The storms were very low-intensity, low-volume storms. It is likely that the conveyance channel and the low flow conditions in the pond were sufficient enough to reduce the pollutant loads regardless of the relatively low detention time. The removal efficiencies calculated after the modification of the orifice were substantially lower than those before modification. The storms monitored following the installation of the smaller orifice produced larger runoff volumes and pollutant loads.

Another key step of DQO development is to identify the quantity of data needed to support the analysis and evaluation of BMPs. The "quantity of data" should address how many samples need to be analyzed from different locations and at different times, as well as how many samples need to be analyzed at each site and time, to provide estimates of sampling design error and measurement error. Should water quality parameters be measured before the BMP is implemented to provide a "before-and-after" comparison, and if so, should these measurements be taken under the same or different conditions? How many samples will be required to provide the best estimate of nutrient concentrations before and after and increase the power of statistically detecting differences between the two scenarios? How many and what kind of samples (e.g., flow-weighted during events or grab during baseflow conditions) are needed to evaluate the quality of the measurements? What analyses will be performed on the data collected (e.g., comparisons between sites or times, or among several BMPs), and how will those analyses affect the number of samples needed?

A determination of the number of samples and constituents to be analyzed should consider the resources available and cost and time constraints, as well as the quality assurance and quality control requirements to be followed to ensure that sampling design and measurement errors are controlled sufficiently to reduce uncertainty and meet the tolerable decision error rates. Several iterations of the DQO process might be required to determine the optimal sample size for different sampling design plans.

## 4.4.2 Sampling Design Plan

Sampling design plans are developed to test specific hypotheses and can be approached in a variety of ways. Elements of plan include (1) an evaluation of approaches to development of sampling design plans; (2) the data collection process and its associated components of site selection, sampling and sensor locations, sampling frequency and type, and sampling data representativeness; (3) equipment needs and selection; and (4) field measurements and sampling methods.

### Monitoring Design Approaches

Two commonly used methods to evaluate the constituent removal effectiveness of a BMP are influent-effluent constituent monitoring and the watershed monitoring approach. An influent and effluent monitoring approach is normally confined to the BMP, whereas the watershed approach evaluates the effectiveness of either a structural or nonstructural BMP program distributed within the watershed. Examples of watershed approaches include upstream-downstream, before and after, and paired watershed (Coffey et al., 1993).

***BMP Influent-Effluent Approach***. The influent/effluent approach is a method of estimating the pollutant removal efficiency of an individual BMP or a series of in-line BMPs. In this approach, the effectiveness of the BMPs is isolated and a mass balance method is usually used to estimate pollutant removal efficiency. In general, pollutant removal efficiencies are based on calculating the difference between influent and effluent loads (Urbonas, 1994). There are several key benefits in applying the influent-effluent approach for BMP efficiency, which include:

- The approach is easily used to evaluate existing BMPs, particularly when the effect of BMP age is a management concern.
- The cost of monitoring is substantially less than that for some watershed approaches since not all environmental factors have to be monitored separately and factored into the overall efficiency.
- The time needed for monitoring can be substantially less than that required for watershed approaches since a specified calibration period is not necessary prior to beginning a monitoring program.
- The evaluation results for a particular type of BMP can be extrapolated to other physiographic regions as long as climate is not a major factor affecting the efficiency.

A drawback to the influent-effluent approach is the difficulty of establishing the downstream benefits of BMP implementation without additional data collection; for example, effectiveness in reducing the impacts of stormwater discharges on aquatic or riparian communities, and streambed and bank stability, due to hydrologic alterations.

***Watershed Approaches***. Watershed approaches to BMP evaluation are used when the physical constraints of a site do not permit adoption of an influent/effluent approach, or in the case of evaluation of the effectiveness of wide-scale application of a number of structural BMPs within a watershed. A watershed approach can also be used to evaluate the effectiveness of nonstructural BMPs such as street sweeping, catch basin cleaning programs, the use of catch basin inserts, and public outreach programs that promote a range of methods to reduce constituent loadings in stormwater. Three commonly used watershed approaches are upstream-downstream, before and after, and paired watershed.

Upstream-Downstream Approach. In contrast to the influent-effluent method, the upstream/ downstream method entails a comparison of data collected from in-stream locations both upstream and downstream of a BMP program or structure. Monitoring at the upstream location accounts for incoming pollutant sources that are unrelated to the land treatment within the study area. This method is more complex because the BMP is no longer isolated, but rather its effectiveness must be factored into other naturally occurring climatic and environmental conditions. For example, this method must take into account the addition of tributaries between the two data collection points, as well as changes in geology. Nonetheless, if this method of monitoring is conducted properly, the results produce clear and essentially irrefutable evidence of BMP influence on the study watershed (Coffey et al., 1993). Figure 41 shows a schematic of an upstream/downstream BMP monitoring design. Station A is sited to monitor the instream concentration of constituents upstream of the land treatment area; station B is sited below the BMP treatment area.

Because of the complex influences that can result from the area between the upstream and downstream monitoring locations, as well as the condition and size of the instream water body, some researchers feel the upstream/downstream approach may not be as effective in detecting changes. The time period over which to extend a sampling program is another important issue that has to be resolved. Year-to-year and seasonal variability in water quality constituent concentrations under certain conditions may surpass the changes contributed to by the BMP over any given time period. To account for some of this variability, a monitoring period of at least two to three years is recommended for both pre- and post-BMP evaluations.

Before and After Approach. The before and after approach requires that baseline data be collected prior to implementation of a watershed-wide BMP program. Year-to-year and seasonal differences also affect this approach, and as in the upstream/downstream approach to monitoring, a two to three year pre- and post-BMP monitoring period is recommended to account for this variability (Coffey et al., 1993). The effect of longer term climatic trends on hydrologic variability may still, however, mask the removal effectiveness of a BMP program. Once the BMPs

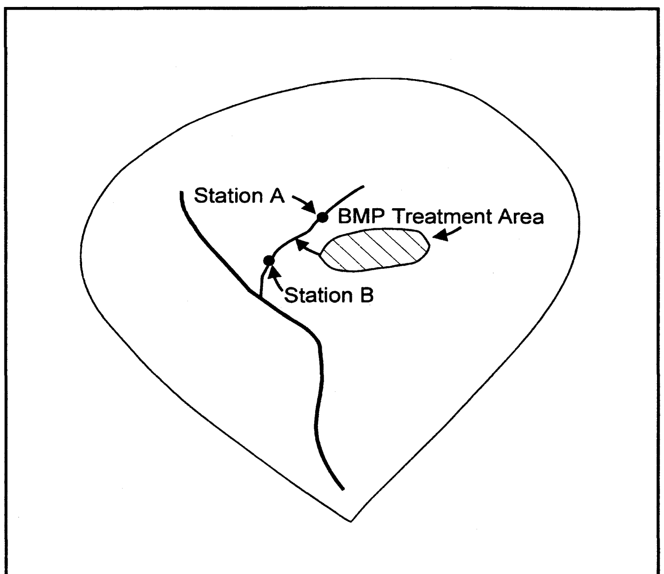


**Figure 41. Upstream-downstream design**

are implemented, an additional shortcoming of this approach is that the baseline data characterization cannot be improved upon. To substantiate a cause-and-effect relationship, the predictor variable should be adjusted for year-to-year changes in hydrologic conditions. Because of these problems, some experts prefer to combine this method with that of the upstream/downstream approach to strengthen the results of the findings (Coffey et al., 1993). Because hydrologic variabilities can occur over longer periods of time, comparative analysis of data collected using a before and after approach over the short term may be dealing with two distinct populations of hydrologic conditions.

Paired Watershed Approach. The paired watershed approach entails the comparison of water quality data from two or more watersheds with at least one regarded as the control (undisturbed) watershed. Data are from concurrent time periods, and any change in these data is taken as being indicative of BMP influence. If properly implemented, this method provides reliable results and is perhaps the most effective design for monitoring BMP program effectiveness (Coffey et al., 1993). A limitation of this approach is that the watersheds compared must be in close proximity for climatic homogeneity, with

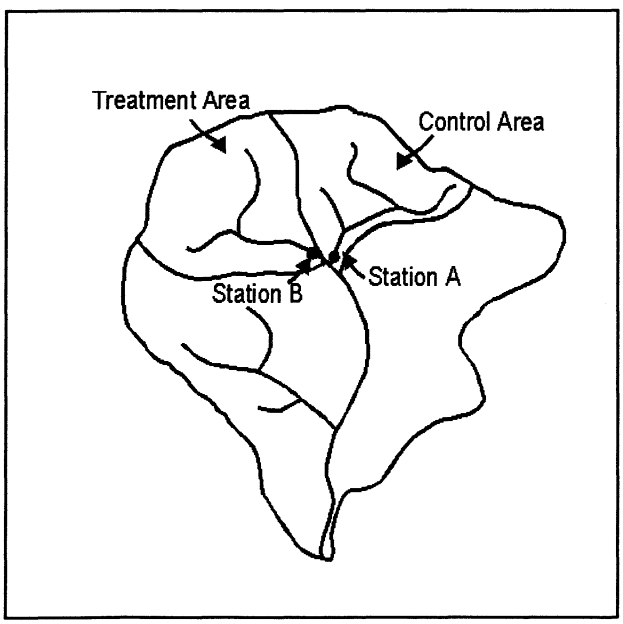


**Figure 42. Paired watershed approach**

similar geology and stable land uses over the study period.

## Data Collection Protocols

Data collection procedures are in large part dictated by the selection of constituents to be monitored and by the data quality objectives set for the sampling program. The expected range of concentrations at which the expected constituents may be detected and the need for auxiliary information such as continuous discharge, pH, temperature, and dissolved oxygen are also important elements of data collection procedures. The availability of staff and resources to complete the data collection must also be considered.

Elements of data collection include the selection of sampling site locations, sampling methods (manual, automated), number of events sampled, and the number of samples collected during both event and baseline conditions.

***Sampling Site Location***. The approach selected for BMP evaluation and a range of field constraints must be considered in the installation of monitoring equipment. Proposed locations must be representative of both the inflows and outflows, and of water quality from the BMP structure when warranted. Similar requirements must also be met by in-stream sampling locations when the design involves watershed scale assessments of BMPs. Manual sampling programs require that the equipment used for collecting samples be capable of safely reaching representative sampling locations (points) for the range of expected flows. Access to the site and the safety of the sampling crew should be considered and given first priority.

In an ultra-urban setting, the location of utilities and other underground facilities may also need to be established before equipment installation. If automated equipment is to be installed permanently at the site, the proximity of an electrical power supply might be an important consideration. If constituents selected for monitoring have short holding times, refrigerated sampling units could be required and alternatives for transport to the laboratory should be evaluated accordingly.

In the selection of monitoring locations to install equipment shelters or for the installation of primary measuring devices such as weirs or flumes, it is necessary to secure the required permission from landowners and any government agencies that have jurisdiction over the land or waterway where equipment will be installed.

A shelter used for housing water quality sampling equipment should be easily and safely accessible, at a location that will not flood during large storm events.

***Sampling and Sensor Locations***. If an in situ stage-discharge relationship (rating curve) is to be developed, the stage sensor should be located along a straight stretch of channel at least 20 channel widths below any upstream bends. The bottom of the channel also needs to be relatively even and the channel configuration sensitive to changes in discharge. The stage sensor for primary measuring devices should be located as per the recommendations of the manufacturer.

The intake line for water quality sampling should be in a well-mixed portion of the main body of the flow path. As a general rule to prevent the sampling of bedload, the intake line for an in-stream location needs to be placed 100-200 mm (4-8 in) above the bottom of the streambed. The actual position should be verified following equipment installation and testing in the implementation phase. For flows with depth greater than 0.76 m (2.5 ft), it also advisable to develop a relationship between the parameters sampled using a single-point automated sampler with that obtained from a hand-held depth integrating sampler such as the hand-held DH-48 (USGS, 1977). Some parameters—in particular, suspended sediment and total phosphorus—can be transported at different concentrations within the water column profile. A sampler intake located at a single point may not accurately reflect an integrated concentration (laterally and vertically) for some pollutants. The results shown in Figure 43 illustrate the concentration gradient with depth that can occur for suspended sediments and $BOD_5$ transported in a storm drain pipe. Samples collected in the lower portion of flow (e.g., automated samplers) may result in above average concentration while, conversely, samples (i.e., grab samples) collected in the upper portion of flow would yield below average concentrations. For other flows and constituents these concentration gradients are likely to be different. It is recommended that sample intake lines be located at a cross-section where flow is turbulent (e.g., close to lateral inflows or vertical drops; Marsalek, 1973).

The sampling station location and sensor placement for an in/out approach for evaluation of an ultra-urban BMP is illustrated in Figure 44. The sampling station located at the inlet illustrates the placement of a monitoring station aboveground, while the outlet station shows the placement of a portable, integrated flow and water sampling equipment station inside an access hole. Water sampling lines and stage sensors for both stations are both placed within a primary flow measurement structure (i.e., a flume in this case). The use of flumes as a primary measuring structure for stormwater flows is advantageous because they clear debris easily and can be used to measure a wide range of flows.

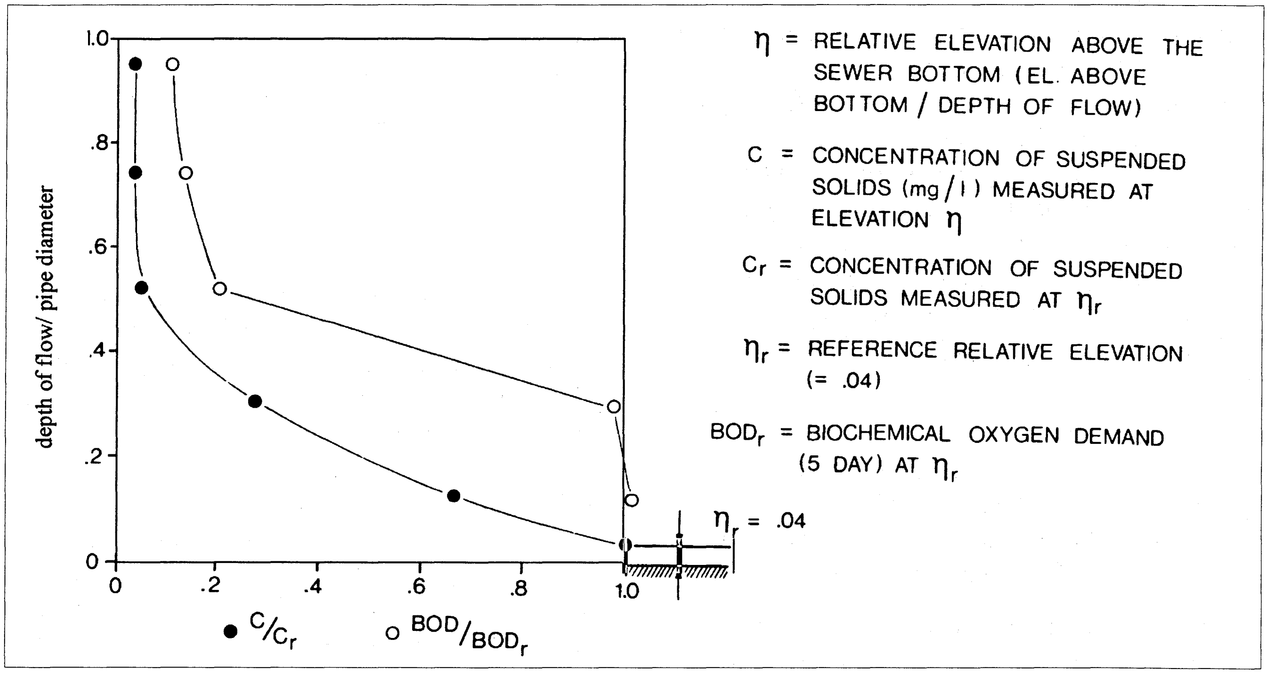


**Figure 43. Distribution of BOD and suspended solids with depth (Marsalek, 1973)**

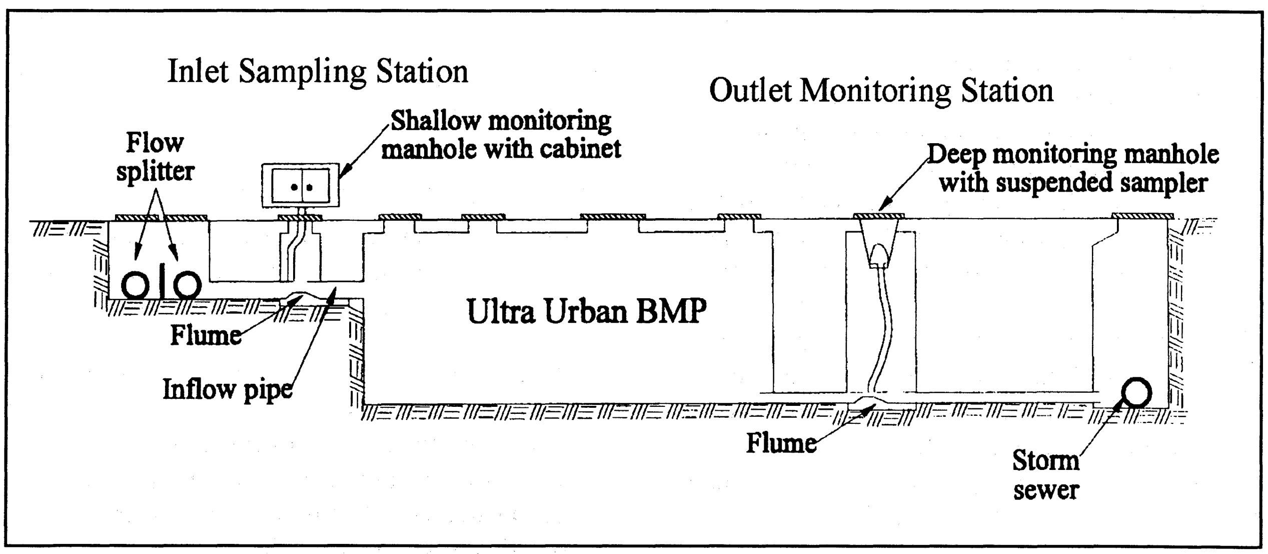


**Figure 44. Sample monitoring configuration (Young et al., 1996)**

***Sampling Frequency***. In some cases, the number of samples that can actually be collected will be dictated by constraints such as a limited sampling budget or a predefined sampling time frame. However, if there is *a priori* information on an acceptable level of error in reporting results, it is useful to estimate the number of samples that would be necessary to estimate a parameter of interest (e.g., the mean pollutant removal efficiency of a constituent) to the desired accuracy.

To determine sample size, it is necessary to have some estimate of the population variance (or relative variance, which is usually expressed as the coefficient of variation). Gilbert (1987) states that this can be done in one of three ways:

- Collect preliminary data (using a small sample) from the population to approximate variance.
- Estimate variance using data collected from the same population at a prior time or on a population from a similar study site.
- Use best judgment when reliable data are not available.

A useful rule of thumb that can be used to estimate variance is to assume the reported range (difference between the reported maximum and minimum values) for a variable is directly proportional to the population standard deviation. For example, if the range reported for a normally distributed variable is assumed to represent the upper and lower limit of the 98 percent confidence limits for the variable, the range will be equal to 4.12 times the standard deviation. Sanders et al. (1983) suggested that if no prior information is available on the variance of a population, the range reported can be assumed to be four times the standard deviation.

Once an estimate of the population standard deviation has been made, the number of samples (n) required to estimate the population mean can be computed from:

$$n = \left( \frac{\left( t_{1-\frac{\alpha}{2},\, n-1} \right) s}{d} \right)^2$$

where $s$ is the estimated standard deviation, $d$ is the acceptable margin of error in the estimated mean (absolute value of difference between the estimated and true means), and $t_{1-\alpha/2,n-1}$ is the value of the $t$ variate that has a nonexceedance probability of $(1-\alpha/2)$[1] on a $t$ distribution[2] with $n$-1 degrees of freedom. Equation 5 is solved iteratively with an initial estimate obtained by setting $t_{1-\alpha/2,n-1}$ equal to the value of the $z$ variate that has the same probability of nonexceedance on the standard normal distribution $(z_{1-\alpha/2})$[3]. When the values of $d$ and $s$ are such that $n \geq 30$ on the first substitution, further iterations are not necessary since the t distribution is essentially equivalent to the $z$ distribution for sample sizes larger than 29 (see example problem below).

[1] $\alpha$ is the probability that the absolute difference between the estimated and true parameter value is greater than or equal to the margin of error.

[2] The $t$ distribution is an unbounded distribution having a mean of zero and a variance that depends on the degrees of freedom. Values of the $t$ variate at a specified probability level for various degrees of freedom are provided in statistical texts such as Gilbert (1987).

[3] The standard normal distribution is an unbounded distribution having a mean of zero and a standard deviation equal to 1. Values of the standard normal ($z$) variate at specified probability levels are provided in statistical texts such as Gilbert (1987).

## Example Problem

The effectiveness of a Delaware sand filter in removing TSS at a site is to be estimated. The acceptable error in determining the mean effectiveness is 10%, with an allowable probability of exceeding the error ($\alpha$) of 0.05. A review of the literature indicated that the TSS removal efficiency for Delaware sand filters ranges from -41.2% to 96.4%. Estimate the number of samples required if the distribution of percent removal efficiencies is approximately normal.

Assuming the reported range is four times the standard deviation, we estimate the standard deviation of removal efficiencies to be s=(96.4-(-41.2))/4=34.4%. The acceptable margin of error (d) is equal to 10% and $\alpha$ = 0.05, therefore, 1-$\alpha$/2 is equal to 0.975. Using equation 5, we obtain the first approximation of the sample size to be

$$n=\left(z_{1-\frac{\alpha}{2}}\frac{s}{d}\right)^2=\left(\frac{(1.96)(34.4)}{10}\right)^2=45$$

Since this is greater than 29, it is not necessary to iterate further to refine the sample size estimate.

There are two basic assumptions in this approach to estimating sample size:

- The data are independent (uncorrelated over time and space).
- The data are approximately normally distributed.

If composite samples are taken and the interval between sampled storms is sufficiently large, the independence assumption is likely to be met. It may be more difficult to justify the normality assumption for some variables of interest. However, if the variable is assumed to be lognormally distributed, Hale (1972) has derived an expression for estimating the number of independent observations required to estimate the population median to a prespecified degree of relative precision:

$$n=\frac{z^2_{1-\frac{\alpha}{2}}\, s^2}{[ln(d_r+1)]^2}$$

where $z_{1-\alpha/2}$ and $s$ are as defined before, and $d_r$ is the acceptable relative error in the estimated median, defined as the absolute value of the difference between the estimated and true medians divided by the true median. The median is generally regarded as a better estimator of central tendency than the mean for skewed distributions.

***Sample Types.*** Sampling types are concerning how and what volumes of either water or sediment are collected in the field. A number of sampling types are summarized in Table 25, including their principle, where their use may be applicable, and some disadvantages. The two most commonly used samples types are the flow-proportional (constant volume - time of sample proportional to flow volume increment) and flow-weighted (constant time - volume proportional to instantaneous flow rate) composites. An example of the use of a flow-proportional sampling strategy is illustrated in Figure 45.

The final selection of a sample type reflects the data quality and monitoring objectives of the monitoring program; in particular, the specification of constituents to be monitored and their analytical detection limits.

## Table 25. Summary of water quality and sediment sampling techniques

| Sample Type | Principle | Comments | Disadvantages |
|---|---|---|---|
| Discrete (individual; water) | Sample quantity is taken over a short period of time, generally less than 5 minutes. | Most commonly used. | Does not describe time variations or representative average conditions. |
| Discrete (sequential; water) | Series of individual discrete samples taken at constant increments of either time or discharge. | Used by some automatic samplers; impracticable to collect manually. Provides a history of variation with time. | Most useful if rapid fluctuations are encountered or detailed characterization is required. Many analyses must be run, with attendant higher cost. |
| Composite (constant time-constant volume; water) | Samples of equal volume are taken at equal increments of time and composited to make an average sample. | This method is not normally acceptable for samples taken for compliance with stormwater permit application regulations. | Useful only if variations are relatively small, say +/-15%. |
| Composite (constant time-volume proportional to flow increment; water) | Samples are taken at equal increments of time and are composited proportional to the volume of flow since the last sample was taken. | Used by few automatic samplers; easily done manually. | Requires a flowmeter; or a flow record if composited manually. |
| Composite (constant time-volume proportional to instantaneous flow rate; water) | Samples are taken at equal increments of time and are composited proportional to the flow rate at the time each sample was taken. | Done by some automatic samplers; easily done manually. | Requires a flowmeter; or a flow record if composited manually. Often used for determining event loads for a constituent. |
| Composite (constant volume-time proportional to flow volume increment; water) | Samples of equal volume are taken at equal increments of flow volume and composited. | Most common type of flow proportional composite. Usually done using automatic equipment. | Requires a flowmeter; or a flow record if composited manually. Often used for determining event loads for a constituent. |
| Sediment/filter media sampling (sediment) | Samples are taken from either surficial sediment deposits within BMPs or at several depths by coring. | Used to support removal efficiencies reported by water sampling and to evaluate hazards for disposal and to aquatic biota. | Difficult to relate sediment concentration of constituents to water concentrations. |
| Large-Volume Sampling (sediment or water) | Sample Volumes of between 100 to 1000 L are processed with a centrifuge. | Used to acquire sufficient sample material for trace organic constituent analyses (i.e., PAHs). | Labor-intensive and cannot be done as frequently as sampling for conventional constituents. |
| Low level trace metals monitoring (water) | Series of individual or sequential discrete samples. | Used when the risk of sample contamination is high such as in waters with very low trace metals concentrations. | Requires specialized sample bottle preparation, sampling equipment and laboratory procedures. |

Source: Adapted from Bellinger, 1980; USEPA, 1992.

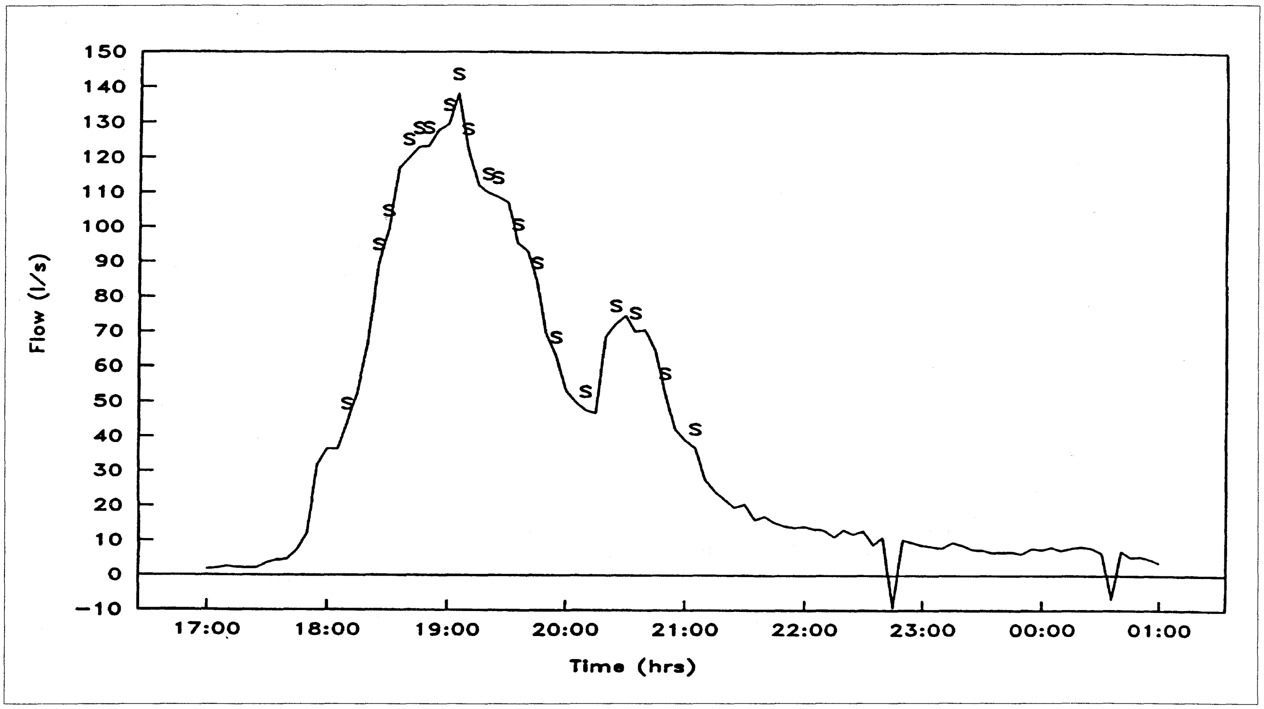


**Figure 45. Flow proportional composite sampling to determine EMC (D'Andrea et al., 1993)**

A selection of detection limits should reflect, with a conservative margin of safety, the lower range at which the constituents monitored have been observed in an actual monitoring program. A review of this characterization information is usually an outcome of the program planning phase (e.g., see Table 21). The specific analytical procedures to obtain these detection limits and their sample volume requirements are available from an analytical laboratory or *Methods for Chemical Analysis of Water and Wastes* (USEPA, 1983b) and *Standard Methods for the Examination of Water and Wastewater* (APHA, 1995).

Higher costs are usually associated with the specification of sampling and analytical procedures with low detection limits. Given the overall costs associated with a monitoring program, these costs should not, however, unduly restrict the sampling design plan. Nonetheless, this requirement should be reviewed and adjusted following a review of the initial data collection and analysis results.

***Sample Representativeness***. Even the best sampling programs are constrained by the hydrologic conditions present over the time period that sampling takes place. As a result, the sampling effort will reflect some or all of the types of storms that occur over a longer period of time at a particular site. Storm types that are monitored can be initially characterized based on an annual or seasonal basis by their total precipitation amount, their maximum intensity over some time period, or their total duration based on some predefined inter-event period. Once the sampling is complete, a thorough analysis can be undertaken.

A major benefit of reviewing sample representativeness during the course of a monitoring program is that it helps to guide subsequent monitoring efforts by identifying those types of storms which to date are underrepresented in the sampling program. Figure 46 illustrates the results from a monitoring

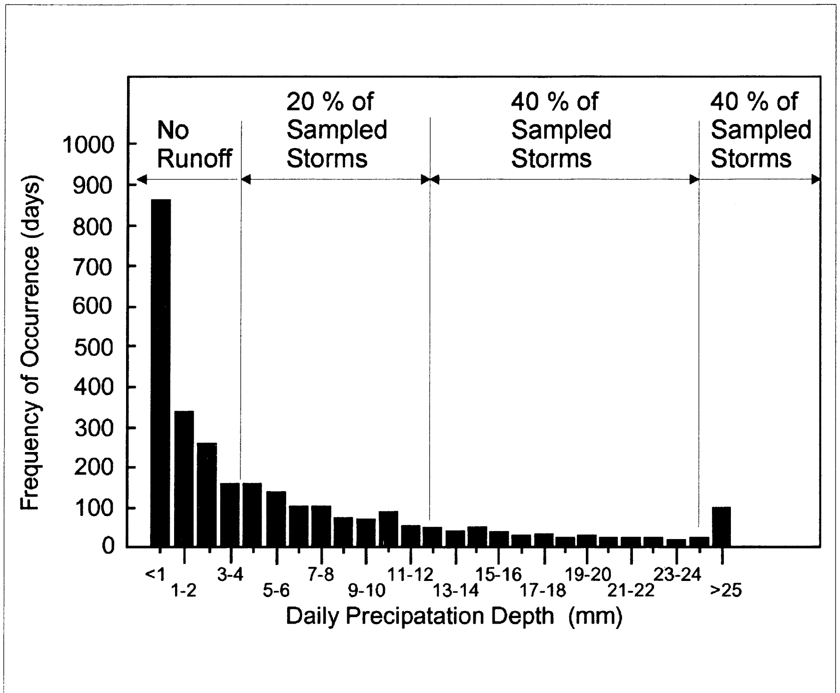


**Figure 46. Rainfall frequency**

program with respect to a long-term study of precipitation volumes at the same site. The results of the program illustrated in Figure 46 are disproportionally weighted to larger storms' depths. A BMP evaluation using this data set would not be representative of the more frequent smaller storms that may have been the basis for the design of the BMP being evaluated.

Since the relationship between rainfall and hydrologic response varies with antecedent conditions, a more accurate representation of sample representativeness can be obtained using a preexisting flow duration curve for the monitoring site. Alternatively, a similar curve can be generated using a locally available rainfall record and a hydrologic/ hydraulic model of the BMP to be evaluated. The flow duration curve can also be used to permit a preliminary evaluation of the types and amounts of flows that may be missed during the course of the monitoring program (Figure 47).

***Equipment Needs and Selection.*** The field equipment requirements for a manual or automated sampling program can be supplied by a wide range of vendors.

Manual Sampling. Manual sampling programs are initiated for several reasons including (1) a preliminary constituent screening process used to identify the occurrence and expected range of particular constituents done in the program design phase; (2) limited resources for equipment purchases and installation; (3) availability of personnel to complete the sampling; and (4) some constituents such as bacteria, oil and grease, and volatile organic compounds (VOCs) are difficult to sample for with automated equipment.

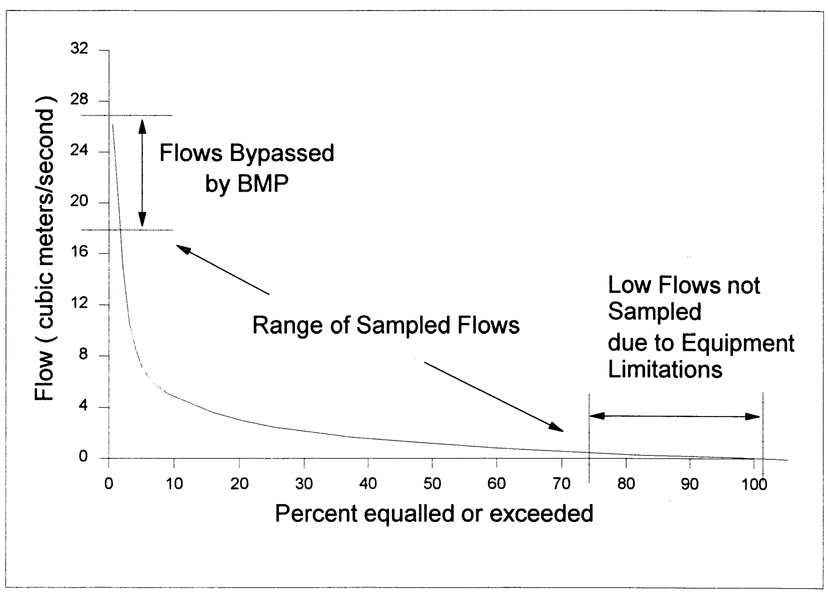


**Figure 47. Example of flow duration curve**

While not as critical as in the case of automated sampling, the selection of equipment to assist in manual grab sampling is also important. It is usually advisable to use a hand-held grab sampler to permit samples to be collected safely and without the risk of contamination (McCrea and Fischer, 1993).

Automated Sampling. For an automated sampling program, the minimum equipment generally needed includes both automated water samplers and stage recording devices located at the inlets and outlets of the BMP to be evaluated or at in-stream locations.

Water sampling equipment selected must have the capability of meeting the requirements for sample volume, and sample numbers specified in the design phase of the monitoring program. The programming capabilities of the sampler must also permit various sampling protocols (discrete, composite). Automated units can be powered from a nearby utility connection or from stand-alone battery units. If power can be supplied from a utility connection, a refrigerated sampling unit is commonly purchased. This ensures that samples are cooled and preserved immediately. Sampling units using battery power generally require the sampler to be packed with ice prior to a sampling event.

A stage or flow recorder and its sensor and a water sampler can be purchased as an integrated unit or purchased as two separate stand-alone units. Operationally, both setups are similar; however, the integrated units are generally smaller and as a result can be placed in confined spaces such as access holes. Integrated units also tend to have greater programming flexibility. A disadvantage of the integrated units is that the flow meter cannot be used separately from the water sampler. The selected sensor for stage recording will need to be sensitive at the expected range of velocities found at the sampling location.

To obtain representative flow information, a hydraulic evaluation of the flow velocities at all sampling points must normally be completed not only for sensor selection, but also for the selection of stage recording or flow metering equipment.

A decision to install a primary measuring device such as a weir or flume or to develop an in situ stage-discharge relationship must also be made in conjunction with the purchase of a stage recorder and sensor. Estimates of the expected depths and discharge rates at the proposed sampling location are required for both methods of determining discharge. Several hydraulic handbooks are available to guide the selection process for a primary measuring structure (for example, Bos, 1988). Recommendations for stage sensor selection and placement, and features of the approach section are normally dependent on the type of structure used.

Hand-held discharge measuring equipment is also required to perform checks on a primary measuring device and to develop an in situ stage-to-discharge relationship. The equipment selected must be physically capable of measuring discharge at the expected range of depths and, as mentioned earlier, flow velocities.

To further characterize the conditions under which samples have been collected, sensors to monitor parameters such as rainfall, temperature, dissolved oxygen, pH, turbidity, or conductivity can also be added to monitoring programs. At a minimum, a rainfall sensor should be considered for assistance in evaluation of BMP performance and of the sampling program's representativeness. More than 50 percent of the monitoring studies reviewed had measured both rainfall amount and intensity during the course of BMP evaluation. Most of the remaining studies did not report rainfall parameters. Continuously monitoring the changes in water temperature, dissolved oxygen concentration, pH, and turbidity is particularly important since changes in these parameters often increase the toxicity or impacts of pollutants in stormwater.

To protect automated monitoring equipmentfrom vandalism and theft, an instrument shelter is often purchased or constructed at the sampling site. Fiberglass enclosures are generally the most commonly used and are easy to handle and install in the field.

Sediment Sampling. Several BMP designs use sedimentation or filtration processes to remove constituents from stormwater. As a consequence, these sediments and filter media become sinks for these constituents, which accumulate over time.

Evaluations of the levels to which these constituents accumulate can be indicative of the removal efficiency of a particular BMP. Their levels can also affect disposal options, as in the case of the removal of accumulated sediment from a BMP, or when filter media is removed from a filtration type BMP.

To collect samples for analyses, a small, hand-operated auger can be used to collect samples from either filter media or accumulated sediments. Additional and more detailed procedures outlining sediment sampling devices and procedures for both sediment grain size and sediment chemistry can be found in USEPA (1991) and Young et al. (1996). Standardized procedures are also available for the sampling of sediment in water flow from the United States Geological Survey (USGS, 1982).

Large Volume Sampling. Special large-volume centrifuge systems are used to recover sufficient material for the analysis of trace organic constituents such as PAHs. These systems are labor-intensive and are practical only for use in low-intensity monitoring programs. Commercially available samplers that have been used in monitoring studies include the Westphalia KDD 605 (Savile, 1980) and the Alfa Laval (Ongley and Blachford, 1982).

### Sediment Sampling

A total of eight modified Delaware sand filter (DSF) BMPs were constructed to treat stormwater runoff from a 5 ha (12.4 ac) container shipping and storage terminal yard for Alaska Marine Lines (Horner and Horner, 1995). In additional to evaluating the pollutant removal effectiveness of the BMPs, a separate analysis was made of the condition of the sediments accumulated in the setting chambers and the condition of the sand beds in the filter chambers to define potential maintenance needs. Sediment samples from the settling chambers and 25.4 mm (1 in) sand cores from the filter chambers were collected separately for analysis. Particle size distributions and pollutant concentrations in sand samples collected from two of the filters were compared with those of clean sand to assess changes that had occurred during the seven months of operation prior to sampling. Pollutant concentrations in sediment and sand were also compared.

Based on sand core analyses after seven months of operation, it is estimated that the sand filter systems will provide several years of service before needing major maintenance. Sediment samples from the settling chambers and whole sand cores from the sand chambers did not come close to violating any leachable metals criteria for designating hazardous or dangerous waste. However, the sediments exceeded total petroleum hydrocarbon (TPH) criteria under toxics control legislation and would have to be treated as hazardous waste when removed during maintenance.

## Field Measurements and Sampling Methods

Each type of field operation will require the development of standard operating procedures (SOPs), which document the data collection and measurement processes, or the requirements for routine maintenance on equipment such as automated samplers. SOPs cover all aspects of field work relating to data quality and assurance, from the type and frequency of equipment maintenance to calibration, cleaning, and adjustment requirements. Records of equipment maintenance, malfunctions, calibrations, and adustments need to be kept for each monitoring station. These SOPs are often based on existing published standards or procedures developed for site-specific conditions. Guidance on the development of SOPs can be found in documents such as the *Guidance for the Preparation of Standard Operating Procedures (SOPs) for Quality-Related Documents* (USEPA, 1995).

For standard operating procedures specific to water quality and discharge monitoring, the *Handbook for Sampling and Sample Preservation of Water and Wastewater* (USEPA, 1982), *Water Quality Monitoring* (USDA, 1993) and *National Handbook of Recommended Methods for Water-Data Acquisition* (USGS, 1977) can be consulted.

## Training and Logistics Program

Monitoring programs are often completed by several different people over the course of months or, in some cases, years. To ensure the long-term consistency of data collection procedures, individuals involved in monitoring programs need to be systematically trained in the use of equipment, and its calibration and maintenance requirements.

The success of monitoring programs that focus primarily on the sampling of storm events relies heavily on the ability of personnel to respond in a timely manner. As a consequence, it is advisable to develop clear procedures for the deployment of sampling personnel and their alternates.

## 4.4.3 Data Management Plan

Monitoring programs can potentially generate a lot of valuable data. The data can be used for multiple purposes as monitoring efforts attempt to address BMP effectiveness at both the local and regional level. Monitoring data may be shared by various agencies to allow more informed decisions to be made about stormwater management and BMP implementation. It is necessary to have a well-structured data management system in place to host monitoring data.

The use of an ad hoc data management system prevents efficient retrieval of the data and can potentially lead to the loss of valuable data. It is important to design and develop a structured database management system (DBMS) once it has been determined what kind of data will be collected during the monitoring program. The preliminary DBMS design should ideally be completed before implementing the monitoring program. A flat-file DBMS may be sufficient to meet the needs of relatively small monitoring programs. However, DBMSs based on more sophisticated data models may be required for larger monitoring programs. Relational DBMSs are widely used in a variety of applications and have become the *de facto* standard for developing large-scale databases.

## Database Design Considerations

A well-designed DBMS offers several advantages, including:

- Storage and rapid access capabilities for large amounts of data.
- Data revision and reuse without extensive reformatting.
- Simplified data reporting.

The database design process should include the following steps:

- Assess the purpose of the database, including data storage needs and possible queries that may need to be processed (e.g., storm characterization, continuous flow characterization, wet weather and dry weather sampling results).
- Based on the assessment of data storage and retrieval needs, divide the information into separate subjects that will be separate tables (e.g., rainfall measurements, flow measurements, wet weather sampling data and dry weather sampling data, BMP characteristics, maintenance requirements).
- Determine the various components (fields or columns) making up the information in each table (e.g., the fields in a rainfall measurements table could be: date storm started, time storm started, date storm ended, time storm ended, and total storm precipitation).
- Test and refine the preliminary design by adding a few hypothetical records and determining if the desired information can be rapidly processed and obtained from the database.

If a relational DBMS is selected for hosting the data, the third step includes establishing links between the various tables and reassessing fields and tables to ensure there will be no data redundancies. Each table in a relational database includes a field or set of fields (referred to as the primary key) that uniquely identifies individual records in the table. Relational databases use primary key fields to efficiently associate data from multiple subject tables.

Regardless of the level of database sophistication, it is advisable to include basic features for checking errors and indicating data quality in the database design. This practice assists in meeting the data quality objectives of the monitoring program and is useful in establishing procedures for data processing and reduction for analysis and reporting. Typical error checking features include measures to prevent the inadvertent entry of data outside a range of acceptable values for a particular constituent. Standard codes should be used to indicate instances when constituent concentrations fall below the analytical detection limit or when data is missing.

Separate fields should be included for flags to indicate data reliability. This occurs when data has been collected, but its representativeness is uncertain for a number of reasons. For example, some samples may be analyzed for a constituent after the maximum recommended holding time for the constituent has expired or samples may have been incorrectly preserved or stored. In other instances, trash or sediment may have accumulated or have may been trapped by the sampler intake, mounting or sampler lines, resulting in some questions about the representativeness of the samples taken. The occurrence of any of these or similar conditions will have been recorded in the field notebook for the monitoring station. While the initial decision concerning acceptability of this data will be, by necessity, the responsibility of experienced field personnel, a final decision should be made by qualified staff during data review and validation process.

### Data Processing

Data processing essentially involves operations on the raw data to provide a new data set that can be directly used in analysis. For example, a common data processing operation involves replacing data generated from chemical analysis that fall below the limit of the analytical procedure by a value equal to one-half of the detection limit if the percentage of nondetects is less than about 15 percent of the total number of samples (USEPA, 1996). When the number of nondetects exceeds 15 percent of the total samples, adjustments are usually made in analysis methodology. Other examples of data processing operations include:

- Estimation of missing values (e.g., through interpolation in continuous flow measurements).
- Data reduction (e.g., the computation of event mean concentrations of constituents by storm event using data for discrete samples [see Section 4.6.1]).
- Data conversion (e.g., the conversion of stage to discharge data using a rating equation [see box]).

Monitoring data should be entered, processed, and reviewed immediately following its collection and reporting and on a periodic basis. This allows corrective action to be promptly taken should problems exist in either the data collection, data processing, or analysis procedures.

## 4.4.4 Quality Assurance Project Plan

The sampling design plan, data management, data collection procedures, training, and logistics considerations, and their QA/QC components are usually compiled into a quality assurance project plan (QAPP). The QAPP is normally prepared prior to beginning monitoring and distributed to all staff involved in any of the activities of the monitoring program to guide implementation of the program (see USEPA, 1994a). The QAPP specifies, in an organizational chart, the roles and responsibilities of each member of the monitoring program team from the project manager and QA/QC officer to the staff responsible for field

## Development of A Rating Equation

The following steps are recommended to develop the rating equation (USDA, 1993):

1. Log transform paired values of discharge (Q) and stage (H)
2. Perform a linear regression of Q vs. H with Q as the dependent variable
3. Obtain intercept (C), and slope (b)
4. Add coefficients to the equation:

   $$\log Q = \log C + b \cdot \log H$$

5. Transform equation to the form:

   $$Q = CH^{b}$$

   by taking the antilog of the equation in step 4, so that:

   $$Q = 10^{C}H^{b}$$

For example, if the intercept (C), was 0.05 and the slope (b) was 2.54, the equation would be:

$$Q = 10^{0.05} \cdot H^{2.54}$$

or

$$Q = 1.12 \cdot H^{2.54}$$

sampling and measurement. Project management responsibilities might include overall project implementation, sample collection, and data management. Quality management responsibilities might include conducting checks of sample collection or data entry, data validation, and system audits. The QAPP also describes the tasks to be accomplished, the data quality objectives for the kinds of data to be collected, any special training or certification needed by participants in the monitoring program, and the kinds of documents and records to be prepared and how they will be maintained.

The term "quality" relates to the degree of confidence that one can have in the results obtained for a particular analysis. Quality control is a system of technical activities that measure the attributes and performance of a process, item, or service against defined standards to verify that they meet stated requirements. Quality assurance is an integrated system of management activities involving planning, quality control, quality assessment, reporting, and quality improvement to ensure that a product or service meets defined standards of quality with a stated level of confidence. QA and QC procedures are detailed in the QAPP, to address the sampling (data collection) design, what methods will be used to obtain the samples, how the samples will be handled and tracked during the project, what specific protocols and analytical methods will be used to estimate the levels of specified water quality parameters in the samples collected, what control limits or other materials will beused to check performance of the analyses (QC requirements), how any instruments or other equipment used will be inspected and calibrated, how supplies will be inspected, how nonmeasurement data will be acquired and used, and how all data generated during the monitoring program will be managed and errors in data entry and data reduction controlled (Keith, 1991).

Standard operating procedures (SOPs) are referenced in the QAPP; SOPs provide a step-by-step description of technical activities to ensure that project personnel consistently perform sampling, analysis, and data handling activities throughout the duration of the project so that data comparability is maintained. The use of standard methods of analysis for water quality parameters also permits comparability of data from different monitoring programs. Changes in equipment or measurement methods are also incorporated into the original SOPs as dated amendments.

The types of assessments to be conducted to review progress and performance (e.g., technical reviews, audits) and how nonconformance detected during the monitoring program will be addressed are also discussed in the QAPP. Finally, procedures are described for reviewing and validating the data generated, dealing with errors and uncertainties identified in the data, and determining whether the type, quantity, and quality of the data will meet the needs of the decision makers.

The QAPP is prepared during the monitoring design phase of the monitoring program to document all technical aspects of the data collection effort that will be implemented and provides the basis on which the data collection effort can be evaluated. The QAPP should be continuously refined to be consistent with changes in field and laboratory procedures. Each refinement should be documented and dated to trace modifications in the original plan.

### Sample Handling and Reporting

Many monitoring programs submit water/sediment samples to an outside analytical laboratory for constituent analysis. As a result, it is important to work out the logistics and QA/QC elements of sample submission prior to collecting any samples. This normally requires establishing written data collection and chain-of-custody standards and ensuring that they are adhered to throughout the monitoring program.

To ensure proper handling and preservation of water quality samples, sample bottles should be clean and appropriately labeled with an indelible marker prior to going into the field. The labels for each sample should contain information concerning the sample location or station, date and time collected, collectors name, air temperature if appropriate, and any preservative added. Methods describing recommendations for preservation, handling, and detection limits for commonly analyzed constituents can be found in *Standard Methods for the Examination of Water and Wastewater* (APHA, 1995).

In addition to proper handling, preservation, and storing, the effectiveness of any monitoring program depends on its quality control (QC) component. The goal of the QC program is to provide a quantitative measure of the accuracy of the collected data. This includes procedures for both the field and analytical portions of the data collection process. For some variables, QC involves calibrating instruments, such as pH and conductivity sensors, with known standards.

To ensure accuracy and precision, analyses of blanks, replicate samples, control samples, and spiked samples may all be required for QC. Field replicates are samples collected simultaneously at the identical source location and analyzed separately. This type of analysis assesses the total sample variability, both random and systematic. Laboratory replicates consist of repeated analyses of a constituent performed on the contents of a single sample. This type of test assesses the random variability or precision in the analytical analysis. Controlled samples or spiked samples determine the ability of the laboratory equipment or procedures to detect specific types of constituents at known concentrations. The procedures used by an individual laboratory are normally well documented and can be obtained upon request. It is still generally advisable, however, to arrange for a small percentage of the samples collected (e.g., 10 percent) to be submitted to a second laboratory.

## 4.5 MONITORING PROGRAM IMPLEMENTATION PHASE

The implementation of a water quality evaluation program requires that decisions made in the monitoring design phase be translated into an operational field monitoring program. Decisions must be made regarding:

- Equipment installation and testing.
- Finalization of field operating procedures.
- Sample handling and processing.
- Preliminary review of testing and/or initial monitoring results.
- Sampling design plan and implementation review.

Public awareness and involvement are also important aspects of the monitoring program. Prior to commencement of the BMP program, community surveys and meetings concerning community expectations of aesthetic and recreational aspects of the design should be considered. A well-informed public would see the need for pollution control and would likely support the BMP program and monitoring effort. The public will also want to be informed in a timely manner. Carefully prepared public releases or articles are very effective in communicating ideas or results to the public. Additional information should be available to those who show a particular interest, and key project personnel should make time to be available for questions.

## 4.5.1 Equipment Installation and Testing Procedures

Proper installation of automated monitoring equipment and operation is critical to the success of the sampling program. All sensors and sensor lines need to be securely fastened, located in a representative location, and positioned so as to minimize the trapping of debris, which may affect their operation. Suppliers of automated monitoring equipment often supply installation equipment and detailed information to help guide this process.

The initial installation of the water intake line needs special attention. Before selecting a final position for the intake line above the channel or streambed, some tests of representativeness should be conducted. This can be done, as mentioned earlier, by collecting depth-integrated samples, using standard sediment sampling procedures (e.g., USGS, 1982), at the same time automatic samples are collected. It can also be done by mounting the intake line on a vertical rod with a hand-adjustable fitting that allows for quick adjustments to the intake position. This arrangement permits a series of water samples, at different depths, to be collected quickly, by manually adjusting the depth of the intake line and at each depth manually triggering the automated water sampling equipment. The analytical results of these samples can be used to guide the final placement of the intake line.

Automated sampling equipment also needs to be calibrated and programmed based on the triggering and sample type requirements of the sample design plan. Testing of the proper triggering of equipment can be performed, for example, by artificially triggering the sampling equipment with a sensor located in bucket of water for triggering procedures that rely on stage height or by pouring some water in a rainfall sensor for rainfall-triggered sampling equipment.

Installation of a staff gauge to visually monitor stage at each sampling site is also strongly recommended for two reasons: (1) to permit the use of chalk to mark the staff plate prior to sampling as means of checking that the stage sensor has operated properly over the entire range of flow depths for a particular event, and (2) to monitor for sensor drift, which may occur over time due to sensor fouling or age.

Development of a rating curve for the site should begin following the completion of equipment testing. While a theoretical rating curve may have been developed in the sampling design plan, a rating curve based on field measurements is required for in situ rating curves and also as a check on the accuracy of an installed primary measuring device. A minimum of 15 pairs of stage and discharge measurements should be used in the development of the rating equation developed from the curve (USDA, 1993). This curve should be checked periodicallysince sediment scouring or deposition in the streambed can cause changes in the rating curve (USGS, 1977).

## 4.5.2 Finalization of Field Operating Procedures

Revisions to SOPs are often the outcome of decisions on equipment selection, site conditions, and staff availability. SOPs must be consistent with site and equipment characteristics, and with the results of field testing of the equipment and of sampling protocols established earlier, and also with the sampling collection, preservation, and sample procedure requirements for the constituents to be sampled.

These SOPs also provide documentation of the data collection methods and sampling procedure used during the course of a monitoring program. Each type of field operation will likely need to develop its own SOP.

These procedures cover all aspects of field work from the type and frequency of equipment maintenance, to calibration, cleaning, and adjustment procedures. Records of equipment maintenance, malfunction, calibration, adjustment, and repairs need to be kept for each monitoring station. These SOPs can be based on existing published standards for flow measurement or water quality sampling (e.g., ASTM) and modified for existing field conditions. Equipment manufacturers and vendors also supply equipment-specific use, calibration and maintenance procedures that can be incorporated into an SOP. Procedures for the handling and holding of water samples before their final submission to the laboratory also need to be well documented. Prior to their completion and incorporation into a monitoring program, all SOPs need to be tested in the field. Data collected in the field should be recorded in a bound notebook. A description of the field conditions such as weather, temperature, or any activity that might affect sampling results needs to be recorded.

In addition to proper sample handling, preservation, and storage, the effectiveness of any monitoring program depends on the successful implementation of the QAPP. The results of this plan provide a quantitative measure of the accuracy of the collected data.

### 4.5.3 Preliminary Review of Testing and/or Initial Monitoring Results

Prior to submission for data analysis, all field data needs to be reviewed, summarized, and put into a format suitable for data analysis. Data of suspect quality must be flagged as such along with the supporting rationale. In some cases, data may have to be summarized or processed prior to submission for analysis. Stage data, for example, must be converted to discharge data using a rating curve before data analysis. The development and accuracy of the rating curve data needs to be submitted with the corresponding discharge information. To prevent the unnecessary reformatting of data submitted for analysis, the final format for data to be used for analysis must be established as early as is feasible.

### 4.5.4 Sampling Design Plan and Implementation Review

Once sampling is under way and as soon as is feasible, a review of the results and operating procedures of the field implementation phase should be completed. Following the first review, a regularly scheduled review process should be implemented. The purpose of the review is to ensure that all automated equipment is operating and functioning as intended. A review of the water quality monitoring results is particularly important. Assumptions made in the design phase concerning analytical detection limit requirements are now being tested. If some parameters are not being detected, changes in either the analytical technique or the sampling methodology may be required.

## 4.6 MONITORING PROGRAM EVALUATION PHASE

The monitoring program culminates in the evaluation phase. In this phase, possible data analysis techniques for answering management questions identified in the planning phase are reviewed and an appropriate data analysis methodology is selected. A good understanding of the data limitations is essential for selecting an appropriate data analysis methodology. Any conclusions or inferences should include a statement on the associated degree of confidence. Important considerations in assessing the degree of confidence associated with any conclusions are (1) the representativeness of the data of short- and long-term variabilities in the hydrologic regime and (2) the sufficiency of the data to answer management questions to the desired degree of confidence.

Understanding the representativeness of samples is crucial to allow meaningful conclusions. Consider, for example, a situation where the mean annual loading of a pollutant from a watershed is to be estimated before initiating BMP implementation. Data are available on event mean concentrations for a range of flows sampled over a

3-year period. Before beginning any data analysis, it is advisable to determine how representative the samples are of the range of conditions generating pollutant loadings in the watershed. Since the pollutant loadings are driven by rainfall, the range of conditions could be assessed by examining historical records of the amount, intensity, and duration of rainfall events. However, establishing the range of pollutant generating conditions based on these variables can be difficult. In addition, pollutant generation will also be impacted by antecedent moisture and land use conditions.

Another approach to assessing the range of conditions generating pollutant loadings is through flow duration curves, which are plots of daily discharge as a function of the percentage of time the discharge is exceeded. Flow duration curves represent the expected streamflow variability at a site and can be used as surrogates for the range of conditions generating pollutant loadings (Richards, 1988). Thus, to determine the representativeness of samples obtained during the monitoring period, the flows associated with each sample could be located on the flow duration curve (Figure 48). Runoff related flows are separated from low flows at some exceedence probability level, assumed to be 10 percent in the figure and indicated by a dashed line. This provides a compact pictorial summary of the data representativeness. The location of sampling points in Figure 48 suggest that relatively few samples were taken under high-flow conditions. If a large part of the variability in pollutant loadings is due to runoff events, this would indicate that any loading estimates derived from the current sample would have a high degree of uncertainty.

To determine whether the data are sufficient to answer management questions to the desired degree of confidence, an approach similar to the one outlined in the data collection protocols, in which the number of samples are estimated, can be employed. However, the population variance required to estimate the number of samples is now determined from data collected in the monitoring program, and is therefore more reliable.

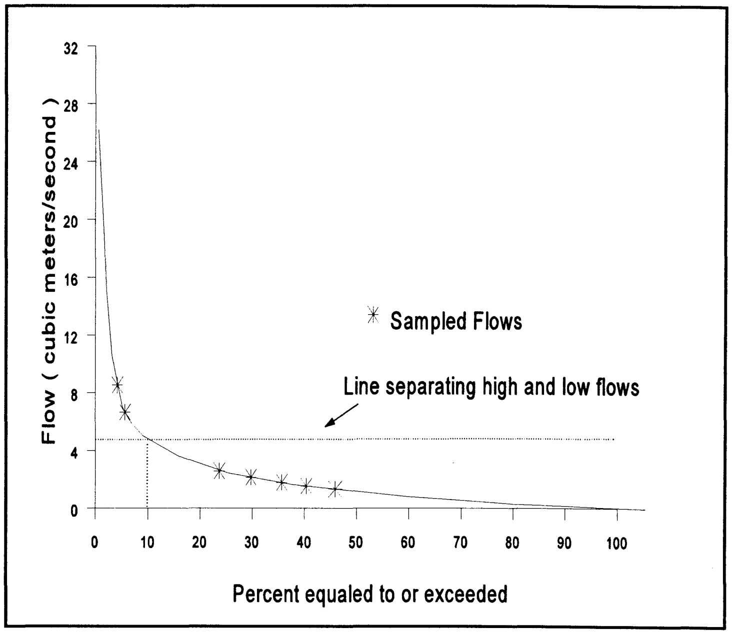


**Figure 48. Example of sampling strategy based on a flow duration curve**

### 4.6.1 Data Analysis Techniques

Data analysis in a monitoring program may involve:

- Obtaining representative values for pollutant removal efficiencies based on concentration or total mass reduction.
- Using statistical inferential techniques to estimate parameters and test a hypothesis (e.g., is the effluent concentration less than the influent concentration at the 5 percent significance level?).

The use of inferential techniques in data analysis lends greater credibility to any statements about BMP effectiveness and allows the monitoring results to be used with greater confidence. However, the majority of studies in the past have based their conclusions on pollutant removal efficiency calculations and have not attempted to use inferential techniques in data analysis. This may be due to several reasons, including budgetary constraints and, in some cases, a reluctance on the part of investigators to interpret their results in probabilistic terms.

## Pollutant Removal Efficiencies

The USEPA (1983b) proposed two basic methods for computing pollutant removal efficiency. The average event mean concentration efficiency ratio ($E_{emc}$) and summation of loads efficiency ratio ($E_{sol}$), expressed as percentages, are computed as follows:

$E_{emc} = (1\text{-}AEMC_{out}/AEMC_{in})*100$

$E_{sol} = (1\text{-}SOL_{out}/SOL_{in})*100$

where AEMC is the average event mean concentration, SOL is the summation of loads, and the subscripts "out" and "in" refer to outlet and inlet, respectively. Loads are computed as the product of event mean concentrations and the associated volume. It should be noted that while these efficiencies are defined using the average event mean concentration or the sums of loads for *all* monitored storms, similar efficiencies can be computed on an event-by-event basis. For example, individual storm removal efficiencies based on input and output event mean concentrations are often used to report maximum and minimum storm removal efficiencies.

Martin and Smoot (1986) have suggested an alternative method of computing pollutant removal efficiency based on a least-squares simple linear regression of loads (ROL). In this method, output loads are regressed against inlet loads with the slope of the regression line constrained to zero. The regression slope is regarded as the transport rate of the constituent through the BMP and one minus the regression slope is defined as the pollutant removal efficiency.

***Data Requirements and Assumptions***. Unlike the AEMC efficiency method, which gives equal weight, by averaging, to each storm event, the SOL and ROL efficiency methods require concomitant data for input and output storm loads. The AEMC and SOL methods assume that monitored storms are representative of normally occurring storms within the region being applied (Martin, 1988). These methods also assume that the inlet and outlet concentrations and loads are statistically significant for estimating percent removal (i.e., the equations are independent of the number of samples collected during a storm event). The SOL method further assumes that the samples collected were sufficient to represent all significant input and output loads. The ROL method assumes that the treatment efficiency is equivalent for any storms that are monitored (Martin, 1988).

***General Results***. Martin (1988) found that in general all three methods yield similar results, but that AEMC efficiencies produce the lowest values, ROL efficiencies yield the highest values, and SOL values lie between the two. However, in the case when there is a loss of runoff volume from inflow to outflow, the SOL and ROL methods will generally yield higher efficiencies. This occurs because any loss of runoff volume contributes to a reduction in the constituent load, but does not necessarily contribute to a reduction in constituent concentration (Martin, 1988). Martin (1988) found that the ROL efficiencies were slightly higher than the SOL efficiencies and attributed this fact to the zero-intercept constraint that is placed on the linear best fit regression line. By constraining the intercept to zero, the effect of small-load storms is minimized, thereby giving more weight to large-load storms. The box below provides an illustration of an urban detention system where pollutant removal efficiencies were calculated using all three methods.

***Advantages and Disadvantages***. The AEMC method is capable of providing information concerning the effect of a BMP on water quality by providing an average event mean concentration of constituents delivered to downstream receiving waters. However, because the AEMC method combines storm data to produce an event mean, the results of using this method may be somewhat biased (Martin, 1988). AEMCs do not show the range of possible values associated with the water quality variable, and they do not provide information about changes in concentrations associated with storm magnitude. The major advantage is that one sample is processed in the laboratory, thereby saving money and time associated with laboratory analyses.

The SOL method provides a good measure of the overall efficiency of a BMP. The SOL method gives somewhat more weight to the large-load storms, but like the AEMC method, it does not provide information on individual storms (Martin, 1988). Laboratory time and cost are increased because individual samples have to be analyzed.

The ROL method provides not only a measure of the overall efficiency of a BMP, but also an indication of efficiency consistency (Martin, 1988). However, because the intercept is constrained at zero (i.e., zero input load = zero output load), the ROL method gives much more weight to larger storms (Martin, 1988). As with the SOL method, laboratory time and cost are increased because individual samples have to be analyzed. To allow comparison of results

## Effectiveness of an Urban Runoff Detention Pond-Wetlands System

The effectiveness of an urban detention system located in Orlando, Florida, for reducing constituent concentrations and loads transported by urban stormwater runoff was investigated (Martin, 1988). The study included measurement and sampling of runoff from 11 storms during a 2-year period. Discharge at the pond inlet was measured with an electromagnetic current meter mounted in the center of the inlet culvert. Discharge at the wetlands outlet was determined from the record of wetlands stage and a weir, calibrated using current-meter discharge measurements. The automatic sampling at the pond inlet was controlled by pond inlet velocity. The sampling at the outlet was controlled by the pond stage. Discrete sampling was used for six of the 11 storms. Four to six samples from as many as 24 that were collected during a single storm event were selected for laboratory analysis. It was assumed that constituent concentrations for periods between samples varied linearly between the selected samples. Composite sampling was used for the remaining five storms. One flow-weighted sample was composited using all of the samples collected during a single storm. The constituent loads were calculated as the product of the composite sample constituent concentration and the total volume of runoff. The event mean concentrations for the discretely sampled storms were calculated by dividing the constituent load by the cumulative discharge at each of the measuring points. Efficiency estimates for selected constituents for the detention pond using the AEMC, SOL, and ROL methods are shown below.

| | Efficiency (%) | | |
|---|---|---|---|
| **Constituent** | **AEMC** | **SOL** | **ROL** |
| TS | 10 | 16 | 22 |
| TP | 28 | 33 | 38 |
| Pb | 31 | 32 | 40 |

reported from different studies, it is important that pollutant removal efficiencies be computed in a consistent manner. In particular, it is difficult to compare results from studies that only report individual storm maximum and minimum removal efficiencies with studies that report removal efficiencies based on the sum of load observed for all monitored storms. Urbonas (1995) recommends that for consistency, the percent removal for any constituent should be calculated and reported for each monitored event using inflow and outflow loads. He further recommends that any summary report should include the mean of individual event percent removal rates and the coefficient of variation over the monitoring period.

Strecker (1995) points out that for BMPs where there is a permanent pool, computing pollutant removal effectiveness for individual storms may not be meaningful since the outflow may have no or only a limited relationship to the inflow. For these BMPs, it may be more appropriate to use total loads over the monitored period to compute removal efficiencies.

## Statistical Inferential Techniques

The basic approach in any data analysis using statistical inference is to formulate a hypothesis. This is done by stating the null hypothesis and an alternative hypothesis. The null hypothesis is usually stated in a no-effect form (i.e., the effect being tested for is not present). The alternative hypothesis is simply a statement of what is true when the null hypothesis is rejected. The null hypothesis is tested by computing a test statistic from the available data. The alternative hypothesis is accepted when the significance level of a statistical test (also called the probability of a Type I error or $p$ value) is less than a prespecified value. The Type I error or $p$ value refers to the probability of rejecting the null hypothesis when it is actually true. Since hypothesis tests are based on inferences made from finite-sized samples drawn from a population, it is necessary to specify an acceptable Type I error rate. It is standard practice to have a Type I error rate of 5 percent (i.e.,when the achieved $p$ value of a statistical test is less than 0.05, the result is regarded as significant and the null hypothesis is rejected).

The significance level of a statistical test is obtained by locating the test statistic in the assumed distribution of the statistic. Depending on how the alternative hypothesis is specified, the test may be described as one-tailed or two-tailed. In a one-tailed test, the alternative hypothesis is stated as an inequality (e.g., the parameter of interest is less than some prespecified value). In a two-tailed test, the alternative hypothesis is stated in a "not equal to" form (i.e., the parameter of interest may be less than *or* greater than some prespecified value). In a one-tailed test, the rejection region (values of the test statistic for which the null hypothesis will be rejected) lies on only one side of the test statistic distribution, whereas in a two-tailed test the rejection region lies on both sides of the test statistic distribution.

Statistical hypothesis tests usually require one or more assumptions about the data. Assumptions made by statistical tests should be clearly understood and every attempt made to verify whether they are valid. Two commonly required assumptions in statistical tests are normality and independence.

The normality assumption requires that the observed data be drawn from a normal (Gaussian) probability distribution. With few exceptions, statistical tests that require the normality assumption (called parametric tests) perform poorly when the underlying distribution is not normal. Since the normality assumption may be difficult to justify for many variables of interest, many authors have suggested that nonparametric (sometimes called distribution-free) statistical tests should be routinely used in the analysis of water quality data. The assumptions on underlying distributions required by nonparametric tests are usually far less stringent, and in some cases there may be no assumptions required. When the assumption of a normal distribution is difficult to verify (e.g., when there are missing data or when the sample size is very small), it is advantageous to employ nonparametric techniques.

The assumption of independence is crucial for both parametric and nonparametric tests. Independent observations (i.e., a random sample) ensure that information obtained from individual observations is maximized. In general, both parametric and nonparametric procedures are not robust to dependencies between data.

Before conducting any formal statistical tests, it is beneficial to conduct an exploratory data analysis using summary statistics and graphical representations of the data. Exploratory data analysis assists in developing a mental picture of the data and can be used to assess the validity of assumptions made in formal statistical tests.

Summary statistics can include measures of central tendency such as the mean and median, measures of dispersion such as variance and the inter-quartile range, and measures of association such as the correlation coefficient. Graphical representations can include histograms, box-and-whisker plots, ranked data (empirical distribution function) plots, and normal probability plots. Details on how to obtain summary statistics and graphical representations of data can be found in USEPA (1996).

Most statistical tests of interest in BMP evaluation are hypothesis tests about a single population (one-sample tests) or tests for comparing two populations (two-sample tests). In hypothesis tests about a single population, current conditions (e.g., current pollutant loads) are compared to a fixed threshold value (such as a regulatory standard or some other acceptable risk level). A hypothesis test for two populations generally involves a "before and after" comparison. For example, consider a situation where monitoring data are available for a number of years on in-stream constituent concentrations before and after BMP implementation. The data obtained before BMP implementation could be used in a one-tailed single-sample test to determine whether in-stream pollutant concentrations were higher than ambient values. Data obtained before and after BMP implementation could be used in a two-tailed two-sample test to determine whether there was a significant difference between the constituent concentrations before and after BMP implementation. If a significant difference were indicated by the test, an estimator for the difference could be obtained and confidence intervals for the estimator could be computed. The various steps involved in performing parametric and nonparametric one-sample and two-sample tests are presented in the boxes below.

## Parametric Single-Sample Test

(one-sample t-test)

**Assumptions**

1. Observations are independent
2. Observations are drawn from a population that is approximately normal

**Components**

1. $H_o$ (null hypothesis): population mean ($\mu$) is equal to some prespecified value ($\mu_o$):

   $\mu = \mu_o$

2. $H_A$ (alternative hypotheses):

   One-tailed test: $\mu < \mu_o$ (or $\mu > \mu_o$)

   Two-tailed test: $\mu \neq \mu_o$

3. Test statistic ($t$) = $(\bar{x} - \mu_o) / (S / \sqrt{n})$ where $\bar{x}$ is the sample mean, $s$ is the sample standard deviation, and $n$ is the number of observations

4. Rejection region:

   one-tailed test : $t < -t_{1-\alpha, n-1}$ (for $H_A: \mu < \mu_o$)

   $t > -t_{1-\alpha, n-1}$ (for $H_A: \mu > \mu_o$)

   two-tailed test : $t < -t_{1-\alpha/2, n-1}$ or $t > -t_{1-\alpha/2, n-1}$

where $\alpha$ is the significance level of the test.

Note: The subscripts for critical $t$ values in the rejection region refer to the probability of non-exceedence and degrees of freedom, respectively. For example, $t_{1-\alpha, n-1}$ is the value of the variate that has a non-exceedence probability of $(1-\alpha)$ on a $t$ distribution with $n-1$ degrees of freedom.

## Parametric Two-Sample Test

(two-sample t-test)

**Assumptions**

1. Independent observations are drawn from two populations. Each observation is independent from other observations in the same population as well as all observations in the other population.
2. Both populations sampled are approximately normal.
3. The variance of both populations is the same.

**Components**

1. $H_o$ (null hypothesis): The difference in population means ($\mu_1$-$\mu_2$) is equal to some prespecified value ($D_o$):

   $\mu_1-\mu_2 = D_o$ ($D_o$ is commonly zero in which case $H_o : \mu_1=\mu_2$).

2. $H_A$ (alternative hypotheses):

   One-tailed test: $(\mu_1-\mu_2) < D_o$ (or $(\mu_1-\mu_2) > D_o$)

   Two-tailed test: $(\mu_1-\mu_2) \neq D_o$

3. Test statistic $$(t)=\frac{(\bar{x}_1-\bar{x}_2)-D_o}{\sqrt{s_p^2\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}}$$

   where $\bar{x}_1$ and $\bar{x}_2$ are the sample means, and $n_1$ and $n_2$ are the number of observations from the first and second populations, $s_p^2$ is the pooled variance estimate computed as:

   $$s_p^2=\frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{n_1+n_2-2}$$

   where $s_1^2$ and $s_2^2$ are sample variances from the first and second populations.

4. Rejection region:

   One-tailed test : $t<-t_{1-\alpha,n_1+n_2-2}$ (for $H_A : (\mu_1-\mu_2)<D_o$)

   $t>-t_{1-\alpha,n_1+n_2-2}$ (for $H_A : (\mu_1-\mu_2)>D_o$)

   Two-tailed test : $t<-t_{1-\alpha,n_1+n_2-2}$ or $t>-t_{1-\alpha,n_1n_2-2}$

   where $\alpha$ is the significance level of the test.

## Nonparametric Single-Sample Test

(Wilcoxon signed rank test)

**Assumptions**

1. Observations are independent.
2. Observations are drawn from a population that has a symmetric frequency distribution curve.

**Components**

1. $H_o$ (null hypothesis): population mean ($\mu$) is equal to some prespecified value ($\mu_o$):
   $\mu = \mu_o$
2. $H_A$ (alternative hypothesis):
   One-tailed test: $\mu < \mu_o$ (or $\mu > \mu_o$)
   Two-tailed test: $\mu \neq \mu_o$
3. Test statistic:
   To compute the test statistics follow these steps:
   a) Subtract $\mu_o$ from each observation to obtain deviations. If a deviation is zero, delete the observation from the analysis and reduce the sample size accordingly.
   b) Assign ranks based on ordering the absolute value of the deviations (i.e., the magnitude of differences ignoring the sign) from smallest to largest (rank 1 is assigned to the smallest value). If there are ties, the average of the ranks which would have been assigned to the tied observations is assigned to each tied observation.
   c) Assign signed ranks to each observation. The signed rank for an observation is positive if the deviation is positive and negative if the deviation is negative.
   d) Calculate the following statistics:
   $T_+$ = sum of positive signed ranks
   $T_-$ = absolute value of sum of signed ranks
   $T$ = smaller of $T_+$ and $T_-$.
4. Rejection region:
   One-tailed test : $T_- \leq T_o$ ( $H_A$: $\mu < \mu_o$)
   $T_+ \leq T_o$ ( $H_A$: $\mu > \mu_o$)
   Two-tailed test : $T \leq T_o$

   where $T_o$ is obtained from a table of critical values of the test statistic in the Wilcoxon signed rank test (e.g., McClave and Dietrich, 1985, page 793) at a given level of significance ($\alpha$) for the number of untied pairs.

   When the sample size is larger than about 25, the test statistic can be estimated from

$$z = \frac{R - \frac{n(n+1)}{4}}{\sqrt{\frac{n(n+1)2n+1)}{24}}}$$

   where z is a standard normal variate and $R=T_-$ for a left-tailed test ($H_A$: $\mu < \mu_o$), $R = T_+$ for a right-tailed test ( $H_A$: $\mu > \mu_o$), and R = T for a two-tailed test. The corresponding rejection regions are: $z < -z_\alpha$ ($H_A$: $\mu < \mu_o$)
   $z > z_\alpha$ ( $H_A$: $\mu > \mu_o$)
   $z < -z_\alpha$ or $z > z_{\alpha/2}$ ( $H_A$: $\mu \neq \mu_o$)

# Nonparametric Two-Sample Test

(Wilcoxon rank sum test)

**Assumptions**

1. Independent observations are drawn from two populations. Each observation is independent from other observations in the same population as well as other observations in the other population.
2. The populations have the same dispersion (variance).

**Components**

1. $H_o$ (null hypothesis): two sampled populations (A and B) have identical probability distributions.
2. $H_A$ (alternative hypothesis):
   One-tailed test: The probability distribution of A is shifted to the right of that for B (or A is shifted to the left of B)
   Two-tailed test: The probability distribution of A is shifted to the right or to the left of B.
3. Test statistic:
   To compute the test statistics follow these steps:
   a) Pool all observations from both samples and rank from the smallest (rank 1) to the largest.
   b) Calculate the sum of ranks of the data from population A ($T_A$) and population B ($T_B$). The rank sum test statistic is the rank sum associated with the sample with fewer measurements. If the sample sizes are equal, either rank sum may be used.
4. Rejection region:
   If $T_A$ is selected as the test statistic, then for
   One-tailed test : $T_A \geq T_u$ (for $H_A$: distribution of A is shifted to the right of B)
   $T_A \geq T_1$ (for $H_A$: distribution of A is shifted to the left of B)

   Two-tailed test : $T_A \geq T_u$ or $T_A \geq T_1$

   where $T_U$ and $T_L$ are obtained from a table of critical values of the test statistic in the Wilcoxon rank sum test (e.g., McClave and Dietrich, 1985, page 792) at a given level of significance ($\alpha$) and the appropriate sample sizes ($n_A$ and $n_B$).

   When the sample size is larger than 10, the test statistic can be estimated from

$$z = \frac{T_A - \frac{n_A(n_A+n_B+1)}{2}}{\sqrt{\frac{n_A n_B(n_A+n_B+1)}{12}}}$$

   where z is a standard normal variate. The corresponding rejection regions are:
   $z > z_\alpha$ ($H_A$ : distribution of A shifted to the right of B)
   $z < -z_\alpha$ ($H_A$: distribution of A shifted to the left of B)
   $z < -z_{\alpha/2}$ or $z_{\alpha/2}$ ($H_A$ : distribution of A shifted to the right or left of B)

In some situations, data may be obtained from two populations where the assumption of independence between the samples is not valid. If the data can be paired in some manner, it is more appropriate to make inferences about the difference between the two populations using the paired data set and analyze the data as a single sample. Pairing is accomplished by subtracting observations in one sample from the equivalent observation in the other sample. An example of a paired sample analysis is presented below.

## Paired Sample Analysis

Influent and effluent concentrations of zinc for a sand filter were measured for 14 storms. The data are provided below:

| Storm | Inflow concentration (mg/L) | Outflow concentration (mg/L) |
|---|---|---|
| 1 | 0.066 | 0.309 |
| 2 | 0.134 | 0.432 |
| 3 | 0.887 | 0.067 |
| 4 | 0.362 | 0.048 |
| 5 | 0.504 | 0.059 |
| 6 | 0.679 | 0.055 |
| 7 | 0.191 | 0.021 |
| 8 | 0.177 | 0.032 |
| 9 | 0.115 | 0.018 |
| 10 | 0.196 | 0.015 |
| 11 | 0.085 | 0.014 |
| 12 | 0.095 | 0.017 |
| 13 | 0.117 | 0.016 |
| 14 | 0.128 | 0.015 |

Determine if a significant reduction in zinc concentration is indicated at the 0.05 level, and obtain an estimator for the reduction in concentration.

The inflow and outflow concentrations cannot be assumed to be independent, so a two-sample test would be inappropriate and a paired sample analysis should therefore be employed. Paired differences are obtained by subtracting the outflow concentrations from the inflow concentrations for each storm. The null hypothesis ($H_0$) and alternative hypotheses ($H_A$) are specified below:

$$H_0: \mu_d = 0$$
$$H_A: m_d > 0$$

where $\mu_d$ is the mean of the paired differences. If the paired differences are assumed to follow a normal distribution, a *t*-statistic can be computed for a one-sample *t* test:

$$t = \frac{\bar{x} - \mu_d}{\frac{s}{\sqrt{n}}} = \frac{0.187 - 0}{\frac{0.297}{\sqrt{14}}} = 2.357$$

where $\bar{x}$ is the mean of observed differences, *s* is the standard deviation of observed differences, and *n* is the number of observations.

We reject the null hypothesis if the *t* statistic is greater than the critical value ($t_{0.05,13}$). From a *t* table, we note that the critical *t* value is 1.771. Therefore, the null hypothesis is rejected at the 0.05 level. Further examination of the *t* table reveals that the achieved level of significance is between 0.01 and 0.05 ($0.01 < p < 0.05$). An estimator for the reduction in concentration is simply the mean of the paired differences (*x*), and is equal to 0.187 mg/L. If the assumption of a normal distribution is not felt to be valid, the equivalent nonparametric test (Wilcoxon signed rank one-sample test) can be conducted on the paired differences. Computing the sum of the ranks with a negative sign and comparing to the critical values for the Wilcoxon signed rank test statistic results in an achieved significance level of between 0.01 and 0.025 ($0.01 < p < 0.025$).

A number of considerations should be kept in mind when the monitoring data contain nondetects. If less than 15 percent of total samples are nondetects, they may be replaced by a small number (such as the detection limit divided by 2) and data analysis performed in the usual manner. However, when the sample data have between 15 and 50 percent nondetects, it is necessary to provide adjusted estimates of central tendency and dispersion that account for data below the detection limit. If the percentage of nondetects is between 50 and 90 percent, it may be necessary to perform hypothesis tests on a parameter that is some percentile greater than the percentage of nondetects. Tests are performed for proportions with the hypothesis written in terms of percentiles (e.g., the null hypothesis would be "the 75th percentile is less than or equal to some value"). It is difficult to make statistical inferences on data that have more than 90 percent nondetects. Table 26 summarizes procedures that should be employed when analyzing data with between 15 and 90 percent nondetects. Details on these procedures can be found in USEPA (1996).

**Table 26. Data analysis with greater than 15% nondetects**

| Percentage of Nondetects | Suggested Procedure for Analysis |
|---|---|
| 15-50 | Provide adjusted estimates of central tendency and dispersion that account for data below the detection limit |
| 50-90 | Perform hypothesis tests on a parameter that is some percentile greater than the percentage of nondetects |

## Reference Conditions

In an evaluation of a porous pavement method by Hogland et al. (1987), reductions in solids and metals were noted; however, there was an increase in the export of soluble forms of nitrogen. The increase in the concentration of nitrogen was linked to the location of the BMP in an old agricultural area. Prior fertilizer use had increased the naturally occurring amount of $NO_3$, $NO_2$, $NH_4$, and even chloride in soil at the site. Decomposition of root masses after clearing had also likely increased the amount of $NO_3$, $NO_2$, and $NH_4$ in soil. Large negative removals (exports) of nitrogen were measured during the course of this BMP evaluation.

### 4.6.2 Reference Conditions

Constituents such as nutrients and metals occur naturally in surface waters and represent the preexisting loadings from a BMP drainage area. In addition, prior agricultural land uses or localized increases in atmospheric deposition due to the proximity of incinerators or industrial smokestacks may have resulted in elevated concentrations of some constituents at a monitoring site. All these inputs are in addition to inputs that result from urban land uses like highways. The incidence and extent of these prior conditions affect the evaluation of BMP removal efficiencies based on a measurement of the differences in mass loading between the inlet and outlet of a structure.

Consider, for example, the loadings of a metal constituent such as lead, which may have a naturally occurring background EMC concentration of 10$\mu$g/L in surface flow from a BMP drainage area. Localized deposition from an incinerator might have elevated this EMC concentration to 25 $\mu$g/L while prior application of municipal sludge to agricultural land that has now been converted to an urban land use might have increased this EMC to 30 $\mu$g/L. Stormwater inputs from the current urban land use result in a final EMC of 50 $\mu$g/L. Monitoring results from a BMP evaluation show a load reduction from an EMC of 50 to 25 $\mu$g/L or 50 percent removal efficiency or 125 percent of the loading, which can be directly attributed to inputs from the current urban land use.

### 4.6.3 Prioritizing Constituents

Prior to the second year of a multi-year monitoring program, or following a point when sufficient data has been collected for the development of a correlation matrix, prioritization of the collection of constituent data may be justified (USDA, 1993). Constituents that have been monitored and which show low coefficients of variation may be candidates for a reduced sampling effort.

## Constituent Prioritization

An evaluation of the suspended sediment and nutrient removal efficiency of a sand filter BMP has been ongoing for a six months. Samples from fifteen events have been collected to date. Resources are available to continue the collection of samples another six months, but the budget for laboratory analysis has almost been used up. The constituents monitored to date include:

- total suspended solids (TSS)
- volatile suspended solids (VSS)
- total phosphorus (TP)
- ortho-phosphate (OP)
- total Kjeldahal nitrogen (TKN)
- ammonia nitrogen ($NH_3$)
- nitrate nitrogen ($NO_3$)

Based on 1997 costs the submission of a water sample for these analyses would cost $230 per sample. Which parameters could be dropped to allow the budget for laboratory analysis to last until the end of the monitoring project?

A correlation analysis based on the data collected to date resulted in the following matrices:

| | | |
|---|---|---|
| | **TSS** | |
| **VSS** | 0.764 | |
| | **TKN** | **$NO_3$** |
| **$NH_3$** | 0.836 | 0.2<br>81 |
| **$NO_3$** | -0.057 | |
| | **TP** | |
| **OP** | 0.915 | |

Correlations between TSS and VSS, TKN and $NH_3$, TP and OP are significant and very high. Adequate monitoring could be achieved by continuing to monitor only TSS, TKN, TP and $NO_3$. This would reduce the cost per sample to $125, reducing the analytical cost by almost half (USDA, 1993).

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# 5. SELECTED BMP MONITORING STUDIES

## 5.1 INTRODUCTION

Monitoring evaluations of BMPs provide a wealth of information on their performance, both in terms of verification of design criteria and evaluation of site-specific performance. Monitoring studies throughout the United States, Canada, and Europe were identified as part of the literature search process. Ultra-urban monitoring studies were selected based on the criteria presented in Chapter 2. They focused on an array of BMP technologies, physical locations, and monitoring program protocols. To illustrate the wide variety of studies accumulated as part of the literature search process, a number of these studies were chosen to amplify and illustrate the information presented in the previous chapters, focusing on ultra-urban characteristics, BMP design criteria, and effective monitoring techniques.

The BMP monitoring studies included here were chosen to illustrate the variety of BMP evaluations being conducted. As mentioned in Chapter 4, BMP monitoring programs can be used to achieve a number of objectives. These objectives can be focused on:

- Evaluating a specific BMP to refine established design criteria.
- Verifying performance under specific site conditions.
- Determining the operation and maintenance requirements of the BMP.
- Evaluating potential impacts on surrounding site conditions (e.g., impacts to groundwater).
- Evaluating modifications to improve BMP performance and constituent removal effectiveness.

The studies selected for presentation in this chapter were chosen because they illustrate one or more of these objectives and provide excellent examples of the type of information that can be gained from a BMP monitoring program. Case studies on a cross-section of the ultra-urban BMP technologies addressed in Chapter 3 have been included in this chapter. The technologies include:

- Infiltration trench.
- Detention pond.
- Underground sand filters.
- Vegetated swale.
- Street Sweeping.
- Vegetated rock filter.

Each of these evaluations provides a unique opportunity to present an array of monitoring and data evaluation techniques, to provide critical information on effective monitoring protocols that achieved the specified goals, and to illustrate how monitoring programs must be adaptable to changing conditions and evaluation results. Depending of the outcome of the study, areas for additional evaluation may be identified by the study.

## 5.2 CASE STUDY PRESENTATIONS

Following are nine detailed summaries of different BMP monitoring studies. The summaries of these comprehensive monitoring reports include citations within each case study presentation. The reader should refer to the original BMP monitoring study for additional information and discussion on the monitoring program and specific BMP evaluation. A brief description of each of the case studies is presented below.

*Two Exfiltration Trenches Located near Miami International Airport in Dade County, Florida-* this study evaluated the effects of stormwater recharge on the water quality of the Biscayne Aquifer, a shallow aquifer in Dade County, Florida. Two exfiltration trenches located at two small commercial sites were investigated, with monitoring performed using wells at two different horizontal distances and vertical depths.

*Modified Dry Pond BMP and Grassed Swale BMP, Charlottesville, Virginia-* a dry detention pond was monitored before and after modification of the outlet structure to increase detention, and a grassed swale was monitored to evaluate its pollutant removal effectiveness. Modifications were made to the swale to improve the accuracy of the mass balance removal estimates.

*Delaware Sand Filter BMPs at AirPark, Alexandria, Virginia-* an evaluation of two modified Delaware sand filters was performed to determine their pollutant removal effectiveness in the Northern Virginia area. In addition, other sand filter design factors were evaluated.

*Modified Delaware Sand Filter BMPs at Alaska Marine Lines, Seattle, Washington-* this study evaluated the pollutant removal effectiveness of a sand filter during typical storm conditions. In addition, core samples of the filter medium were taken to determine the operational condition of the medium and predict potential maintenance requirements for the filter.

*Compost Stormwater Treatment System, Hillsboro, Oregon-* a prototype leaf compost stormwater treatment facility was evaluated to determine its pollutant removal effectiveness.

*Vertical Volume Recovery Structure (VVRS), Orlando, Florida-* an evaluation of a VVRS was performed to determine the efficiency of the sump, the effectiveness of the VVRS overall, and the backwash requirements for the system.

*Vegetated Water Quality Buffer Strips, Austin, Texas-* four different vegetation compositions were evaluated to determine whether a relationship exists between vegetation cover and infiltration capacity, pollutant removal effectiveness, and buffer width.

*Street Sweeping BMP Evaluation, Port of Seattle, Washington-* a stormwater quality computer model was calibrated using pollutant accumulation data from several sites in different activity areas of a container storage yard. The model was then used to evaluate the pollutant removal effectiveness of high-efficiency pavement sweepers in conjunction with conventional catch basins, and compared to the pollutant removal effectiveness of wet vaults.

*Packed Bed Filter BMP near Lake Beardall, Orlando, Florida-* a packed bed filter system, consisting of 10 separate cells, was evaluated. Two different media were used, and four different types of vegetation were evaluated. The beds were evaluated separately, and as a system, at three different flow rates.

# MONITORING CASE STUDY—TWO EXFILTRATION TRENCHES LOCATED NEAR MIAMI INTERNATIONAL AIRPORT IN DADE COUNTY, FLORIDA

This case study is based on an evaluation of the effects of two exfiltration trenches on groundwater by McKenzie and Irwin (1988).

This study was part of a continued effort to monitor the effects of urban stormwater recharge on the water quality of the Biscayne Aquifer, a shallow aquifer in Dade County, Florida. Two exfiltration trenches were investigated at two small commercial areas near the Miami International Airport. The first study area was located in an asphalt parking area adjacent to the airport with a drainage area of about 3 ha (8 ac) overlying a sandy soil. This exfiltration trench network is designed for stormwater retention with no outflow pipe. The capacity of the parking lot is about 1,000 vehicles. The second study site was located at the Miami International Free Trade Zone. It had a drainage area of about 4 ha (10 ac), consisting of asphalt-covered parking lot, with an exfiltration network in predominantly limestone rock. The capacity of the parking lot is several hundred vehicles. Figure 49 shows the locations of the two study areas in Dade County, Florida. The subsurface exfiltration trench is a stormwater management practice that is commonly used in south Florida. Exfiltration trenches in south Florida are usually constructed near or beneath the water table to induce artificial recharge (exfiltration) of stormwater. Some exfiltration trenches are designed to retain all stormwater from a drainage basin with no outflow other than recharge; others are designed to detain the first inch of stormwater before overflow begins by means of a discharge pipe.

## STUDY OBJECTIVE

- Monitor stormwater runoff pollutant concentrations and their impact on aquifer water quality at two different depths for two exfiltration trenches overlayed by two different types of soil.

## DESIGN AND OPERATION

Exfiltration trenches can be designed as single stand-alone units or connected to other catch basins to form a series of drainage networks. Figure 50 shows a schematic cross-section of a typical exfiltration trench and catch basin. The catch basin is the point of entry of the stormwater runoff into the trench system. The catch basin of the exfiltration trench not only passes stormwater runoff to the trench, but also functions as an initial sediment trap. The catch basin contains a perforated pipe, generally 900 mm (36 in) in diameter, which extends longitudinally into the trench from the catch basin. The pipe functions as an exfiltration conduit for the stormwater runoff and provides a secondary sediment trap. The area between the pipe and the trench walls is filled with a coarse aggregate, which prevents trench side wall collapse and plugging of pipe perforations, as well as serving as a conveyance to distribute exfiltrated stormwater to the trench walls. The trench is generally 1.5 m to 1.8 m (5 ft to 6 ft) wide, with the base typically 0.76 m (2.5 ft) beneath the water table. A nonwoven filter fabric is used along the periphery of the trench to deter filling in of the voids in the coarse aggregate by fine soils during reverse flow conditions that result from high groundwater levels. The filter fabric also prevents the migration of native soil into the trench, which would cause a reduction in infiltrative capacity. A 15.2 cm (6 in) layer of pea gravel is placed over the coarse aggregate and covered with builders' felt to prevent vertical infiltration of silts and sediment and to prevent subsidence.

## MONITORING PROGRAM

At each trench site, two wells were placed about 0.3 m (1 ft) outside the exfiltration trench perimeter, and two additional wells were placed at

6.1 m (20 ft) outside the trench perimeter. For each cluster of two wells, one well was drilled to a bottom depth of 30.5 cm (1 ft) and the other was drilled to a bottom depth of 4.6 m (15 ft). Polyvinyl casing was seated in the borehole and the annular space grouted, leaving the bottom of the well exposed to the soil. This well configuration was designed to estimate both horizontal and vertical variation of water quality within the immediate zone of stormwater exfiltration. To measure the water levels in the exfiltration trench and immediate surrounding perimeter, two water-level recorders were installed, one in the catch basin and one immediately outside of the trench. An automated rain gage was installed at each site to measure the amount of rainfall for sampling events.

Water quality sampling at the two sites was conducted during five storms and one nonstorm period from April 1985 through May 1986. Stormwater samples were collected using grab-sampling techniques. Eleven water quality variables were targeted for collection: total Kjeldahl nitrogen (TKN), nitrate, ammonia nitrogen, orthophosphate, total phosphorus (TP), iron (Fe), lead (Pb), zinc (Zn), chemical oxygen demand (COD), total organic carbon (TOC), and color.

# CONCLUSIONS

- In general, the pollutant parameters were greater in the stormwater sampled from the exfiltration trenches than in the ground water from the wells located 30.5 cm (1 ft) from each trench. The reduction in concentration suggested the possibility that some target variables in stormwater were partially removed within the exfiltration trench prior to recharge.
- Of all of the pollutant parameters, lead and zinc were the only target variables that indicated a significant difference between stormwater and adjacent groundwater monitoring at both the airport and free trade zone study areas. This suggests the possibility that the exfiltration trenches might function to some extent as traps for heavy metals found in stormwater.
- Aerobic microbial activity might have accounted for reductions in concentrations of nitrate and phosphorus.
- Comparison of the concentrations of some of the pollutant parameters in stormwater from the trenches and stormwater sampled in the wells located 6.1 m (20 ft) from the trenches indicated some vertical removal. However, except for ammonia nitrogen, the concentrations were greater in the 4.6 m (15 ft) sampled depth. This might have resulted from dilution in the upper zone by stormwater recharge.

# REFERENCES

McKenzie, D.J., and G.A. Irwin. 1988. *Effects of Two Stormwater Management Methods on the Water Quality of Water in the Upper Biscayne Aquifer at Two Commercial Areas in Dade County, Florida.* U.S. Geological Survey Water Resources Investigations Report 88-4069, Tallahassee, FL.

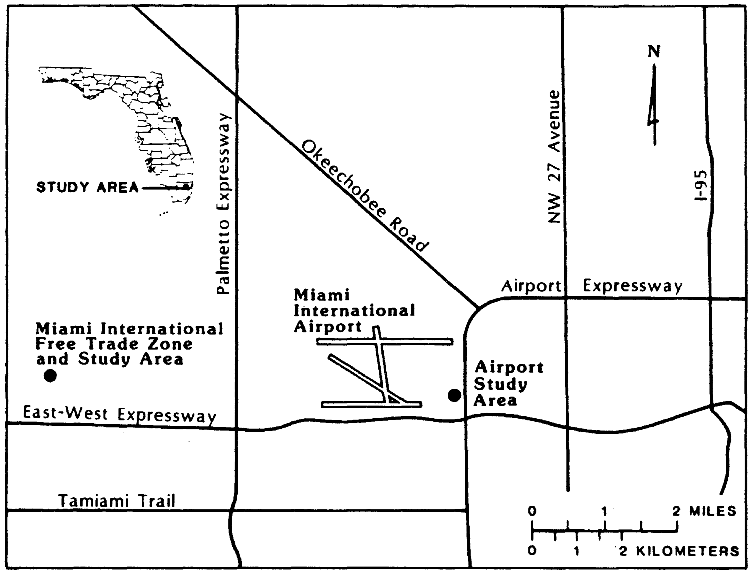


**Figure 49. Locations of the two study areas in east-central Dade County (McKenzie and Irwin, 1988)**

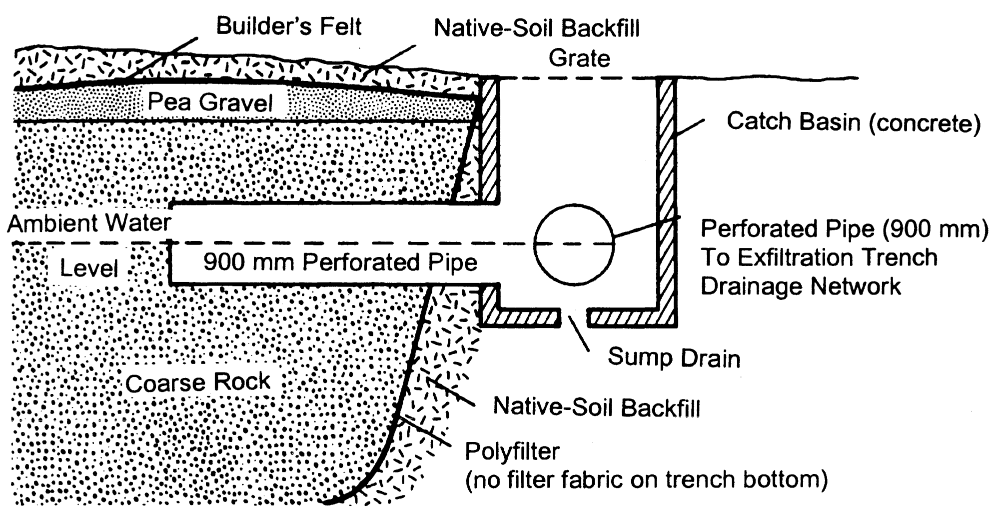


**Figure 50. Schematic of section of a typical exfiltration trench (adapted from McKenzie and Irwin, 1988)**

# MONITORING CASE STUDY— MODIFIED DRY POND BMP AND GRASSED SWALE BMP, CHARLOTTESVILLE, VIRGINIA

This case study is based on an evaluation conducted in two phases of a modified dry pond and grassed swale by Yu et al. (1993) and Yu et al. (1994).

In 1991, the Virginia Department of Transportation initiated a two-phase field study to test the pollutant removal efficiency of selected BMPs to obtain detailed information necessary to develop design guidelines for the stormwater BMP section in its *Stormwater Management Manual.* This study focuses on two BMPs: a dry detention pond located on the grounds of the University of Virginia near the intersection of Massie Road and Emmett Street, and a grassed swale located in the median strip of U.S. Highway 29 at the intersection with Hydraulic Road in Charlottesville, Virginia. The grassed swale operates by settling and infiltrating stormwater runoff from roads or highways along its entire length. The immediate drainage basin for the pond is a parking facility for daily commuters and athletic event traffic. The entire watershed contributing to the detention pond is approximately 3.2 ha (7.9 ac) in size, with 60 percent of the drainage area consisting of the paved parking facility.

## STUDY OBJECTIVES

- Evaluate the pollutant removal efficiency of a dry pond detention facility.
- Evaluate the pollutant removal efficiency of a grass swale that collects runoff from an urban highway.
- Recommend design guidelines for stormwater BMPs.

## DESIGN AND OPERATION

### Pond

The detention pond was initially designed and constructed solely for stormwater quantity purposes. Figures 51 and 52 show both the detention pond and parking area and a more detailed layout of the detention pond. The pond was sized to detain the additional post-development peak runoff flow for the 2- and 10-year storm events in order to release at the predevelopment conditions. No provisions were made for water quality improvements.

Extending the retention time of a dry pond is an effective and low-cost means of removing particulate pollutants and reducing the downstream effects of runoff such as stream bed and bank erosion. To create an extended detention dry pond, the outlet structure was modified to provide a slow release of the runoff from a designated storm (i.e., 2-year frequency or less). A three-sided concrete structure was cast around the inlet of the outfall pipe, with the sides of the open end of the structure grooved to allow insertion of plywood templates. For this study, the plywood template contained a 7.6 cm (3 in) diameter orifice; however, any type of orifice shape or size could be used in future studies. Figure 53 shows the outfall modification.

### Swale

The grass swale is approximately 128 m (420 ft) in length and receives runoff from approximately 0.6 ha (1.5 ac) of drainage area. The grass in the swale is mowed on a regular basis, yielding an average grass height between 7.6 and 15.2 cm (3 and 6 in). No fertilizers are applied to the swale area. In Phase I, the swale was subdivided into four sections based on length and slope, with the entire length of the swale evaluated. Table 27 gives the section and slope information for the divided swale. In Phase II of the study, wooden barriers were constructed to limit lateral inflows into the swale so that pollutant mass balance estimates could be made more accurately (see Figure 54). In addition to this modification, only the lower 30.5 m (100 ft) of the swale were evaluated. Figure 54 shows the modified lower portion of the swale that was studied during Phase II.

**Table 27. Swale section and slope data**

| Station (m) | Drainage Area (ha) | Longitudinal Slope (%) |
|---|---|---|
| 0 | 0.05 | — |
| 33 | 0.11 | 0 m - 33 m: 3.2 |
| 68 | 0.19 | 33 m - 68 m: 3.8 |
| 100 | 0.25 | 68 m - 100 m: 6.5 |
| Total | 0.6 | |

# MONITORING PROGRAM

## Pond

For the first phase of the study, data from seven storms were collected. For the first three storms, only the pollutant concentration was determined. The flow monitoring equipment was not yet assembled for measuring the corresponding flows into and out of the pond. The remaining four storms were monitored for both flows and concomitant pollutant concentrations. Of the remaining four storms monitored, the first two were a baseline study of efficiency only since the orifice was not in place; however, the last two storms were monitored with the extended detention orifice in place.

Rainfall data were measured using a Plexiglas wedge gage located at the site. The information was corroborated using a nearby rainfall gaging station. Flow was measured at all inflow and outflow points at the detention pond. Measurements were made using a conventional 90 degree V-notch weir and a portable Plexiglas weir designed to fit into a circular pipe. The V-notch weir was installed at inflow location 2, and the Plexiglas weirs were installed at inflow location 1 and the outflow (see Figure 51). Manual grab samples were taken at both the inflow and outflow at 15- to 30-minute time intervals during each storm event. Between three and seven samples were collected for each parameter. The parameters analyzed included total suspended solids (TSS), total phosphorus (TP), zinc (Zn), and particle size distribution (PSD). TSS and TP were measured for all storms; however, Zn was measured for the seventh storm only. Pollutant removal efficiency was calculated based on an average mass balance percentage removed. Table 28 gives the removal efficiency for the storms for which both flow and pollutant data were measured. A dash (-) entry indicates that removal efficiency data were not collected. Under the first phase of the study, the detention times for storms 4, 5, 6, and 7, were 1.5, 1.5, 3.1, and 3.2 h, respectively.

The data collection during Phase I appears to suggest that a detention pond with a short detention time of 1.5 h could provide a fairly significant amount of pollutant removal; however, it should be noted that storms 4 and 5 were low-intensity storms with low concentrations of pollutants. It is likely that the riprap conveyance channel to the pond and the low flow channel through the pond provided a mechanism sufficient to reduce the pollutant loads as they moved through the system. As Table 28 shows, once the orifice was in place, the removal efficiencies decreased; however, storms 6 and 7 were long-duration, high-intensity storms.

For the second phase of the study, analyses for chemical oxygen demand (COD) were added to the study. To reduce the need for chemical analysis, a rectangular weir was installed below the confluence of inflows 1 and 2 so that only one point needed to be monitored (see Figure 51). In Phase II, four storms were monitored for both flow and pollutant concentration. Water quality samples were taken using both manual grab sampling and automatic samplers. The detention times for storms 8, 9, 10, and 11 were 0.34, 1.55, 0.09, and 1.45 h, respectively.

**Table 28. Pond pollutant removal efficiency (individual storms)**

| Parameter | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|
| TSS | 74.2 | 93.5 | 67.5 | 80.7 | 12.3 | 41 | 81.3 | 60.4 |
| TP | 93.8 | 91.8 | 74.9 | -18.6 | 76.5 | 42.5 | 53.3 | 59.8 |
| Zn | - | - | - | 92.5 | 51.3 | 21.9 | 19.4 | 23.7 |
| COD | - | - | - | - | 50.6 | 10.5 | 46.9 | 46.1 |

## Swale

For the first phase of the study, six storms were monitored from March to June of 1992. Water quality samples were collected for all six of the storms, but flow measurements were taken for the last four storms only. Therefore, only the last four storms were reported for this phase. Sampling stations were located at four lengths starting 25 meters from the edge of the asphalt at the intersection. Figure 55 shows swale cross sections at each of the four locations. Flow and water quality were measured at each station to determine a mass balance between inflow and outflow concentrations. The drainage area for each station was then used to determine a mass flux per unit drainage area. A normalization was needed due to the amount of untreated lateral inflow at each section of the swale.

Flow was measured using 90 degree V-notch weirs. Depth was manually measured at each sampling time and converted to flow. Due to the low-flow conditions in the swale, the use of automatic flow meters was deemed impractical. Manual grab samples were collected as the water flowed over the V-notch at each station, with 500-mL grab samples taken during the first 30 minutes of the storms. Three to six samples were collected at each station for each storm. Total suspended solids (TSS), total phosphorus (TP), and zinc (Zn) were evaluated; however, zinc was evaluated only for the last storm monitored. Table 29 gives the pollutant removal efficiency for the four storms monitored. The percent removal efficiencies were determined using a mass balance method. A dash (-) entry indicates that data were not collected.

For the second phase of the study, five storms were monitored from November to July of 1993. Flow and water quality were measured to determine a mass flux. The drainage area for the lower 30.5 m (100 ft) portion was then used to determine a mass flux per unit drainage area. Because of the wooden barrier modification to reduce lateral inflow, normalization was not required (see Figure 53). Flow was measured using 90 degree V-notch weirs. Depth was manually measured at each sampling time and converted to flow. Automatic samplers were used to take runoff samples at timed intervals.

In addition to the pollutant parameters measured in Phase I, chemical oxygen demand (COD) was also measured. Table 29 gives the pollutant removal efficiency for the five additional storms monitored. The pollutant removal efficiencies were calculated using the mass balance method. The negative removal efficiencies given in Table 29 were caused by a higher flow leaving the swale than entering the swale because the mass flux equation used to determine removal efficiency is flow-dependent. During the first two storm events (7 and 8), the wooden barriers failed to prevent flow from entering the swale laterally. During the remaining period of monitoring, a plastic liner was placed along the lateral barriers to improve their performance.

**Table 29. Swale pollutant removal efficiency (individual storms)**

| Parameter | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|
| TSS | 72 | 95 | 21 | 82 | -77 | -44 | 89 | 100 | 73 | 86 |
| TP | 70 | 85 | 32 | 52 | -14 | -32 | 92 | 100 | 94 | 80 |
| Zn | -- | -- | -- | 74 | -- | -117 | 88 | 100 | 89 | 58 |
| COD | -- | -- | -- | -- | -128 | -54 | 88 | 100 | 81 | 67 |

# CONCLUSIONS

- A dry detention pond filled with a small outlet orifice can provide pollutant removal rates ranging from 30 percent for Zn to about 55 percent for TSS. The average overall pollutant removal efficiency was about 40 percent.
- Detention pond storage volume and outlet structure are important design parameters. Riprap low-flow channels and vegetation at the pond bed help increase removal efficiency.
- Detention time is usually considered to be one of the most important pollutant removal factors; however, based on the findings presented in this study, it appears that it is not the only determinant of pond efficiency.
- Highway swales, when properly designed and maintained, can be cost effective in removing pollutants in highway runoff, especially for smaller and low-intensity, long-duration storms.
- Swale length, longitudinal slope, and vegetation type are important considerations in swale design. Swale check dams may improve pollutant removal efficiency, but they get in the way of periodic mowing.

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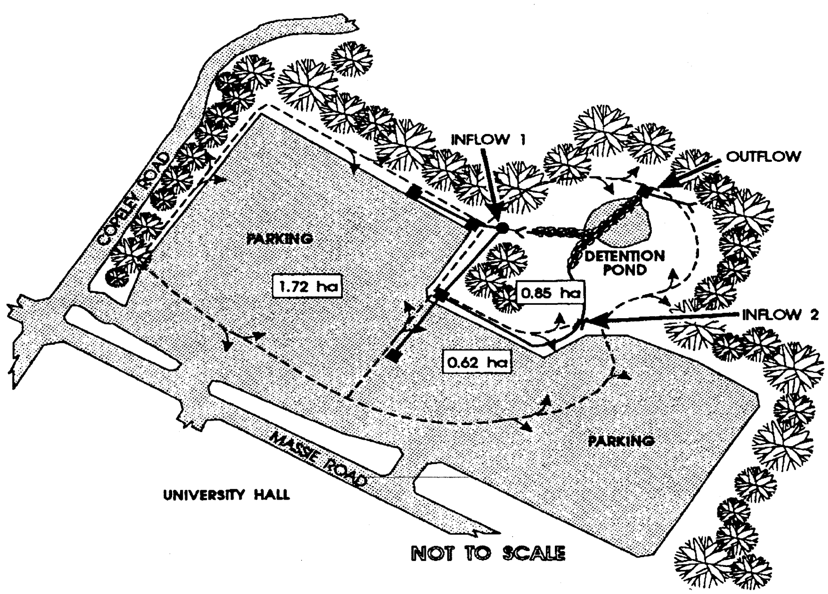


**Figure 51. Sketch of Massie Road parking lot and detention pond (Yu et al., 1993)**

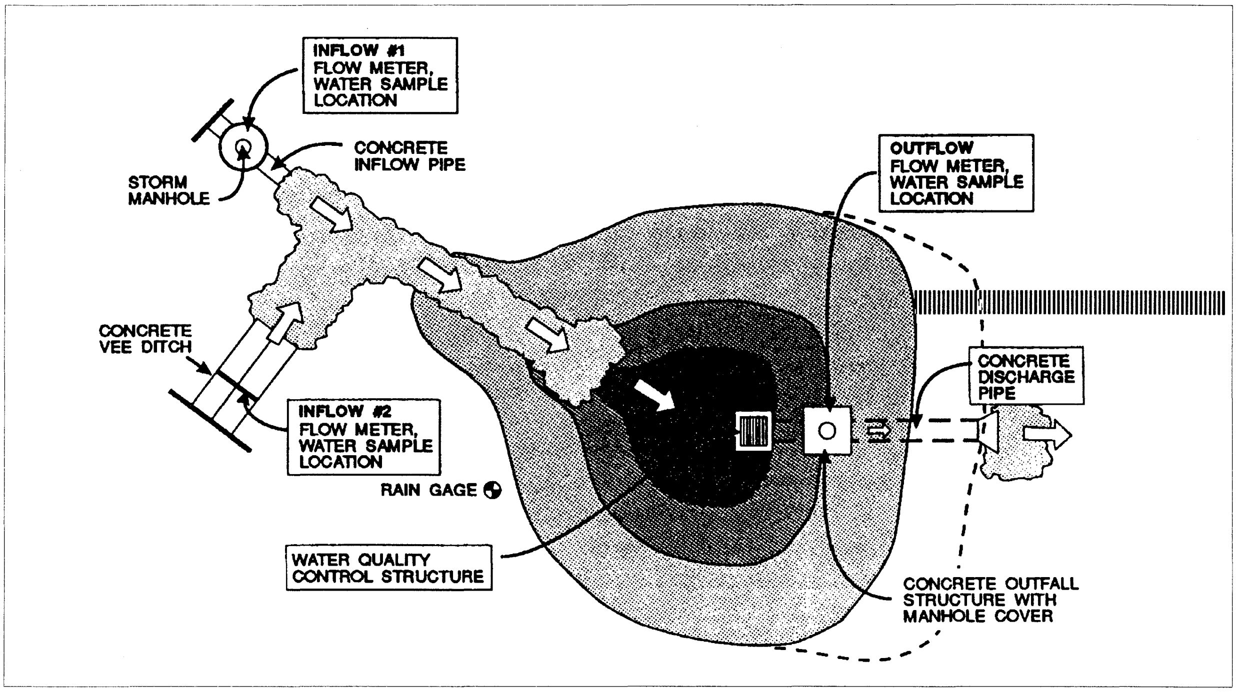


**Figure 52. Layout of detention pond (Yu et al., 1993)**

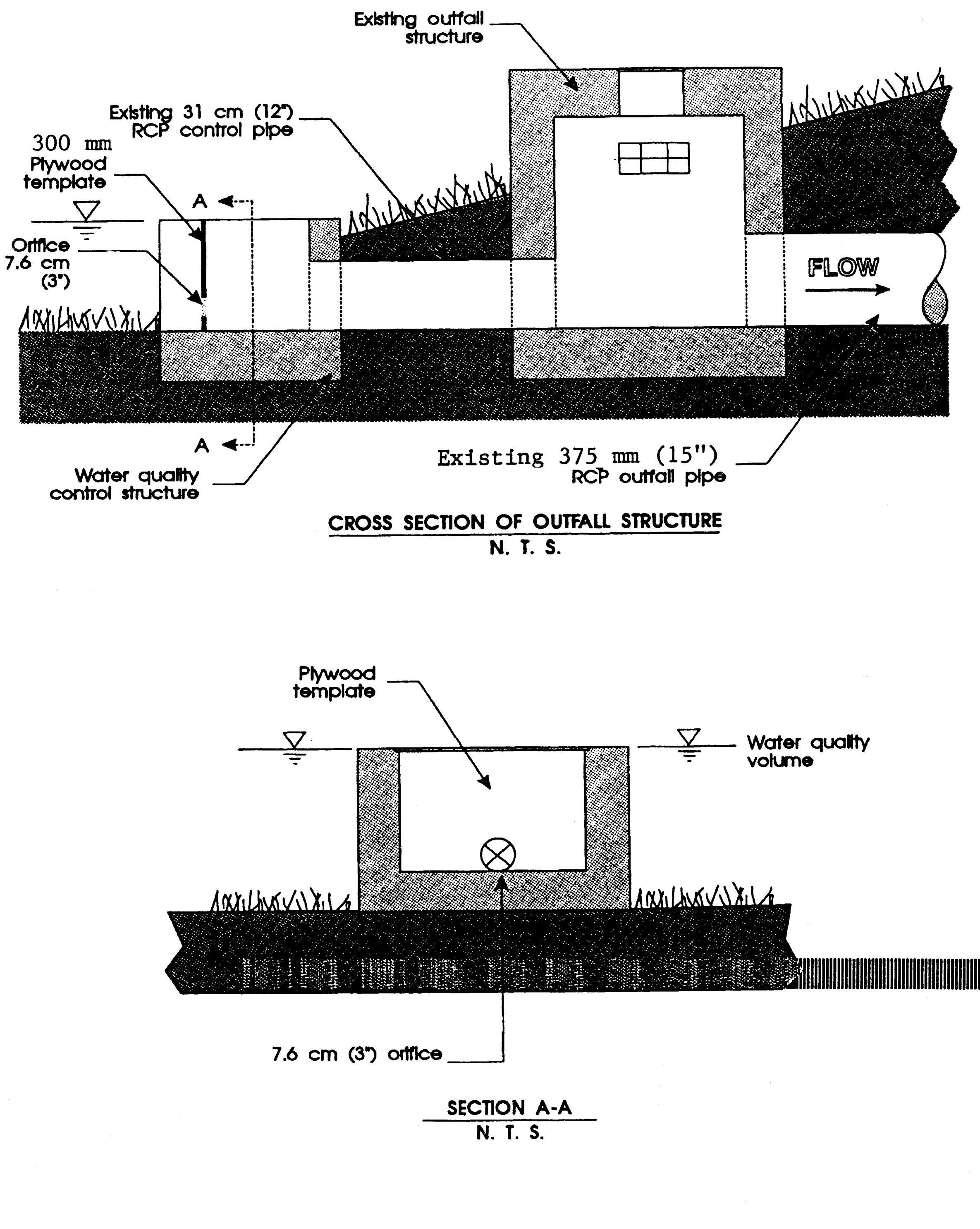


**Figure 53. Outfall structure details at detention pond (adapted from Yu et al., 1993)**

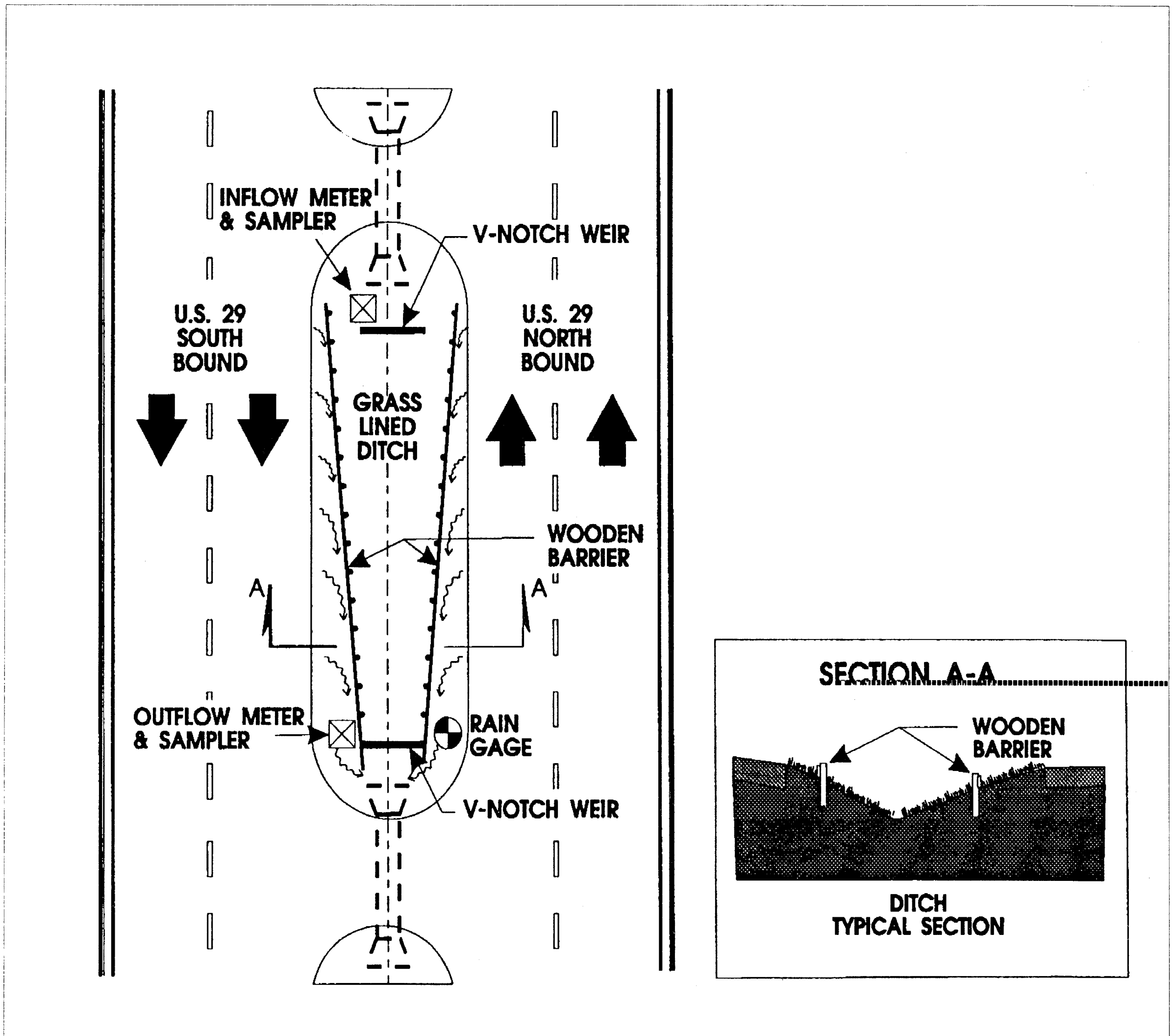


**Figure 54. Modified swale with barrier to lateral flow (Yu et al., 1993)**

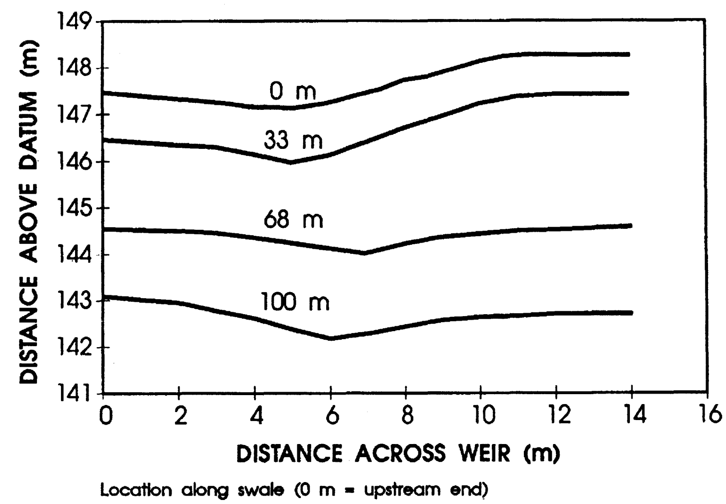


**Figure 55. Cross section of swale at each of four weir locations (Yu et al., 1993)**

# MONITORING CASE STUDY— DELAWARE SAND FILTER BMPs AT AIRPARK, ALEXANDRIA, VIRGINIA

This case study is based on an evaluation of Delaware sand filter BMPs by Bell et al. (1995).

Two large Delaware sand filter (DSF) BMPs were constructed to treat the runoff from AirPark, a 0.7 ha (1.7 ac) commercial parking lot near National Airport in Alexandria, Virginia. Construction was completed in the fall of 1992 with funding from a grant by the Virginia Chesapeake Bay Local Assistance Department. The performance of these BMPs were monitored for six months to establish the actual pollutant removal efficiency of a DSF treating northern Virginia's acid rainfall with locally available sands. Confirmation that efficiencies in the range experienced by other jurisdictions (namely, the city of Austin, Texas) can be attained in northern Virginia would allow economic use of a greater amount of property and substantially reduce the cost of compliance by developers with the Chesapeake Bay Preservation Act.

## STUDY OBJECTIVES

- Define the pollutant removal efficiency of the DSF BMP in the northern Virginia area.
- Due to the variability found in the coefficients of permeability (k) for sand filters, determine the actual k value for the filter being monitored.
- Use data on iron (Fe) in input and output samples to determine the aerobic condition of DSFs for a specific storm.
- Investigate whether considerable buffering might be occurring on the asphalt surface, as evidenced by previous pH testing in the city, by collecting samples of direct rainfall from some storms. Direct rainfall samples were also used to perform limited testing on how much of the pollutant loading was occurring from wet weather atmospheric deposition.
- Determine whether adsorption to sand particles is a significant component of phosphorus removal due to substantial iron and aluminum content in the filter sand by conducting Langmuir isotherm tests.
- Due to anaerobic activity within the AirPark South Filter, development of a compound stormwater filter that enhances total nitrogen (TN) removal efficiency results was proposed.

## DESIGN AND OPERATION

The South Filter was one of the first large stormwater intermittent sand filter BMPs constructed in northern Virginia, one of two filters treating stormwater runoff from a 0.8 ha (1.95 ac) commercial parking lot located just south of National Airport. Impervious surfaces cover 95 percent of the site. Following the original DSF design with steel grates and covers, the cost of the filters exceeded $100,000 due to the high cost of the grates and covers. By modifying the original design and using a slotted curb design, the actual cost of the two filters was just over $40,000.

The 0.8 ha (1.95 ac) paved lot is graded so that runoff sheet flow enters the West Filter; both sheet flow and flow along the curb line enter the South Filter (Figure 56). Reversed sloped curbs are provided at the lower ends of each filter to act as flow-splitters; once the storage capacity of the filter shell is exceeded, runoff backs up on the pavement until it flows around the nose of the reverse sloped curb and on into a curb inlet. The wedge of water stored on the pavement is part of the storage capacity of the overall BMP.

After construction, both filters were found to take an inordinate amount of time to drain down. Two flat plastic drain tiles were installed along the entire length of the South Filter to decrease flow-through time and decrease the time that vehicles parked along the filter were inaccessible due to pooling of water to be treated. The outflow drain of the South Filter was also found to be approximately 5 cm (2 in) above the invert of the filter box rather than at the invert. With a bottom slope of 0.5 percent, approximately 10 m (33 ft) of the bottom filter sand remains continually saturated, creating potential anaerobic conditions. Other design parameters are provided in Table 30; where design values differ from the actual system, both values are provided.

**Table 30. Design parameters**

| Parameter | Design | Actual |
|---|---|---|
| Length | 29 m | 28.8 m |
| Filter Area | 22.3 $m^2$ | 22 $m^2$ |
| Area of Sedimentation | 22.3 $m^2$ | 22 $m^2$ |
| Area of Storage above Weir | | 47 $m^2$ |
| Average Filter Depth | | 0.44 m |
| Maximum Depth of Ponding | | 0.26 m |
| Maximum Volume of Runoff Processed by the Filter | | 13.4 $m^3$ |
| Runoff Coefficient for the Watershed | | 0.9 |
| Design Storm Filter will Store and Treat | | 5.3 mm |
| Sand Media (two samples) | ASTM C-33 | |
| - Effective Size | 0.12mm/0.125 mm | |
| - Uniformity Coefficient | 7.2/7.8 | |
| - Iron Content | 3,000 mg/L | |
| - Aluminum Content | 3,000 mg/KG | |

# MONITORING

Monitoring problems with the West Filter required the team to shift their focus to the South Filter, where input samples could be collected from a sloping curb line uphill of the filter, and the underdrain system provided a flow rate that was much easier to monitor. Severe weather between December 1993 and April 1994, causing freezing problems in the sedimentation pools in the filters and freeze-up of the automatic monitoring equipment delayed the start of the monitoring study. Rainfall totalling 105 mm (4.13 in) fell at the airport (just across U.S. Route 1 from AirPark) immediately preceding the first sample taken for this study, so the filters had been saturated for almost two weeks immediately prior to the beginning of the monitoring effort. Active monitoring was resumed on April 4, 1994, and continued for 20 storm events through September 23, 1994.

Input and output samples for the AirPark South Filter were collected utilizing a purpose-built monitoring manhole with Palmer-Bolus flume installed in the outflow pipe for the output samples; input samples were collected from the concrete gutter that conveys the runoff from the upper part of the parking lot to the filter. Both samplers were activated by transducer-type flowmeters. Rainfall data were collected directly at the AirPark site by an American Sigma rainfall gauge. Composite sampling was utilized to obtain a relatively unbiased approximation of the mass loads of pollutants processed by the filter by multiplying the event mean concentration for each storm by the volume of runoff treated; total sampling time was adjusted to approximate the time during which the "first-flush" of the filter was processed. The storm outflows measured by the flow meter in the outflow monitoring unit were originally intended to be used to compute mass balance efficiencies of the filter. However, volumes recorded by the meter were far short of the estimates of volume treated obtained from hydrological calculations. The outflow drain was found to be installed 5 cm (2 in) above the bottom of the filter box, and the outflow pipe directly above the Palmer-Bolus flume was found to have a slope of 3.4 percent (rather than the specified 0.76 percent), which fell outside the requirements for accurate flow measurement (maximum slope 2.2 percent) for the flume and flow meter computer program. The project team decided to use the calculated treatment volumes for calculating weighted mean concentrations and mass balance removal efficiencies. Table 31 presents the results of the monitoring study.

Monitoring results for the fourteenth storm on the South Filter led the project team to reassess the work plan due to radically different outcomes than had been previously experienced. Phosphorous

**Table 31. Pollutant removal efficiencies (%)**

| Parameter | Minimum Removal Efficiency | Maximum Removal Efficiency | Average Storm[1] Removal Efficiency | Average Conc.[2] Removal Efficiency | Mass Balance[3] Removal Efficiency |
|---|---|---|---|---|---|
| Copper | 0.0 | 50.0 | 25.0 | - | - |
| Zinc | >57.9 | >98.2 | >81.8 | >91.5 | >90.7 |
| Iron | -57.1 | 79.3 | 18.8 | - | - |
| Ammonia N | -100.0 | 75.6 | >6.7 | >43.2 | >39.0 |
| Nitrite N | -236.0 | 92.9 | >-25.6 | >39.4 | >45.8 |
| Nitrate N | -674.2 | 66.8 | -102.0 | -56.3 | -62.7 |
| TKN | 0.0 | 90.4 | 59.9 | 73.4 | 70.6 |
| TN | -129.0 | 84.2 | 32.5 | 52.1 | 47.2 |
| Total P[4] | -14.3 | 91.8 | 58.6 | 66.0 | 63.1 |
| Total P[5] | 56.3 | 91.8 | 71.1 | 73.6 | 72.3 |
| Ortho-P[4] | -10.0 | 92.9 | >-59.8 | >73.2 | >68.3 |
| Ortho-P[5] | 16.7 | 92.9 | >68.6 | >78.3 | >74.4 |
| TSS | -41.2 | 96.4 | >60.5 | >78.7 | >78.8 |
| TSS[6] | 15.4 | 96.4 | 70.2 | 84 | 83.9 |
| Hardness | -56.3 | 85.3 | 20.6 | 45.5 | 38.5 |
| $BOD_5$ | 8.3 | >97.1 | >62.5 | >77.7 | >77.5 |
| TOC | -100.0 | 90.0 | 45.0 | 67.1 | 65.9 |

[1] Average of individual storm removal efficiencies
[2] [Average Input Conc.-Average Output Conc.] X 100/AIC
[3] [Total Input Load-Total Output Load] X 100/TIL
[4] With Anaerobic Incident Data Included
[5] Excluding Anaerobic Incident Data
[6] Excluding storms with heavy iron export

and orthophosphorous removal fell to negative values, while the rates of nitrogen components fluctuated widely. It was suspected that the anaerobic zone had suddenly expanded to encompass the majority of the filter; precipitation records at National Airport showed rainfall during 12 of the 18 days immediately preceding the incident. Monitoring of the South Filter was continued until all results indicated the filter had returned to a predominantly aerobic condition.

# CONCLUSIONS

- The sedimentation pools in DSFs are prone to freezing during periods of low temperatures. The sand filters, however, continue to function when underdrain pipes are provided beneath the filter media. DSFs are susceptible to anaerobic conditions unless positive drainage features are provided. Anaerobic environments have a negative impact on total phosphorous removal but a positive effect on total nitrogen removal.
- The major source of pollutants in runoff at AirPark appear to be atmospheric deposition. Most of the constituents measured in the input runoff fell within the ranges of the Nationwide Urban Runoff Program (NURP) data. No detectable readings of total petroleum hydrocarbons were found.
- The AirPark South Filter was found to have a TP removal efficiency of 72.3 percent when in a predominantly aerobic state, based on mass

balance calculations. Phosphorous removal efficiencies were also found to increase with higher input concentrations in the runoff being treated. TN removal efficiency based on mass balance calculations was 47.2 percent. TSS also varied with input TSS concentrations, with removal efficiencies exceeding 80 percent.

- Acid rain runoff from asphaltic concrete parking lots will likely be buffered to a neutral state before reaching stormwater BMPs.
- Coefficient of permeability for the sand filter section of the AirPark South Filter was found to be 2.6 m/day (8.5 ft/day) median, rather than the 0.6 m/day (2 ft/day) used in design assumptions. However, further study is needed before a decision is made to change this design assumption.
- Isotherm results of the filter media showed that monolayer adsorption of phosphorous to the sand particles was not a significant factor in the overall removal results.
- Placing a 33 cm (13 in) flooded gravel (anaerobic) filter beneath the sand filter may enhance nitrogen removal if sufficient organic carbon is present.

## REFERENCES

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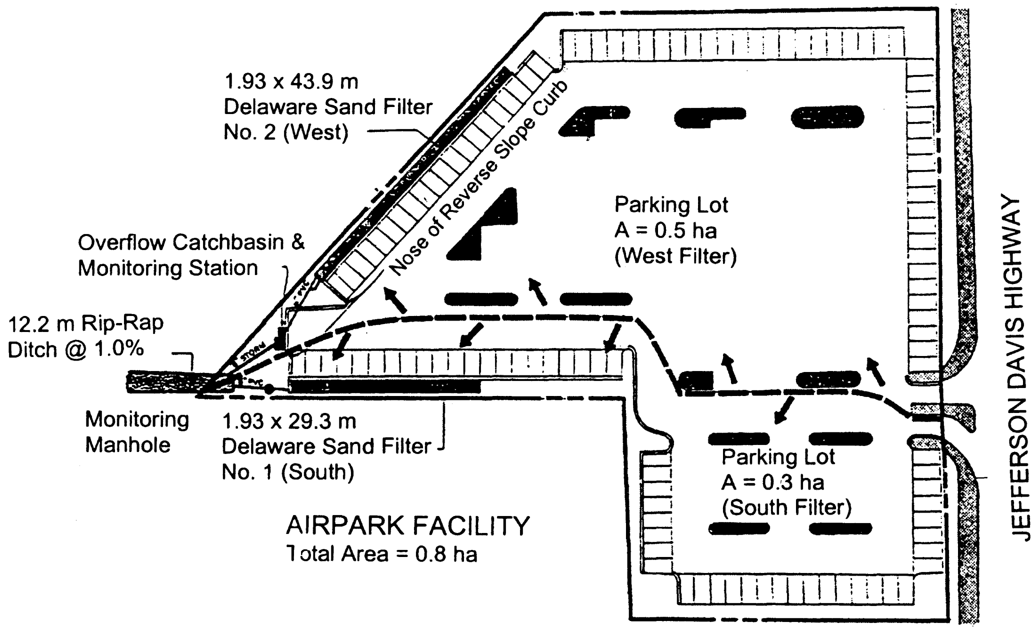


**Figure 56. General layout of AirPark filters (adapted from Bell et al., 1995)**

# MONITORING CASE STUDY—MODIFIED DELAWARE SAND FILTER BMPs AT ALASKA MARINE LINES, SEATTLE, WASHINGTON

This case study is based on an evaluation of two modified Delaware sand filters by Horner and Horner (1995).

The Alaska Marine Lines (AML) Filter BMP, which is an adaptation of the Delaware Sand Filter (DSF) BMP, was the first application of sand filters for stormwater treatment in the Pacific Northwest. The AML stormwater filter system, which consists of eight individual sand filter units, was constructed to treat stormwater runoff from a 5 ha (12.4 ac) container shipping and storage terminal yard. The AML site fronts both the West Marginal Way South (a major industrial arterial in Seattle's industrial area), and the Duwamish Waterway (a man-made waterway at the mouth of the Duwamish River approximately 4.8 to 6.4 km (3 to 4 river miles) upstream from Puget Sound). Construction of the redeveloped site and sand filter systems was completed in 1993. In accordance with local regulations, AML provided funding to monitor and evaluate the performance of its sand filter BMP system for one year.

## STUDY OBJECTIVES

- Assess the water quality improvement efficiency of the sand filter system during typical storm conditions.
- Evaluate the operational condition of the filter medium after one wet season.

## DESIGN AND OPERATION

The AML site is a completely paved L-shaped property of approximately 5 ha (12.4 ac) that has been redeveloped to ship, handle, and store cargo containers. Sand filters were selected for stormwater treatment based on their proven ability to handle petroleum-based contaminants washed from paved surfaces during typical storm events. In addition, because limited area for the terminal required paving and using the entire upland area available, the sand filter system offered an effective and practical alternative to other BMP designs. Based on state requirements for treatment of two-thirds of the runoff volume of a 2-year, 24-hour storm event, the sand filter system was designed to treat the first 31.2 mm (1.23 in) of runoff, allowing the excess to bypass the system. The AML sand filter system is designed with the majority of the eight units arranged along the perimeter of the site.

The AML site is graded so that runoff sheet flow drains at a 1 percent slope from the interior to the L-shaped perimeter of the site. A typical filter unit length is 53.4 m (175 ft), up to a maximum length of 73.2 m (240 ft). Filter unit widths were standardized to either 1.5 m (5 ft) or 3 m (10 ft). The filter chamber is filled to a minimum depth of 45.7 cm (18 in) of sand. The characteristics of the filter medium are given in Table 32. The completed trench is covered with a segmented concrete lid, having scuppers for stormwater inflow. Each filter chamber is equipped with inspection and clean-out ports to facilitate light maintenance without having to remove the concrete lids. Figure 57 shows a typical cross-section of an AML concrete sand filter trench unit.

Stormwater runoff is initially retained within the first chamber, designed for settling and collecting sediment in the bottom of the chamber. Sedimentation chamber sizes are based on a surface area of 124 $m^2$/ha (540 $ft^2$/acre) of impervious catchment. This size provides a 10-

**Table 32. Filter medium characteristics**

| Characteristics | Provided | Target |
|---|---|---|
| Uniformity Coefficient (UC) | 3.13 | <3.5 |
| Fines passing 0.13 mm (%) | 0.2 | <1.0 |

minute detention time for the design storm. When the chamber is full, stormwater flows over control weirs located on top of the center wall separating the sedimentation chamber from the filter chamber (see Figure 57). The runoff then enters the sand filter chamber and percolates through for additional treatment. The design percolation rate through the sand filter medium is 2,523 L/m$^2$ (62 gal/ft$^2$) of sand per day.

The AML sand filter system contains several key innovative design modifications from earlier DSF BMPs, due to monitoring experiences from earlier DSF designs as well as the need to accommodate site-specific conditions for the AML site. The bed of each filter chamber contains a continuous, perforated drain pipe wrapped in filter fabric, which leads to a tee where a permanent vertical test well pipe is installed. A controlled overflow feature has been incorporated to accommodate the 100-year storm event. An appropriately sized overflow pipe in one end of the sediment chamber is set for a water elevation above that of the center wall weirs. The overflow pipe has a baffle to control discharge of oil and sediment during overflow conditions. Outflow from adjoining ends of adjacent filter trench units is then piped to an access hole. Each access hole receives water from both the filtered collection pipe and the sediment chamber overflows. The access holes are connected to the main underground header pipe, which discharges to the waterway. The trench lids with scuppers and inspection ports were constructed of AASHTO H-20 loading concrete panels to support potentially significant vehicle loads.

## MONITORING PROGRAM

Of the eight filters designed and constructed, two were chosen to be included in the monitoring program. The two filters chosen received runoff from areas of distinctly different activities, representing two different magnitudes of potential runoff and pollutant loading. The first installation of monitoring equipment was placed at Filter No. 3, located on the north edge of the property line. Filter No. 3 was categorized as a location of intense truck loading and unloading activity and movement. The second monitoring location was at Filter No. 6, categorized as a location of low activity with no truck loading or unloading.

The goal of the stormwater monitoring program was to sample as many winter, spring, and summer storms as possible to develop a representative sample. The target sample number was set at 20 storm events minimum. Unfortunately, only nine natural storms had been monitored by the target date, so it became necessary to supplement the missing 11 storms using artificial runoff created by spraying from a nearby fire protection system. Careful attention was paid to the amount of runoff produced using artificial spraying in order not to exceed the target design storm. Artificial storms were representative of the general characteristics of natural storms, except for having higher hydraulic loading rates.

A series of samples were composited during each monitored storm in 10-liter carboys on a flow-weighting basis. Flow weighting was achieved by programming the flow meter to transmit pulse signals to the samplers to take a set volume each time a specific flow volume registered. Sampling intervals were programmed to allow monitoring of runoff from the mean 24-hour (31.2 mm [1.23 in]) of runoff) storm falling on the area of the sand filter catchments without overfilling the carboys. The water quality variables examined in the monitoring program were pH; temperature; total suspended solids (TSS); turbidity; zinc (Zn); fats, oils, and grease (FOG); total petroleum hydrocarbons (TPH); total phosphorus (TP); and copper (Cu). The results of the monitoring program are shown in Tables 33 and 34 (treatment efficiencies are based on mean concentration removal efficiencies).

A separate analysis was made of the condition of the sediments accumulated in the settling chambers and the condition of the sand beds in the filter chambers to define potential maintenance needs. Sediment samples from the settling chambers and sand cores from the filter chambers were collected separately for analysis. Particle size distributions and pollutant concentrations in sand samples collected from the two filters were compared with those of clean sand to assess changes that had occurred during the seven months of operation prior to sampling. Pollutant concentrations in sediment and sand were also compared.

**Table 33. Effectiveness for filter no. 3 (%)**

| Parameter | Natural Storm | Artificial Storm | Combined Storm |
|---|---|---|---|
| TSS | 88 | 80 | 83 |
| Turbidity | 43 | 1 | 17 |
| FOG | 76 | >88 | >84 |
| TPH | >83 | >86 | >84 |
| Cu | -133 | 61 | 22 |
| Zn | -39 | 86 | 33 |
| TP | 61 | 36 | 41 |

**Table 34. Effectiveness for filter no. 6 (%)**

| Parameter | Natural Storm | Artificial Storm | Combined Storms |
|---|---|---|---|
| TSS | -48 | 45 | 8 |
| Turbidity | -98 | -63 | -81 |
| FOG | >60 | 76 | >69 |
| TPH | >31 | >71 | >55 |
| Cu | -4 | 65 | 31 |
| Zn | 55 | 83 | 69 |
| TP | 16 | 25 | 20 |

# CONCLUSIONS

- Monitoring was fairly representative of the prevailing conditions and generally met the criteria established at the beginning of the program.
- The sand filter system consistently reduced total suspended solids (TSS); total petroleum hydrocarbons (TPH); fats, oils, and grease (FOG); zinc (Zn), and copper (Cu). Removal efficiencies approached on average 80 percent, except for copper which averaged 62 percent.
- Effectiveness in reducing total phosphorus (TP) was generally lower and less consistent than for the other pollutants.
- The sand filter system is less effective in capturing small solids that most influence turbidity.
- Based on sand core analyses after seven months of operation, it is estimated that the sand filter systems will provide several years of service before needing major maintenance.
- Sediment samples from the settling chambers and whole sand cores from the sand chambers collected after seven months of filter operation did not come close to violating any leachable metals criteria for designating hazardous or dangerous waste. However, the sediments exceeded TPH criteria under toxics control legislation and would have to be treated as hazardous waste if removed during maintenance.
- Analysis of the monitoring results indicates that the filters performed more effectively when there were higher concentrations of pollutants in the influent runoff. These observations suggest there may be thresholds of pollutant concentration below which the water quality benefits of the technology are marginal.

# REFERENCES

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Spearman, J.W., and S.R. Beard. 1995. *Design, Construction, and Evaluation of a Sand Filter Stormwater Treatment System. Part I. Design and Construction.* Report to Alaska Marine Lines, Seattle, WA.

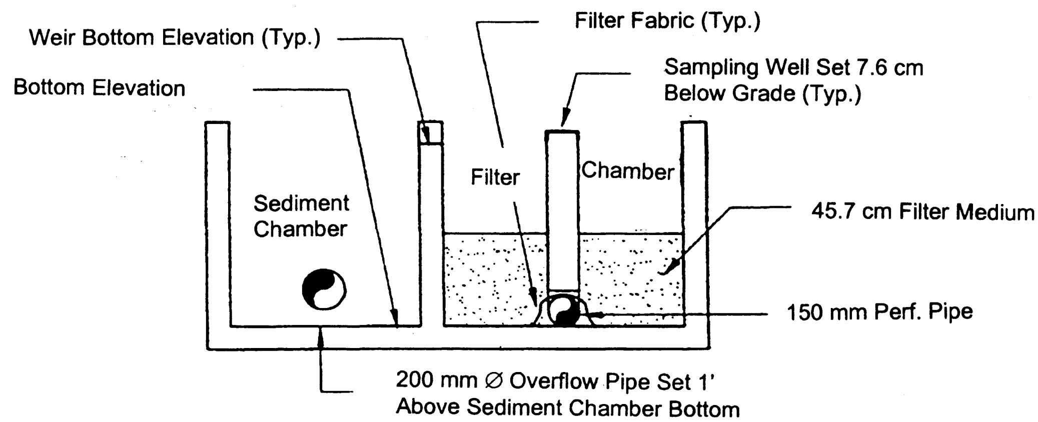


**Figure 57. Cross-section of filter chamber (adapted from Spearman and Beard, 1995)**

# MONITORING CASE STUDY—COMPOST STORMWATER TREATMENT SYSTEM, HILLSBORO, OREGON

This case study is based on an evaluation of a leaf compost filter system. The initial evaluation of the system was reported by Stewart (1992), with a summary three-year evaluation of the same site reported by Stormwater Management (1994).

A prototype of a compost stormwater treatment facility (CSF) was constructed at southwest 185th Avenue in Washington County, Oregon. Southwest 185th Avenue was widened in 1987 to five lanes with additional bike lanes and sidewalks. As part of this road widening, a relatively narrow water quality swale was constructed downstream from a storm runoff outlet. The prototype CSF was constructed at the head of the swale, with the swale (1.8 m [6 ft] wide and 76.3 m [250 ft] long) draining into a wetland mitigation pond, and then into Beaverton Creek. The CSF was constructed to treat runoff from 30 ha (74 ac) that drained to the existing water quality swale via the stormwater pipe. The area that drains to the site consists of 1.6 ha (3.9 ac) of five-lane arterial and 28.4 ha (70.1 ac) of mixed residential land use. Because it is widely reported that high-quality composts have a very high capacity for adsorbing heavy metals, oils, greases, nutrients, and organic toxins, compost was used as a filter medium for this test facility. Construction of the full-scale prototype was completed in August 1991. Funding was provided by the Unified Sewerage Agency (USA) to evaluate the performance of the CSF for three years.

## STUDY OBJECTIVE

- Develop, construct, and monitor a compost stormwater treatment system for use in highly urbanized areas where land area availability is considered to be a constraint.

## DESIGN AND OPERATION

The CSF was sized primarily based on the results of pilot study permeability tests, which were conducted prior to the start of construction. Due to its high quality, Portland leaf compost was selected for the filter medium. The results of the permeability tests using the Portland leaf compost mixture produced an average flow rate of 91.6 Lpm/m$^2$ (2.25 gpm/ft$^2$) for the first half hour of flow through a drained compost bed. This is equivalent to a compost bed surface area requirement of 656 m$^2$/m$^3$/s (200 ft$^2$/cfs) of flow. The peak design flow for the drainage basin was estimated using the rational method. For this basin, the peak design flow for the test facility was determined to be 0.2 m$^3$/s (6.7 cfs). According to this peak flow rate, the treatment facility would require 124.6 m$^2$ (1,340 ft$^2$) of compost bed surface area. Due to site restrictions, the CSF was downsized by approximately 10 percent to accommodate a bed surface area of 111.6 m$^2$ (1,200 ft$^2$). The construction bid price was $12,500, with only minor problems and clarifications needed. The prototype filter required 91.8 m$^3$ (120 yd$^3$) of leaf compost, at a delivered cost of $1,200.

The compost prototype test facility was designed to be retrofitted into the existing stormwater runoff quality swale of southwest 185th Avenue. To accommodate the compost system, the existing swale was widened to 3.1 m (10 ft) and given a 2:1 side slope. The longitudinal slope of the swale was graded at 2 percent from the influent to the effluent end. A typical cross section of the compost treatment system is shown in Figure 58. A polyethylene liner was installed along its length to prevent percolation of stormwater into the ground and to minimize effluent loss for monitoring purposes. A riprap geotextile fabric was installed over this liner to minimize tearing of the polyethylene liner during construction. Two 100 mm (4 in) perforated PVC drain pipes were installed along the entire length of the compost facility to facilitate drainage through the system and provide an effluent sampling point for monitoring.

The original design called for the drain pipes to be covered with a 15.2 cm (6 in) layer of 5.1 cm (2 in) washed drain rock and an additional 5.1 cm (2 in) layer of pea gravel to provide the underdrain system. After a nonwoven filter fabric was secured on top of the drain rock (see Figure 58), a 45.7 cm (18 in) layer of 1.9 cm (3/4 in) Portland leaf compost was placed over the nonwoven filter fabric. However, at the time of construction, the washed 5.1 cm (2 in) drain rock was not available and a substitute nonwashed 5.1 cm (2 in) drain rock was used in its place. It became apparent to USA that the dirt on the nonwashed drain rock would affect the sampling program results. The USA laboratory obtained samples of the rock and conducted tests in which the samples were washed and analyzed. The washings contained high levels of total suspended solids (TSS), total phosphorus, aluminum, barium, cobalt, chromium, copper, iron, nickel, and vanadium. As a result, tests of effluent from the first few storms probably contained contaminants contributed by the drain rock.

The compost filter system is divided into two 15.3 m (50 ft) cells that are 3.66 m (12 ft) wide at the surface. A layer of riprap was placed over the compost next to the wooden barriers in Cells 1 and 2 to distribute the flow coming over the wood barriers and to prevent washing out the compost next to the barriers. (Figure 59 shows a plan view of the compost filter system with the wooden barriers.) Unfortunately, an excessive amount of riprap was placed, causing the underlying compost to settle rapidly. The riprap also caused the stormwater flow to create small channels in the medium and flow through an isolated section of the compost bed. This problem was rectified by removing the majority of the riprap that had been placed beneath the wooden barriers.

The operation of the filter begins at an existing 600 mm (24 in) stormwater pipe that discharges into a forebay area prior to entering the compost filter system (see Figure 59). The cells are subdivided using wooden baffles to guide the flow as it leaves the forebay area. Wood baffle No. 1 is entrenched into the ground so all of the stormwater passes from the forebay area into the compost filter system. Wood baffles No. 2 and No. 3 have 5.1 cm (2 in) gaps at their bases to allow free drainage of treated stormwater through the rock underdrain and out to the effluent end (see Figure 60). The effluent ends of the two 100 mm (4 in) parallel drain pipes were coupled to provide for a single effluent sampling point for monitoring purposes (see Figure 59).

## MONITORING

The monitoring program for the newly constructed compost facility began in August 1991. Sampling and laboratory analyses were conducted by USA using standard USEPA sampling protocols. A sampling of 1/37,850 L (1/10,000 gal) was based on rainfall of 5 mm (0.2 in) and the size of the drainage basin. One sampler was located at the influent end and the other at the effluent end. The monitoring program included both first-flush and flow-paced sampling, using programmable automatic samplers. First-flush runoff represents the most critical need for stormwater treatment due to the effect of high pollutant loadings on receiving waters. The first-flush portion (first half hour) of a storm event carries a significantly higher pollutant loading than the remaining or flow-paced portion. The automatic sampler was programmed so that when the flow meter detected a flow depth of 6.1 cm (0.2 ft) in the discharge pipe, it was set to trigger both samplers to take two time-paced (first-flush) samples (with a 10-min delay for the effluent sampler). The automatic sampler then switched to flow-paced or weighted composite sampling. Each time the flow meter sensed 3,785 L (100 gal), it triggered a flow pulse to the samplers. The samples were collected following cessation of each sampled storm event.

During the first year of testing (1991-1992), a total of seven storm events were sampled. A total of eight storm events, four for each year, were sampled during the second (1992-1993) and the third years (1993-1994) of testing. The results of three years of monitoring are given in Table 35. Table 35 presents average mass balance pollutant removal efficiencies for both first flush and combined first flush and flow paced testing. A blank entry indicates that data was not available or not collected.

**Table 35. Mass balance pollutant removal efficiencies for three seasons of testing(%)**

| Parameter | 1991-92 | 1992-93 | 1993-94 |
|---|---|---|---|
| **Turbidity** | | | |
| Combined | 84.2 | 78.4 | 78.4 |
| First Flush | 93.4 | 85.3 | 81.4 |
| **TSS** | | | |
| Combined | 94.8 | 88.5 | 86.0 |
| First Flush | 98.3 | 91.4 | 89.0 |
| **COD** | | | |
| Combined | 66.9 | 76.3 | 74.0 |
| First Flush | 89.5 | 82.1 | 79.8 |
| **Total P** | | | |
| Combined | 40.5 | 53.2 | 65.5 |
| First Flush | 67.3 | 68.9 | 72.9 |
| **TKN** | | | |
| Combined | 55.9 | 50.5 | 66.7 |
| First Flush | 84.0 | 60.8 | 69.0 |
| **Fe** | | | |
| Combined | 89.0 | 95.5 | 79.6 |
| First Flush | 94.0 | 97.5 | 82.9 |
| **Cr** | | | |
| Combined | 61.2 | 74.5 | 64.3 |
| First Flush | 92.4 | 80.8 | 72.8 |
| **Cu** | | | |
| Combined | 66.7 | 63.5 | 64.1 |
| First Flush | 83.7 | 73.9 | 70.7 |
| **Pb** | | | |
| Combined | N/A | 85.1 | 81.4 |
| First Flush | | 89.0 | 84.0 |
| **Zn** | | | |
| Combined | 88.3 | 75.8 | 79.9 |
| First Flush | 92.8 | 83.1 | 83.1 |

# CONCLUSIONS

- The CSF operated very effectively in the first three seasons of operation, with overall mass balance pollutant removals averaging 81 percent for oils and grease, 84 percent for petroleum hydrocarbons, 58 to 94 percent for solids and nutrients, and 68 to 93 percent for metals.
- Although nutrient removals were not as good as expected, the removal of total phosphorus was 65.5 percent by the third season.
- First-flush removal rates were significantly higher than flow-paced removal rates for all of the pollutants and years tested. This would tend to indicate that the system operates most efficiently above some threshold pollutant load that is closely related to the first half hour of stormwater runoff.
- Results of the monitoring indicate that the CSF shows particular promise for treating heavily polluted stormwater runoff from industrial areas, heavily traveled urban streets, waste transfer stations, airports, and parking lots. In addition, the CSF design permits existing water quality swales to be retrofitted to improve pollutant removal rates. Unlike water quality swales that are not designed to retain stormwater runoff and tend to allow intense influent flows to pass over without proper treatment, a properly sized CSF will retain and treat the design storm runoff.
- Although the peak design storm never occurred during the testing period, the system performed very efficiently for all of the storm events that it treated.
- Future specifications should require double-washed drain rock with no exceptions.
- In future designs, more efficient horizontal flow distribution can be accomplished by using flat-plate notched weirs, bolted to the wooden barriers, and setting the first two wooden barriers closer together to form a more effective ponding section.

## REFERENCES

Stewart, W.S. 1992. *Compost Storm Water Treatment System.* W&H Pacific Consultants, Portland, OR. Final Report.

Stormwater Management. 1994. *Three Year Performance Summary of Stormwater Pollutant and Treatment - 185th Avenue, Hillsboro, Oregon.* Technical Memorandum. Stormwater Management, Portland, OR.

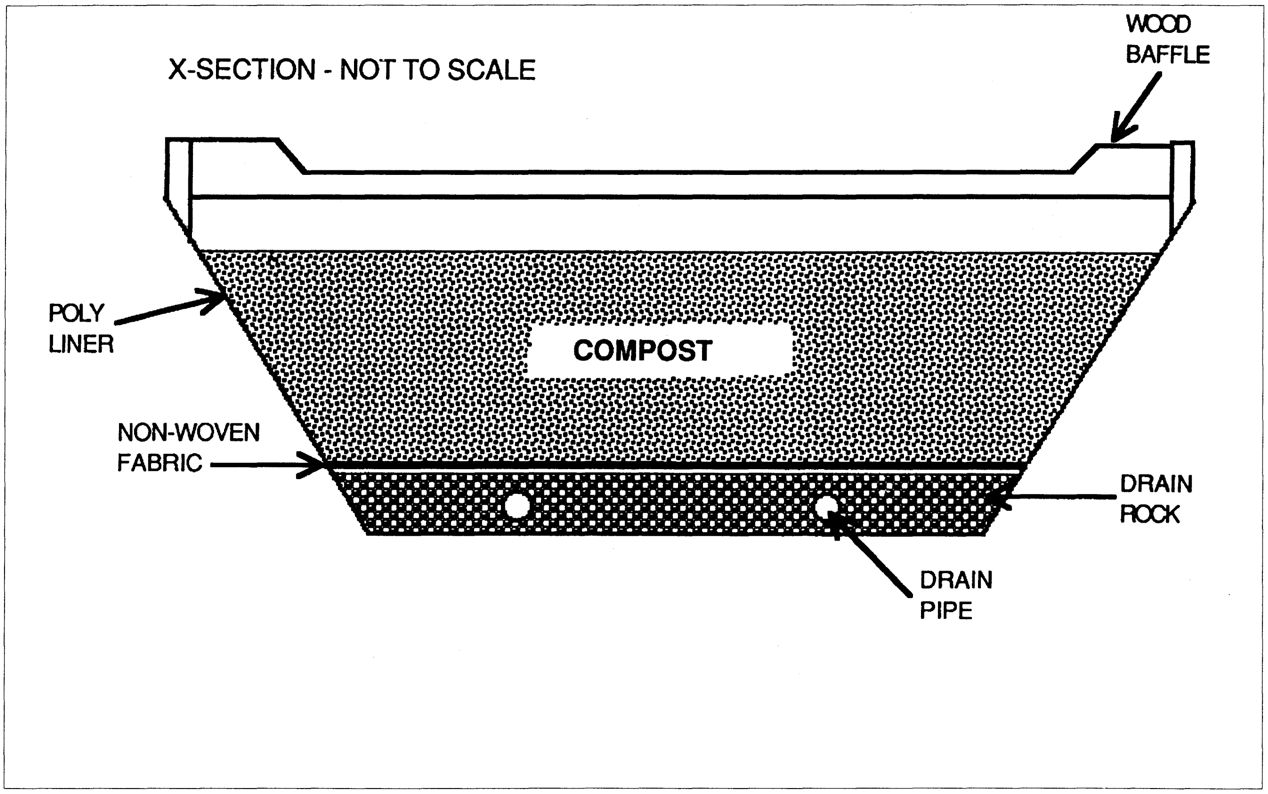


**Figure 58. Prototype compost stormwater filter (cross section) (Stewart, 1992)**

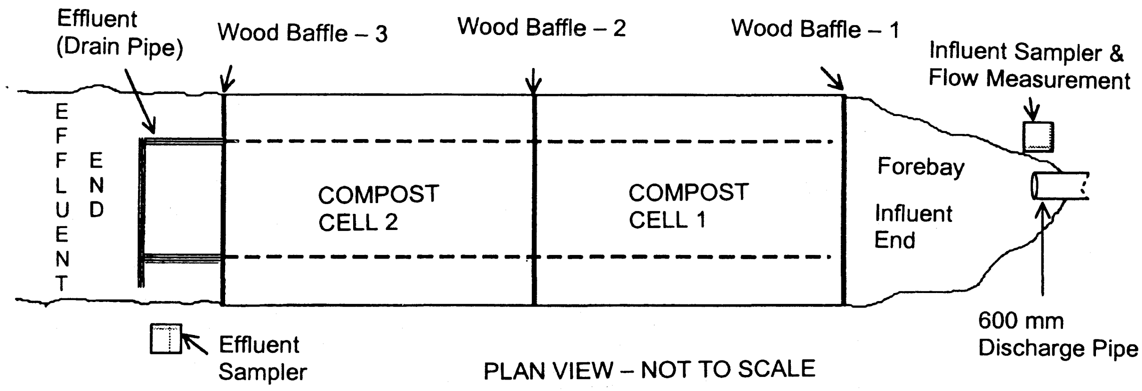


**Figure 59. Prototype compost stormwater filter (plan view) (adapted from Stewart, 1992)**

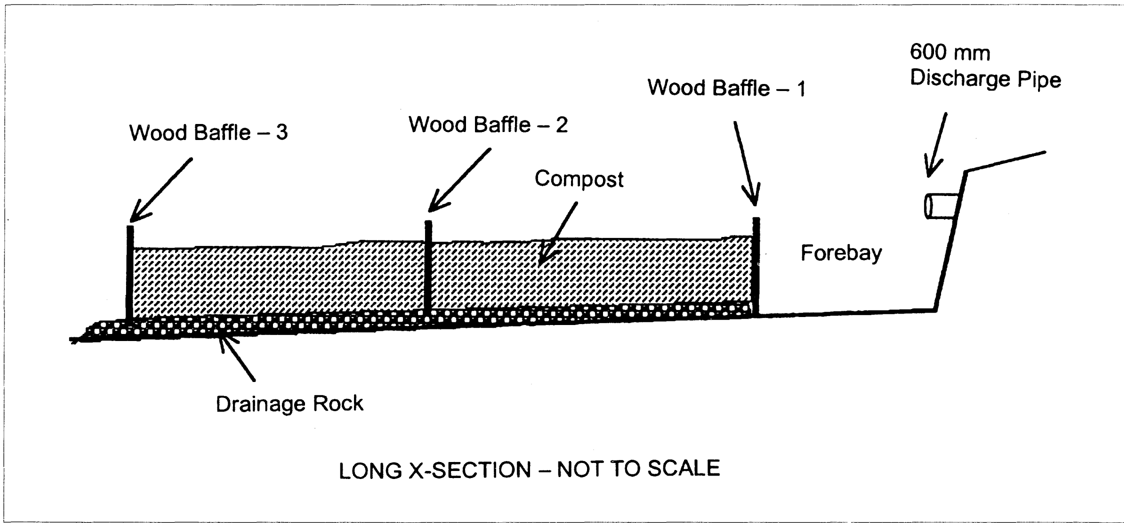


**Figure 60. Prototype compost stormwater filter (long cross section) (adapted from Stewart, 1992)**

# MONITORING CASE STUDY—VERTICAL VOLUME RECOVERY STRUCTURE (VVRS), ORLANDO, FLORIDA

This case study is based on an evaluation of a vertical volume recovery structure by Dyer, Riddle, Mills, & Precourt, Inc. (1996).

Due to chronic flooding problems within a highly urbanized section of the drainage basin of Lake Olive, Florida, the City of Orlando proposed to divert approximately 10 ha (25 ac) of the Lake Olive drainage basin to nearby Lake Lawsona. In addition to basin runoff diversion, it was requested that a system be designed that could provide both underground storage and treatment of the stormwater to reduce pollutants entering Lake Lawsona. The engineers at Dyer, Riddle, Mills, & Precourt, Inc. (DRMP) recommended investigating a sand filter structure known as the Vertical Volume Recovery Structure (VVRS). A VVRS, which is an underground stormwater runoff treatment and conveyance facility, combines in-pipe storage, a sump device (sediment settling), and a sand filter (fine sediment and pollutant removal) in its runoff treatment operation. The VVRS system for the City of Orlando was designed to treat 25.4 mm (1 in) of runoff from the diverted basin area, and was installed under Pine Street just west of Lake Lawsona.

## STUDY OBJECTIVES

- Measure the effectiveness of the sump to remove larger sediment particles.
- Measure the effectiveness of the VVRS at removing a wide range of stormwater pollutants.
- Establish backwash requirements for the VVRS system designed for the City of Orlando.

## DESIGN AND OPERATION

The VVRS system is located within the Pine Street right-of-way, between the intersection of Pine Street and Hyer Avenue, and just west of Lake Lawsona, in Orange County, Florida. The basic design of the system consists of a sump device, which acts as an initial settling basin, and a sand filled trench that acts as a filter to remove stormwater runoff pollutants. The system is designed to contain and treat the first 25.4 mm or the first inch of diverted runoff. Figure 61 shows a VVRS system prior to a rainfall event. The main weir crest acts as an overflow device for storm runoff occurrences greater than the design storm. The hypothetical flow path of a 25.4 mm ( in) or greater storm event through the VVRS system is shown in Figure 62. The sump is used to capture and settle larger sediments carried through the storm sewer (see Figure 61, station 1). The slope of the 600 mm (24 in) connector line (see Figure 61) prevents the transmission of floatables to the VVRS; however, in the event that floatables reach the filter box and collect within the sand pores, they can be removed by backwashing the filter using the effluent pipe that drains the VVRS. This was an important design feature of the VVRS. To accomplish this, a backflush system was constructed that forces potable water up through the sand medium to dislodge the accumulated particles. The sump area was designed to be cleaned using the opening through the main overflow weir structure. Figure 63 shows a schematic of the VVRS backwash operation.

Two significant operational problems were observed during the monitoring phase of the VVRS study. The first problem was structural failure of the sump device. After a storm event of approximately 38 mm (1.5 in), the sump structure was observed to have a large crack in its foundation floor. The problem was corrected by pouring additional concrete onto the slab of the slump; however, this reduced the depth and consequently the storage volume of the sump. The second problem was the surface blinding of the filter medium. During the first several storm sampling events, the sand filter medium was found to have an unacceptable rate of drawdown. After careful analysis of the filter medium, it was determined that the surface of the medium was "blinding", preventing significant flow through the system. The manufacturer of the filter medium recommended that a larger grain size medium be placed over the existing sand. This would allow the larger particles that were blinding the fine grained sand to be trapped without reducing the flow rate. It was determined that anthracite coal would be used because it was less dense than the existing sand medium, and would remain on top during backwashing of the system. Three-tenths of a meter (1 ft) of the existing sand was removed and replaced with the coal. After the anthracite coal was installed, field inspection of a storm event found surface blinding was still a factor. The sampling program was continued by frequent probing of the filter during bleed down, and frequent backwashing after storm events to reduce the effects of surface blinding and improve the drawdown rate.

## MONITORING PROGRAM

Three monitoring locations were established within the VVRS system to determine the pollutant removal efficiency. Station 1 is located in the inflow storm sewer pipe, and samples the stormwater runoff entering the system. Station 2 is located within the filter box, above the filter media. Station 3 is located in the outfall pipe, just beyond the filter media. All three sampling stations are schematically shown in Figure 61. Composite samples were collected from station 1 during six storm events, and stations 2 and 3 during 11 storm events. A storm event was defined as a minimum of 2.54 mm (0.10 in) of rainfall, separated from other storm events by at least 24 hours. The pollutant removal efficiency results of the monitoring study are given in Tables 36, 37, and 38. Table 37 shows the mean removal efficiency for three sampling events at the sump device. Only three samples from the six storm events at station 1 were used due to limitations on paired samples

**Table 36. Removal efficiency of the sump**

| Parameter | Mean Removal[1] (%) |
|---|---|
| Cadmium | 36.7 |
| Chromium | 0 |
| Copper | 5.3 |
| Lead | 65.7 |
| Mercury | 0 |
| Zinc | 47.3 |
| Ammonia | 30.7 |
| Nitrate | 50 |
| Nitrite | 0 |
| TKN | 35.7 |
| Total Nitrogen | 40.7 |
| TP | 41.7 |
| Orthophosphate | 52 |
| TSS | 40.3 |

[1] Three sampling events

**Table 37. Removal efficiency of the VVRS**

| Parameter | Mean Removal[1] (%) |
|---|---|
| Cadmium | 0 |
| Chromium | 0 |
| Copper | 3.4 |
| Lead | -9.8 |
| Mercury | 0 |
| Zinc | -2.8 |
| Ammonia | -248.1 |
| Nitrate | 5.4 |
| Nitrite | 0 |
| TKN | -1.7 |
| Total Nitrogen | -1.5 |
| TP | 9.9 |
| Orthophosphate | -18.6 |
| TSS | 12.2 |

[1] Eleven sampling events

**Table 38. VVRS system removal efficiency**

| Parameter | Mean Removal (%) |
|---|---|
| Cadmium | 0 |
| Chromium | 0 |
| Copper | 3 |
| Lead | -10 |
| Mercury | 0 |
| Zinc | -3 |
| Ammonia | -248 |
| Nitrate | 5 |
| Nitrite | 0 |
| TKN | -2 |
| Total Nitrogen | -1 |
| TP | 10 |
| Orthophosphate | -19 |
| TSS | 12 |

from stations 1 and 2. Table 37 gives the mean removal efficiency for 11 sampling events at the filter mechanism, and Table 38 shows the mean pollutant removal efficiency for the entire VVRS system. Mean removal efficiencies were calculated using a mass balance approach. The mean efficiency was determined as the sum of the individual removals divided by the total number of events.

# CONCLUSIONS

- The sump device is somewhat effective at removing several heavy metals (cadmium, lead, and zinc), total nitrogen, total phosphorus, orthophosphate, and total suspended solids. The slow bleed down time associated with the blinding of the filter media may have contributed to this result.
- The filter media is almost completely ineffective at removing dissolved or suspended pollutants. The drawdown problems associated with the blinding of the filter media may be partly responsible for this result. When the stormwater sat in the filter box for extended periods, much of the settling and chemical action may have occurred prior to the water flowing through the filter.
- The use of larger grain size filter media would result in a lower filtering efficiency, but would likely eliminate the surface blinding problem.
- Pulsing, which is a very brief backwash event triggered automatically, can be used in lieu of using the larger grain size filter media.

# REFERENCES

Dyer, Riddle, Mills, & Precourt, Inc. 1996. *Vertical Volume Recovery Structure*. Final Report, Project No. WM436. Prepared for City of Orlando Stormwater Utility Bureau. Submitted to the Florida Department of Environmental Protection.

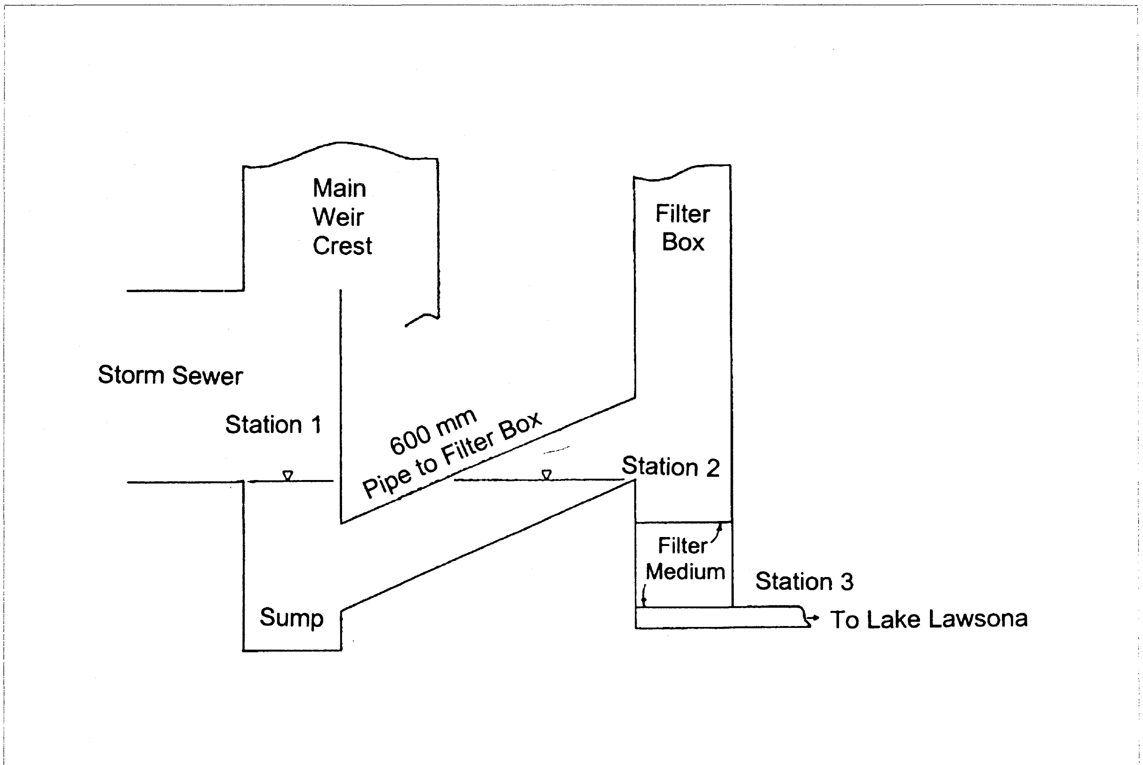


**Figure 61. Vertical Volume Recovery Structure system at rest prior to rainfall event (adapted from Dyer, Riddle, Mills, & Precourt, 1996)**

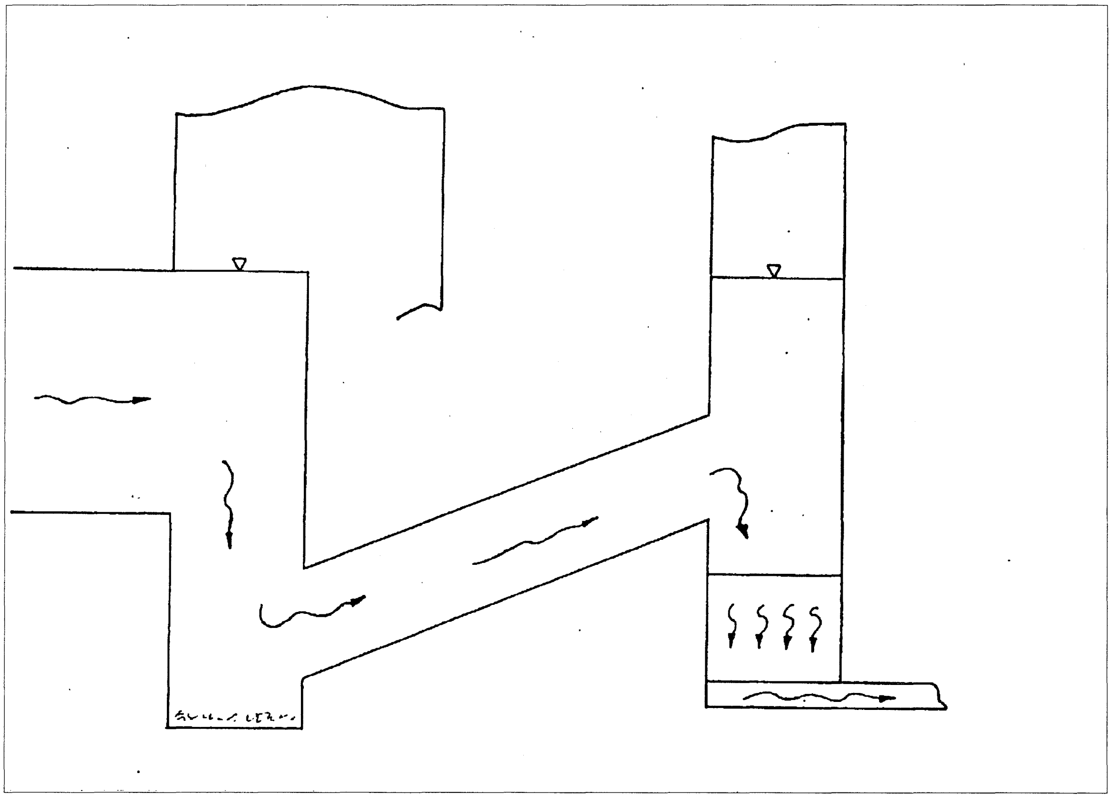

**Figure 62. Vertical Volume Recovery Structure full utilization of treatment volume (Dyer, Riddle, Mills, & Precourt, 1996)**

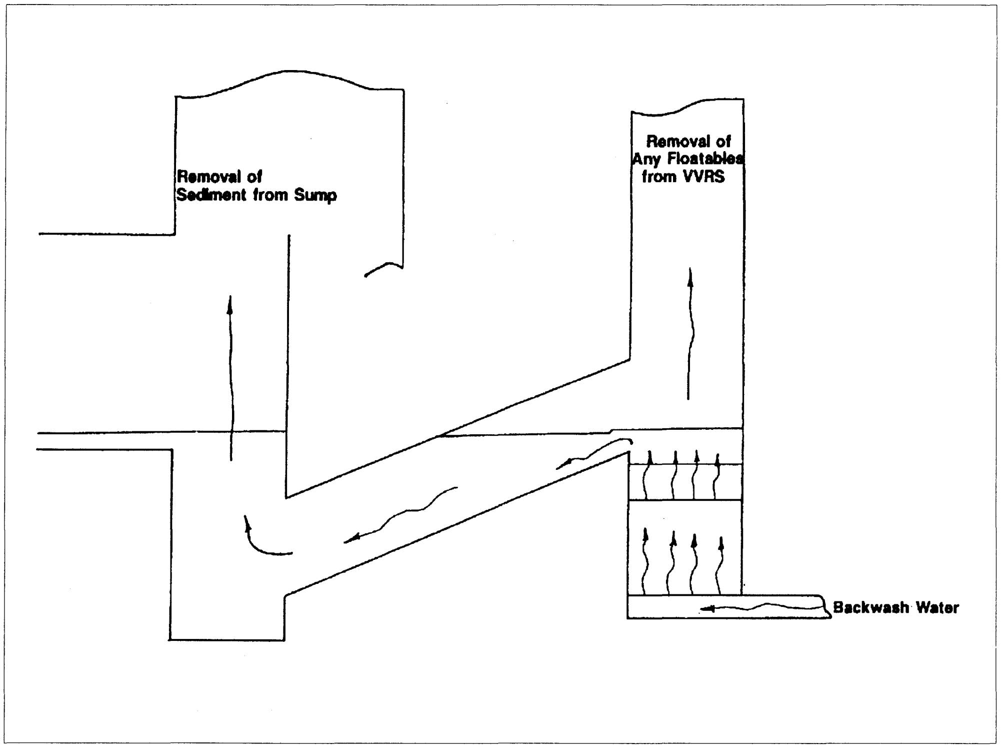


**Figure 63. Vertical Volume Recovery Structure backwash operation (Dyer, Riddle, Mills, & Precourt, 1996)**

# MONITORING CASE STUDY—VEGETATED WATER QUALITY BUFFER STRIPS, AUSTIN, TEXAS

This case study is based on a study of vegetated buffer strips by Glick et al. (1993).

A field study to determine the influence of vegetation composition, buffer width, and infiltration rate on the effectiveness of native vegetation buffer zones for treatment of urban runoff was conducted. The study site was located in Austin, Texas, with the runoff originating in a parking lot with a drainage area of approximately 1 ha (2.47 ac). The soil on the site is categorized as shallow, well-drained clay overlying limestone; however, some of the soil in the buffer strips was fill from construction of the parking lot. Four different vegetation compositions were used as stormwater runoff treatment areas (1) mowed native grasses, (2) unmowed native grasses, (3) wooded area cleared, and (4) wooded area with woody debris. A grant from the Department of the Interior, U.S. Geological Survey, through the Texas Water Resource Institute was provided to fund the study. Additional non-Federal matching funds were provided by the City of Austin, Texas.

## STUDY OBJECTIVE

- Determine the influence of vegetation composition, slope, buffer width, and infiltration rate on the effectiveness of native vegetation buffer zones as water quality BMPs.

## DESIGN AND OPERATION

The field study developed to monitor the pollutant removal efficiency of different water quality buffer zones was established adjacent to an existing parking lot in Austin, Texas. Test plots were established to monitor the runoff quality through the buffer. Each plot was approximately 10 m (32.8 ft) by 20 m (65.6 ft) in size. The vegetation types included mowed native grasses (3 plots), unmowed native grasses (3 plots), undisturbed woodland (1 plot), and cleared woodland (1 plot). The vegetation in the mowed and unmowed areas was primarily composed of Johnson grass, Bermuda grass, and mixed legumes. The grassed buffer was followed by a wooded buffer dominated by common red cedar with scattered live oak and Ashe juniper. The ground cover was juniper debris and scattered Texas wintergrass. Figure 64 shows the test plot configuration for the field study site. Water sampling devices were constructed using a series of overland flow collection flumes that were placed at four locations in each of the eight test plots. In the wooded areas, only three locations were used because of parkland restrictions on land clearing. Four flumes were placed at each sampling location (see Figure 64). The slope of the test site was approximately 10 percent between the entrance of the mowed area to about one-third into the unmowed area. Elsewhere, the slope was between 17 and 30 percent. Sample bottles were placed in sample tubes only when a rainfall event greater than 10 mm (0.39 in) was likely. This was done to reduce sample bottle contamination. Bottles were collected and sent for laboratory analyses if more than one-half of the bottles were at least half full. If the bottles could not be collected for analysis within 36 hours after placement, they were emptied and cleaned for future use. Figure 65 shows a typical collection flume and collection bottle layout.

Infiltration characteristics for each of the four test plots were determined using adjacent areas with similar slope, soil, and vegetation for each strip to prevent any disturbances of the test sites. A drip-type rainfall simulator was used to produce runoff on the adjacent similar plots. The simulated rainfall was applied at a rate of 150 mm/hr (5.8 in/hr) for 1 hour or until the final infiltration rate was reached. The runoff was collected and weighed every five minutes. Infiltration was computed as the arithmetic difference between the applied rainfall and the collected runoff. The infiltration test was repeated on each slope and vegetation type except the cleared woodland. The infiltration characteristics could not be determined on cleared woodland due to restrictions in the amount of land that could be cleared in the city park.

## MONITORING PROGRAM

The goal of the buffer strip monitoring program was to collect as many samples as possible between July 1990 and October 1991. For each grass sample collected, 12 runoff pollutant constituents were measured: fecal streptococci (FS), fecal coliform (FC), dissolved nitrate (D $NO_3$-N), total nitrate (T $NO_3$-N), dissolved total phosphorus (D TP), total phosphorus (TP), dissolved ammonia (D $NH_3$-N), total ammonia (T $NH_3$-N), dissolved total Kjeldahl nitrogen (D TKN), total Kjeldahl nitrogen (T TKN), total lead (Pb), and total suspended solids (TSS); however, only constituents that were found to be statistically different at the 0.10 level of significance were reported. Because dissolved samples were not collected in the cleared or wooded areas due to space limitations, only seven runoff pollutant constituents were measured in those areas. Analyses of variance were conducted to determine the individual effects of vegetation composition and buffer width and the combined effect of the treatments on buffer effectiveness.

Water samples were collected from 12 rainfall events that occurred during the monitoring program, specifically 425 samples of the total pollutants and 125 samples for the dissolved pollutants were collected. The samples from three of the flumes at each location were analyzed for TSS, TKN, T $NH_3$-N, T $NO_3$-N, TP, Pb, and FC. Standard USEPA testing protocols were followed for each analysis. The fourth sample at each grass location was tested for D $NH_3$-N, D $NO_3$-N, D TKN, D TP, and FS. Mean concentrations for pollutants that showed a significant difference (0.10 level of significance) due to buffer width are given in Table 39. Table 40 gives the mean concentrations for pollutants that showed significant difference (0.10 level of significance) due to the type of vegetative cover. A dash (-) in Table 40 indicates that the parameter was not measured due to space restrictions.

**Table 39. Mean of sample concentrations based on buffer width[1]**

| Parameter | 0 m | 4 m | 8 m | 12 m |
|---|---|---|---|---|
| Pb | 0.0166 | 0.0152 | 0.0230 | 0.0223 |
| TSS | 228.0 | 347.9 | 478.2 | 612.8 |
| T TKN | 2.14 | 2.78 | 3.25 | 3.32 |
| D TP | 0.184 | 0.320 | 0.440 | 0.438 |

[1] Constituents with buffer width as a significant factor at the 0.10 level of significance.

**Table 40. Mean of sample concentrations based on vegetative cover[1]**

| Parameter | Mowed Grass | Un-mowed Grass | Cleared Area | Wooded Area |
|---|---|---|---|---|
| Pb | 0.0149 | 0.0173 | 0.0220 | 0.0261 |
| TSS | 331.0 | 321.2 | 383.0 | 630.2 |
| T TKN | 3.22 | 2.41 | 2.58 | 3.12 |
| D TP | 0.326 | 0.267 | - | - |
| D $NO_3$-N | 0.820 | 0.457 | - | - |

[1] Constituents with cover as a significant factor at the 0.10 level of significance.

## CONCLUSIONS

- Infiltration results showed that mowed areas had final infiltration rates of 30 to 80 mm/h (1.1 to 3.1 in/h), unmowed areas had infiltration rates of 110 to 140 mm/h (4.2 to 5.4 in/h), and the wooded areas had infiltration rates greater than 140 mm/h (5.4 in/h). These results indicate that infiltration capacity and vegetative cover are highly correlated.
- Seven of the 12 pollutants tested in the study (TSS, Pb, T TP, T TKN, T $NO_3$, D TP, and D $NO_3$) exhibited a significant relationship between concentration and vegetative cover and buffer width. Vegetative cover was a significant factor for five pollutants (Pb, TSS, T TKN, D TP, and D $NO_3$-N). Vegetative composition of the buffer influences its effectiveness.
- Examination of the infiltration rates shows that the wooded area had the greatest infiltration rate; however, the mean pollutant

concentrations for total pollutants also were the highest. It appears that the infiltration rate is a secondary influence on buffer strip performance with type of vegetation and ground cover being the primary factors.

- Of the five pollutants that had buffer width as a significant factor, only D $NO_3$-N had a lower concentration at the end of the buffer compared to the start. From the data gathered, it appears that buffer width negatively influences buffer performance.
- The effects of changing the slope are inconclusive. The slope of the buffer changed at 4 m (13 ft) in the mowed and unmowed areas; the difference in the change in concentration between 0 and 4 m (13 ft) and 4 and 8 m (26 ft) was found not to be statistically significant.

## REFERENCES

Glick, R.H., M.L. Wolfe, and T.L. Thurow. 1993. *Effectiveness of Native Species Buffer Zones for Nonstructural Treatment of Urban Runoff.* Texas Water Resources Institute, College Station, TX.

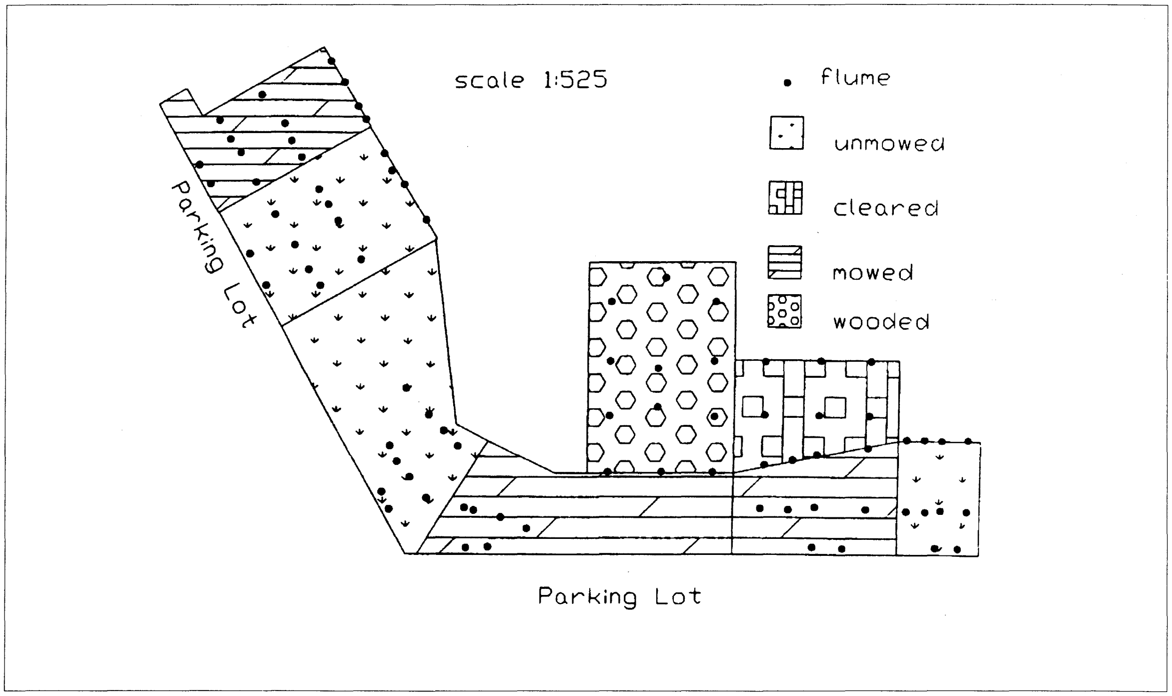


**Figure 64. Test plot configuration (Glick et al., 1993)**

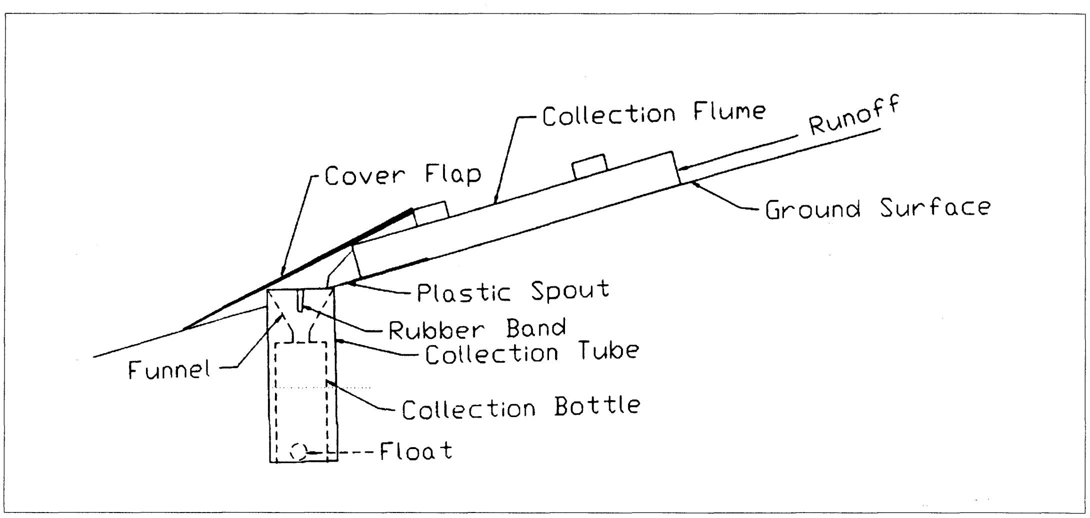


**Figure 65. Collection flume and collection bottle layout (Glick et al., 1993)**

# MONITORING CASE STUDY—STREET SWEEPING BMP EVALUATION, PORT OF SEATTLE, WASHINGTON

This case study is based on a study evaluating street sweeping technology by Kurahashi and Associates, Inc. (1997).

The Port of Seattle owns five cargo container yards, covering a total area of approximately 162 ha (400 ac), which serve its marine terminals. A major expansion effort currently under way at two of the five yards will result in a substantial increase in the container yard area. At the present time, the only stormwater treatment BMP that is technically feasible and approved for new marine facilities is the wet vault. In May 1996, the Port of Seattle contracted with Kurahashi and Associates to evaluate the effectiveness of new high-efficiency pavement sweepers in combination with conventional sediment-trapping catch basins to determine if the combination technology provided pollutant reduction benefits that were comparable to those of wet vaults. The evaluation was prompted by the results of recent studies conducted by Kurahashi and Associates that indicated significant reductions in pollutant loadings could be achieved through the use of high-efficiency sweepers. Older studies, dating back to the Nationwide Urban Runoff Program (NURP), had indicated that street sweeping was of limited benefit in improving the quality of urban runoff. The use of high-efficiency pavement sweepers in combination with conventional sediment-trapping catch basins would result in substantial savings for the Port of Seattle compared to the use of wet vaults (estimated life cycle costs of $2 million for high-efficiency sweepers in combination with conventional sediment-trapping catch basins versus $18 million for wet vaults).

## STUDY OBJECTIVES

- Calibrate a stormwater quality computer model using pollutant accumulation data from nine sites in various activity areas of a container storage yard in the Port of Seattle.
- Use the calibrated model to evaluate the stormwater pollutant removal effectiveness of new high-efficiency pavement sweepers used in combination with conventional sediment-trapping catch basins and determine if the removal effectiveness was equivalent to that obtained through wet vaults.

## MODELING APPROACH, DATA COLLECTION, AND CALIBRATION

The Simplified Particulate Transport Model (SIMPTM) was used in the study. SIMPTM is a continuous stormwater quality model that has been shown to accurately simulate the accumulation and washoff of sediment and associated pollutants, and the load reductions expected through the implementation of BMPs. SIMPTM accounts for sediment deposition, armoring, and resuspension processes, and models scheduled cleaning of streets, parking lots, catch basins, and maintenance hatches. The model aggregates hourly precipitation data into rainfall events and provides continuous simulation of sediment and bound pollutant transport.

Data on pollutant accumulation was obtained over a 2-month period at nine sites within three areas in the container yard that were deemed to be representative of various ongoing activities. The activity areas selected were the alleyways between stored containers, the alleyways between parked trailers, and the area beneath the trailers. One site in each activity area was sampled every week; the second and third sites were sampled every two weeks and four weeks, respectively. Samples were collected on designated days by hand sweeping and mechanical vacuuming. A mechanical grain size analysis and chemical analysis for metals and total petroleum hydrocarbons was performed on each sample.

The SIMPTM model was calibrated using data on pollutant accumulation obtained over the 2-month sampling period and rainfall data for the same period collected at a nearby airport. Calibration essentially entailed adjusting the values of washoff and accumulation parameters until the best overall match was obtained between predicted and observed sediment accumulations for each of the activity areas during the two month sampling period. The best match was determined by visually comparing line graphs of predicted and actual sediment accumulation values for different parameter combinations.

The calibrated model for each activity area was used to simulate the average annual total suspended solids (TSS) loadings using an "average year" of rainfall events, synthesized from the analysis of a 29-year precipitation record at the airport. SIMPTM simulations included copper, lead, zinc, and phosphorus. Estimates of the particulate (suspended) fraction of each pollutant were based on the mean mass-fraction of the pollutant found in the analysis of samples collected from the container yard. These estimates were that 50 percent of the copper, phosphorus, and zinc washoff at any given time was assumed to be dissolved, while only 20 percent of the lead was assumed to be dissolved.

Alternative frequencies of sweeping (daily to monthly) and alternative sizes of catch basins (normal or enlarged)) were considered in the SIMPTM simulations. Since the model does not allow alteration of basic performance characteristics of the sweeper for a given model run, two sets of results were obtained to simulate performance characteristics of dry sweeping (high pickup efficiency) and damp pavement sweeping (reduced pickup efficiency).

Wet vaults are not explicitly modeled by the SIMPTM model. Sediment and associated pollutant removals for wet vaults were computed based on a modification of Stoke's Law for determining settling velocities for various grain sizes. SIMPTM model outputs (with no sweeping assumed) were used as inputs for these computations.

# RESULTS AND CONCLUSIONS

The expected range of annual pollutant load reductions for various sweeping frequencies indicated by SIMPTM are summarized in Table 41. The table also provides the expected range of pollutant load reductions for wet vaults. The following conclusions were drawn from the simulation study:

- Pollutant removals obtained with high-efficiency sweeping at a weekly frequency in combination with normal catch basin inlets cleaned annually are comparable to removals obtained by wet vaults.
- High-efficiency sweeping appears more effective than wet vaults in the removal of highly dissolved pollutants (copper, zinc, and phosphorus).
- Wet vaults appear more effective than high-efficiency sweeping in the removal of TSS and sediment-bound pollutants such as lead.
- High-efficiency sweeping carried out on a weekly basis in combination with normal catch basin inlets is a viable, cost-effective BMP, with overall pollutant removals comparable to those obtained by wet vaults.

**Table 41. Comparison of pollutant load reductions from various sweeping frequencies and wet vaults (%)[1]**

| Pollutant | Twice Weekly Sweeping | Weekly Sweeping | Biweekly Sweeping | Wet Vaults |
|---|---|---|---|---|
| TSS | 45-70 | 45-65 | 40-60 | 75-90 |
| TP | 35-60 | 30-55 | 20-40 | 35-45 |
| Total Lead | 40-60 | 35-60 | 30-50 | 65-80 |
| Total Zinc | 30-55 | 25-50 | 20-40 | 35-45 |
| Total Copper | 35-60 | 30-55 | 20-40 | 35-45 |

[1] The low end of each range is obtained under the assumptions that none of the dissolved pollutants are captured by sweeping during damp pavement conditions and that parked trailers do not block the potential transport of material beneath trailers.

## REFERENCES

Kurahashi & Associates, Inc. 1997. *Port of Seattle - Stormwater Treatment BMP Evaluation.* Prepared for Port of Seattle, Pier 66. Prepared by Kurahashi & Associates, in association with AGI Technologies.

# MONITORING CASE STUDY— PACKED BED FILTER BMP NEAR LAKE BEARDALL, ORLANDO, FLORIDA

This case study is based on an evaluation of a packed bed filter by Dyer, Riddle, Mills, & Precourt, Inc. (1995).

In response to growing concerns over long-term water quality issues in the Clear Lake drainage basin, the city of Orlando proposed using vegetated rock media filters to treat urban stormwater runoff that drains into the lake. The Clear Lake drainage basin consists of over 777 ha (3 $mi^2$) of highly developed urban area. Because of land constraints, conventional BMPs were considered to be impractical. The Florida Department of Environmental Regulation provided funding for the construction and research of a packed bed filter system. In December 1990, Dyer, Riddle, Mills, & Precourt, Inc. (DRMP) were retained by the city of Orlando to perform the engineering design of the project. Because remedial measures to implement water quality improvements for the entire basin were cost-prohibitive, DRMP prepared a design for a packed bed filter in the vicinity of Lake Beardall to remove pollutants from a 48.9 ha (120.9 ac) basin of highly industrial land use. The system consists of a storage treatment pond used for sedimentation and detention, followed by a packed bed filter system planted with wetland macrophytes for nutrient uptake.

## STUDY OBJECTIVES

- Evaluate the effectiveness of the packed bed system as a whole.
- Evaluate the effectiveness of each packed bed separately.
- Estimate the pollutant removal efficiency for three different flow rates.

## DESIGN AND OPERATION

The design of the packed bed filter treatment system consists of (1) an off-line storage facility to capture the first flush (first 12.7 mm or first-half inch of a 2-year storm) of stormwater runoff; (2) implementation of diversion weirs to shunt the first flush to the storage facility while allowing the remaining stormwater runoff to bypass the facility; (3) creation of a sedimentation area within the storage facility; (4) creation of 10 packed bed filters consisting of five crushed concrete and five granite media beds, vegetated with native aquatic plants; (5) use of two pumps to supply water to the packed beds from both the storage facility and Clear Lake; (6) control valving to allow for varied water flow rates through the packed beds; and (7) automated flow measurement combined with composite samplers to quantify pollutant removal within the packed beds. Clear Lake is used as a source of continuing flow during dry periods to maintain the planted beds.

To determine the optimum residence time for pollutant removal using different flow rates, separate valves and meters were installed for each filter bed. The packed filter system consists of 10 beds that are individually excavated cells, measuring 24.4 m (80 ft) wide by 9.1 m (30 ft) long by 1.06 m (3.5 ft) deep. Each filter bed is lined with a plastic liner to help eliminate the influence of groundwater and filled with 91.4 cm (36 in) of 3.8 to 7.6 cm (1.5 to 3 in) diameter crushed concrete or granite. Header pipes are installed on the inflow and outflow ends to provide equivalent cross-sectional flow through the filter medium. To ensure that an even water level was maintained in each filter bed because of varying flow rates, outfall weirs, consisting of 10.1 cm (4 in) PVC risers, were installed. An important component of the filter system was the design of a stormwater detention pond. Since the pollutant removal mechanism of a packed bed filter is similar to a trickling filter, the packed beds required a slow, constant flow rate to effectively remove particulate matter. Because stormwater runoff occurs at high flow rates for short periods of time, a detention pond was designed to capture the first-flush runoff, settle out larger particulate matter, and provide a slow, steady flow to the filter beds for treatment. Native vegetation was planted into the rock without soil to enhance the pollutant removal capabilities of the filter. The vegetation consisted of maidencane, giant bulrush, and fireflag, as illustrated in Table 42. The treated stormwater runoff is collected from the controlled outlets into a 300 mm (12 in) PVC collection pipe. The collection pipe transports the effluent through gravity flow to an existing 900 mm (36 in) storm drain outfall point on the drainage canal.

# MONITORING PROGRAM

To determine the pollutant removal efficiency rates of the packed bed filters, automated, flow-proportional composite samplers were installed at the inlet and outlet of the total packed bed filter system. Figure 66 shows a schematic of the packed bed filter sampling stations. To sample the overall inflow to the beds, one sampler was placed at the storage facility pump (see Figure 66, station 1) with the intake tube fitted inside the pump wet well. The flow-proportional sampling was set such that 100 mL were taken every 10 minutes of pump run time, thus producing a composite flow-proportional sample. Another sampler was placed directly downline of the confluence of all individual bed outfalls to provide data on the overall bed system outflow. By determining the time required for a particle of water to flow through the bed system (residence time) and delaying the start of the outflow sampler by the residence time, the entire removal efficiency for the packed bed system can be determined. The range of residence times varied between 6 hours and 24 hours depending on the flow rate. During the monitoring program, three distinct flow rates were used to evaluate removal efficiencies: 454.2 L/min, 227.1 L/min, and 113.5 L/min (120 gal/min, 60 gal/min, and 30 gal/min). The sampling period lasted for nearly four months, at which time 15 simulated storm events were sampled at various flow rates.

**Table 42. Medium type and vegetation for packed bed filter system**

| Filter | Media Type | Vegetation Type |
|---|---|---|
| 1 | Crushed Concrete | Maidencane |
| 2 | Crushed Concrete | Giant Bulrush |
| 3 | Crushed Concrete | Fireflag |
| 4 | Crushed Concrete | Giant Bulrush & Fireflag |
| 5 | Crushed Concrete | Void of Vegetation |
| 6 | Gravel | Void of Vegetation |
| 7 | Gravel | Giant Bulrush & Fireflag |
| 8 | Gravel | Fireflag |
| 9 | Gravel | Giant Bulrush |
| 10 | Gravel | Maidencane |

The samples were analyzed for the following constituents: cadmium, chromium, copper, lead, zinc, ammonia, total dissolved solids (TDS), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), total nitrogen (TN), total phosphorus (TP), orthophosphate, nitrate, nitrite, and volatile suspended solids (VSS). Grab samples were taken for the same 15 events from a spigot on the pump 2 (station 1) discharge line and from the system outfall (station 2) and analyzed for fecal coliform (FC) and total organic carbon (TOC). Pollutant loads entering and leaving the entire packed bed system were determined using a mass balance approach. To evaluate the pollutant removal rates of individual packed beds, water quality samples were taken of the inflow and outflow of each bed separately. In an effort to save costs, it was assumed that the inflow to all beds was well mixed; therefore, the composite sampler of station 1 was used to collect a single inflow composite sample representing the inflow concentrations of all beds. Due to time and budget constraints, grab samples were taken at each bed outfall structure. The overall system removal efficiency is given in Table 43. Table 44 gives the overall system removal efficiency for three different flow rates. A discussion of the individual bed performances is provided in the conclusions.

**Table 43. Overall system mass balance removal efficiency**

| Parameter | Removal Efficiency (%) |
|---|---|
| Cadmium | 80 |
| Chromium | 38 |
| Copper | 21 |
| Lead | 73 |
| Zinc | 55 |
| TN | 63 |
| TKN | 62 |
| Ammonia | 6 |
| Nitrate | 75 |
| Nitrite | 9 |
| TP | 82 |
| Orthophosphate | 14 |
| TDS | 8 |
| TSS | 81 |
| VSS | 80 |
| TOC | 38 |
| FC | 78 |

**Table 44. Overall system removal efficiency (%) for three different flow rates**

| Parameters | High Flow Rate | Mid Flow Rate | Low Flow Rate |
|---|---|---|---|
| Cadmium | 71 | 52 | 90 |
| Chromium | 27 | 18 | 36 |
| Copper | 60 | 26 | 33 |
| Lead | 85 | 70 | 77 |
| Zinc | 70 | 46 | 60 |
| TN | 69 | 60 | 73 |
| TKN | 69 | 57 | 73 |
| Ammonia | 40 | 10 | 15 |
| Nitrate | -55 | 57 | 73 |
| Nitrite | -5 | 50 | 73 |
| TP | 83 | 71 | 80 |
| Orthophosphate | 4 | -1 | -49 |
| TDS | 3 | 18 | 31 |
| TSS | 85 | 83 | 88 |
| VSS | 80 | 83 | 88 |
| TOC | 20 | 15 | 16 |
| FC | 74 | 79 | -46 |

# CONCLUSIONS

- The average percent removals in Table 44 for cadmium, chromium, TN, TKN, nitrate, nitrite, TDS, TSS, and VSS seem to indicate that the low flow rate is the most effective in removing these parameters. However, when the need for available storage within the detention pond and the mass of pollutant removed per hour of operating time are factored in, the high rate is the most cost-effective alternative flow rate for all parameters except nitrate, nitrite, and TDS.
- The concrete media control (bed 5) was consistently better at pollutant removal than the granite media control (bed 6). One possible explanation is that the difference in pH (7.5 in the concrete vs. 6.9 in the granite beds) influenced biological and chemical reactions within the beds. Another explanation is that the different textures of the media affected the amount and type of epilithic algae that was able to grow. Within the concrete media beds, the vegetated beds exhibited no advantage over the control bed (unvegetated bed 5) in the removal of any of the pollutants studied.
- In contrast to the concrete beds, the vegetated granite media beds provided additional pollutant removal when compared to the unvegetated granite control bed. With the exception of Pb, ammonia, TN, TSS, VSS, and FC, removal efficiencies for the vegetated granite media beds were statistically significant at the 5 percent level of significance.

# REFERENCES

Dyer, Riddle, Mills & Precourt, Inc. 1995. *Packed Bed Filter*. Final Report, Project No. SP214. Prepared for City of Orlando Stormwater Utility Bureau. Submitted to the Florida Department of Environmental Protection.

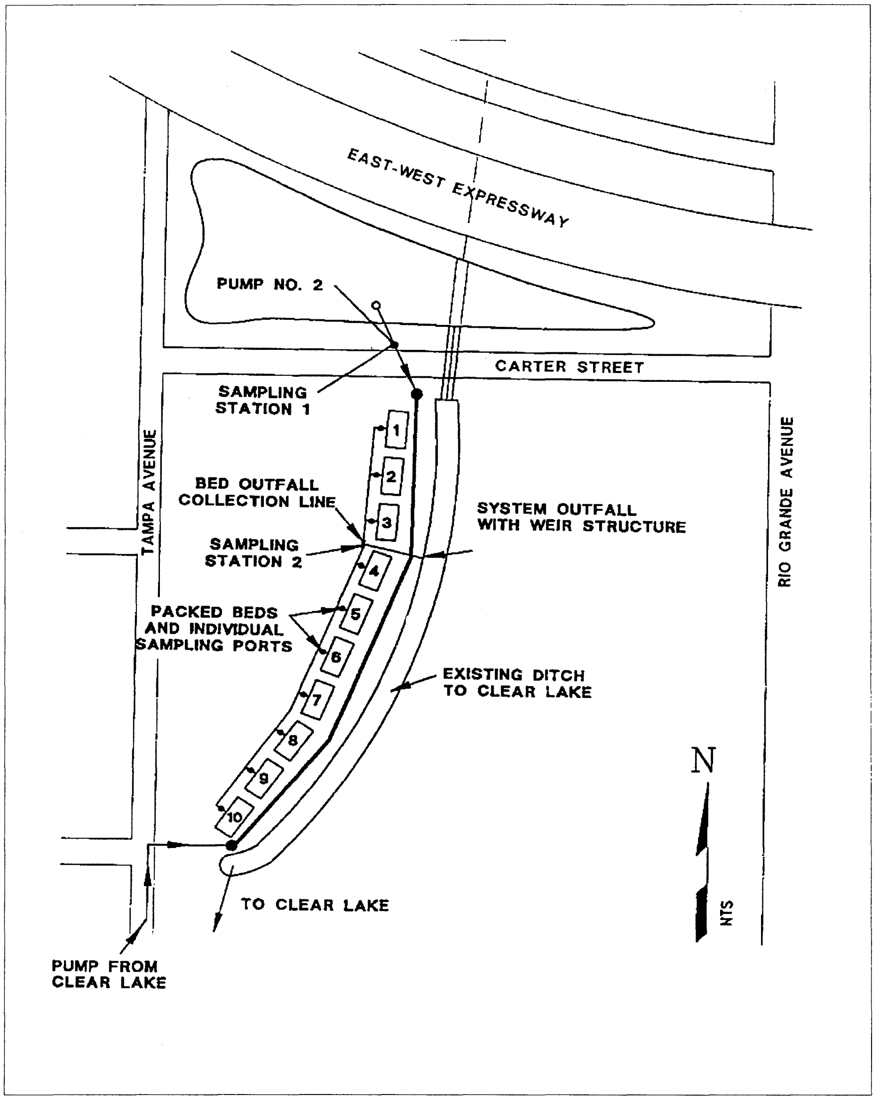


**Figure 66. Sampling locations (Dyer, Riddle, Mills, & Precourt, 1995)**

# 6. SELECTION OF BEST MANAGEMENT PRACTICES

## 6.1 INTRODUCTION

Agencies dealing with intense urban development and a high percentage of impervious areas are faced with new challenges in selecting cost-effective stormwater management alternatives to assist in implementing environmental protection and water quality goals and objectives. In many cases, controlling stormwater discharges in ultra-urban areas addresses multiple objectives and concerns. These concerns may include protection from flooding generated by highly impervious surfaces, protection of sensitive downstream conditions such as stream physical stability, or maintenance of in-stream water quality. To address these concerns comprehensively through the development of effective stormwater management alternatives, both structural and nonstructural practices may be considered.

Structural BMPs control runoff and improve water quality through storage, flow attenuation, infiltration, filtration, and biological degradation processes. Their use in the ultra-urban environment, however, generally requires deviations from standard designs to meet space limitations and other site restrictions. As these design modifications become significant, evaluation of the performance of the BMP in controlling stormwater runoff becomes increasingly subjective; available information on the performance of the BMPs might not be applicable. A BMP selection process must therefore weigh these and other concerns before making a final and often complex decision.

Nonstructural BMPs include planning, education, management, and operational procedures to prevent or mitigate impacts from stormwater runoff at the source. Areas with insufficient space, cost-prohibitive conditions, or in situations where the targeted water quality constituents are not effectively controlled using structural stormwater BMPs, may be appropriate applications for nonstructural BMPs.

In addition to weighing the options that structural and nonstructural BMPs offer, issues regarding the selection of stormwater management practices for retrofitting existing ultra-urban areas may include (1) the lack of space to construct on-site controls, (2) limited incentives due to a lack of specific regulatory requirements for retrofit situations, (3) difficulty in characterizing problem sources and their corresponding constituent loadings, (4) inconsistency in the reported performance of BMPs, (5) limited funding, and (6) limited experience with source control and prevention programs. Another challenging issue is the selection of compatible and complimentary combinations of BMPs consisting of both nonstructural and structural measures that cost-effectively maximize overall constituent load reduction.

In this chapter, a three-step decision-making process employing both quantitative and qualitative criteria for sequentially screening BMP alternatives is described. A preferred management alternative (a single BMP or a combination of BMPs) suited to site-specific conditions is the result of this process. This process builds on the knowledge and information summarized in previous chapters of this report and on other BMP selection processes reported in the literature (City of Portland, 1995; Claytor and Schueler, 1996; Driscoll and Mangarella, 1990; NVPDC, 1992; Schueler, 1987; Young et al., 1996).

## 6.2 THE ELEMENTS OF A BMP SELECTION PROCESS

The proposed BMP selection process is designed as a sequential approach that incorporates a series of checks and balances at each stage, integrates management objectives and site conditions, and relies on current knowledge of stormwater BMP technology and demonstrated experience and case studies. The process is designed to allow decisions to progress from a preliminary screening level to a more detailed evaluation and selection of candidate best management alternatives. The three steps of this selection process are illustrated in Figure 67 and include (1) a scoping phase, (2) an evaluation phase, and (3) a final selection phase. A brief description of the selection process within each phase is provided below.

The key processes used during the *scoping phase* consist of sequential elimination of nonapplicable structural and nonstructural options based on a predefined set of criteria. These criteria are derived from an in-depth understanding of the management objectives and the anticipated functional role of the BMP in preventing or controlling stormwater discharges. An understanding of site conditions, predominant sources or causes of the constituent release, and key processes governing the removal of constituents from stormwater is also essential to this process. Analysis in this phase results in a set of feasible BMPs that could potentially be used to completely or partially achieve the program objectives.

The *evaluation phase* consists of three types of analyses. First, the list of potential structural BMPs is further narrowed down using criteria derived from the physical characteristics of the site. Examples of physical site characteristics are drainage area, soil type and infiltration capacity, depth to groundwater, and site topography. Second, BMP effectiveness information is used to identify and rank BMPs with demonstrated performance in controlling targeted constituents in stormwater runoff. Design modification of BMPs for adaptation to the ultra-urban environment should be evaluated and the potential impact on performance considered. Third, combinations of the remaining nonstructural and structural BMPs should be evaluated for their compatibility and complimentary performance. The maintenance burden (e.g., frequency of cleanouts) should also be considered. Analyses performed in the evaluation phase result in management alternatives composed of either a single BMP, a combination of structural and nonstructural BMPs, or a combination of BMPs (multiple-BMP treatment train) to treat identified water quality problems.

The *final selection phase* consists of additional analysis of the management alternatives to refine the list of BMPs and BMP combinations developed in the *evaluation phase*. These analyses consist of (1) evaluation of cost and expected benefits associated with each management alternative; (2) evaluation of any additional benefits including aesthetics, recreational value, and habitat expansion; and (3) consideration of overall public acceptance and support. These analyses will result in the final selection of the preferred management alternative. For a successful BMP selection process, several supporting data collection activities are critical, as illustrated in Figure 67. Data collected include (1) available information on BMPs and their use in similar ultra-urban settings; (2) drainage area characteristics and qualitative evaluation of the sources and magnitude of constituents; (3) physical constraints at the site; (4) local cost elements including land acquisition, construction and maintenance cost; and (5) public acceptance and any additional benefits provided (e.g., aesthetics, recreational value).

## 6.3 THE SCOPING PHASE

The *scoping phase* provides an initial screening analysis of potential structural and nonstructural BMPs. Structural BMPs are generally designed to remove constituents in stormwater runoff, whereas nonstructural measures focus on the prevention of source-related constituent-generating activities from contaminating stormwater (e.g., covering salt piles) and on the removal of constituents that might contaminate stormwater (e.g., street sweeping). In the scoping phase, the ability of structural and nonstructural BMP options to meet management objectives is evaluated. The scoping phase may address the following questions:

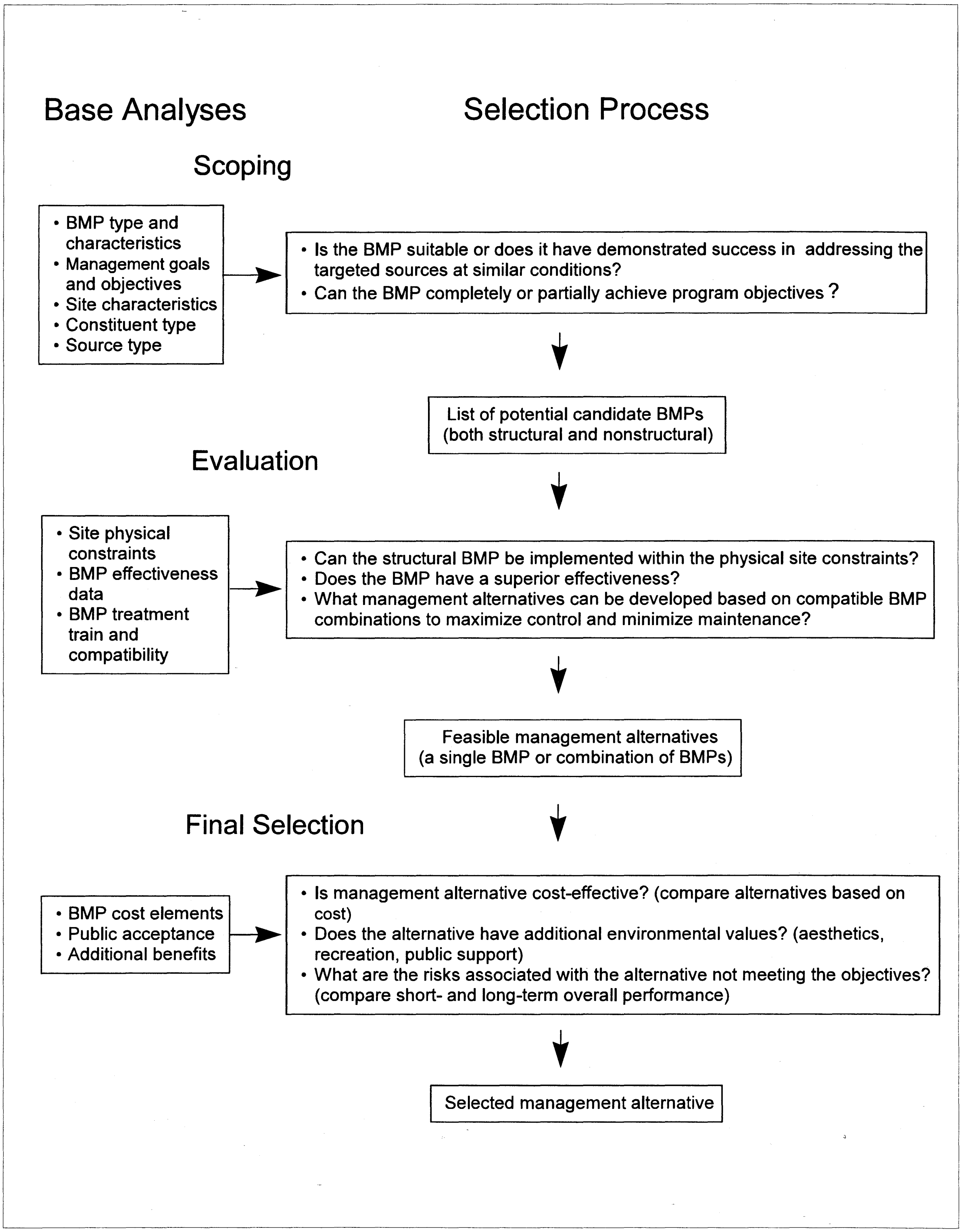


**Figure 67. Key phases of a BMP selection process**

- ✓ Does the BMP address one or more management objectives?
- ✓ Does the BMP provide both stormwater quantity and quality control?
- ✓ Are data available on BMP effectiveness?
- ✓ Is the BMP applicable to site conditions?
- ✓ Does the nonstructural BMP help to reduce long-term structural BMP maintenance requirements?
- ✓ Is the BMP costly to implement?
- ✓ Does the BMP provide auxiliary benefits such as public education?

A number of different factors are used to evaluate BMPs in the scoping phase. Management goals and objectives, the characteristics of the site (in terms of constituent sources and types and general site characteristics), and the characteristics of the BMP provide the framework for evaluating the applicability of both structural and nonstructural BMPs.

### 6.3.1 Management Goals and Objectives

An effective ultra-urban stormwater management program focuses on meeting well-defined environmental protection goals and public needs in a cost-effective manner. In many cases, an ultra-urban management plan is designed to address multiple environmental and safety concerns at various scales ranging from site-specific to a larger watershed scale. The development and implementation of stormwater management plans are driven by a variety of conditions including public pressure, applicable regulations and policies, downstream impacts on sensitive resources, or a combination of any of these conditions. Within these plans, downstream impacts are usually expressed qualitatively in terms of objective statements such as "control of flooding conditions", "control of stream degradation and associated sediment loadings", "restoration of a water quality impairment", or "protection of aquatic habitat".

Meeting these multiple objectives may require that several potential BMP siting locations be identified and considered. Potential BMPs can be determined for each site location to form a comprehensive management action plan. These selected BMPs, as well as the overall management actions (whether at the site-specific drainage area or at the watershed scale), will contribute to achieving the predefined management objective(s). An in-depth understanding of stormwater management objectives prior to the selection of a BMP or combination of BMPs is essential to the development of a successful management plan. This understanding should facilitate the development of management objectives into measurable indicators or criteria that can be used to screen out nonapplicable BMPs. Table 45 provides a set of potential screening criteria that can be derived for different management objectives.

Typical stormwater management objectives applicable to ultra-urban settings include:

1. Flood protection.
2. Reduction in loadings of nonpoint source constituents.
3. Measures for stabilization of downstream erosion to reduce sediment loading.
4. Aesthetic enhancement.
5. Public safety.
6. Reduced public facilities maintenance costs.
7. Provisions for recreation.

The numbers shown for each objective are included in the summary tables provided later in this chapter. The objectives provided here will be used to help illustrate which of these objectives may be achieved by the BMPs analyzed during the selection process.

### 6.3.2 Site Characterization

Site characterization includes evaluation of the drainage area to identify runoff and constituent-generating activities and sources, and characterization of the magnitude and the areal extent of each source. Several procedures can be used to assess loadings from ultra-urban areas (USEPA, 1983), including highway runoff in particular (Driscoll et al., 1990), and to define probable impacts on receiving water bodies. Chapters 2 and 4 of this document describe additional site characterization elements that can assist in evaluating the runoff potential and source-specific loading. Characterization of dominant sources and constituents, definition of the constituent fate and transport pathways, and identification of the method and processes by which constituents enter stormwater runoff are key elements supporting the selection of appropriate ultra-urban BMPs.

### 6.3.3 Screening of Structural BMPs

The screening of structural BMPs is intended to eliminate those BMPs that are obviously impractical, implausible, or ineffective. It is unlikely that any single BMP will be able to completely meet all management objectives; trade-offs between cost and performance almost always occur. Often, more than one BMP will be necessary. The resources and effort required to evaluate these trade-offs make it desirable to remove from consideration any BMPs that do not fulfill—or do not contribute significantly in combination with other BMPs to fulfilling—management objectives. The nature and scope of the planned project, water quantity and quality management objectives, and any other limiting management objectives should be used to evaluate the suite of available structural BMPs.

#### Nature and Scope of Planned Project

The nature of a proposed project in an ultra-urban area often dictates which BMPs are impractical due to size or settings. For example, the placement of an elevated highway over a busy roadway in an ultra-urban setting may present an opportunity to retrofit small stormwater BMPs into an existing drainage system. Developing the list of feasible BMP options for this site would begin with a recognition of its key features, which are (1) limited available surface area, (2) limited airspace between the original roadway and the elevated roadway, and (3) the need to sustain the

**Table 45. Example of how management objectives can be used to derive screening criteria**

| Overall Goal | Management Objective | Measure | Potential Evaluation Criteria |
|---|---|---|---|
| Environmental Protection | Control of nonpoint source pollution | Constituent loadings | Maximize percent load reductions |
| | Provide flood protection | Peak flow | Maintain peak flows at or lower than predevelopment conditions (generally 10- and 100-year storm event)<br>Protect floodplain areas from development |
| | Control stream stability problems downstream | Flow frequency<br>Flow duration | Reduce velocities and bottom shear stress below erosive levels<br>Reduce flow frequency and duration to mimic predevelopment levels |

existing operability of the roadway during BMP installation and maintenance. It would be inappropriate to install area-intensive BMPs like ponds and wetlands at this site, so these can be quickly screened from further consideration. Small BMPs such as infiltration trenches and water quality inlet devices could be considered potentially feasible at this point in the process.

Table 46 indicates which BMPs are most compatible with the ultra-urban setting because of their relatively small footprint, design adaptability, and effectiveness in removing typical constituents from stormwater. It should be noted that BMPs that may not be compatible with ultra-urban settings do have applicability for roadway projects in less urban and nonurban settings where larger land areas are available and greater flexibility in siting BMPs exists.

Table 47 provides the site considerations needed to evaluate the feasibility of various BMPs based on the nature and scope of proposed projects. This includes the percent of the drainage area that must be set aside for BMP installation and a consideration of whether the design is dependent on in situ soils. Both of these elements will impact on the screening of structural BMPs.

## Water Quantity and Quality Management Objectives

Local ordinances or state and federal regulations frequently mandate a design level of performance for both water quantity and quality

**Table 46. Primary function of BMPs and ability to address management objectives**

| BMP Types | Ultra-Urban Compatible | Water Quantity | Water Quality Constituent Removal Effectiveness | |
|---|---|---|---|---|
| | | | Suspended[1] | Dissolved[1] |
| Infiltration Trench | yes | no | ●●● | ●●○ |
| Infiltration Basin | no | yes | ●●● | ●●○ |
| Bioretention | yes | no | ●●● | ●●○ |
| Extended Detention Wet Pond | no | yes | ●●○ | ●●○ |
| Wet Pond | no | yes | ●●○ | ●●● |
| Extended Detention Dry Pond | no | yes | ●●● | ●●○ |
| Wetlands | no | no | ●●● | ●●● |
| Underground Detention Tanks | yes | yes | ○○○ | ○○○ |
| Underground Sand Filters | yes | no | ●●● | ●○○ |
| Surface Sand Filters | no | no | ●●○ | ●●● |
| Organic Media Filters | yes | no | ●●● | ●●● |
| Vegetated Swales | yes | no | ●●○ | ●●○ |
| Vegetated Filter Strips | no | no | ●○○ | ●○○ |
| Oil-Grit Separators | yes | no | ●○○ | ●○○ |
| Catch Basin Inserts | yes | no | ●○○ | ●○○ |
| Manufactured Systems | yes | no | ●○○ | ●○○ |
| Porous Pavement | yes | yes | ●○○ | ●●○ |

[1]Note: Suspended constituents include suspended solids as well as oil/grease, metals, nutrients, and trace organics associated with suspended solids. Dissolved constituents include soluble trace metals, nutrients, and trace organics.
○○○ = None, ●○○ = Low, ●●○ = Moderate, ●●● = High.

management. For example, a proposed highway project may be required to manage stormwater runoff such that the 25-year peak runoff rate does not exceed the preconstruction condition (Driscoll et al., 1990; Young et al., 1996). The required flood protection and water quantity management for the highway would not be provided by BMPs like oil-grit separators and vegetated filter strips. While these BMPs can facilitate the process of flood protection by providing pretreatment of sediment and other constituents, they alone cannot fulfill the flood protection objectives. BMPs that are obviously unable to fulfill dictated management objectives related to water quantity can be identified using the information in Table 46 as primarily water quality BMPs, and screened out from further consideration. BMPs that can be utilized for pretreatment are supplementary water quality management measures and can be retained for further evaluation.

Water quality control is usually defined by identified pollutants of concern and the desired level of removal expected. Typical constituents of concern associated with management objectives include nitrogen and phosphorus, suspended sediments, and trace toxics such as heavy metals. For highways, an in-depth listing of constituents and their sources can be found in Tables 48 and 49. Due to high levels of imperviousness and road density, stormwater from ultra-urban areas will likely contain similar constituent loadings. Loadings for some constituents, particularly those associated with

**Table 47. Site considerations for structural BMPs**

| BMP | Area Typically Served (ha) | Area Required for BMP[6] | In Situ Soils | Minimum Head Requirement[1] (m) | Configuration | Climate a Significant Factor?[2] |
|---|---|---|---|---|---|---|
| **Structural BMPs** | | | | | | |
| Infiltration Trench | 0.8-1.6 | 2-4% | dependent | 0.9-2.4 | off-line/on-line | Yes |
| Infiltration Basin | 0.8-8.0 | 2-4% | dependent | 0.9-1.2 | off-line | Yes |
| Bioretention | 0.4-20.0 | 4-10% | independent[3] | 0.6-1.2 | off-line/on-line | Yes |
| Detention Ponds | 0.8 min | 10-20% | independent | 0.9-1.8 | off-line/on-line | No |
| Wetlands | 0.4 min | 10% | dependent | 0.3-2.4 | off-line/on-line | Yes |
| Detention Tanks[4] | 0.4-0.8 | 0.5-1% | independent | 1.5-2.4 | off-line | No |
| Underground Sand Filters | 0.8-2.0 | 2-3% | independent | 0.3-2.4 | off-line | No |
| Surface Sand Filters | 0.8-2.0 | 2-3% | independent | 1.5-2.4 | off-line | Yes |
| Organic Media Filters | 0.8-2.0 | 2-3% | independent | 1.5-2.4 | off-line | Yes |
| Vegetated Swales | 0.8-1.6 | 10-20% | dependent | 0.6-1.8 | on-line | Yes |
| Vegetated Filter Strips | NA | 25%[5] | dependent | negligible | on-line | Yes |
| Oil-Grit Separators | 0.4-0.8 | <1% | independent | 0.9-1.8 | on-line | No |
| Catch Basin Inserts | < 0.4 | None | independent | 0.3-0.6 | on-line | None |
| Manufactured Systems | 0.4-4 | None | independent | 1.2 | on-line | None |
| Porous Pavement | 0.8-1.6 | NA | dependent | NA | NA | Yes |

Adapted from Claytor and Schueler, 1996; Young et al., 1996; and others.
NA = Not Applicable or Not Available
1 Either the depth of water in the typical design or the total drop in water level for flow-through designs.
2 Climate issues to consider include prolonged drought and freeze periods.
3 When equipped with an underdrain system.
4 Based on storage of 12.7 mm (0.5 in) of runoff per acre of imperviousness.
5 Minimum recommended for best treatment efficiency.
6 Expressed as a percent of the total drainage area, can be modified to accommodate ultra-urban conditions.

specialized commercial or industrial land use activities, however, may be significantly different. These specialized land use activities may include the introduction into stormwater of dissolved constituents that are more difficult to remove using structural BMPs.

Most structural BMPs rely on sedimentation and infiltration/filtration processes to remove constituents from stormwater. These practices may have a limited effect when dealing with dissolved and highly mobile constituents. The removal effectiveness of structural BMPs on a wide range of potentially harmful, primarily trace organic constituents is not known. Some structural BMPs such as wetland complexes may achieve the removal of dissolved nutrients through biochemical processes such as the nitrification of nitrate-nitrogen or through temporary storage of nutrients in plant tissue. Typical constituents of stormwater runoff, their primary transport phase and their control mechanisms are provided in Tables 48, 49, and 50. The ability of a structural BMP to meet constituent removal criteria depends on the removal mechanisms inherent in its design. Table 46 categorizes BMPs on their general ability to remove two broad categories of pollutants—suspended constituents and dissolved constituents. Suspended constituents include suspended solids as well as those constituents that can be removed by physical processes (e.g., sedimentation and filtration) including oil and grease, metals, nutrients, and trace organics associated with suspended solids.

Dissolved constituents that are predominately removed through adsorption and bio-chemical processes include the soluble phases of metals, nutrients, and trace organic constituents. The actual removal performance of individual BMPs will be highly dependent on their hydraulic design and the hydrologic conditions encountered during stormwater treatment. Screening out BMPs that are obviously ineffective for targeted pollutants facilitates the selection of an effective BMP. Detailed information on the demonstrated removal effectiveness of BMPs for specific constituents is provided in Table 51.

## Other Management Objectives

Initial screening of the suite of available BMPs can also be performed based on elements that are

**Table 48. Constituents and sources in highway runoff**

| Constituent | Source |
|---|---|
| Particulate | Pavement wear, vehicles, atmospheric deposition, maintenance activities |
| Nitrogen, Phosphorus | Atmospheric deposition and fertilizer application |
| Lead | Leaded gasoline from auto exhausts and tire wear |
| Zinc | Tire wear, motor oil, and grease |
| Iron | Auto body rust, steel highway structures such as bridges and guardrails, and moving engine parts |
| Copper | Metal plating, bearing and brushing wear, moving engine parts, brake lining wear, fungicides and insecticides |
| Cadmium | Tire wear and insecticide application |
| Chromium | Metal plating, moving engine parts, and brake lining wear |
| Nickel | Diesel fuel and gasoline, lubricating oil, metal plating, bushing wear, brake lining wear, and asphalt paving |
| Manganese | Moving engine parts |
| Cyanide | Anti-caking compounds used to keep deicing salts granular |
| Sodium, Calcium, Chloride | Deicing salts |
| Sulphates | Roadway beds, fuel, and deicing salts |
| Petroleum | Spill, leaks, antifreeze and hydraulic fluids, and asphalt surface leachate |

Source: Adapted from USEPA, 1993.

not related to the performance of the BMP. For example, fiscal management objectives such as providing stormwater management for a specified dollar amount or a percentage of the total project cost can serve as a means to remove high-cost BMPs from further consideration. Table 52 indicates the relative cost for various BMPs, and the BMP Fact Sheets (see Chapter 3) contain additional cost-estimating data that can be used to generate budgetary cost estimates. A final comparative analysis of costs for recommended BMP alternatives is completed in the final selection phase.

## 6.3.4 Screening Nonstructural BMPs

Nonstructural BMPs provide a flexible method of protecting water quality and improving water resources. Improper handling, use, and disposal of materials in an ultra-urban environment may generate a range of constituents that can contaminate nearby waterways. Contamination of stormwater runoff can often be prevented through the use of nonstructural BMPs, such as covering deicing materials, employee training, and minimizing the use of hazardous products. This is particularly true for a wide range of potentially harmful trace organic constituents that can be prevented from contaminating stormwater through the implementation of nonstructural BMPs. An added benefit to their use is that maintenance requirements for downstream structural BMPs may be reduced.

Nonstructural measures can include activities ranging from pesticide and fertilizer management to chemical storage practices (Young et al., 1996). The nonstructural BMPs that can be applied in both ultra-urban and highway areas can be grouped into six general categories:

- Litter and debris control.
- Education and training.
- Landscaping and vegetated practices.
- Chemical handling and storage.
- Containment and diversion.
- Pesticide and fertilizer management.

The methods or techniques that fall under these categories can be implemented to address constituents at a variety of spatial scales for a specific site or at community or watershed scales. In addition, nonstructural BMPs have little, if any, space requirements, making their use ideal for ultra-urban areas. Screening procedures for nonstructural BMPs require an

**Table 49. Constituents of highway runoff, ranges of average values reported in the literature**

| Constituent | Concentration (mg/L unless indicated) | Load (kg/ha/year) | Load (kg/ha/event) |
|---|---|---|---|
| Solids | | | |
| Total | 437 - 1147 | | 58.2 |
| Dissolved | 356 | 148 | |
| Suspended | 45 - 798 | 314 - 11,862 | 1.84 - 107.6 |
| Volatile, dissolved | 131 | | |
| Volatile, suspended | 4.3 - 79 | 45 - 961 | .89 - 28.4 |
| Volatile, total | 57 - 242 | 179 - 2518 | 10.5 |
| Metals (totals) | | | |
| Zinc | .056 - .929 | .22 - 10.40 | .004 - .025 |
| Cadmium | ND - .04 | .0072 - .037 | .002 |
| Arsenic | .058 | | |
| Nickel | .053 | .07 | |
| Copper | .022 - 7.033 | .030 - 4.67 | .0063 |
| Iron | 2.429 - 10.3 | 4.37 - 28.81 | .56 |
| Lead | .073 - 1.78 | .08 - 21.2 | .008 - .22 |
| Chromium | ND - .04 | .012 - 0.10 | .0031 |
| Magnesium | 1.062 | | |
| Mercury, x $10^3$ | 3.22 | .007 | .0007 |
| Nutrients | | | |
| Ammonia, total as N | .07 - .22 | 1.03 - 4.60 | |
| Nitrite, total as N | .013 - 2.5 | | |
| Nitrate, total as N | .306 - 1.4 | | |
| Nitrite + nitrate | 0.15 - 1.636 | .8 - 8.00 | .078 |
| Organic, total as N | .965 - 2.3 | | |
| TKN | 0.335 - 55.0 | 1.66 - 31.95 | .17 |
| Nitrogen, total as N | 4.1 | 9.80 | .02 - .32 |
| Phosphorus, total as P | .113 - 0.998 | .6 - 8.23 | |
| Miscellaneous | | | |
| Total coliforms organisms/100 mL | 570 - 6200 | | |
| Fecal coliforms organisms/100 mL | 50 - 590 | | |
| Sodium | | 1.95 | |
| Chloride | | 4.63 - 1344 | |
| Total organic carbon | 24 - 77 | 31.3 - 342.1 | .88 - 2.35 |
| Chemical oxygen demand | 14.7 - 272 | 128 - 3868 | 2.90 - 66.9 |
| Biological oxygen demand (5 day) | 12.7 - 37 | 30.60 - 164 | 0.98 |
| Polyaromatic hydrocarbon (PAH) | | .005 - .018 | |
| Oil and grease | 2.7 - 27 | 4.85 - 767 | .09 - .16 |

Source: Barrett, et al., 1995.

**Table 50. General transport and BMP removal processes for selected constituents**

| Constituents | Primary Transport Phase(s) | Primary Control Mechanisms |
|---|---|---|
| Suspended Solids (TSS, VSS) | Particulate | Sedimentation (adsorption, settling, precipitation)<br>Physical filtration |
| Nutrients (TP, OP, TKN, $NH_3$,,$NO_3$) | Particulate/Dissolved | Sedimentation<br>Physical filtration<br>Adsorption<br>Bioaccumulation |
| Trace Metals ( Zn, Cd, As, Ni, Cu, Pb, Cr ) | Particulate/Dissolved | Sedimentation<br>Physical Filtration<br>Adsorption |
| Trace Organics (PAHs) | Particulate/Dissolved | Sedimentation<br>Physical filtration<br>Adsorption<br>Biodegradation |
| Oil and Grease | Particulate | Adsorption<br>Filtration<br>Sedimentation<br>Biodegradation |
| Bacteria (Total, Fecal) | Particulate | Physical filtration<br>Sedimentation<br>Decay (die-off) |

analysis of specific constituent-generating activities or practices within a drainage area that may contribute constituents to stormwater and an assessment of their ability to qualitatively meet management objectives if controlled.

## Analysis of Constituent-Generating Activities

The analysis of constituent-generating activities in a drainage area focuses on the feasibility of practices that avoid the exposure of any potential constituent-generating activity to stormwater. These practices may reduce the need for any structural treatment BMP by altering, enclosing, covering, or segregating the activity. Many industrial facilities include this analysis in their Storm Water Pollution Prevention Plans required for NPDES permits (see Section 3.9, *Other Nonstructural BMPs*). A flow chart that identifies constituent pathways, and both existing and potential management measures is a useful tool to help identify and assess potential nonstructural BMPs. Each nonstructural BMP, for example, uses a specific constituent removal process or mechanism. For nonstructural BMPs, the processes or mechanisms used to remove constituents include:

- *Prevention* (elimination) of an activity (e.g., pesticide use).
- *Change in process* to minimize the constituent loss (e.g., optimize salt application).
- *Segregation* of the constituent from the stormwater runoff to prevent its loss (e.g., berms to control spills).
- *Education and training* about the proper use and disposal of materials (e.g., employee training programs).

Table 53 provides a listing of potential nonstructural BMPs and their associated constituent removal processes.

## Table 51. Pollutant removal effectiveness (%)

| BMP | TSS | TP | TN | $NO_3$ | Metals | Bacteria | Oil & Grease | TPH | References |
|---|---|---|---|---|---|---|---|---|---|
| Infiltration Trench[1] | 75-99 | 50-75 | 45-70 | NA | 75-99 | 75-98 | NA | 75 | Young et al. (1996) |
| Infiltration Basin[1] | 75-99 | 50-70 | 45-70 | NA | 50-90 | 75-98 | NA | 75 | Young et al. (1996) |
| Bioretention[1] | 75 | 50 | 50 | NA | 75-80 | NA | NA | 75 | Prince George's County (1993) |
| Detention Ponds | 46-98 | 20-94 | 28-50 | 24-60 | 24-89 | NA | NA | NA | City of Austin (1990); City of Austin (1995); Harper & Herr (1993); Gain (1996);Martin & Smoot (1986);Young et al. (1996); Yu & Benelmouffok (1988); Yu et al. (1993 & 1994) |
| Wetlands | 65 | 25 | 20 | NA | 35-65 | NA | NA | NA | USEPA (1993) |
| Detention Tanks | NA | NA | NA | NA | NA | NA | NA | NA | |
| Underground Sand Filters | 70-90 | 43-70 | 30-50 | NA | 22-91 | NA | NA | NA | Bell et al. (1995); Horner & Horner(1995); Young et al. (1996) |
| Surface Sand Filters | 75-92 | 27-80 | 27-71 | 0-23 | 33-91 | NA | NA | NA | City of Austin (1990); Welborn & Veenhuis (1987) |
| Organic Media Filters | 90-95 | 49 | 55 | NA | 48-90 | 90 | 90 | 90 | Claytor and Schueler (1996); Stewart (1992); Stormwater Management (1994) |
| Vegetated Swales | 30-90 | 20-85 | 0-50 | NA | 0-90 | NA | 75 | NA | City of Austin (1995); Claytor and Schueler (1996); Kahn et al. (1992); Yousef et al. (1985); Yu & Kaighn (1995); Yu et al. (1993 & 1994) |
| Vegetated Filter Strips | 27-70 | 20-40 | 20-40 | NA | 2-80 | NA | NA | NA | Yu and Kaighn (1992); Young et al. (1996) |
| Oil-Grit Separators | 20-40 | <10 | <10 | NA | <10 | NA | 50-80 | NA | Young et al. (1996) |
| Catch Basin Inserts | NA | NA | NA | NA | NA | NA | up to 90 | NA | King County (1995) |
| Manufactured Systems | NA | NA | NA | NA | NA | NA | up to 96 | NA | Bryant et al. (1995) |
| Porous Pavement | 82-95 | 60-71 | 80-85 | NA | 33-99 | NA | NA | NA | MWCOG (1983); Hogland et al. (1987); Young et al. (1996) |

NA = Not Applicable or Not Available. Removal efficiencies may be based on either mass balance or average concentration calculations. The values may originate from evaluation of multiple events or from long-term monitoring. Ranges are provided wherever possible.

[1] Based on capture of 12.7 mm (0.5 in) of runoff volume. Effectiveness directly related to volume of captured runoff.

**Table 52. Relative rankings of cost elements and effective life of structural BMP options**

| BMP | Capital Costs | O&M Costs | Effective Life[1] |
|---|---|---|---|
| Infiltration Trench | Moderate to High | Moderate | 10-15 years |
| Infiltration Basin | Moderate | Moderate | 5-10 years before deep tilling required |
| Bioretention | Moderate | Low | 5-20 years[2] |
| Detention Ponds | Moderate | Low | 20-50 years |
| Wetlands | Moderate to High | Moderate | 20-50 years |
| Detention Tanks | Moderate to High | High | 50-100 years |
| Underground Sand Filters | High | High | 5-20 years |
| Surface Sand Filters | Moderate | Moderate | 5-20 years |
| Organic Media Filters | High | High | 5-20 years |
| Vegetated Swales | Low to Moderate | Low | 5-20 years |
| Vegetated Filter Strips | Low | Low | 20-50 years |
| Oil-Grit Separators | Moderate | High | 50-100 years |
| Catch Basin Inserts | Low | Moderate to High | 10-20 years |
| Manufactured Systems | Moderate | Moderate | 50-100 years |
| Porous Pavement | Low | Moderate | 15-20 years |

Adapted from Young et al. (1996); Claytor and Schueler (1996); USEPA (1993); and others
NA = Not Applicable or Not Available
[1] Assumes regular maintenance, occasional removal of accumulated materials, and removal of any clogged media.
[2] As a relatively new BMP, the effective life is uncertain. It is reasonable to assume an effective life at least as long as a vegetated swale.

## Ability to Meet Management Objectives

Potential nonstructural BMPs are also screened on their ability to achieve management objectives. This can be done on an individual or combined basis. Table 53 illustrates the nonstructural BMPs that have the potential to address the seven management objectives identified previously (see Section 6.3.1).

### Management Objectives for Ultra-Urban Areas

Due to chronic flooding and excess constituent loadings from stormwater within a highly urbanized section of the Lake Olive, Florida, drainage basin, the city of Orlando proposed to divert a portion of the stormwater runoff to nearby Lake Lawsona. In addition to this diversion, the city requested that a system be developed and designed that could provide both underground storage and treatment of the stormwater to reduce constituent loads entering Lake Lawsona (Dyer, Riddle, Mills, & Precourt, 1996).

## Table 53. Nonstructural BMPs and their constituent removal mechanisms

| BMP | Removal Mechanism | Management Objectives Addressed[1] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **Ultra-Urban Areas** | | | | | | | | |
| **Litter and Debris Control** | | | | | | | | |
| Property maintenance | Process | | ●○ | | | ●○ | ●○ | ●○ |
| Proper dumpster placement | Segregation | | ●● | | | ●● | | ●● |
| Parking lot sweeping | Process | | ●● | ●○ | ●○ | ●○ | | ●● |
| Frequent storm drain maintenance | Process | | ●○ | | | | ●○ | |
| Stream cleanups | Process | ●○ | ●○ | ●○ | ●● | ●○ | ●○ | |
| **Education and Training** | | | | | | | | |
| Storm drain stenciling | Education<br>Prevention | | ●○ | | | | | ●● |
| Employee education | Education | | ●○ | | | | ●○ | ●● |
| **Landscaping/Vegetated Practices** | | | | | | | | |
| Landscaping/groundskeeping programs | Process | | ●● | | | ●○ | | ●○ |
| **Chemical Handling and Storage** | | | | | | | | |
| Covered raw material storage | Prevention | | ●● | | | ●○ | ●○ | ●○ |
| Hazardous materials handling and disposal | Prevention | | ●● | | | | ●○ | ●○ |
| Spill control plans | Process | | ●● | | | | ●● | |
| Proper hazardous materials and chemical storage | Process | | ●● | | | | ●● | ●○ |
| **Containment and Diversion** | | | | | | | | |
| Covered fueling stations | Prevention | | ●● | | | | | |
| Loading dock covers and proper location | Prevention | | ●● | | | | | |
| Elimination of non-stormwater discharges and connections | Process | | ●● | | | | ●○ | |
| **Highways** | | | | | | | | |
| **Litter and Debris Control** | Segregation | | | | | | | |
| Road maintenance | Process | | ●● | ●○ | | ●○ | | |
| Street sweeping | Process | | ●● | ●○ | ●○ | ●○ | | |
| Adopt-A-Road program | Process | | | ●○ | | ●○ | | ●● |
| Adopt-A-Stream program | Process<br>Education | ●○ | ●○ | ●○ | ●○ | ●○ | ●○ | ●● |
| **Pesticide/Fertilizer Management** | | | | | | | | |
| Pesticide application control | Process<br>Education | | ●● | | | | ●○ | ●● |
| **Landscaping/Vegetated Practices** | | | | | | | | |
| Mowing reduction | Process | | ●○ | | ●● | ●○ | | ●● |
| **Containment and Diversion** | | | | | | | | |
| Sediment and erosion control | Process | ●○ | ●● | ●● | | ●○ | | |
| **Chemical Handling and Storage** | | | | | | | | |
| Road salt application and storage | Process | | ●● | | | ●○ | ●○ | ●○ |
| Municipal fleet maintenance | Process | | ●● | | | | | |
| Proper hazardous materials use storage | Process | | ●● | | | | ●○ | ●○ |

[1](1) Flood protection, (2) Water quality, (3) Stream stability, (4) Recreation, (5) Aesthetics, (6) Public safety, (7) Cost.
●○ = Possible, ●● = Likely.

## 6.4 EVALUATION PHASE

The evaluation phase provides a more detailed process to evaluate the ability of structural and nonstructural BMPs to meet management objectives. This process results in a final list of BMP options that can be ranked to optimize selection. Questions that should be asked during the evaluation phase include:

- ✓ Do any structural or nonstructural BMPs have limited constituent removal effectiveness?
- ✓ Is there one (or more) structural or nonstructural BMPs that outperform other BMPs?
- ✓ Is a combination of structural and nonstructural BMPs warranted?

### 6.4.1 Evaluation of Structural BMPs

In the evaluation phase, a detailed analysis of the physical characteristics of the site will generate criteria for evaluating the constructability and feasibility of various structural BMPs. The effectiveness of the BMP in meeting management objectives for water quantity or quality control can be evaluated, along with any requirements for pretreatment that may increase the cost of the BMP.

Criteria for constructability include:

- ▫ Site soils and topographic features. (Infiltration trenches typically require soils with an infiltration rate at least 12.7 mm/h [0.5 in/h].)
- ▫ Depth to groundwater and bedrock. (Bioretention facilities require at least 1.8 m [6 ft].)
- ▫ Land area commitments and availability of open space. (Detention ponds typically require 10 to 20 percent of the total drainage area.)
- ▫ Site slope and hydraulics features. (Wetlands require very mild slopes to facilitate long residence times.)
- ▫ Existing stormwater drainage pathways, storm drains, swales, etc. (Inverts of existing drainage pathways establish the minimum discharge elevation of any retrofit BMP.)

**BMP Selection Based on Physical Site and Treatment Effectiveness**

A prototype of a compost stormwater treatment facility (CSF) was constructed in Washington County, Oregon. The avenue was widened in 1987 to five lanes with additional bike lanes and sidewalks. An existing water quality swale that was constructed prior to the road widening was determined inadequate to treat the additional stormwater runoff (the swale acted as a pretreatment for a wetland pond that drained into Beaverton Creek). The compost filter was selected based on its ability to be retrofitted into the existing water quality swale, and its widely reported ability for adsorbing heavy metal, oils, greases, nutrients, and organic toxins (Stormwater Management, 1994).

Effectiveness criteria include:

- ▫ Stormwater quantity control and constituent removal effectiveness.
- ▫ Effective integration with other BMPs and stormwater management efforts.

There are several good sources available for detailed design and construction procedures and information, which can assist in evaluation of structural BMPs. These sources include *Design of Stormwater Filtering Systems* (Claytor and Schueler, 1996); *Evaluation and Management of Highway Runoff Water Quality* (Young et al., 1996); *Urban Drainage Design Manual Hydraulic Engineering Circular 22* (Brown et al., 1996); and *Retention, Detention, and*

*Overland Flow for Pollutant Removal from Highway Stormwater Runoff; Volume II: Design Guidelines* (Dorman et al., 1996b). Design specifications for new, commercially available BMPs can be obtained from their manufacturers along with information on installation or construction procedures.

## Constructability

Of the two broad categories of evaluation, criteria related to construction will probably have a stronger influence on the selection of structural BMPs in an ultra-urban setting. Screening potential BMPs based on construction issues requires significant effort to collect and then to evaluate site-specific information on the proposed site. Most of the required information is available from sources like USDA soil surveys, USGS topographic maps, and roadway feasibility studies. To evaluate BMPs and determine the feasibility of their use for a specific site requires information regarding:

- The topography of the drainage area and the proposed general location of the BMP (vertical contours of less than 1.5 m [5 ft] is preferred).
- Estimates of the volume of stormwater runoff to be managed for water quality and quantity.
- Local information on any existing stormwater drainageways, including, where possible, information on open channel and storm drain size and inverts.
- Information on soils in the vicinity of the proposed BMP.
- Depth to bedrock and seasonal high groundwater levels.
- General information on utility rights-of-way and land ownership.

This information can be used to eliminate structural BMPs that are not feasible based on the existing site conditions. It also can be used to estimate the preliminary design size for each remaining candidate BMP. This preliminary design size may then be used to confirm whether the BMP will meet management objectives and whether a detailed design for the BMP should be considered. This highly iterative process may entail visits to the BMP site, division and redivision of the drainage area, and evaluation of local features and their spatial relationships in order to determine the feasibility of different structural BMP options.

It is recommended that the preliminary size of candidate BMPs be determined based on assumptions about the runoff volume from the estimated impervious surface area contributing to the BMP. For water quality BMPs, this usually means management of a volume resulting from either the water quality storm (e.g., the 1-year event) or a designated water quality depth (e.g., 12.7 mm [0.5 in] of runoff). For BMPs focused on water quantity management, this means management of a runoff volume originating from a design rainfall event (e.g., the 10-year rainfall event). For water quality and quantity BMPs, a tentative size can be estimated by assuming that all rainfall contacting the estimated impervious surface area will become runoff, all of which must be managed in the BMP. With the water quality or quantity volume, it is possible to make a first-cut estimate of the surface footprint of the BMP. For example, the surface area of a detention pond or infiltration trench can be estimated based on the runoff volume and other site information such as the depth to bedrock. Or, the surface area of an infiltration basin can be established based on the runoff volume and the general infiltration rate of the local soils. Concurrently, the surface footprint of candidate BMPs can be used to judge whether the required surface relief is present to incorporate the BMP into existing drainage ways or storm drains. Many BMPs require several feet of hydraulic drop between the BMP and any downstream outlet (Table 47). Too much or too little surface relief will prevent installation of a BMP either because the BMP cannot be tied into the existing network or because it physically cannot be constructed on the site. With approximate dimensions of candidate BMPs, it is possible to see which BMPs will fit within the existing drainage way and utility rights-of-way.

Evaluation of readily available information on the candidate project and on-site visits to assess conditions usually are sufficient to determine which BMPs are feasible. In considering a BMP, it is important to recognize that incorporating access for BMP maintenance and standard design slopes for earthwork (e.g., 3 vertical to 1 horizontal) will probably increase the required BMP surface area over that estimated as part of the preliminary design.

## Effectiveness

Effectiveness issues considered in the evaluation phase relate to management of both water quantity and water quality. In assessing constructability, it might be determined that no single BMP can fully satisfy the management objectives for both runoff quantity and quality. As a result, consideration of off-site management (e.g., management in a regional facility) might be necessary. Evaluation of site characteristics might demonstrate that it is best to manage stormwater runoff water quality on site and provide stormwater control for flood protection off site. For this reason, BMPs are frequently used in combinations of two or more; designers must determine how candidate BMPs will interact with other existing stormwater controls. For example, the designer would need to consider how a section of porous pavement will decrease the required size of a downstream infiltration trench, which also affects inflows to a downstream wet pond.

To determine which candidate BMPs will effectively remove stormwater constituents of concern, an in-depth review of prior monitoring study reports would be beneficial. In this way candidate BMPs with a history of solid performance for the pollutants of concern in locations or situations similar to the proposed project can be identified. A review of applicable monitoring studies will also help identify which BMPs may require special features (e.g., flow equalization basins) that will impose an additional cost on implementation.

The Fact Sheets provided in Chapter 3 will help designers identify any pretreatment recommendations or requirements, or seasonal limits that exist for candidate BMPs. For example, a BMP might have limited effectiveness without forebays or a presettling area or might fail to work during prolonged periods of drought or extreme climatic conditions. An in-depth understanding of the operational environment of candidate BMPs will probably decrease the number of potential candidates requiring further evaluation.

For example, assume initial screening of structural BMP options for an ultra-urban site has resulted in a list of possible BMPs that include an underground sand filter, a vegetated rock filter, and a multi-chambered treatment train (MCTT). The primary constituents of concern for water quality treatment are total suspended solids (TSS), total phosphorous (TP), and zinc. A review of ultra-urban BMP monitoring studies identifies the removal efficiencies reported in the

### BMP Selection Based on Site Characterization

The Alaska Marine Lines site, in Seattle, Washington, is an L-shaped property that fronts two waterways. The site was redeveloped to ship, handle, and store cargo containers. Due to the large amount of vehicular and forklift traffic in and around the cargo-handling area, the site was characterized as having high concentrations of petroleum-based contaminants. Sand filters were selected for stormwater treatment based on their proven ability to handle petroleum-based contaminants washed from paved surfaces. In addition, because limited area for the terminal required paving and using the entire upland area available, the sand filter system offered an effective and practical alternative to other BMP designs. Sand filters were conveniently sited along the perimeter of the L-shaped property to treat stormwater runoff entering the Duwamish Waterway (Horner and Horner, 1995).

literature for the constituents and BMPs of interest (Table 54).

Assume the objective is to achieve a minimum of 50 percent removal efficiency for all constituents. Though the performance of the MCTT for phosphorus removal has not been established it is projected to be in the range of 70 percent. Based on this, the MCTT might be eliminated from further consideration or weighted differently than the other BMPs that have a proven record of performance.

As another example, assume a 4 ha (10 ac) redevelopment site located in the downtown of a major metropolitan area. The receiving water is a "brackish" waterbody that is phosphorus limited. The site is located over historic tidal wetlands (now fill) and the site terrain is flat. The proposed redevelopment project will cover 90 percent of the site with building and parking (surface parking is proposed for 10 percent of the site area). State water quality regulations require 80 percent removal of total suspended solids and 50 percent removal of total phosphorus.

The initial scoping analysis determined that water quantity (flooding and channel protection) was not a management goal, that nutrient load and sediment removal were the primary management objectives for controlling nonpoint source pollutants, and that the site was not considered a "hotspot." The BMPs eliminated during the broad scoping analysis were the ponds, wetlands, and the underground storage tank. The remaining BMP groups are the swales, bioretention, sand filters, organic media filters, vegetated filter strip, infiltration trench, oil/grit separator, catch basin inserts, and some of the manufactured systems.

Because the project site lies over an historic tidal wetland that was filled in the last century, infiltration is not feasible. The site's open space area is severely restricted by the proposed project so the BMPs that consume larger surface areas would not be practical. This site restriction excludes the swales, surface sand filter, bioretention, and vegetated filter stip. The remaining BMPs are the underground sand filter, the organic media filter, oil/grit separator, catch basin inserts, and some of the manufactured systems.

The pollutant removal capability of the oil/grit separator, catch basin inserts, and the manufactured systems will eliminate them from further consideration for a stand-alone BMP. However, these practices can be considered for pre-treatment for other BMPs. The remaining structural practices include the underground sand filter and the organic media filter.

**Table 54. Mass-balance pollutant removal efficiencies for constituents and BMPs of interest**

| BMP | Study Location | Land Use | Mass-Balance Removal Efficiency (%) | | |
|---|---|---|---|---|---|
| | | | TSS | P | Zinc |
| Underground Sand Filter | Virginia[1] | Parking Lot | 79 | 63 | 91 |
| Vegetated Rock Filter | Florida[2] | Industrial | 92[4] | 87[4] | 63[4] |
| MCTT | Alabama[3] | Parking Lot | 83 | N/A | 91 |

[1] Bell et al. (1995).
[2] DRMP (1995).
[3] Pitt (1996).
[4] Median of several reported values.

## 6.4.2 Evaluation of Nonstructural BMPs

In the evaluation phase, limited information is available to characterize the improvements nonstructural controls may provide to the quality of receiving waterbodies. Although there is not an extensive body of information demonstrating the effectiveness of nonstructural BMPs, a significant reduction in nonpoint source constituent loads can often be achieved by controlling their sources.

Information does, however, exist for some nonstructural BMPs such as street sweeping (see Chapter 3) while other nonstructural BMPs can be evaluated through programmatic assessments. For example, an annual analysis of the frequency of vehicle maintenance, reduction in metric tons of salt applied per snow event, and percent of loading docks covered in a drainage area can all be used to determine the "effectiveness" of nonstructural BMP implementation. Further analysis of nonstructural BMPs must by necessity rely on qualitative assessments. Table 55 provides qualitative constituent removal information on selected nonstructural BMPs and on their ability to improve the functioning of structural BMPs. Information from this table can be used to further refine the list of feasible nonstructural BMPs by eliminating those that do not provide stormwater constituent removal for particular constituents of concern. For example, if the primary constituents of concern generated from a drainage area are oil and grease, nonstructural BMPs such as landscaping and ground maintenance programs and covered raw material storage, among others, can be eliminated from further consideration.

## 6.4.3 Multiple BMP Treatment Train

A multiple BMP treatment train is a combination of BMPs to treat water quality problems. The ability of a nonstructural BMP to remove specific constituents prior to contamination of stormwater makes them ideal for combining with and enhancing the effectiveness of structural BMPs. Nonstructural and structural BMPs can be used together and structural BMPs can be combined in an ultra-urban environment to optimize pollution control. Once the structural BMP selection process has produced a narrowed set of options, the feasibility of their combination with selected nonstructural BMPs can be evaluated. The result of this analysis might be a BMP or group of BMPs specifically grouped to address the ultra-urban area in question. Nonstructural BMPs can enhance the performance of structural BMPs by preventing the entry of constituents that are difficult for structural BMPs to remove, and/or reducing the structural BMP maintenance requirements. As illustrated in Table 55, only 10 out of the listed 25 nonstructural BMPs can provide the added benefit of reducing structural BMP maintenance.

To determine whether one BMP or multiple BMPs are necessary, a few management questions should be addressed:

- ✓ Does any one BMP meet all of the stormwater management objectives?
- ✓ Does a structural BMP meet all of the objectives?
- ✓ To what degree does a structural BMP meet the objectives?
- ✓ Can an existing structural BMP be retrofitted to increase its effectiveness?
- ✓ Does a nonstructural BMP meet all of the objectives?
- ✓ To what degree does a nonstructural BMP meet the objectives?
- ✓ Can an existing nonstructural BMP or nonstructural BMP management program be modified or enhanced to increase its effectiveness?
- ✓ Does a nonstructural BMP improve the performance of a structural BMP?
- ✓ Does a nonstructural BMP reduce the maintenance requirements of a structural BMP?

## Table 55. Nonstructural BMP constituent removal effectiveness

| BMP | May Provide Stormwater Constituent Removal[1] | | | | | | | Provides Direct Pre-Treatment for Structural BMP | Reduces Maintenance Requirements for Structural BMP |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | |
| **Ultra-Urban Areas** | | | | | | | | | |
| **Litter and Debris Removal** | | | | | | | | | |
| Property maintenance | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Y | Y |
| Proper dumpster placement | | | ✓ | | ✓ | | ✓ | Y | Y |
| Stream Clean-ups | | | ✓ | ✓ | ✓ | | ✓ | N | N |
| Frequent storm drain maintenance | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | Y | Y |
| Parking lot sweeping | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Y | Y |
| **Education and Training** | | | | | | | | | |
| Storm drain stenciling | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Y | N |
| Employee education | ✓ | | ✓ | | ✓ | | | N | N |
| **Landscaping and Vegetated Practices** | | | | | | | | | |
| Landscaping/Grounds keeping programs | ✓ | ✓ | ✓ | | | ✓ | ✓ | Y | Y |
| **Containment and Diversion** | | | | | | | | | |
| Covered fueling stations | | ✓ | ✓ | ✓ | ✓ | | ✓ | Y | N |
| Covered raw material storage | | ✓ | ✓ | | | | ✓ | Y | Y |
| Elimination of non-stormwater discharges and connections | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Y | N |
| Loading dock covers and proper location | | ✓ | ✓ | ✓ | ✓ | | ✓ | Y | N |
| **Chemical Handling and Storage** | | | | | | | | | |
| Hazardous materials handling and disposal | | | | ✓ | ✓ | ✓ | ✓ | Y | N |
| Proper hazardous materials and chemical storage | | | | ✓ | ✓ | ✓ | ✓ | Y | N |
| Spill control plans | | | | ✓ | ✓ | ✓ | ✓ | Y | N |
| **Highways** | | | | | | | | | |
| **Litter and Debris Control** | | | | | | | | | |
| Road maintenance | | ✓ | ✓ | ✓ | ✓ | | | Y | Y |
| Street sweeping | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | Y | Y |
| Adopt-A-Road program | | | ✓ | | | | | Y | Y |
| Adopt-A-Stream program | | | ✓ | ✓ | ✓ | | | N | N |
| **Pesticide and Fertilizer Application** | | | | | | | | | |
| Pesticide application control | | | | | | ✓ | ✓ | Y | N |
| **Landscaping and Vegetation Practices** | | | | | | | | | |
| Mowing reduction | ✓ | ✓ | | ✓ | | | | N | N |
| **Chemical Handling and Storage** | | | | | | | | | |
| Road salt application and storage | | ✓ | | | | | ✓ | Y | N |
| Municipal fleet maintenance | | | | ✓ | ✓ | | | Y | N |
| Proper hazardous materials use and storage | | | | ✓ | | ✓ | ✓ | Y | N |
| **Containment and Diversion** | | | | | | | | | |
| Sediment and erosion control | ✓ | ✓ | | ✓ | | | | Y | Y |

[1](1) Nutrients, (2) Suspended solids, (3) Trash, (4) Trace metals, (5) Oil and grease, (6) Trace organics, (7) Other.

The preferred management strategy is to use nonstructural BMPs to prevent stormwater contamination rather than have to manage and treat stormwater runoff; source elimination is equal to 100 percent removal effectiveness. If the pollutant source cannot be controlled, however, the effectiveness of an appropriate nonstructural management technique to reduce its losses can be evaluated. The type of nonstructural BMP and associated pollutants controlled will dictate the need for additional pretreatment or treatment controls provided through structural BMPs. For example, if a nonstructural BMP, such as parking lot sweeping, effectively prevents some particulates from entering stormwater, a structural pretreatment facility like a vegetated filter strip might not be necessary. As another example, implementing a street sweeping program according to specifications (refer to Chapter 3), may reduce 55 to 93 percent of dust, dirt, and particulate build-up on ultra-urban roadways and paved surfaces (NVPDC, 1992), thereby reducing the need for structural BMPS that employ sedimentation as a primary removal mechanism.

Table 55 lists a large range of nonstructural practices that can be used in conjunction with structural BMPs or by themselves to reduce stormwater pollution. A lack of monitoring information on their effectiveness in combination with structural BMPs, however, makes recommendations concerning the use of combinations of various nonstructural and structural BMPs difficult.

## 6.5 FINAL SELECTION PHASE

Preferred BMP options at this stage of the selection process may include incorporating structural BMPs, retrofits to an existing structural BMP, or the use of nonstructural measures or the modification of an existing nonstructural BMP program. It is possible that some combination of these may be the preferred method of achieving a particular objective. In the final selection process the preferred BMPs are evaluated based on cost-effectiveness and their ability to gain management and community support. This evaluation will result in an alternative that will reflect the unique features of a particular site.

### 6.5.1 Cost-Effectiveness

In the case of a structural BMP, its relative cost-effectiveness can be established based on published reports concerning its construction costs, annual operation and maintenance expenses, and effective life (how soon the BMP may need to be replaced). This cost information and the use of reported removal efficiencies for a structural BMP would complete a cost/benefit analysis for constituent removal. In making a final decision, additional less quantified management objectives (e.g., control of downstream stream stability, public acceptance) and other considerations (e.g., level of maintenance required) might also be evaluated.

The evaluation of cost-effectiveness of nonstructural BMPs is more problematic, particularly with respect to measuring their ability to meet specific water quality objectives. Nonstructural BMPs that focus, for example, on litter and debris management are likely to have widespread community support for aesthetic reasons. Their effectiveness in reducing loadings of targeted constituents cannot be established, however, without the implementation of targeted monitoring programs. Where there is a strongly identified need for a nonstructural program or where nonstructural BMPs can reduce the maintenance requirements of existing structural BMPs, cost-effectiveness can be established by reviewing existing programs and assigning a value to the performance of the nonstructural BMP.

The evaluation of alternatives that incorporate structural and nonstructural BMPs carries the limitations outlined earlier. The water quality benefits associated with the interaction of the two alternatives are difficult to evaluate and would likely require that implementation be accompanied by a monitoring program. In addition to the need for water quality monitoring, records of the before and after costs of maintaining the structural BMP would be required. The example on the following page illustrates an approach to evaluating the cost-effectiveness of management alternatives.

## 6.5.2 Management and Public Acceptance

To increase the level of both management and public acceptance for BMPs targeted primarily at water quantity/quality control, selection of cost-effective choices is essential. Management and public acceptance will rely heavily on issues such as aesthetics, public safety, recreational and educational value, and/or local resource protection (e.g., wetlands, stream stability). The preferred BMPs can then be ranked according to their ability to provide these additional benefits. Potential ranking factors for this analysis are given in Table 56; these ranking factors are provided as an example of how they can be determined. Specific requirements and objectives for a specific area will dictate the appropriate ranking factors.

Assigning a value for meeting the additional objectives is difficult and often requires professional judgment as well as consensus. For example, determining the aesthetic value of a particular BMP such as a constructed wetland is arbitrary and depends on the values and judgment of the evaluator. One way to address this concern is to weight the ranking factors equally.

The extended detention pond in the previous example was identified as the highest rated BMP. It will have an effective life of approximately 20 to 50 years but could potentially pose a high risk to public safety. The constructed wetland identified for alternative 5 poses a lower public safety risk. The nonstructural street sweeping BMP identified as alternative 2 poses minimal risk but has an effective life of only four to eight years. This effective life will contribute to an overall increase in relative costs when compared on cost per year of effectiveness. Table 57 can be used to evaluate these considerations.

**Table 56. Example of potential ranking factors for final selection**

| Ranking Factor | Assessment | Ranking Value |
|---|---|---|
| Aesthetics (visual, odor) | Poor | 0.33 |
| | Good | 0.66 |
| | Excellent | 1.0 |
| Public Safety | Low Risk | 1.0 |
| | Moderate Risk | 0.66 |
| | High Risk | 0.33 |
| Recreational Value | Yes | 1.0 |
| | No | 0.0 |
| Educational Value | Yes | 1.0 |
| | No | 0.0 |
| Local Resource Protection Value | Low | 0.33 |
| | Medium | 0.66 |
| | High | 1.0 |
| BMP Effective Life | <5 years | 0.25 |
| | 5-20 years | 0.50 |
| | 20-50 years | 0.75 |
| | 50-100 years | 1.0 |

The final result of the evaluation process is a prioritized list of preferred BMPs (or BMP combinations). The following example summarizes and illustrates the BMP selection process from scoping to evaluation to final selection.

**Example #1:**

*Site Description*: Ultra-urban area with a drainage area of 2 ha (5 ac) with 80 percent impervious surfaces. Available space for constructing structural controls is approximately 2-3 percent of the total drainage area. However, it is highly desired to have any BMPs located

**Table 57. Relative rankings of cost elements and effective life of BMP options**

| BMP | Capital Costs | O&M Costs | Effective Life[1] |
|---|---|---|---|
| **Structural BMPs** | | | |
| Infiltration Trench | Moderate to High | Moderate | 10-15 years |
| Infiltration Basin | Moderate | Moderate | 5-10 years before deep tilling required |
| Bioretention | Moderate | Low | 5-20 years[2] |
| Detention Ponds | Moderate | Low | 20-50 years |
| Wetlands | Moderate to High | Moderate | 20-50 years |
| Detention Tanks | Moderate to High | High | 50-100 years |
| Underground Sand Filters | High | High | 5-20 years |
| Surface Sand Filters | Moderate | Moderate | 5-20 years |
| Organic Media Filters | High | High | 5-20 years |
| Vegetated Swales | Low to Moderate | Low | 5-20 years |
| Vegetated Filter Strips | Low | Low | 20-50 years |
| Oil-Grit Separators | Moderate | High | 50-100 years |
| Catch Basin Inserts | Low | Moderate to High | 10-20 years |
| Manufactured Systems | Moderate | Moderate | 50-100 years |
| Porous Pavement | Low | Moderate | 15-20 years |
| **Nonstructural BMPs** | | | |
| Road and parking area street sweeping | Moderate | NA | 4-8 years |
| Proper chemical and fuel storage, use, handling, containment, and spill response procedures | Moderate to High | Low | 4-8 years |
| Vehicle and equipment, maintenance, storage and washing areas | Moderate | Low | long term |
| Bridge cleaning, maintenance and deck drainage (painting and sanding activities) | Moderate | NA | NA |
| Litter and debris management (dumpsters, trash piles, equipment storage, waste management practices) | Low | Low | 4-8 years |
| Modification of existing nonstructural BMP programs or structural BMP maintenance schedule or procedure | Low to Moderate | Low to Moderate | long term |
| Education programs (employee, adopt-a-road, adopt-a-stream, outreach) | Low | Low | long term |
| Elimination of illicit discharge and connections | Moderate | Low | long term |

**Table 57. (Continued)**

| BMP | Capital Costs | O&M Costs | Effective Life[1] |
|---|---|---|---|
| **New and Innovative Practices** | | | |
| Alum Injection | Moderate | Moderate | 5-20 years[3] |
| MCTT | High | High | 5-20 years [3] |
| Biofilters (e.g., StormTreat System) | Moderate | Moderate | 5-20 years[3] |
| Vegetated Rock Filters | High | High | 5-20 years |

Adapted from Young et al. (1996); Claytor and Schueler (1996); USEPA (1993); and others
NA = Not Applicable or Not Available
[1] Assumes regular maintenance, occasional removal of accumulated materials, and removal of any clogged media.
[2] As a relatively new BMP, the effective life is uncertain. It is reasonable to assume an effective life at least as long as that of a vegetated swale.
[3] Estimated based on best professional judgement.

below-grade if possible. Low permeability soils limit the use of infiltration-type BMPs.

*Objective:* Reduce oil and grease loadings to nearby river.

*Criteria*: Reduce oil and grease loading by 85 percent.

*Activity/Runoff Characteristics*: Two uncovered fueling stations with large paved parking area for transport trucks; high levels of suspended solids and oil and grease in dissolved and particulate form.

*Existing BMPs*: None, however a subsurface storm drain system does exist.

Table 58 illustrates the outcome of the BMP evaluation for the site. Based on the site description and stormwater management objectives, it is possible to quickly identify five candidate structural BMPs, and three potentially beneficial nonstructural BMPs. A description of the process used to make the selection is included below.

First, any structural BMPs considered should fit below-grade such that the land area over the BMP can be used. Given the active use of the surface area, BMPs with a modular design and the ability to fit in a small footprint are desirable. Also, infiltration-based BMPs are not applicable because existing soils have low infiltration. In addition, there is an existing storm drain system that will limit the hydraulic drop available in the proposed BMP. This means any candidate BMPs must have the flexibility to operate under a wide range of head. Of the BMPs listed in Table 58, five BMPs could operate as stand-alone units and provide the required design features (numbers 9, 11, 14, 15, 16).

The constituent of concern factors strongly in the selection of candidate structural BMPs. The constituent of concern (oil and grease) will be attached to suspended sediment and will be floating on top of the stormwater. Of the most promising structural BMPs, organic media filters provide the most consistent and highest removal of oil and grease for all physical phases. As a result, an underground organic media filter is the preferred structural BMP assuming all design and constructability issues can be addressed.

Selected nonstructural BMPs can greatly enhance the performance of the proposed underground organic media filter. In particular there are three nonstructural BMPs that provide additional stormwater management benefit: 1) street and parking lot sweeping, 2) education and training, and 3) containment and diversion.

**Table 58. BMP selection process illustration : example #1**

| No. | BMP Alternatives[1] | Scoping | Evaluation | | Final Selection |
|---|---|---|---|---|---|
| | | Applicable BMPs | Preferred Single BMPs | Multiple BMP Treatment Train | Prioritized BMPs |
| | | | **Structural BMPs** | | |
| 1 | Infiltration Trench | ✓ | x | | |
| 2 | Infiltration Basin | ✓ | x | | |
| 3 | Bioretention | ✓ | x | | |
| 4 | Ext. Detention Wet Pond | x | | | |
| 5 | Wet Pond | x | | | |
| 6 | Ext. Detention Dry Pond | x | | | |
| 7 | Wetlands | x | | | |
| 8 | Underground Detention Tanks | x | | | |
| 9 | Underground Sand Filters | ✓ | ✓ | 9, 18, 19, 21 | 2 |
| 10 | Surface Sand Filters | x | | | |
| 11 | Organic Media Filters | ✓ | ✓ | 11, 18,19, 21 | 1 |
| 12 | Vegetated Swales | x | | | |
| 13 | Vegetated Filter Strips | x | | | |
| 14 | Oil-Grit Separators | ✓ | ✓ | 14, 18,19, 21 | 3 |
| 15 | Catch Basin Inserts | ✓ | ✓ | 15, 18,19, 21 | 5 |
| 16 | Manufactured Systems | ✓ | ✓ | 16, 18,19, 21 | 4 |
| 17 | Porous Pavement | x | | | |
| | | | **Nonstructural BMPs** | | |
| 18 | Street and parking lot sweeping | ✓ | ✓ | | |
| 19 | Education and training | ✓ | ✓ | | |
| 20 | Landscaping and vegetated practices | x | | | |
| 21 | Containment and diversion | ✓ | ✓ | | |
| 22 | Chemical handling and storage | x | | | |
| 23 | Pesticide and fertilizer application | x | | | |

[1] To simplify the illustration, not all BMPs are listed here.

## Illustration of Final Selection Phase : Example #1

Implementation of a stormwater BMP in an ultra-urban area is needed to reduce total phosphorus (TP) loadings to a receiving stream by 60 percent. Based on the site characterization, the only source of the constituent in stormwater is from a highway maintenance yard. Drainage from this site is already controlled by an existing detention pond that provides quantity control for the site. In the evaluation phase, alternatives were reduced to (1) annual catch basin maintenance and the use of street-sweeping equipment (nonstructural option), (2) retrofit of the existing detention pond to provide extended detention (structural option), (3) the combination of the retrofitted pond and the nonstructural BMPs, (4) the combination of the retrofitted pond and a constructed wetland to provide enhanced constituent removal, and (5) the addition of a constructed wetland to provide enhanced constituent removal for the combination of the retrofitted pond and the nonstructural BMPs.

The existing detention pond removes 20 to 40 percent of the TP entering the facility (Table 51). The effectiveness of annual catch basin cleaning and a twice-weekly sweeping program is estimated at 35 to 60 percent (Chapter 5, Table 41). Phosphorus removal for an extended detention facility ranges up to 80 percent, while constructed wetlands are reported to have a removal efficiency of 25 percent (Table 51). The following table summarizes the possible alternative types, the range of expected removal efficiencies, and their estimated costs.

**Illustration of BMP alternatives**

| BMP Alternatives | Range of Expected Removal Efficiencies (%)[1] | Relative Cost[2] | Meets Objective | Cost-Effectiveness Rating |
|---|---|---|---|---|
| 1) Street sweeping (twice weekly)/Annual catch basin maintenance | 35-60 | ●●●○○ | yes | 3 |
| 2) Retrofit of detention pond for extended detention | up to 80 | ●○○○○ | yes | 1 |
| 3) Street sweeping and retrofit of pond | 70-100 | ●●○○○ | yes | 2 |
| 4) Retrofit of pond and constructed wetland | 48-70 | ●●●●○ | yes | 4 |
| 5) Street sweeping (e.g., quarterly) and retrofit of pond and constructed wetland | 82-100 | ●●●●● | yes | 5 |

[1]Analysis assumes that removal efficiencies are cumulative.
[2] Estimated costs.

BMP alternative 2 would likely meet the constituent removal criteria at a comparatively low cost. However, the wide range of constituent removal effectiveness reported in the literature leaves doubt as to whether this facility could adequately control the phosphorus load. Based on the above analysis, BMP alternative 3 has a higher cost-effectiveness assuming adequate design, construction, and function. Street sweeping improves the efficiency of the extended detention pond and reduces its maintenance needs by removing trash and debris.

Consideration of additional management objectives at this stage could significantly alter these results. The feasibility of using the constructed wetland as a potential mitigation site for a project in the immediate vicinity and reluctance to purchase and maintain street sweeping equipment could also have resulted in the selection of alternative 4; however, implementation costs would be significantly higher.

The first nonstructural BMP will help minimize the large diameter material (e.g., sand and trash) reaching the underground filter. The next two nonstructural BMPs will help limit the amount of spilled fuel, and improve the cleanup of spills (large and small) before they come into contact with stormwater. However, the expense and compatibility of proposed nonstructural BMPs must be evaluated in light of existing funding, resources, and compatibility with existing nonstructural programs.

Prior to designing the preferred structural BMP it is important to evaluate its comparability with existing BMP O&M programs and program funding limits. Below-grade filters require periodic cleaning and replacement of the media. If the funding does not exist for this type of maintenance, then other less expensive structural BMPs should be considered even if they provide less effective stormwater management.

**Example #2:**

*Site Description*: The drainage area includes a 305 m (1000 ft) length of highway through a downtown metropolitan area. The area for stormwater BMPs is limited to the roadway median and shoulder drainage system and small open areas in the interchange. The highway is adjacent to a high visibility pedestrian area. The site has very flat terrain and shallow depth to watertable.

*Objective*: The receiving water is a major river system where flooding is not a concern. Reducing phosphorus loadings to the river is of primary concern.

Implementation of a stormwater control strategy was needed for a segment of highway in an ultra-urban setting. The broad scoping phase identified that flood and channel protection were not required, that the nutrient and sediment loading to the river were of primary concern, and that the ultra-urban highway was considered a "hotspot."

Table 59 illustrates the outcome of the BMP evaluation for the site. The structural BMPs that were eliminated included the ponds, wetlands, vegetated filter strip, underground storage tank, and infiltration practices. The remaining options consist of the dry swale, bioretention, sand filters, organic media filters, oil/grit separator, catch basin inserts, and some of the manufactured systems. The nonstructural BMPs identified in the broad scoping phase included weekly street sweeping and an "adopt-a-road" litter control program.

In the final selection phase, the BMP alternatives were evaluated using a combination of elimination and addition. Table 59 illustrates the components that went into this decision process.

The selected structural BMP options include the dry swale in the median of the highway and the underground sand filter along the shoulders. The nonstructural options include weekly street sweeping and litter control through an "adopt-a-road" program. The dry swale can only accommodate a relatively small portion of the highway drainage, but has high nutrient and sediment removal capability coupled with a more aesthetically acceptable practice in the vicinity of the high visibility pedestrian area. The underground sand filter fits into the linear nature of the roadway and can be designed for very shallow, low head conditions. Pollutant removal capability is good to excellent.

Although the nonstructural street sweeping practice could help capture the coarsest sediments to help improve pollutant removal efficiencies and prolong the design life of the structural BMPs, it was not selected due to safety considerations. The high speed roadway limits the practical use of street sweeping. The "adopt-a-road" program is designed to minimize litter in the vicinity of the high visibility pedestrian area.

**Table 59. Final selection phase illustration : example #2**

| BMP Alternative | Avg. Pollutant Removal Efficiency (%) | | Relative Capital and O&M Cost | Meets Manage-ment Objectives | Meets Physical Feasibility Tests | Selected as Stand-alone or Treatment Train |
|---|---|---|---|---|---|---|
| | TSS | TP | | | | |
| **Structural Practices** | | | | | | |
| Dry Swale | 75% | 50% | Moderate | Yes | Yes | Yes |
| Bioretention | 75% | 50% | Moderate | Yes | No | |
| Underground SF | 80% | 60% | High | Yes | Yes | Yes |
| Surface SF | 85% | 60% | Moderate | Yes | No | |
| Organic Media Filer | 90% | 50% | High | Yes | Yes | |
| Oil-Grit Separator | 30% | 5% | High | No | | |
| Catch Basin Inserts | 20% | 5% | Moderate | No | | |
| Manufactured Systems | 25% | 5% | Moderate | No | | |
| **Nonstructural Practices** | | | | | | |
| Street Sweeping | 50% | 40% | Moderate | Yes | | No |
| Adopt-A-Road | N/A | N/A | Moderate | Yes | | Yes |

**Example #3:**

*Site Description:* A 1 ha (2.5 ac) transportation department maintenance yard is located in a densely urban area. Vehicle maintenance and equipment and material storage activities occupy all of the site's impervious area. The impervious coverage of the site is 90 percent. The site drains to an urban stream that is highly impacted from hydrologic alterations (accelerated channel erosion). The steam channel is deeply incised, consequently, flooding is not a problem. The channel drains to an urban river that is phosphorus limited. Low permeability soils limit infiltration practices.

*Objective:* Avoid additional disruptions to receiving channel and reduce pollutant loads for oil and grease, sediment, and phosphorus to receiving waters.

*Criteria:* Provide stormwater management to mitigate for accelerated channel incision and reduce loadings of key pollutants by the following: oil and grease (85 percent), sediment (80 percent), and phosphorus (60 percent).

*Activity/Runoff Characteristics:* The site is characterized by several ongoing road maintenance activities including vehicle maintenance and refueling, vehicle wash facilities, sand and salt storage (a northern climate), storage of miscellaneous highway maintenance equipment, and stockpiled construction debris. Stormwater runoff from the site exhibits high sediment levels, highly elevated chloride concentrations, and oil and grease.

*Existing BMPs*: Catch basins with a 0.6 m sump. The catch basins drain to a subsurface storm drainage system that discharges directly to the urban stream.

Table 60 lists the results of the BMP selection analysis. Based on the scenario, the ponds, wetlands, and all infiltration practices are removed from consideration in the scoping phase. Infiltration is not practical given the soils. The additional element of potentially receiving toxic "hotspot" runoff is a primary concern. A "treatment train" approach is recommended to meet the multiple objectives of the management scenario. First, given the land use and activity, nearly all structural BMPs should fit below grade such that the land above can be utilized. Additionally, as is often the case in the ultra-urban environment, existing drainage and utility constraints will require a BMP that operates over a wide range of head conditions.

A structural BMP is required to provide storage for the "channel protection" volume. In the ultra-urban setting, about the only BMP to meet the storage and space limitations of the site is the underground storage tank.

The objective of reducing pollutant loading requires a more complicated solution. Sediment, oil and grease, and phosphorus are all generally captured by the same pollutant pathways. But due to the high salinity, particulate settlement may be partially compromised in traditional settling chambers.

The structural BMPs selected include:

- Bioretention as a surface facility sized to about four percent of the drainage area. This practice has a good to excellent removal capability for sediment, total phosphorus, and metals (see Table 51). Since almost all the other feasible BMPs rely on settling as the primary treatment, bioretention will help augment pollutant removal.
- An underground sand filter, utilizing the perimeter technique (also called the Delaware sand filter). This practice has a proven performance record. Given the nature of the site as among the highest pollutant sources in the urban landscape, the multiple BMP approach is warranted.
- The existing catch basins on the site are to be cleaned to provide additional capture of the coarsest sediments. Sand storage areas appear to have a disproportionately high amount of this size particle in the stormwater, making this practice more important.

The nonstructural BMPs selected include:

- Street sweeping, particularly in the winter months (for this northern climate), once a week to remove street particles.
- Maintenance of catch basins (discussed above).
- Education and training of employees on the proper use and disposal of materials.
- Vegetative plantings combined with the bioretention system.
- Covering and handling road sands and salts. One of the primary sources of pollutants at many road and highway maintenance departments is the exposure of sand and salts to surface runoff. Most NPDES permits now require the covering of these materials. Yet, one the biggest sources remains these loading and transfer areas. Extra covered area may be warranted depending on the extent of the activities.

The selected BMPs, both structural and nonstructural, were chosen based on an array of criteria. The bioretention provides potential removal for high salinity runoff while improving the aesthetics of the maintenance yard (people do work in these areas). The underground sand filter is a flexible, easy to access, BMP that lends itself to these types of land uses. The system can be designed for a wide array of structural loading conditions. The underground storage tank can be designed in conjunction with the sand filter to capture the channel protection storage volume as well as act as a potential spill containment facility.

The selected nonstructural BMPs can enhance the performance and design life of the structural facilities. The five nonstructural BMPs listed above can each play a role in the stormwater management effort. The final practices implemented may depend as much on staff and financial resources as on physical feasibility. The expense and compatibility of proposed nonstructural BMPs must be evaluated in light of existing funding, resources, and program capability.

Prior to designing the proposed structural BMPs, it is important to evaluate the capability of the owner's or agency's O&M program and program funding limits. All BMPs require maintenance, but a multiple BMP treatment train system requires routine and major maintenance at proscribed intervals. If the funding does not exist to maintain this type of program, then other less expensive structural and nonstructural BMPs should be considered even if they are less effective.

## Table 60. BMP selection process illustration : example #3

| No. | BMP Alternatives | Scoping<br>Applicable BMPs | Evaluation<br>Suitable for BMP Treatment Train[1] | Final Selection |
|---|---|---|---|---|
| | | **Structural BMPs** | | |
| 1 | Dry Swale | ✓ | ✓ | |
| 2 | Wet Swale | ✓ | × | |
| 3 | Bioretention | ✓ | ✓ | ✓ |
| 4 | Underground SF | ✓ | ✓ | ✓ |
| 5 | Surface SF | ✓ | ✓ | |
| 6 | Organic Media Filters | ✓ | ✓ | |
| 7 | Veg. Filter Strips | × | | |
| 8 | Infiltration Trench | × | | |
| 9 | Infiltration Basin | × | | |
| 10 | Porous Pavement | × | | |
| 11 | Wetland | × | | |
| 12 | Wet Pond | × | | |
| 13 | Dry ED Pond | × | | |
| 14 | Underground Storage Tank | ✓ | | ✓ |
| 15 | Oil-Grit Separator | ✓ | × | |
| 16 | Catch Basin Inserts | ✓ | ✓ | ✓ |
| 17 | Manufactured Systems | ✓ | ✓ | |
| | | **Nonstructural BMPs** | | |
| 18 | Street Sweeping | ✓ | ✓ | ✓ |
| 19 | Catch Basin Cleaning | ✓ | ✓ | ✓ |
| 20 | Employee Education | ✓ | ✓ | ✓ |
| 21 | Landscaping and Vegetative Practices | × | ✓ | ✓ |
| 22 | Road Salt Handling and Storage | ✓ | ✓ | ✓ |

[1] To simplify the illustration, not all BMPs are listed here.

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