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Decentralized Stormwater Controls for Urban Retrofit and Combined Sewer Overflow Reduction

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DECENTRALIZED STORMWATER CONTROLS FOR URBAN RETROFIT AND COMBINED SEWER OVERFLOW REDUCTION

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ABSTRACT AND BENEFITS

Abstract:

Decentralized stormwater controls provide a significant and promising alternative strategy to limit the number of overflows from combined sewer systems. This research evaluates the functional processes employed by decentralized controls and possible methods of quantifying stormwater retention and detention mechanisms. Pilot installations and modeling are demonstrating significant reductions in runoff volumes especially when targeted at problematic catchment areas of the collection system. The technical considerations and perceived impediments of urban retrofits are analyzed and a methodology for modeling effectiveness is outlined. The comprehensive benefits gained from decentralized controls, in addition to stormwater volume reductions, are also presented.

The results of this research provide a framework for communities to begin implementing decentralized controls as a component of a combined sewer inflow reduction program. Analytical assessments of categorical controls are provided to aid in the selection of appropriate decentralized techniques and strategies.

Benefits:

- Identifies functional processes of decentralized controls and provides methods to quantify reductions in stormwater volumes.
- Provides control strategies that reduce the quantity and volume of combined sewer overflows.
- Details a methodology that can be used to evaluate and enhance the effectiveness of the installation and application of stormwater controls.
- Provides an alternative environmental protection strategy aimed at improving water and air quality, promoting economic and community development, and enhancing urban aesthetics.

Keywords: Runoff volume, water quality, peak flow control

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BMP	Best Management Practices
CWA	Clean Water Act
CSO	Combined Sewer Overflow
CSS	Combined Sewer System
ET	Evapotranspiration
HEC-HMS	Hydrologic Engineering Center's Hydrologic Modeling System
LTCP	Long-Term Control Plan
MS4	Municipal Separate Storm Sewer System
NPDES	National Pollutant Discharge Elimination System
SWMM	EPA Storm Water Management Model
TMDL	Total Maximum Daily Load
TSS	Total Suspended Solids
U.S. EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WWC	Wet Weather Controls
WWTP	Wastewater Treatment Plant

EXECUTIVE SUMMARY

Combined sewer systems exist in 746 municipalities in 31 states and the District of Columbia. They are largely the legacy of past engineering practices that reflected a *collect and convey* philosophy and associated approach to stormwater management. Rainwater runoff that is diverted from roads, parking lots, and the roofs of buildings during storm events contribute to combined sewer overflows (CSOs). The country-wide magnitude of the CSO impact is estimated at an annual discharge volume of 850 billion gallons. The volume and concentration of pollutants, including trash, bacteria, and toxic substances has created serious health hazards and impairments to aquatic resources.

Decentralized controls have the potential to reduce the frequency and volume of CSO events by using natural hydrologic cycle elements to dampen the stormwater surges that overwhelm the conveyance capacities of combined systems. The decentralized approach is flexible, dynamic, and allows communities to be responsive to evolving economic and environmental conditions.

Scope of Research: This report synthesizes the results of a research initiative commissioned by the Water Environment Research Foundation (WERF) and had two main objectives:

- ♦ Provide a document that defines the current state of decentralized source controls for capturing rainwater where it falls.
- ♦ Present a plan for implementation of decentralized controls in an urban environment specifically for the goal of CSO mitigation.

The primary focus of the applied research was *how* decentralized controls can reduce the volume of rainwater runoff generated and, consequently, entering the combined sewer system in urban areas.

Report Structure: This report is comprised of six chapters, summarized as follows in the table below. This Executive Summary distills the research results into a set of key topics in order to provide a concise readers' guide.

Chapter 1.0: Introduction Provides an overview of the *Clean Water Act* and the provisions that create opportunities for adopting a decentralized approach to CSO reduction.	**Chapter 4.0: Implementation Strategies, Incentives, and Disincentives** Presents a five-step framework for evaluating and selecting source control elements of a rainwater management implementation strategy.
Chapter 2.0: Decentralized Source Controls Defines what is meant by *decentralized controls*, and explains how to evaluate their effectiveness.	**Chapter 5.0: Simulation and Cost-Effectiveness Analysis for Decentralized CSO Controls** Describes how contemporary simulation and optimization software for rainfall-runoff analysis can be used to evaluate decentralized control options for CSO reduction.
Chapter 3.0: Technical Issues and Practicability Examines what is involved in actually implementing a decentralized approach on-the-ground.	**Chapter 6.0: Ancillary Benefits** Identifies holistic benefits that stem from reintroduction of natural processes and functions into the design of highly urbanized environments.

ES.1 Factors Driving Change

The traditional solution to CSO mitigation has been a centralized end-of-pipe approach. This has typically involved construction of tunnels or tanks to provide storage or detention volume during heavy rainfall events. There are several disadvantages to this approach:

- Financial burden on taxpayers to pay for major projects.
- Disturbance to communities during construction.
- Ongoing maintenance costs.
- Limited and unpredictable effectiveness.
- Inability to address a wider range of water protection issues.

The combination of these factors has provided the driver for communities to look for alternative solutions that are affordable and effective. Capturing rain where it falls offers an appealing set of technical alternatives for preventing rainwater runoff generation. This decentralized approach has the potential to mitigate CSO events.

Decentralized Stormwater Controls: Decentralized controls are small-scale, distributed rainwater runoff management devices or measures that are constructed to capture rain where it falls. They have the capability to meet multiple rainwater runoff management objectives, including:

- flow rate attenuation;
- volume reduction; and
- water quality improvement.

Decentralized controls use unit processes of the hydrologic cycle, such as infiltration and evapotranspiration, to meet these objectives. An evaluation process has yielded a shortlist of eleven classes of decentralized controls deemed suitable for urban retrofit and CSO reduction. Table ES-1 synthesizes the evaluation and is complete with a qualitative rating of effectiveness.

Site Level Solutions: The ability to use multiple hydrologic and hydraulic processes allows the controls to be combined into a *treatment train* to meet targeted rainwater management objectives. They can be integrated into many common urban land uses on both public and private property, which enhances flexibility in siting rainwater runoff control measures.

Because they can be constructed on an individual basis or in conjunction with other projects, a variety of funding options is possible. Most importantly, these practices provide source control of rainwater runoff, allowing management strategies to be targeted at specific sites rather than requiring the planning and construction of large-scale, capital-intensive centralized controls.

All of these characteristics give decentralized source controls the potential to reduce the volume of rainwater that enters a combined sewer system, thus mitigating the number of combined sewer overflows in a watershed.

Table ES-1. Assessing the Effectiveness of Decentralized Controls.

Source Control	Volume	Peak Discharge	Water Quality
Downspout Disconnection	⦿	⦿	⦿
Filter Strips	○	○	⦿
Infiltration Practices	⦿	○	⦿
Pocket Wetlands	●	●	●
Porous Pavement	●	●	⦿
Rain Barrels/Cisterns*	⦿	○	○
Rain Gardens	●	●	●
Soil Amendments	⦿	⦿	⦿
Tree Box Filters	⦿	⦿	●
Vegetated Roofs	⦿	●	●
Vegetated Swales	⦿	⦿	●
* Cisterns are typically larger vessels that provide greater volume reduction than a single rain barrel.			
Key: ● High effectiveness	⦿ Medium effectiveness	○ Low effectiveness	

Rankings are qualitative. The rationale for ranking individual rainwater management objectives is given in Section 2.2.2.

- "High effectiveness" means that the one of the source control's primary functions is to meet the objective.
- "Medium effectiveness" means that a source control can partially meet the objective but should be used in conjunction with other source controls.
- "Low effectiveness" means that the source control contribution to the objective is a byproduct of its other functions, and another decentralized control should be used if that objective is important.

ES.2 Retrofit Challenges

The challenges in retrofitting collection areas with decentralized controls are considerable because most combined systems are found in highly urbanized areas that are typically characterized by the following:

- highly connected impervious surfaces;
- aged infrastructure; and
- limited pervious or open areas.

Because the retrofit focus is primarily on individual properties, physical conditions and perceived concerns take on added significance.

Perceived Concerns and Retrofit Feasibility: A key challenge is overcoming fear and doubt regarding hydrologic performance, mainly because decentralized controls for rainfall capture and runoff volume reduction rely to a large extent on landscaping-type solutions. This means their feasibility often depends on soil characteristics. Three areas of concern are addressed:

- **Standing Water:** This concern has three aspects—nuisance, aesthetic, and public health. Scale is a consideration—for example, homeowners like their yards to be well-drained and dry year-round.
- **Structural:** This concern also has three aspects—basement flooding; potential for undermining of building and roadway foundations if the soil is either reactive to saturation or not well-drained; and utility conflicts that result in limited space.
- **Maintenance:** The degree of concern is a function of scale—it makes a difference whether the decentralized control is a rain garden on a single family lot, or a vegetated roof on a major building.

Fear and doubt, even if without foundation, can have a material bearing on community acceptability of an implementation strategy for runoff volume reduction.

Long-Term Performance: Evaluation of decentralized source controls includes consideration of the need for maintenance over time. Table ES-2 identifies maintenance factors affecting long-term feasibility.

The level of effort required for maintenance is a measure of the amount of work that is needed for the successful completion of a single maintenance event. A measure of the level of effort required, combined with the frequency of maintenance required, can be used to estimate the maintenance burden of a particular control.

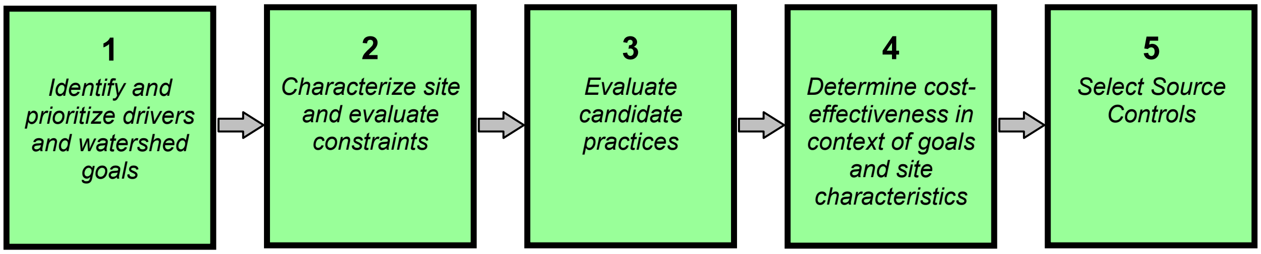
Controls that require no replacement of media, no vegetation maintenance and no removal of accumulated pollutants are considered as low level maintenance effort controls (e.g. disconnected roof downspouts, rain barrels, and cisterns). The highest level of maintenance effort is assigned to controls such as infiltration practices that may require vegetation maintenance, removal of captured materials, and occasional rejuvenation or complete replacement of media.

Table ES-2. Assessing Long-Term Performance.

Source Control	Responsibility	Level of Effort	Frequency
Downspout Disconnection	Owner	**Minimal:** No vegetation management; no removal of captured pollutants	**Low:** Provides few water quality benefits
Filter Strips	Owner	**Moderate:** Management of vegetation; occasional removal of captured pollutants	**Moderate:** Need vegetation management
Infiltration Practices	Owner	**Moderate to High:** Rejuvenation may be needed (scarifying surface/raking); possible removal of vegetation; removal of captured materials; media may have to be completely changed	**Low:** Need removal of accumulated pollutants Need occasional vegetation management Pre-treatment is very important
Pocket Wetlands	Owner	**Moderate to High:** Management of vegetation; removal of floating debris and trash; sediment and vegetation removal	**Low:** Need removal of accumulated pollutants Need occasional vegetation management Sediment forebay
Porous Pavement	Owner/Municipality	**Moderate to High:** Rejuvenation may be needed (vacuum sweeper/power washing); vegetation management; pavement may have to be completely changed	**Low:** May need vegetation management
Rain Barrels/Cisterns	Owner	**Minimal:** No vegetation management; no removal of captured pollutants Treatment for mosquitoes may be necessary. Periodic draining.	**Low:** Provide little or no water quality benefits
Rain Gardens	Owner	**Minimal to Moderate:** Vegetation management required	**Moderate:** Need vegetation management
Rooftop Storage	Owner	**Minimal:** No vegetation removal; minimal removal of captured pollutants	**Low:** Provides little pollutant removal
Tree Box Filters	Owner	**Moderate:** Minimal removal of debris	**Low:** May require vegetation management
Planter Boxes	Owner	**Low:** Underdrains may need to be replaced if clogged.	**Low:** Periodic removal of weeds for aesthetics
Vegetated Roofs	Owner	**Moderate:** Vegetation management	**Moderate:** Require vegetation management
Vegetated Swales	Owner	**Low to Moderate:** Minimal removal of captured pollutants; vegetation management	**Moderate:** Require vegetation management; may require removal of accumulated material

ES.3 Customizing Implementation Strategies

Urbanized areas have a broad mix of land uses, distinctive community characteristics, complex environmental and design regulations, and a wide range of community and economic goals. Hence, development of a customized implementation strategy for retrofitting decentralized controls in an urban area is an iterative process because quantity and quality benefits in capturing rain where it falls must be balanced with planning goals and site constraints. The process for developing an affordable and achievable implementation strategy involves five basic steps:



Factors Affecting Feasibility: Once the drivers, watershed planning goals and site characteristics are well understood, specific decentralized controls can be evaluated for their suitability. Source control selection must be compatible with the land use and activity, blend into the community fabric, and be accepted by the residents in order to become a community asset and to ensure long-term effectiveness.

Feasibility considerations serve as screening criteria, and are based on site characteristics. This is illustrated by Table ES-3, the most relevant of a set of four related tables in Chapter 4.0 of this report. These tables provide a synthesis of factors affecting the feasibility of decentralized controls.

Cost-Effectiveness Analysis: In recent years, the rainwater runoff modeling focus has shifted to assess whether traditional simulation tools could be reasonably downscaled to evaluate micro-scale processes such as rainfall and runoff at the individual parcel scale. To provide an answer, SWMM was applied to a catchment in the Portland region to test the modeling process. The lesson learned is this: While SWMM can be used to model much of the complexities of decentralized controls and CSO systems, the number of parameters can become unwieldy.

In a nutshell, evaluation of decentralized options for CSO control is more complex than the evaluation of traditional centralized controls. The simple explanation is that there are a large number of decentralized controls, combined with the fact that many decentralized controls rely on infiltration, which is complex to evaluate. For these reasons, a sophisticated model such as SWMM is unlikely to be used by local regulatory agencies for routine assessment of decentralized controls.

The alternative is to apply a spreadsheet approach because it is understandable to the many professionals who use spreadsheets routinely. The elements of a practitioner-oriented decision support tool for cost-effectiveness analysis include: functional spatial databases; a single or a continuous rainwater runoff process simulation model; cost functions for distributed land use options and a storage-release system; and a spreadsheet optimization feature.

Table ES-3. Feasibility of Implementing Decentralized Controls.

Source Control	Reliability/Confidence in Fundamental Design	Design Flexibility
Downspout Disconnection	Potential for large reduction in 'directly connected impervious area' (DCIA), but must infiltrate or provide storage	May be used with many other source controls.
Filter Strips	Provide hydrologic control depending on design. Sediment can be resuspended during large storms.	Many options for incorporating into landscaped environment. Higher WQ performance associated with check dams, shallow slopes, and low velocities. Soil amendments can be used to improve infiltration and retention capacity.
Infiltration Practices	Prone to clogging and bypass if not maintained frequently or sedimentation pretreatment not provided.	Trenches more amenable to urban environment than basins. Various soil amendments possible to improve pollutant adsorption capacity. Can be used in conjunction with detention.
Planter Boxes	Low potential for clogging. Provides volume reduction and peak discharge control.	Can be integrated into most building landscape designs and practically any shape or configuration is possible.
Pocket Wetlands	Effluent quality generally good for most parameters. May release nutrients during dormant periods. Some detention provided, but negligible volume reduction.	More difficult than some practices to incorporate into the ultra-urban environment.
Porous Pavement	Clogging common; requires vacuum sweeping or power washing to restore hydraulic capacity. Moderate volume losses possible when properly maintained.	Not very flexible. Should be designed to infiltrate incident rainfall only, however, porous shoulders may receive runoff from the primary travel lanes.
Rain Barrels/ Cisterns	Typically small storage volumes so minimal hydrologic benefits.	Installed above or below ground, as well as on rooftops. Below ground may require pumping for reuse.
Rain Gardens	Substantial hydrologic benefits possible due to retention, infiltration, and evapotranspiration. Pollutant reductions may also be high due to plant uptake and microbial degradation.	Very flexible in that practically any shape is possible. Many options for incorporating into landscaped environment. Underdrains may be installed for low permeable soils.
Rooftop Storage	Provide good peak control for small storm events, but no water quality benefits.	Not many options for design alternatives, but easy to incorporate into urban environment. Innovative outlet controls possible.
Tree Box Filters	Similar to rain gardens, with underdrain.	Similar to rain gardens with underdrain.
Vegetated Roofs	Substantial hydrologic benefits possible due to retention and evapotranspiration, but benefits are realized primarily for small, frequently-occurring storm events.	Many options for design and configuration of vegetation. Roof gardens where plants are placed in pots and planter boxes are one design variation.
Vegetated Swales	Same as filter strips.	Same as filter strips.

ES.4 A Look Beyond

Increasingly, the focus of design professionals is on how to build and/or rebuild communities in balance with the natural environment. Capturing runoff where it falls in urban areas introduces ancillary benefits into the community that extend beyond runoff volume reduction. The use of decentralized source controls in conjunction with redeveloping land in urban regions creates opportunities, over time, to develop greener communities that will achieve higher levels of ecological and receiving water protection.

Green Infrastructure: Benefits stem from the fact that implementation of *green infrastructure* reintroduces natural processes and functions into highly urbanized environments. The goal in 'designing with nature' is to achieve a community vision for sustainability and livability that will yield tangible environmental, community, educational and economic benefits. The design with nature approach promotes the watershed as a fundamental planning unit, and emphasizes that:

- the Built Environment and the Natural Environment are connected;
- improving the Built Environment can protect or help restore the Natural Environment;
- how we (re)develop individual sites has ripple effects at the watershed scale; and
- actions on the ground can result in cumulative benefits over time.

In short, the integration process that is at the heart of a design with nature philosophy involves consideration of land, water, air and living organisms—as well as interactions among them.

The Larger Context: Green infrastructure that uses vegetation and soil to reduce rainwater runoff volume may also reduce air pollution and air temperature (through evapotranspiration) and help to minimize the urban heat island effect, while at the same time providing ground cover that serves a habitat function. Designing with nature can also be seen in a larger sense as land development that is more sustainable—economically, environmentally and socially. This is illustrated by these three examples:

- **Green Space and Human Health:** The design with nature approach embraces what environmental psychologists know**:** greenspace is fundamental to human health and social well-being. So, as communities across the United States redevelop and densify to accommodate more and more people, creation of greenways and greenspace/landscaping takes on increasing importance.

- **Transportation Synergies:** In addition, integration of rainwater management solutions (such as reducing impermeable surfaces) with sustainable transportation strategies can ultimately achieve streets that are are greener in various ways as well as safer and more liveable.

- **Water-Energy Nexus:** At the other end of the spectrum, the design with nature approach also takes into account the 'water-energy nexus'—that is, we get energy from water, and we use energy to supply, treat and use water. Water use involves significant energy inputs which must be considered. So reducing the need for landscape irrigation water through a 'rainwater-friendly' solution has a direct benefit.

CHAPTER 1.0

INTRODUCTION

1.1 Purpose of Decentralized Stormwater Controls

Combined sewer overflows (CSOs) continue to occur throughout major cities in the Northeast, Great Lakes, and Northwest regions of the U.S., primarily as a result of rainwater that is diverted from roads, parking lots, and the roofs of buildings during storm events. The rapid transport of water away from the built environment to natural water bodies has dominated engineering for the past 130 years, with combined sewer systems initially used as a cost-effective means of transporting sewage and stormwater. With wide-scale application of municipal wastewater treatment in the mid-twentieth century, flow rate limitations of treatment plants, and the combined sewer systems that directed wastewater to them, became apparent. Combined sewer systems remain in 746 municipalities in 31 states and the District of Columbia and discharge an estimated 850 billion gallon of stormwater and wastewater annually. The United States Environmental Protection Agency (U.S. EPA) estimates that over $55 billion (2005 dollars) of capital improvements are needed for CSO control.

CSOs persist as a concern because of the pollutants that are discharged. In addition to toxics, nutrients, suspended solids, floatables, and oxygen-depleting substances, microbial pathogens present in untreated wastewater pose a direct threat to human health. Urban expansion from population growth and development will continue to replace natural surfaces with impervious ones, leading to ever greater amounts of stormwater runoff. The potential for increased contamination of natural water bodies will further degrade natural habitats and resources.

Traditionally, communities have used centralized end-of-pipe approaches, such as tunnels or tanks, which are designed to provide storage or detention to control large storm events. The large-scale capital improvement cost for construction and maintenance, high life-cycle costs, disturbance to communities during construction, sometimes limited and unpredictable effectiveness, and the inability to address a wide range of water protection issues have caused many communities to look for other solutions. Decentralized stormwater management offers an appealing set of technical alternatives. Developing best management practices (BMPs) to minimize stormwater runoff generation, prevent runoff contamination, remove pollutants before runoff enters the combined sewer system, and retain or detain the movement of stormwater in a decentralized fashion can potentially mitigate CSO events.

There are a variety of technical components that can be incorporated into a decentralized stormwater management system, and a variety of methods that can be used for the design and analysis of the system. The challenge for communities is to select the technical components and the methods of design and analysis in the most cost-effective way. The ideal outcome will not only reduce CSOs and the need for large detention facilities, but also provide ongoing runoff reduction and water quality benefits for the smaller and more frequent storm events, producing a more sustainable watershed.

1.2 Federal Regulations

1.2.1 Clean Water Act

The Federal Water Pollution Control Act, more commonly referred to as the Clean Water Act (CWA), provides the regulatory framework for limiting pollutant discharges into waters of the United States. The CWA regulates both point and nonpoint discharges including stormwater and municipal wastewater. Decentralized controls can be implemented to comply with stormwater-related discharges subject to CWA limitations.

The CSO Control Policy promulgated by U.S. EPA in 1994 (59 FR 18688) is the primary regulatory mechanism driving municipalities to mitigate CSOs. Under this policy, the majority of National Pollutant Discharge Elimination System (NPDES) permitted CSO communities are required to implement the “Nine Minimum Controls” and develop a Long-Term Control Plan (LTCP). These requirements are intended to optimize the operation of existing collection systems and treatment plants and develop a strategy that allows the eventual attainment of water quality standards. As of July 2004, 708 active CSO permits required the development and implementation of a LTCP.

While municipalities with combined sewers are required to develop mitigation strategies, they are simultaneously tasked with meeting other stormwater or NPDES regulations and natural resource objectives, such as protection of aquatic species. Decentralized stormwater controls not only provide opportunities to mitigate CSOs, but also have the potential to meet other regulatory and programmatic requirements. There are several regulatory programs with requirements suitable for the application of decentralized stormwater controls.

1.2.1.1 Section 303

Section 303 of the CWA defines a multi-step process for establishing water quality standards. Under Section 303, each state, territory, and authorized tribe must designate uses for each of its waterways. CWA requirements generally dictate that designating entities ensure a level of water quality protective of aquatic species and allowing for human recreation. States must then identify water quality standards that are needed to support and sustain the designated uses. Designated uses and water quality standards are likely to vary at different locations along a waterway. When water quality standards have been determined by the state, they must be submitted to U.S. EPA for approval.

Once water quality standards are approved, each waterway is surveyed to determine if it is meeting the standards. States must identify and report to U.S. EPA those waterways that fail to meet water quality standards, referred to as the 303(d) list. For waterways where implementation of the technology based effluent guidelines for point sources would not result in a waterway achieving water quality standards, states are required to determine the total maximum daily load (TMDL) of pollutants and nutrients that can be discharged to the waterway which allow it to meet water quality standards. TMDLs are determined for individual parameters and must include a margin of safety and consider seasonal variations. As with water quality standards, TMDLs must be submitted to U.S. EPA for approval.

Approved TMDLs serve as the guidelines to apportion waste load allocations among various point and nonpoint dischargers that degrade a waterway's water quality. However, Section 303 of the CWA does not explicitly require the regulation of nonpoint sources. The CWA does stipulate that effluent guidelines for point sources are made sufficiently stringent to achieve water quality standards, but in many instances these limitations will not in themselves be adequate for achieving the necessary pollutant reductions. Although regulation of nonpoint sources is not authorized by Section 303, states use the TMDL process to allocate pollutant loadings among pollution sources in a watershed and to provide a basis for establishing controls to reduce both point and nonpoint source pollutant loadings. Waterways or sections of waterways that meet water quality standards must establish antidegradation policies intended to maintain good water quality.

Decentralized controls can be used to help states meet TMDL targets in designated watersheds by reducing target loads incrementally through new or retrofit construction. The use of decentralized controls allows for quantifiable accounting of both stormwater volume and pollutant loadings. Decentralized controls can also be used as part of an antidegradation program intended to prevent deterioration of water quality by enhancing the ability of stormwater management programs to meet watershed goals.

1.2.1.2 Section 401 Certification and Wetlands

Section 401 of the CWA gives states, territories and authorized tribes the authority to review and approve, deny, or condition all Federal permits or licenses that might result in a discharge to State or Tribal waters, including wetlands. States are able to use Section 401 to improve or protect the water quality of their wetlands and waterways. States have the authority to review federal projects to ensure that discharges are consistent with CWA requirements including applicable water quality standards. State wetland water quality standards will limit the degradation of its waters and wetlands resulting from Federal activity.

Decentralized controls may potentially reduce the stormwater volume entering wetlands. Their small footprints allow for the construction of upland stormwater management controls, avoiding or minimizing the disturbance to wetlands resulting from the construction of stormwater management infrastructure.

1.2.1.3 Section 402 National Pollutant Discharge Elimination System (NPDES) Program

Section 402 of the CWA prohibits the discharge of any pollutant to waters of the United States from a point source unless the discharge is authorized by a NPDES permit. Point sources have been defined to include facilities and municipalities that discharge stormwater from certain activities (including industrial activities, construction activities, and municipal stormwater collection systems) requiring NPDES permits. Because stormwater discharges are wet weather events, the NPDES permits most likely will stipulate the use of BMPs rather than end-of-pipe treatment alternatives. Municipalities must implement commonly-accepted stormwater discharge programs or controls to effectively reduce or prevent the discharge of pollutants into receiving waters.

The 1987 amendments to the CWA required U.S. EPA to establish NPDES requirements for stormwater discharges. In response, U.S. EPA issued the Phase I requirements of the NPDES stormwater program in 1990 affecting medium and large municipal separate storm sewer systems (MS4s) located in incorporated places or counties with populations of 100,000 or more. The new regulations required municipal stormwater discharges to be covered by a NPDES permit.

U.S. EPA issued Phase II requirements in 1999 for small municipalities with populations less than 100,000. For many municipalities, the CWA Stormwater Phase II rule will expand their NPDES permitting requirements. Under the CWA Stormwater Phase II rule, U.S. EPA (or a state which has assumed CWA enforcement authority) can require a municipality with a stormwater system to obtain a permit, even if it is not automatically regulated, if the municipality's stormwater system discharges via a point source to an impaired water (the CWA 303(d) list) or to sensitive waters. Municipalities that fall under the Phase II rule will have to develop and implement various BMPs including expanded stormwater management.

Decentralized controls can help municipalities to meet stormwater control requirements in a manner that minimizes impacts to the jurisdiction and natural environment and reduces the amount of infrastructure to be constructed and maintained. Additionally, using decentralized controls to eliminate the volumes of effluent discharges of permit-requiring activities can help reduce the need for NPDES permits.

1.3 Organization of the Report

The objectives of this study are two fold: to provide a document to the subscribers of WERF that defines the current state of decentralized controls; and to present a developmental plan for implementation of decentralized controls in an urban environment specifically for the goal of CSO mitigation. To this end, this report will focus primarily on how decentralized controls can reduce the volume of stormwater runoff generated and consequently reduce the volume of stormwater entering the combined sewer systems in urban areas.

In Chapter 2.0, decentralized controls are defined and the variables used to evaluate them are presented. The technical information needed to evaluate them is also introduced. The effectiveness of the individual practices and implementation strategies is identified. A determination of the effectiveness of various decentralized controls in terms of their hydrologic, hydraulic, and water quality performance is presented. A discussion of how decentralized approaches may address regulatory programs or watershed restoration needs completes the chapter.

In Chapter 3.0, an analysis of the technical issues and practicality of integrating decentralized controls into all aspects of the urban infrastructure is discussed. A candidate set of individual practices and strategies is selected that represents typical objectives (e.g., volume reduction), and protocols are developed for assessing how communities can determine the feasibility of design and construction. Physical as well as perceived conditions (e.g., maintenance) are addressed. These include the required information on utilities, construction time, construction sequencing, traffic control, and other impacts of construction.

The evaluation of alternative implementation strategies, incentives, and disincentives is presented in Chapter 4.0. A set of CSO control objectives and scenarios are developed that represent a range of strategies for implementation and maintenance of decentralized controls. This includes retrofits of streets, urban renewal, and new development. The Prince George's County Low Impact Development (LID) model and the U.S. EPA Optimization model that is being developed by members of the project team are used to evaluate the effectiveness of the strategies. The team examines existing strategies for ownership, construction, and maintenance and development of new approaches for the management of the system. Optimization routines evaluate the life-cycle costs and effectiveness of each of the scenarios. Comparisons are made of different funding sources for construction and maintenance for public and private financing and for partnerships. This will allow communities to recognize the benefits of each approach and the information that is needed to effectively communicate the benefits of different approaches to capitalization.

An evaluation of implementation costs for education, planning, and design is presented in Chapter 5.0 of this report. The project team has prepared a model guide for communities to integrate the evaluation, design, construction, and maintenance of decentralized controls into their programs. The municipal partners on this project have shared their experience, including information from other municipal programs that were identified in a previous cataloguing effort.

Chapter 6.0 identifies ancillary benefits associated with decentralized controls. Benefits extending beyond stormwater control, such as energy and water conservation, community stewardship, and community economic benefits are evaluated. This chapter includes information derived from the experience of the project team members and the municipal project partners on these issues. Case studies and recommendations for protocols to help achieve the multiple benefits of decentralized controls are presented.

Chapter 7.0 provides guidance and protocols for evaluating, organizing, targeting, and prioritizing decentralized controls. The limitations and the lessons learned from this project and the experiences of the team and municipal partners are presented. A candidate set of control issues is presented for the use of stormwater managers in municipalities that are evaluating the use of decentralized controls. This last chapter includes a comparison of alternate implementation strategies and a model that demonstrates the effectiveness of these approaches. Protocols are developed for the evaluation and selection of strategies to implement a decentralized control program. These protocols are readily adaptable and flexible to meet both simple and complex objectives.

CHAPTER 2.0

DECENTRALIZED STORMWATER CONTROLS

2.1 Introduction

Decentralized controls are small-scale, distributed stormwater management devices that are constructed at individual sites. They have the capability to meet multiple stormwater management objectives, including peak attenuation, volume reduction, and water quality improvement. Decentralized controls use unit processes of the hydrologic cycle, such as infiltration and evapotranspiration, to meet these objectives. The ability to use multiple hydrologic and hydraulic processes allows the controls to be combined into a “treatment train” to meet targeted stormwater management objectives. They can be integrated into many common urban land uses on both public and private property to enhance flexibility in siting stormwater controls. Because they can be constructed on an individual basis or in conjunction with other projects, a variety of funding options is possible. Most importantly, they provide source control of stormwater, allowing management strategies to be targeted at specific sites rather than requiring the planning and construction of large-scale, capital-intensive centralized controls. All of these characteristics give decentralized controls the potential to reduce the volume of stormwater that enters a combined sewer system, thus mitigating the number of combined sewer overflows in a watershed. Section 2.1.1 details these characteristics.

This chapter will focus on decentralized controls and their applicability to the stormwater management objectives of urban areas. The purpose of this chapter is to:

- define decentralized controls, the hydrologic cycle elements they use, and the stormwater management objectives they are designed to meet;
- differentiate decentralized controls from conventional approaches;
- develop criteria used to define decentralized controls and to select the controls included in this report;
- identify the urban land uses appropriate for siting decentralized controls;
- summarize studies that demonstrate how decentralized controls meet stormwater management objectives; and
- report on data gaps and potential future research areas.

2.1.1 Characteristics of Decentralized Controls

2.1.1.1 Decentralized Controls are Multi-Dimensional

Conventional end-of-pipe devices are typically designed to meet a single stormwater management objective, such as peak discharge attenuation. By contrast, most decentralized controls, also referred to as Best Management Practices (BMPs), can be designed to simultaneously meet multiple stormwater management objectives, which are listed below.[1]

Volume: Reduce or delay the volume of stormwater that enters the combined system.

Peak Discharge: Reduce the maximum flow rate into the combined system by decreasing the stormwater volume and lengthening the duration of discharge. This inherently lowers the frequency of combined sewer overflows.

Water Quality: Improve water quality through volume reduction, filtering, and biological and chemical processes.

2.1.1.2 Decentralized Controls are Process-Based

Decentralized controls employ multiple elements of the natural hydrologic cycle. These unit processes are the building blocks for meeting the stormwater management objectives mentioned above.

Infiltration The downward movement of water into the soil via percolation through pore spaces.

Evapotranspiration The combined effects of evaporation and transpiration in reducing the volume of water in a vegetated area during a specific period of time.

Interception A form of detention and retention storage that occurs when leaves, stems, branches, and leaf litter catch rainfall.

Conveyance The transport of surface runoff, from where a raindrop falls to where it enters the receiving body of water.

Detention The temporary storage of stormwater, which is released over a period of hours or days after rainfall ceases.

Retention The permanent capture of a volume of stormwater that never enters the combined system.

Reuse Capture of rainwater for later use by other processes such as non-potable water applications or landscaping.

2.1.1.3 Decentralized Controls Allow for a Treatment Train Approach

The process-based nature of decentralized controls makes a treatment train approach possible. A treatment train is a series of BMPs working in concert to achieve overall site stormwater objectives, and is analogous to wastewater or drinking water treatment. Each BMP serves as the site of one or more hydrologic processes which partially satisfy the overall objective(s). Therefore, BMPs with complementary processes can be combined. Treatment trains offer virtually unlimited opportunities for customization. To achieve water quality goals, treatment trains employ natural biological and chemical processes which have been demonstrated to be the most efficient and effective means of improving water quality.

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[1] Integrated Management Practices (IMPs) is another term for decentralized stormwater controls, but BMP is used here because it is a more widely recognized term.

2.1.1.4 Decentralized Controls Can Easily Be Integrated into Urban Sites

Conventional BMPs such as detention ponds often do not easily integrate into urban sites for the following reasons:

- They are usually intended to treat large volumes of runoff, and therefore may consume large amounts of developable land;
- Placing conventional BMPs below ground may result in extensive utility conflicts; and
- Construction of conventional BMPs may create long-term economic and community disturbance.

By contrast, decentralized controls treat stormwater near the source, and therefore require a significantly smaller footprint (and overall storage volume) in most cases. The small scale of decentralized controls allows them to be integrated into many areas of a site (e.g., on a roof, in a parking lot, or in landscaped green space). Decentralized controls blend in with the landscape and infrastructure; in some cases, such as a permeable parking lot, the BMP *is* the infrastructure. Decentralized controls often serve additional purposes besides stormwater management, as described in Chapter 6.0. This approach to land use works well with the space constraints that exist in ultra-urban areas.

Decentralized controls can adapt to the physical constraints of the site, such as available open space, degree of soil compaction, and the vertical location of sewers, utilities, and the groundwater table. For instance, the depth of ponding in a swale can be reduced if the groundwater table is high, or if sewers are near the ground surface. With conventional controls, urban site constraints may severely limit the degree to which stormwater objectives can be met. Because decentralized controls can be part of an overall site design or redevelopment strategy, construction and maintenance costs may be able to be molded into other programs or funding streams such as mobilization.

2.1.1.5 Decentralization Allows Source Control of Stormwater

Because they prevent, intercept, and/or treat stormwater near the source, decentralized controls can be customized to meet the stormwater management objectives of a specific site, at the site. Conventional controls typically do not address these objectives until discharges from contributing subwatersheds converge at a single, centralized point. Centralized approaches allow for the transport of pollutants or large runoff volumes, which presents opportunities for the large-scale dispersion or accumulation of toxins. By contrast, decentralized controls treat relatively small, dispersed volumes of stormwater before they have a chance to accumulate or spread out over a larger area. Customizing and distributing the benefits of decentralized controls also presents the opportunity to distribute maintenance responsibilities among the various properties.

Many CSO Long Term Control Plans (LTCPs) have proposed constructing massive storage/conveyance tunnels to intercept the effluent that would otherwise overflow into local waterbodies. After the storm ends, the tunnels gradually release the effluent to wastewater treatment plants (WWTPs). Decentralized controls can be used in conjunction with this approach, reducing the infrastructure requirements of centralized facilities. First, BMPs will collectively reduce the required tunnel storage volume by retaining and detaining stormwater at the source. Secondly, once LTCPs are implemented, all stormwater runoff from the CSO area will eventually pass through the WWTP, requiring the facility to process a variety of non-point source urban pollutants as well as trash and sediment. BMPs that address water quality will reduce the need for WWTP upgrades and improve biosolids quality by controlling urban pollutants at the source. In other words, the pollutants will never enter the system.

2.1.2 Selection of Decentralized Controls

2.1.2.1 Selection Criteria

The characteristics of decentralized controls described in Section 2.1.1 were used as the basis for forming the following nine (9) selection criteria. A class of BMPs that meets most or all of these criteria can be considered to be a decentralized control. Based on the selection criteria, the 11 classes of BMPs listed in Section 2.1.2.2 were chosen for their ability to provide decentralized control of stormwater for urban retrofit and CSO reduction.

Volume Reduction Near the stormwater source, the BMP should reduce or delay the volume that potentially enters the combined system. Reducing the volume of runoff generated by small, frequently-occurring storms is a central goal of CSO control.

Water Quality Improvement The BMP should reduce the concentrations of common urban pollutants, including Total Suspended Solids (TSS), oil and grease, heavy metals, and nutrients, in order to address the problem of urban non-point source water pollution.

Demonstrated Success Quantitative and qualitative monitoring data from actual installations of the BMP should confirm that the BMP can successfully meet one or more of the stormwater management objectives presented in Section 2.2.

Multiple Objectives The BMP should not be one-dimensional (i.e., satisfy only a single stormwater management objective) but must at least partially meet more than one of the objectives presented in Section 2.2.

Hydrologic Cycle Elements The BMP's constituent processes should be identifiable as elements of the natural hydrologic cycle. The function of the BMP should be able to be described and quantified entirely in terms of those processes.

Treatment Train The BMP should be able to be combined with other BMPs to form a stormwater treatment train described in Section 2.1.1.3. This way, other BMPs can provide functions that the BMP in question lacks.

Site Integration The BMP should be able to be integrated into other functional components of the site, such as the landscaping and infrastructure, without impeding or significantly affecting their function. Land that the BMP occupies should be able to serve purposes in addition to stormwater management, such as open space or parking.

Design Storm The BMP should satisfy stormwater management objectives for small, frequently-occurring storms in order to reduce the incidence of CSOs and mitigate urban non-point source pollution.

Source Control The BMP should be able to meet the stormwater management objectives for relatively small quantities of stormwater at or near the source, rather than at a centralized collection point. The BMP should be able to be used in different locations at a site, if necessary, to ensure distributed control of stormwater.

2.1.2.2 List of BMP Classes

Most of the BMP classes listed below encompass several distinct variations, so there are many more than 11 individual technologies available for decentralized stormwater control. For example, the porous pavement class of BMPs includes interlocking paver blocks, plastic grid systems, permeable asphalt, and permeable concrete; these technologies were grouped together because they have similar hydraulic and hydrologic functions. Definitions of BMPs and their variations are presented in Appendix B.

- Downspout Disconnection
- Filter Strips
- Infiltration Practices
- Pocket Wetlands
- Porous Pavement
- Rain Barrels/Cisterns
- Rain Gardens
- Soil Amendments
- Tree Box Filters
- Vegetated Roofs
- Vegetated Swales

2.1.3 Reasons for Excluding BMPs

Some BMPs generally regarded as conventional stormwater controls, such as pocket wetlands, were included in the list of decentralized controls because they satisfy most or all of the criteria presented in Section 2.1.2.1 above. Other conventional BMPs, notably detention and retention basins, were not included because they did not satisfy most of the criteria. Excluded BMPs had some or all of these characteristics:

- Not able to reduce or delay the volume of stormwater entering the combined system;
- Not intended to replicate elements of the natural hydrologic cycle;
- Only able to treat a limited range of pollutants, such as TSS and oil and grease;
- Not intended to meet more than one stormwater management objective;
- Not readily adaptable to a treatment train approach;
- Not able to be integrated into the physical constraints of an ultra-urban environment without compromising its ability to meet its stormwater control objective;
- Not intended to control small, frequently-occurring storms, which are the primary source of the CSO problem;
- Not able to provide source control of small quantities of stormwater from sub-drainages across a site; and

- Not able to provide other environmental or social benefits in addition to stormwater management.

For example, detention ponds are one-dimensional controls: they primarily provide attenuation of peak discharges. Also, they are intended for relatively large, infrequent storms and are not easily adaptable to the physical constraints of an ultra-urban environment. By contrast, while wetlands often serve as centralized, end-of-pipe devices, they can also be scaled down in size, so that multiple pocket wetlands can treat several smaller sub-drainages. The same cannot be said for detention basins: scaling them down would severely curtail their usefulness in reducing the peak discharge from relatively large, infrequent storms. Also, it may be difficult or impossible to find the land area or vertical space in the ground (i.e., free of utilities) to construct large basins in urban areas, and land reserved for detention ponds cannot be used for any other purpose.

2.2 Stormwater Management Objectives

BMP effectiveness was evaluated against the following stormwater management objectives: volume, peak discharge, and water quality. The extent to which a BMP meets these objectives, especially volume, helps to determine its effectiveness in preventing or mitigating CSOs. Section 2.2.1 defines the hydrologic objectives and Section 2.2.2 discusses the qualitative ranking approach for each objective. Section 2.3 and Table 2-2 describe the individual elements of the hydrologic cycle, such as infiltration, that BMPs use to achieve these objectives.

Two other parameters commonly used to evaluate stormwater BMP effectiveness, frequency and duration, will not be evaluated as independent management objectives. Runoff frequency control is the effectiveness of a BMP at reducing the annual number of stormwater discharges that exceed a target depth or discharge rate. The frequency of stormwater discharges from a given watershed is directly dependent upon the volume of stormwater generated. Therefore, a reduction in stormwater volume will result in a reduction in frequency. Because stormwater volume directly influences frequency, for the purposes of this report, volume will be analyzed as a stormwater management objective and be understood to influence the frequency of discharges.

Similarly, the goal of duration control is to increase the length of time over which stormwater enters the combined system, in order to decrease its rate so as not to overwhelm the capacity of the combined sewer system. Peak discharge control directly indicates the duration of stormwater discharge. For a given volume of stormwater discharge, decreasing the peak rate of discharge necessarily increases duration. Because peak discharge directly influences duration, for the purposes of this report, peak discharge will be analyzed as a stormwater management objective and be understood to influence the duration of discharges.

Table 2-1. Effectiveness of BMPs in Meeting Stormwater Management Objectives.

BMP	Volume	Peak Discharge	Water Quality
Downspout Disconnection	◉	◉	◉
Filter Strips	○	○	◉
Infiltration Practices	◉	○	◉
Pocket Wetlands	●	●	●
Porous Pavement	●	●	◉
Rain Barrels/Cisterns*	◉	○	○
Rain Gardens	●	●	●
Soil Amendments	◉	◉	◉
Tree Box Filters	◉	◉	●
Vegetated Roofs	◉	●	●
Vegetated Swales	◉	◉	●

* A single cistern typically provides greater volume reduction than a single rain barrel.

Key: ● High effectiveness ◉ Medium effectiveness ○ Low effectiveness

Rankings are qualitative. "High effectiveness" means that one of the BMP's primary functions is to meet the objective. "Medium effectiveness" means that a BMP can partially meet the objective but should be used in conjunction with other BMPs. "Low effectiveness" means that the BMP's contribution to the objective is a byproduct of its other functions, and another decentralized control should be used if that objective is important. The rationale for ranking individual stormwater management objectives is given in Section 2.2.2.

2.2.1 Definitions of Stormwater Management Objectives

2.2.1.1 Volume

Volume control is the effectiveness of a BMP at reducing or delaying the total volume of stormwater that leaves the BMP and enters the combined system. This includes the volume of runoff that *flows into* the BMP as well as rainwater that *falls on* the BMP (as in pervious pavement). Retention and detention control the stormwater volume. Retention permanently takes a volume of stormwater "out of the system." Detention intercepts stormwater and allows it to enter the combined system slowly over several hours or days, rather than all at once. Many BMPs provide volume control by both retention and detention, and both methods alleviate CSO events.

2.2.1.2 Peak Discharge

Peak discharge is the maximum stormwater flow rate, resulting from a given storm, that leaves a site and enters the combined system. Control of peak discharge has traditionally been the primary objective of conventional stormwater management, which directly controls peak discharge by restricting the flow exiting a centralized detention structure.

Decentralized controls indirectly control peak discharge by reducing or delaying the volume of stormwater that enters the combined system, and by lengthening the amount of time over which it enters. Because decentralized controls treat stormwater at the source, discharges from individual sites remain dispersed, which reduces the kinetic energy of stormwater entering a given design point.

2.2.1.3 Water Quality

Water quality treatment decreases the concentrations of common non-point source urban pollutants, including TSS, nutrients, oil and grease, and heavy metals. Decentralized controls achieve water quality improvements through volume control, filtering, and biological and chemical processes in soil and vegetation.

2.2.2 Ranking Approach

BMP effectiveness at meeting each of the stormwater management objectives was qualitatively categorized as low, medium, or high. A ranking of "high effectiveness" was given when one of the primary functions of the BMP is to meet the given objective. All BMPs have at least a ranking of "low effectiveness" for most categories.

2.2.2.1 Volume

Volume rankings were based on the BMP's ability to retain or detain stormwater. Methods of reducing volume by retention include

- vegetative interception;
- evaporation;
- transpiration of soil moisture; and
- rainwater reuse.

Ponding and temporary storage in soil and gravel detain stormwater. BMPs with a combination of the greatest storage depth, minimal footprint, and ability to infiltrate over an extended period of time received higher rankings.

2.2.2.2 Peak Discharge

The volume and duration rankings determine the peak discharge ranking. BMPs that detain a large volume of water and release it over an extended period of time receive a high ranking for peak discharge. The effect of retention storage on the peak discharge ranking is minor because retained stormwater is never discharged into the combined system.

2.2.2.3 Water Quality

All BMPs received at least a "low effectiveness" ranking because they all provide at least a minor amount of volume control, decreasing the amount of surface runoff available to convey pollutants. Vegetated BMPs providing detention and retention storage received "high effectiveness" rankings because they employ a combination of biological, chemical, and physical processes to reduce pollutant concentrations.

2.3 Hydrologic Cycle Elements

Table 2-2 shows the use of natural hydrologic cycle elements by BMPs. These unit processes allow BMPs to achieve the stormwater management objectives described in Section 2.2 and Table 2-1. Section 2.3.1 defines the hydrologic cycle elements and Section 2.3.2 discusses the qualitative ranking approach.

Table 2-2. Use of Hydrologic Cycle Elements by BMPs.

BMP	Infiltration	ET*	Interception	Conveyance	Detention	Retention	Reuse**
Downspout Disconnection	◉	○			○	◉	
Filter Strips	○	○	○	○		○	
Infiltration Practices	◉			○		◉	
Pocket Wetlands	◉	◉	○		●	◉	
Porous Pavement	●				●	◉	
Rain Barrels/Cisterns						◉	●
Rain Gardens	●	◉	○		●	◉	
Soil Amendments	◉				○	◉	
Tree Box Filters	◉	◉	○		◉	◉	
Vegetated Roofs	◉	◉	○		●	◉	
Vegetated Swales	◉	○	○	◉	●	○	

* Evapotranspiration

** Collected water can be used for landscaping, non-potable building uses (e.g., toilets), or as raw water to be treated for drinking.

Key: ● High reliance ◉ Medium reliance ○Low reliance Blank: N/A

Rankings are qualitative. “High reliance” means that the process is integral to the BMP’s ability to meet stormwater management objectives, and that the BMP uses the process to its full potential in the urban environment. “Medium reliance” was assigned when a process is a secondary component of the BMP’s operation, or when the BMP does not use the process to its full potential. “Low reliance” means that the process only marginally contributes to the BMP’s ability to meet stormwater management objectives. The rationale for ranking hydrologic cycle elements is given in Section 2.3.2.

2.3.1 Definitions of Hydrologic Cycle Elements

2.3.1.1 Infiltration

Infiltration is the downward movement of water into the soil via percolation through pore spaces. In an open system such as a meadow, this movement is unrestricted and water can infiltrate down to, and recharge, the groundwater table. Groundwater recharge is a basic component of the natural hydrologic cycle. In urban areas, unrestricted infiltration may exacerbate infiltration and inflow (I/I) problems in both separate and combined sewer systems; the likelihood of this scenario must be evaluated before constructing unlined infiltration BMPs.

In urban BMPs, collected stormwater is often unable to exfiltrate from the BMP into the surrounding subsoils because of functionally impervious (i.e., compacted) soils or an impermeable liner that limits the downward movement of water (designs often include underdrains and high flow bypass pipes to ensure adequate drainage). In these instances, BMPs that utilize infiltration and exfiltration to surrounding subsoils in suburban settings provide temporary soil storage in urban applications. Stormwater that infiltrates into the BMP is held within the BMP until it is taken up by vegetation or the field capacity of the BMP is exceeded, causing a discharge to an underdrain or overflow structure.

Open infiltration BMPs and BMPs that provide temporary soil storage contain one or more layers of engineered soil media ranging in thickness from a few inches (as in a green roof) to several feet. Two basic processes occur in these layers:

- Volume reduction through the filling of soil pores; and

- Pollutant removal through filtering and sorption by organic matter and other soil constituents.

In urban areas, some of the infiltrated stormwater will be retained and its volume permanently taken "out of the system." Stormwater may also be detained, which temporarily reduces the amount of stormwater that would otherwise be in the combined system and allows it to enter the combined system over an extended period of time.

The soil moisture content determines the volumes of stormwater that are retained and detained. In a given BMP, the volume of retained water is the volume for which the soil moisture content equals the soil's field capacity. The retained water leaves the soil through evapotranspiration. The field capacity is the point at which free drainage by gravity ceases and the remaining water is held in the soil pores by capillary and osmotic forces. At this moisture content, the soil is unsaturated. The volume of additional stormwater that causes the soil moisture content to exceed the field capacity will be detained, and will drain by gravity into the underdrains over a period of several hours or days. Figures 2-3 and 2-4 graphically depict the relationship between detention and retention.

In this report, the capacity for groundwater recharge is not required for a BMP to be considered as an infiltration device. Infiltration BMPs may be open systems or provide temporary soil storage. In highly urban areas, open systems are rare for a variety of reasons discussed in Chapter 3.0.

2.3.1.2 Evapotranspiration

Evapotranspiration (ET) refers to the combined effects of evaporation and transpiration in reducing the volume of water in a vegetated area during a specific period of time. The volume of water in the root zone of soils is taken up by roots and then transpired by being diffused through leaves (uptake by roots also removes a variety of pollutants from stormwater).

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

$$V_t = D_r A_s (FC - WP) \tag{2.1}$$

where: V_t is the volume transpired
D_r is the rooting depth
A_s is the soil surface area
FC is the field capacity
WP is the wilting point

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

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

2.3.1.3 Interception

Interception is a form of detention and retention storage that occurs when leaves, stems, branches, and leaf litter catch rainfall. Interception is considered to be detention storage if raindrops drain off vegetation by "through fall" (dripping off a leaf onto the ground) or by stemflow (flowing down stems or trunks). Through fall accounts for the majority of the movement of intercepted rainfall. Intercepted rainfall that is retained is lost to the atmosphere by evaporation from the surface of leaves.

The percentage of rainfall that is intercepted increases with the density of vegetation, including all vertical layers from canopy to leaf litter. At maximum density, both trees and grasses may intercept 10-20% of precipitation from an individual storm. Per unit of ground area, some grass species have the same leaf area as many trees.[2]

Volume reductions from interception should be expected to be minor in urban BMPs. However, interception also absorbs some of the kinetic energy of rainfall; this reduces the magnitude of raindrop erosion. Similarly, interception preserves soil permeability because less eroded material is available to clog soil pores and less soil compaction by raindrops occurs.

2.3.1.4 Conveyance

Conveyance is the transport of surface runoff and includes the entire flow path from where a raindrop falls to where it enters the receiving body of water. In conventional stormwater designs, conveyance is synonymous with the efficient drainage of runoff. By contrast, decentralized controls that provide conveyance also promote infiltration, improve water quality, and increase runoff travel time, or time of concentration (T_c). They are often critical components of the treatment train approach. In this report, "conveyance" refers to the act of transporting runoff, rather than the carrying capacity of a BMP or other structure.

2.3.1.5 Detention

Detention is the temporary storage of stormwater, which is released over a period of hours or days after rainfall ceases. Detained stormwater may exist as ponded free water or can be held within moist soil. In urban areas, detained runoff ultimately enters the combined system. In a vegetated BMP, ponded water and any soil moisture above the field capacity are detained, rather than retained, because that portion of the stormwater slowly percolates by gravity through the soil column into the underdrain. For small, frequently-occurring storms, however, the release of detained water will not usually contribute to CSOs because the stormwater will enter the system over a much longer period of time, and at a lower rate, than if decentralized controls were not in place.

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[2] Dunne and Leopold 88.

2.3.1.6 Retention

Retention captures stormwater permanently. The volume of retained runoff never enters the combined system; vegetative interception, evaporation, transpiration of soil moisture, and reuse eliminate this volume. Evaporation may occur from soil, vegetation, or hard surfaces. Transpiration reduces the water volume within the root zone of soil. As stormwater enters a BMP, infiltrating water will be retained up to the point that the soil moisture content equals the field capacity. If the rainfall is sufficiently light, such that the soil moisture content in a vegetated BMP never reaches field capacity, ET alone will eliminate the volume of stormwater in the soil.

2.3.1.7 Reuse

Capturing rainwater in rain barrels and cisterns prevents it from entering a combined system during the storm. Because this water is usually used for landscaping during dry periods, it can be considered to be retained.

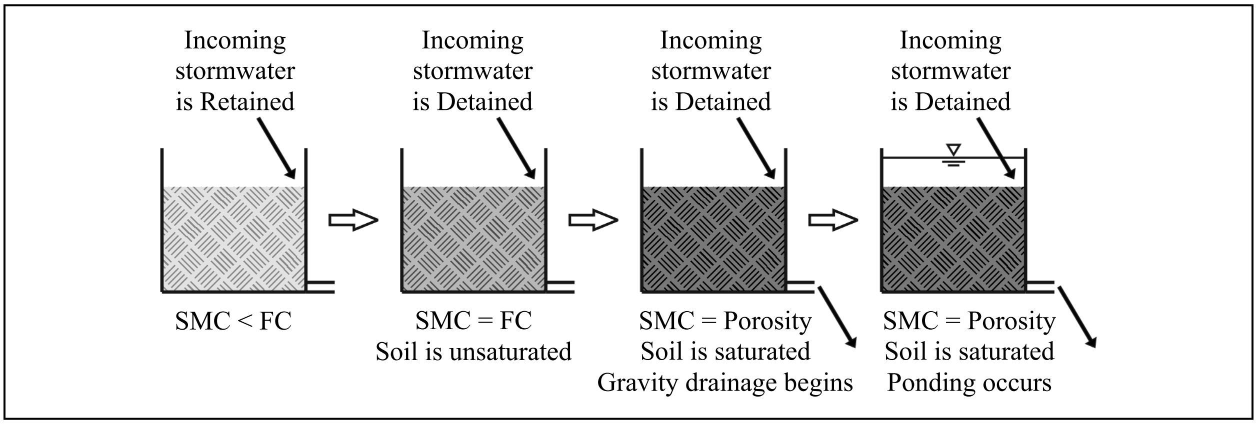


Figure 2-1. Conceptual Diagram of Retention and Detention in a Vegetated Urban BMP Filling with Stormwater. SMC = Soil Moisture Content, FC = Field Capacity

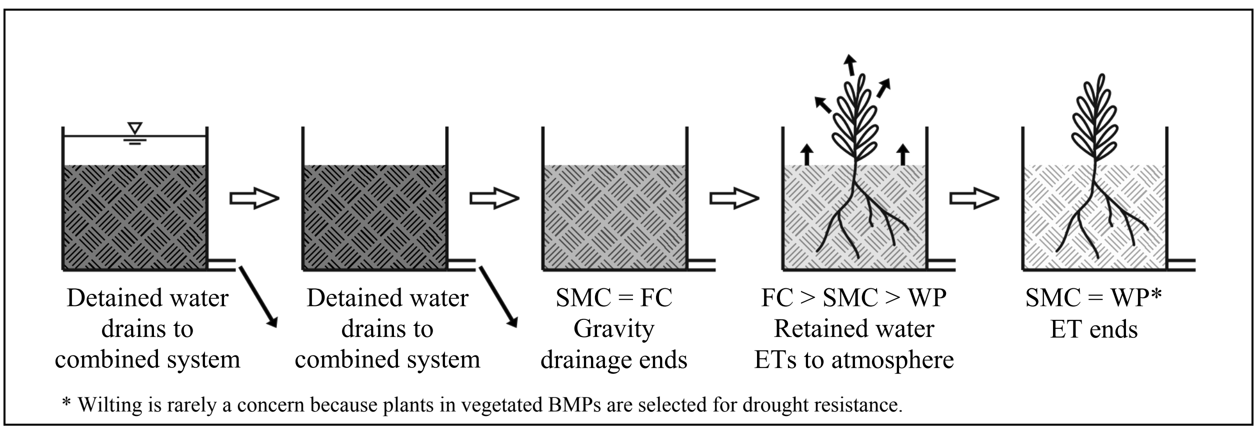


Figure 2-2. Conceptual Diagram of Retention and Detention in a Vegetated Urban BMP Emptying of Stormwater. WP = Wilting Point, ET = Evapotranspiration

2.3.2 Ranking Approach

BMPs rely on each element of the hydrologic cycle to varying degrees. In Table 2-2, reliance by each BMP on a given process was ranked as high, medium, or low. A cell was left blank if a given BMP did not rely on a particular hydrologic cycle element at all. In general, the rankings reflect an estimate of how important each element is to the BMP's ability to meet stormwater management objectives. The validity of a particular ranking can be tested by asking, "How effectively will this BMP function, and how distinct will it be from other BMPs, if this hydrologic cycle element is not allowed to occur?" Also, the urban hydrologic cycle is heavily skewed toward surface runoff because of the extent of imperviousness. Therefore, the rankings also reflect the degree to which each BMP can *restore* a particular element of the hydrologic cycle (e.g., infiltration) within the urban environment, in place of surface runoff occurring.

2.3.2.1 Infiltration

Infiltration BMPs may slow the movement of stormwater into the combined system (detain), permanently take stormwater "out of the system" (retain), or both. Filter strips received a "low reliance" ranking because runoff may pass over them too rapidly to fully infiltrate. Porous pavement and rain gardens received a "high reliance" ranking because each contains an engineered subbase, often several feet thick, designed to maximize infiltration over an extended period of time.

2.3.2.2 Evapotranspiration

Evapotranspiration rankings were based upon a judgment of how effective a vegetated BMP will be in reducing soil moisture content below the field capacity, beginning two (2) to three (3) days after the soil has been saturated (i.e., when free drainage ceases).

2.3.2.3 Interception

All vegetated BMPs except filter strips were assigned a "low reliance" ranking for interception by default, because the height, density, extent, and type of vegetation in any of these BMPs can potentially provide minor volume reductions for small, frequently-occurring storms.

2.3.2.4 Conveyance

BMPs for which the movement of surface runoff is integral to their function, or makes them distinct from other BMPs, received at least a "low reliance" ranking for conveyance. Vegetated swales received a "medium reliance" ranking because of their potential to convey relatively large volumes of stormwater.

2.3.2.5 Detention

BMPs were ranked for detention if they eventually release stored stormwater into the combined system. The most effective detention BMPs are those with the greatest storage depth, footprint, and ability to pond stormwater in order to infiltrate after the storm has ended.

2.3.2.6 Retention

No BMP received a "high reliance" ranking for retention. This reflects the fact that in nature, most retention occurs as the result of unrestricted infiltration into the soil and down to the groundwater. Unrestricted infiltration is rare in urban BMPs because they are lined or because soils are compacted. Urban BMPs will only retain the volume of water at which the soil moisture content equals the field capacity. Because retention occurs only in the BMP itself (i.e., exfiltration into the surrounding soil usually does not occur), the highest ranking any BMP received was a medium reliance on retention.

2.3.2.7 Reuse

All stormwater intercepted by rain barrels and cisterns can be reused for a variety of purposes including landscaping and non-potable building uses. These BMPs have a "high reliance" ranking for reuse because they cannot collect stormwater until the rainwater from the previous storm is used.

2.3.3 Quantitative Analysis of Hydrologic Processes

The dominant hydrologic processes described above occur at varying degrees in the facilities identified as urban BMPs. The design of these facilities is founded primarily on a hydrologic water balance:

$$\frac{dS}{dt} = I_t - Q_t \tag{2.2}$$

where: dS/dt is the change in storage in the system over time
I_t is the rate of inflow (includes surface inflow and direct rainfall) at time t
Q_t is the rate of outflow (includes surface discharge rate, infiltration and evapotranspiration) at time t

In order to size a facility, the equation above (or at least a simplified numeric form of it) must be solved. Assuming that the influent hydrologic processes (i.e., I_t) can be adequately described using design storm (e.g., rational method) or continuous simulation (e.g., SWMM) approaches, the following paragraphs focus on methods for estimating the effluent hydrologic processes (i.e., Qt).

2.3.3.1 Infiltration Estimation for BMP Design

Infiltration into homogenous porous media follows Darcy's Law, which states that the volumetric flux (flow rate per unit area) is directly proportional to the hydraulic gradient (Chow et al., 1988). The proportionality constant is the hydraulic conductivity coefficient of the media, which must be estimated based on soil moisture and texture or determined in the field or laboratory. In practice, applying Darcy's Law is an extremely complex endeavor because the hydraulic gradient varies over time as ponding depth varies and as soil suction head changes with moisture content (Ferguson, 1994).

Beneath a ponded water surface, moisture content varies with depth. As shown in Figure 2-5, there are four distinct moisture zones: a saturated zone near the surface, a transmission zone of unsaturated flow and relatively constant moisture content, a wetting zone where moisture content decreases with depth, and a wetting front where there is a sharp change from wet to dry soil (Chow et al., 1988).

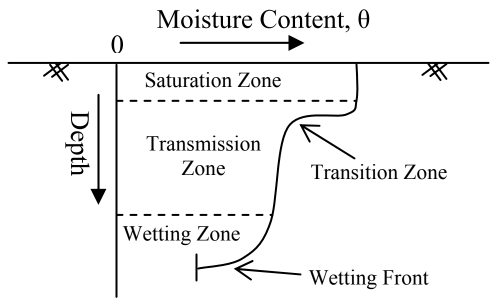


Figure 2-3. Moisture Zones During Infiltration (Adapted from Chow et al. 1988).

The hydraulic gradient during vertical infiltration is a function of both gravity and soil suction. Initially, soil suction dominates the process until the moisture content exceeds the field capacity of the soil and free drainage begins. As water penetrates deeper into the soil column, the transmission zone lengthens and the influence of soil suction head on the infiltration rate becomes negligible (Ferguson, 1994). Eventually, gravity becomes the dominant force controlling infiltration as the hydraulic gradient is reduced to unity and the infiltration rate approaches the saturated hydraulic conductivity. When surface ponding ceases, drainage through the vadose zone continues until the moisture content is reduced to the field capacity. Further reductions in moisture content are caused by evapotranspiration (discussed separately in Section 2.3.3.2).

In order to appropriately size an infiltration BMP, both the infiltration rate and the infiltration volume must be estimated. Infiltration BMPs are commonly designed to infiltrate a water quality design storm or an annual volumetric percent capture. In choosing an analytical method to determine infiltration rates, many factors must be considered. Table 2-3 provides a list of commonly used equations for estimating infiltration rates and volumes including the SCS curve number method, Horton's method, Philip's method, and the Green-Ampt method.

Table 2-3. Commonly Used Equations for Estimating Infiltration Rates and Volumes.

Method	General Equations	Volume/ Rate	Benefits	Drawbacks	Difficulty and Required Information
Horton's Method	$f = f_c + (f_0 - f_c)e^{-kt}$ $F = f_c t + ((f_0 - f_c)/k)(1 - e^{-kt})$ F = total infiltration (in) f = infiltration rate (in/hr) f_0 = initial infiltration rate (in/hr) f_c = final infiltration rate (in/hr) k = decay constant (hr^{-1}) t = time since start of rainfall (hr)	Volume and Rate	More accurate than curve number method, derived from approximate solutions to Richard's Equation.	Strongly dependant on starting time of rain, critical when rainfall starts at low intensity. Also, assumes hydraulic conductivity and soil diffusivity are independent of initial soil moisture.	Need measured initial and final infiltration rates, easy calculations once infiltration rates determined or estimated.
Philip's Method	$f = 1/2St^{-1/2} + K$ $F = St^{1/2} + Kt$ F = total infiltration (in) f = infiltration rate (in/hr) S = sorptivity ($in/hr^{0.5}$) K = hydraulic conductivity of soil (in/hr) t = time (hr)	Volume and Rate	Less restrictive solution to Richard's Equation; allows hydraulic conductivity and soil diffusivity to change with soil moisture content. Easy calculations once parameters are determined	Not as common as other methods because sorptivity values are not easily obtained. Sorptivity is a function of the soil suction head.	Need sorptivity of soil; can be measured onsite or in a laboratory, or estimated by soil class. Easy calculations once parameters are determined
Green-Ampt Method	$F = Kt + \varphi\Delta\theta \ln(1 + (F/\varphi\Delta\theta)$ $f = K((\varphi\Delta\theta / F) + 1)$ f = infiltration rate (in/hr) φ = suction head (in) Δθ = porosity – initial soil moisture F = total infiltration (in)	Volume and Rate	Widely used in modeling programs, with published tables of values of assumed parameters for all soil types. While more approximate in physical theory, exact numerical calculations are possible.	Generalizations of soil classification are not as accurate as on-site infiltration tests. Requires iterative calculations.	Moderately difficult calculations. Soil sampling is needed to accurately determine model parameters.

When on-site infiltration testing has been performed for both saturated and dry soil conditions, the Horton Method can be very accurate. The method assumes that infiltration begins at an initial rate, f_o, and then exponentially decreases until it reaches a constant rate, *fc* (Chow et al., 1988). This method assumes hydraulic conductivity and diffusivity are constant.

Philip's method improves upon Horton's approximation by allowing these two soil parameters to vary with moisture content. Philip's method introduces an additional term, sorptivity, which is a function of soil suction (Chow et al., 1988). Sorptivity can be very site specific and should therefore be determined through field or laboratory measurement.

The Green-Ampt method has more of a physical basis than the other three methods (Chow et al., 1998). It is based on an approximate solution of the one-dimensional Richard's equation. The principal assumptions of the method are stable and homogenous soils, unlimited supply of ponded water at the surface, uniform moisture content in the transmission zone, and a definable wetting front (Ferguson, 1994). Application of the Green-Ampt equation requires estimates of several parameters including saturated hydraulic conductivity, porosity, and the wetting front soil suction head. Table 2-4 provides estimates of parameters in the Green-Ampt model according to soil texture class.

In field testing, the USGS found that the Green-Ampt method produced slightly more accurate results over the Horton Method when compared with measured field data (Trommer et al., 1996). Both Horton and Green-Ampt are featured in SWMM and HEC-HMS hydrologic models.

Table 2-4. Parameters in the Green-Ampt Model (Ferguson 1994).

Soil Texture	Effective Porosity θ_e (cm^3/cm^3)	Suction Head ψ Below Wetting Front (cm)	Saturated Hydraulic Conductivity K (cm/h)
Sand	0.417 (0.354 – 0.480)	4.95 (0.97 – 25.36)	21.00
Loamy sand	0.401 (0.329 – 0.473)	6.13 (1.35 – 27.94)	6.11
Sandy loam	0.412 (0.283 – 0.541)	11.01 (2.67 – 45.47)	2.59
Loam	0.434 (0.334 – 0.534)	8.89 (1.33 – 59.38)	1.32
Silt loam	0.486 (0.394 – 0.578)	16.68 (2.92 – 95.39)	0.68
Sandy clay loam	0.330 (0.235 – 0.425)	21.85 (4.42 – 108.0)	0.43
Clay loam	0.309 (0.279 – 0.501)	20.88 (4.79 – 91.10)	0.23
Silty clay loam	0.432 (0.347 – 0.517)	27.30 (5.67 – 131.50)	0.15
Sandy clay	0.321 (0.207 – 0.435)	23.90 (4.08 – 140.2)	0.12
Silty clay	0.423 (0.334 – 0.512)	29.22 (6.13 – 139.4)	0.09
Clay	0.385 (0.269 – 0.501)	31.63 (6.39 – 156.5)	0.06

2.3.3.1 Evapotranspiration Estimation for BMP Design

Evapotranspiration is a highly complex natural process. The degree of accuracy of evapotranspiration calculations is correlated to the availability and quality of meteorological records in the study area. Even with precise and in-depth meteorological records, evapotranspiration determinations are little more than estimates (EWRI, 2002). Generalized regional weather data can be substituted for localized project area data, but will lead to less accurate results. There are some computer models available for predicting and estimating various parameters that fit the Penman-Monteith equation (EWRI, 2002). Freeware versions of REF-ET are available at http://www.kimberly.uidaho.edu/ref-et/. Users must input meteorological data, but do not need detailed records to complete the equation by hand. Programs such as REF-ET use generalized assumptions and may provide highly inaccurate results if inadequate information is supplied.

Table 2-5. Commonly Used Equations for Estimating Evapotranspiration Rates and Volumes.

Method	General Equations	Vol./ Rate	Benefits	Drawbacks	Difficulty and Required Information
Maximum Transpiration Potential	$\mathrm{V}_{\mathrm{trans}} = D_r \cdot A \cdot \left(FC - WP\right)$ V_{trans} = Transpired volume D_r = Rooting depth A = Soil surface area FC = Field capacity WP = Wilting point	Volume	Easy to use	Only estimates the maximum volume that ET can potentially remove once the soil moisture content equals the field capacity (FC)	Site-specific soil information
ASCE Std. Penman-Monteith	$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma(C_n / T + 273)u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$ ET_{sz} = standardized evapotranspiration (mm/day) R_n = calculated net radiation at the grass surface (MJ/m^2-day) G = soil heat flux density at soil surface (MJ/m^2-day) T = mean daily or hourly temperature at 2 m (^{o}C) u_2 = mean daily or hourly wind speed at 2 m (m/s) e_s = saturation vapor pressure at 2 m (kPa) e_a = mean actual vapor pressure at 2 m (kPa) Δ = slope of the saturation vapor pressure-temperature curve (kPa/^{o}C) γ = psychometric constant (kPa/^{o}C) C_n = numerator constant (from table) C_d = denominator constant (from table)	Rate and Volume	This equation has been widely tested and accepted by the ASCE as accurate and suitable for engineering calculations	The result is greatly dependant on the quality of the weather data provided. As with any determination with an excessive amount of variables, computed values are only estimates.	Requires measures or estimates for air temperature, solar radiation, humidity and wind speed. General site elevation is required to determine the psychometric constant.

Table 2-6a. Evapotranspiration Equation Variables.

Calculation Time Step	Short Reference, ET_{os}		Tall Reference, ET_{rs}		Units for ET_{os}, ET_{rs}	Units for R_n, G
	C_n	C_d	C_n	C_d		
Daily	900	0.34	1600	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly during daytime	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly during nighttime	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

Table 2-6b. Evapotranspiration Equation Variables.

Term	ET_{os}	ET_{rs}
Reference vegetation height, h	0.12 m	0.50 m
Height of air temperature and humidity measurements, z_h	1.5 – 2.5 m	1.5 – 2.5 m
Height corresponding to wind speed, z_w	2.0 m	2.0 m
Zero plane displacement height	0.08 m	0.08 m
Latent heat of vaporization	2.45 MJ kg^{-1}	2.45 MJ kg^{-1}
Surface resistance, r_s, daily	70 s m^{-1}	45 s m^{-1}
Surface resistance, r_s, daytime	50 s m^{-1}	30 s m^{-1}
Surface resistance, r_s, nighttime	200 s m^{-1}	200 s m^{-1}
Value of R_n for predicting daytime	> 0	> 0
Value of R_n for predicting nighttime	≤ 0	≤ 0

2.4 Site Integration

By their nature, decentralized controls can be integrated into a variety of existing land uses in the urban environment. However, from both a functional and maintenance point of view, some land uses are better suited for a particular BMP than others. Urban land uses can be divided into three basic categories: open space, support infrastructure, and the buildings themselves. Depending on whether a BMP is located in a right-of-way, BMP maintenance will either become part of the overall responsibilities of the local public works department(s), or it will be the responsibility of the landowner of a particular site. Six (6) BMPs can be maintained in either manner.

Table 2-7. Integrating BMPs into Sites.

	Land Use			Ownership	
BMP	**Open Space**	**Infrastructure***	**Building**	**Public Right-of-Way**	**Private Property**
Downspout Disconnection		✓			✓
Filter Strips	✓			✓	✓
Infiltration Practices	✓			✓	✓
Pocket Wetlands	✓				✓
Porous Pavement		✓		✓	✓
Rain Barrels/Cisterns	✓		✓		✓
Rain Gardens	✓			✓	✓
Soil Amendments	✓			✓	✓
Tree Box Filters		✓		✓	
Vegetated Roofs			✓		✓
Vegetated Swales	✓			✓	✓

* Defined as roadways and stormwater conveyance systems that may be publicly or privately maintained.
A BMP received a check in a given category if it can feasibly be constructed and maintained in that land use.

2.4.1 Definitions of Site Categories

2.4.1.1 Open Space

Open space is any potentially pervious surface, including vegetated areas and bare dirt. Most open space available for BMP construction in urban areas is covered by grass, mulch, or shrubs. Redevelopment may also create new open space. Urban soils are often compacted, even in open areas; amending or soil replacement may be necessary if infiltration is to occur. Even small areas of "green" space, such as vacant tree pits, may be candidates for BMP construction. Because open space is usually at a premium in urban areas, the potential benefits of BMPs must be weighed against the benefits that the open space currently provides.

2.4.1.2 Infrastructure

Infrastructure includes all aspects of the transportation (vehicular, pedestrian, mass transit) and stormwater management systems in an urban area. It may be publicly or privately maintained. It excludes pervious surfaces, which count as open space. BMPs in this category must be able to be integrated into the hardscape common in urban areas, such as parking lots and curbs and gutters. Downspout disconnection counts as an infrastructure BMP because it results in a separation from the combined system. Until disconnection occurs, downspouts are effectively an extension of the combined sewer system.

2.4.1.3 Building

BMPs in this category must be able to be integrated into the structure or support system (i.e., water supply) of a building. (Rain barrels are usually located adjacent to a building on open space, which accounts for the check in the open space category.)

2.4.1.4 Public Right-of-Way

Land in this category may be pervious or impervious, and is usually related to transportation (e.g., sidewalks, median strips). While it is not uncommon for private maintenance to occur within a public right-of-way, in this instance it is allowed that the local public works department maintains this property. For this discussion, this is the main distinction between land identified as public right-of-way and private property.

2.4.1.5 Private Property

This category encompasses all BMPs for which it is feasible for the landowner to be responsible for routine maintenance. This definition also includes government property other than rights-of-way. Only BMPs that are typically located in a right-of-way and expected to be maintained by public works departments are excluded from this category.

2.4.2 Ranking Approach

A BMP received a check in a given category if it can feasibly be constructed and maintained in that land use. All BMPs except rain barrels and cisterns are appropriate for only one land use. In the Public Right-of-Way and Private Property columns, a check was given to BMPs that are typically maintained by those two landowners.

CHAPTER 3.0

TECHNICAL ISSUES AND PRACTICABILITY

3.1 Introduction

Technical issues and the practicability of integrating decentralized controls into the urban environment are identified in this chapter. This chapter is intended to provide a technical foundation upon which owners and operators can evaluate the feasibility of retrofitting their individual combined sewer collection areas with decentralized controls to achieve or partially achieve CSO reduction goals. It will also assist them in determining practices that are most appropriate in meeting their individual system needs, prior to performing detailed quantitative evaluations. This chapter will discuss the selection objectives of various decentralized controls, the physical conditions that affect the feasibility of retrofitting a site, perceived conditions affecting site retrofit, construction practices of implementation, and examples of successfully completed projects integrating decentralized stormwater controls into urban infrastructure.

3.2 Selecting Objectives

The primary challenges of using decentralized controls for controlling CSOs are that most combined sewer systems are found in urbanized areas with highly connected impervious surfaces, aged infrastructure, and limited pervious or open areas. These challenges are often compounded further when the open space that is available is not amenable to decentralized controls. The goals of decentralized controls are to reduce the volume of stormwater, attenuate the peak discharge of stormwater flow, and improve the quality of the water that enters the combined sewer, while also reducing the number of storms that produce CSOs in a given watershed.

3.3 Physical Conditions Affecting Retrofit Feasibility

Based on site constraints, objectives given in Section 3.1 may not always be fully met. However, multiple objectives can often be met simultaneously. For instance, infiltration practices both improve water quality and reduce volume. Knowing the physical attributes and constraints within an area of interest will assist in evaluating the practicability of specific decentralized controls for that area. As such, geographic data should be collected on the following physical attributes:

- Impervious areas (including impervious areas that could potentially be removed);
- Pervious areas;
- Utilities;
- Building locations; and
- Known groundwater contamination or hazardous waste facilities.

These attributes are discussed in more detail in the following sections.

3.3.1 Lack of Pervious Areas

A lack of pervious area makes infiltration into the subsoil impractical. Impervious areas can generally be defined as any location where the natural infiltration of water into the soil is inhibited. The primary impervious areas of the urban environment include rooftops, roadways, parking lots, driveways, sidewalks, and various other paved surfaces. Impervious areas contribute nearly all of the stormwater runoff that enters the combined sewer system and are therefore the areas requiring the most attention when devising a BMP retrofit plan. When assessing impervious areas it is also important to understand their interconnectivity, as well as their connectivity to pervious areas and the stormwater conveyance system. It is also important to identify areas where impervious areas can be removed.

3.3.1.1 Imperviousness

Rooftops In highly urbanized areas, rooftops may constitute a significant proportion of the total impervious surfaces. For instance, rooftops represent about 40% of all impervious areas in Portland, Oregon[1]. Since downspouts of urban roofs are often directly connected to the storm drain system, these surfaces are likely major contributors of CSOs. Depending on site specific constraints (e.g., spatial, financial, logistical, social, political, etc.), as discussed below in Section 3.5, there may be several options for reducing the volume and/or rate of runoff from rooftops. However, since the majority of rooftops are privately owned, the willingness to implement rooftop stormwater management practices may be limited without an incentive program or mandated requirements.

When evaluating potential BMP opportunities for rooftops, it is helpful to classify roofs according to the use of the underlying structure. Rooftops can be generally classified as:

- Single family homes;
- Apartment buildings and condos;
- Office and commercial buildings;
- Warehouses and industrial buildings;
- Institutional buildings; and
- Parking garages.

It is important to identify if roofs are drained to the property, directly to the street, or directly to the combined sewer system. Also, the location of the roof downspouts and whether they drain to pervious or impervious areas are critical.

Roadways Nearly all urban roadways drain to subsurface storm drain systems. While there may be significant sections of road where stormwater is routed along the curb and gutter, runoff originating on roadways eventually discharges to the storm drain system. Thus, considering the extent of roads in urban areas, these surfaces likely contribute nearly as much to CSOs as rooftops. When devising methods to reduce the volume or rate of runoff from roads using decentralized controls, the traffic volume and setting of roads are important characteristics to

[1] Lipton, T. and Strecker, E. (2003). "EcoRoofs (GreenRoofs) - A More Sustainable Infrastructure." *Proc. Nat. Conf. on Urban Storm Water: Enhancing Programs at the Local Level*, Chicago, IL., February, 2003. EPA/625/R-03/003

consider. The traditional approach to classifying roadways is based on their vehicular functional use, such as arterials, collector streets, and local streets. An alternative, though not entirely different, classification scheme has been proposed that links functional use to the surrounding land use[2]:

- Throughways (freeways and highways);
- Boulevards (regional and community);
- Streets (regional and community);
- Urban roads; and
- Local roads.

It is important to determine roadways where there may be extra right-of-way that is not being used for transportation or pedestrian uses that could be utilized for decentralized controls. These areas can include medians, overly large sidewalks, adjacent right-of-ways, and larger than needed lane widths.

Parking Lots Next to rooftops and roadways, parking lots are probably the largest impervious surfaces in the urban environment and in many cases one of the most easy to retrofit. Parking lots vary in size from a couple of thousand square feet to many acres, and may constitute a significant fraction of urban runoff, particularly in catchments with large shopping centers, sports arenas, and other large public serving facilities. When considering stormwater retrofit options for parking lots, occupancy characteristics are very important. For instance, the willingness to sacrifice parking spaces for stormwater management (e.g., swales, bioretention, etc.) primarily depends on whether the lot is space-limited or under-capacity during the main hours of operation or if there are hardened or under-utilized medians or adjacent areas that can be retrofitted to receive runoff. For instance, some parking lots are designed with landscaped medians and adjacent areas, but the existence of curbs prevents parking lot runoff from entering these areas. Also, some parking lots may only be periodically space-limited, such as with concert and sports arenas where only during events are the majority of the parking spaces occupied. The retrofit options for these various types of parking lots may vary drastically (e.g., perhaps permeable pavements in these infrequently used areas are more viable). As such, the classification of parking lots for the purposes of decentralized controls includes:

- Space-limited;
- Under-capacity; and
- Under-utilized medians and adjacent areas.

Other Paved Surfaces In addition to rooftops, roadways, and parking lots, the remaining impervious surfaces common in the urban environment consist of other paved surfaces such as driveways, sidewalks, walkways, patios, common areas, stairways, blacktops, and other sports-related tracks and courts (e.g., racetracks, basketball courts, tennis courts, etc.). In comparison to the other urban impervious surfaces, these areas likely represent a smaller fraction of the total imperviousness of an urban area. Nonetheless, there are often simple solutions for incorporating decentralized controls for these surfaces, and if implemented over large areas, may provide significant stormwater and ancillary benefits. For instance, the planting of trees within

[2] Metro (2002). *Green Streets - Innovative Solutions for Stormwater and Stream Crossings.* www.metro-region.org

schoolyard blacktops may significantly reduce the volume and flow rate of runoff, as well as reduce the heat-island effect of large asphalt areas. Thus, other paved surfaces have been classified accordingly:

- Driveways;
- Sidewalks and walkways;
- Patios and common areas;
- Stairways;
- Blacktops; and
- Tracks and sport courts.

3.3.1.2 Functionally Impervious Soils

A common challenge when retrofitting urban areas is the presence of functionally impervious soils. Soils may be functionally impervious because of a high clay content or because of a high degree of compaction from past construction activities. By not allowing percolation into the subsoil, functionally impervious soils may prevent significant volume reductions from occurring in infiltration BMPs such as rain gardens.

BMPs located in functionally impervious soils must be constructed with an underdrain system that ties into the storm drain to allow positive drainage. The BMP will be similar in function to a lined BMP. Modest volume reductions may still be possible, but water quality and peak discharge reductions should be largely unchanged.

3.3.2 Groundwater Contamination

Besides the types of impervious and pervious surfaces, another important feature of the urban environment with respect to the practicability of decentralized controls is groundwater contamination. If an aquifer is currently impaired or is a primary drinking water source, infiltration practices may be subject to strict regulation. The quality of site soils should be assessed if groundwater contamination is a concern. Some areas may require more careful design to allow for their use (e.g., underdrains may be needed to prevent excessive infiltration from bioswales).

3.3.2.1 Contamination from Polluted Existing Soil

Unrestricted (i.e., unlined) infiltration is not advisable in cases where existing soils are contaminated. Wide scale implementation of decentralized controls can significantly impact ground water quality. Practices that rely on infiltration as the primary control process have the most impact on ground water quality. Most decentralized controls can provide some level of infiltration; however, some controls depend on infiltration as the dominant control mechanism. Sites that have contaminated soils or contaminated runoff can be negatively impacted by infiltration practices.

Infiltrating stormwater runoff through contaminated soils can leach contaminants into ground water supplies, aggravating ground water quality problems. In situations where existing soils are determined to be polluted, infiltration practices must be avoided in favor of other volume reduction controls that utilize evaporation/evapotranspiration and storage/reuse processes. While there may be opportunities for incorporating decentralized controls during

Brownfield development projects, the use of infiltration in these areas may be limited unless polluted soils are first removed or remediated.

In summary, if the quality of the groundwater is determined to be contaminated, BMPs that rely on infiltration as the primary treatment mechanism should be avoided. Also, a basic understanding of the connectivity of groundwater resources may help determine the overall threat that a particular BMP may pose to receiving waters and drinking water supplies. Decentralized controls that depend on infiltration as the primary mechanism are considered as the most likely to aggravate groundwater concerns. Other controls, such as filter strips and vegetated swales that incorporate other conveyance mechanisms in addition to infiltration, are considered of medium impact. Decentralized controls that are essentially disconnected from groundwater, such as vegetated roofs and stormwater planter boxes, are considered to have negligible impact on groundwater. However, decentralized controls can be designed with liners to eliminate any complications or problems from infiltration.

3.3.2.2 Contamination from Runoff Constituents

Infiltrating contaminated runoff can eventually lead to contamination of existing soils. Contaminated runoff may initially be filtered as it travels through layers of soils. However, highly polluted runoff may eventually exceed the pollutant removal capacity of the soil resulting in ground water contamination. Coarse soils with little organic material provide very limited removal of dissolved stormwater constituents. For these reasons, the infiltration of highly contaminated runoff without prior treatment or treatment via filtering by finer soils is not recommended and may even be illegal.

3.3.3 Proximity to Building Foundations

Lining infiltration practices and providing underdrains will prevent any potential damage to foundations from infiltrating stormwater. Lined rain gardens or swales will only reduce the runoff volume to the extent that the soil media becomes saturated and ponding occurs.

One of the primary drivers for selecting and sizing a BMP for a site is the existing infrastructure. Concern over the structural integrity of building foundations, roadways, bridge abutments, and retaining walls may discourage the use of certain BMPs. The class of decentralized controls most likely to impact existing structures is infiltration practices. However, any practice that holds water next to a structure may impact its integrity. High moisture levels can adversely affect building foundations and basements in a number of ways. Retaining walls are often designed with weep holes to prevent water buildup and avert failure due to high hydrostatic pressures. For these reasons, infiltration practices are considered to have the highest impact on existing structures.

Aside from structural damage, decentralized controls may impact the functionality of existing structures. For instance, tall trees may obscure traffic signs and obstruct sight triangles at intersections, or wetlands sited near airports may increase bird populations, which may conflict with the safe operation of aircraft. Decentralized controls that impact the functionality of existing structures or infrastructure directly or indirectly are considered to have a medium impact with respect to this constraint, while BMPs with no perceivable impacts are considered as low impact controls.

3.3.4 Lack of Vertical Relief

As with proximity to the drainage system, controls that depend on the transportation of the effluent and/or the influent input flows from a different location through conduits such as pipes or open channels are more susceptible to prevailing slope and elevation differences between the source, the control, and the receiving waterbody. A slope that is too gradual may cause ponding and backwater effects, which in turn may cause premature sedimentation and clogging of inlet pipes or other conveyances to the BMP. A slope that is too steep may cause scour at the inlets and outlets of a facility. Typically, given adequate vertical relief, most designs may be modified to compensate for less than perfect site slopes through grading and excavation or by utilizing modifications such as check dams and energy dissipaters.

Stormwater drainage systems typically rely on gravity rather than pumps to convey water to and from the various components of a system. Therefore situations often arise whereby, due to lack of vertical relief, it becomes infeasible to either get the influent flows to a site or convey flows from a site to the receiving waterbody, even though the site may have adequate slopes. Storage and conveyance-type controls that import and export both influent and effluent streams tend to be the most susceptible to vertical relief constraints. Infiltration facilities typically only require influent flows to be transported to the site since the effluent goes directly into the ground. Hence infiltration controls are considered to be moderately susceptible to this constraint. Specialized infiltration facilities such as porous pavement and roof gardens that only drain themselves are considered to be the least impacted by this constraint since both the influent and the effluent streams may not require conveyance structures, and hence are least likely to be impacted by differences in elevation.

3.3.5 Distance from a Suitable Storm Drain Tie-In

Stormwater management controls with concentrated influent and effluent streams should ideally be located close to the drainage system so as to minimize piping costs, reduce chances for utility conflicts, minimize disturbed areas, and cut construction times. Facilities that require conveyance of flows to and from the site (e.g., swales, vault filters, etc.) are considered highly susceptible to this constraint, facilities that only require conveyance in one direction (e.g., bioretention, infiltration practices, cisterns, etc.) are considered to have a moderate level of susceptibility to this constraint. Facilities that require no conveyance to or from the site (e.g., porous pavement) are considered to have a low level of susceptibility. With regard to conveyance feasibility, the elevation of the runoff area with respect to the BMP is also an important consideration related to proximity to the storm drainage system. Generally in an urban area this should not usually be a problem.

3.3.6 Pervious Areas

Although often less prevalent than impervious areas, pervious surfaces are also present in the urban environment. Pervious areas often provide the best opportunities for incorporating some of the more "green" BMPs, but the use of and demand for these limited spaces is often high. In some cases, pervious areas include lawns where runoff still occurs much more frequently than from other types of landscapes.

Urban pervious areas have been classified in this chapter as landscaped areas, vacant lots, parks and playfields/lawns, and urban open space corridors.

3.3.6.1 Landscaped Areas

Due to the built-out nature of the urban environment, landscaped areas and lawns probably make up the majority of urban perviousness. Landscaped areas are often a prime location for incorporating decentralized controls, since the primary purpose of landscaping an area, to aesthetically enhance the appearance of land by altering its contours and planting trees and shrubs, does not conflict with decentralized controls. For instance, in many cases only minor modifications to drainage patterns are necessary to convert a landscaped area into biofiltration or bioretention areas. Landscaped areas can be primarily classified as:

- Residential yards;
- Planter boxes; and
- Grassed areas.

3.3.6.2 Vacant Lots

Another type of pervious area common to the urban environment is vacant lots. Vacant lots may exist either because no structure had ever been constructed or an aged structure had been demolished. The primary distinction between these two scenarios is the amount of soil disturbance that may have occurred. For example, a lot that was a previous site of a building probably would have highly compacted soils, and thus may not be an adequate site for infiltration practices; however, it could still provide an area for bioretention/biofiltration systems that focus on evapotranspiration losses and reduced peak flows. While evaluating the previous use of vacant lots, consideration must also be given to any planned future use of area redevelopment. In addition, some vacant lots are used by the community for urban gardening projects. These gardens are often socially important features of the community that may take precedence over stormwater management. Vacant lots can be classified as:

- Compacted urban soils;
- Undisturbed open spaces; and
- Community gardens.

3.3.6.3 Parks and Playfields

As with community gardens, parks and sport playfields are important features of an urban community, particularly when many residents have little to no open spaces near their residences. However, these areas can often be designed as multi-use areas without infringing significantly on their primary function. For instance a park, if properly contoured, may be used as a bioretention area that would only become inundated during storm events when the use of the park is at its lowest. The following classification will be used to refer to the various types of parks and playfields.

- Sports fields;
- Wooded or shrub areas; and
- Grassed open space.

3.3.6.4 Urban Open Space Corridors

The term “urban open space corridor” refers to the open spaces near linear features such as roads, railroad tracks, power and phone lines, and urban streams. Roadside right-of-ways are ideal locations for vegetated bioswales and filter strips for reduction and treatment of road runoff. Open areas within or adjacent to active or historical railroad corridors may also present some opportunities for stormwater treatment, but the structural integrity of the soils beneath the tracks may be a major concern for infiltration facilities and their proximity to the tracks.

Utility corridors, if strategically placed, may also be good candidates for bioretention or other practices. However, as with railroad tracks, infiltration/soil soaking near utility towers may be a structural concern (addressable with proper designs). Vegetation growing along roadsides, train tracks, and utility corridors are usually well maintained to reduce fire danger and to ensure trees and vegetation do not come in contact with overhead power lines. Since the use of herbicides for vegetation control is common in these areas, as well as the fact that pollutants may leach from road construction materials, railroad ties, and utility poles, soil contamination may be an issue in these areas; it may require alternative weed and vegetation control strategies that ultimately also improve water quality.

Urban streams and drainage systems are increasingly being recognized as valuable multipurpose resources in urban areas that, in addition to flood control, can provide aesthetically pleasing escapes from the city as well as vital wildlife habitat. In highly urbanized areas, these streams flow primarily in underground pipes and concrete channels, and therefore may not necessarily qualify as pervious areas. In many instances, however, there is pervious open space near these creeks and channels that may be used for treating tributary runoff prior to discharging to the creek. Stream restoration projects may provide additional opportunities for integrating decentralized controls into the urban environment. When referring to urban open space corridors the following classification scheme will be used:

- Roadside rights-of-way;
- Railroad corridors;
- Utility corridors; and
- Riparian corridors.

3.4 Perceived Conditions Affecting Retrofit Feasibility

Decentralized controls may not appear to be as “engineered” as conventional inlets and gutters, especially because of ponded water. There may be doubts as to whether distributed practices can provide enough storage. The public acceptance of decentralized controls can be measured by market and preference surveys, reported nuisance problems, visual aesthetics, and the potential impact that a control would have on neighborhood property values (plus and minus). Public acceptance is an important consideration because the successful and efficient operation of decentralized controls is facilitated in an atmosphere of cooperation and partnership with the people who use the spaces where the controls are located. Also, mass opposition to the construction and implementation of decentralized controls can lead to projects being delayed or abandoned altogether.

3.4.1 Standing Water

Like most drainage system components, decentralized controls could potentially create a public nuisance by increasing habitat availability for aquatic stages of mosquitoes and by creating harborage, food, and moisture for other reservoir and nuisance species. Emerging public health threats, such as the detection in 2001 of the exotic Asian tiger mosquito and the westward expansion of mosquito-borne West Nile virus illustrate the importance of considering vectors in the design of stormwater controls. Studies done by Caltrans have shown that controls that maintained permanent sources of standing water in sumps or basins provided excellent habitat for mosquitoes and frequently supported large populations relative to other designs. In contrast, controls designed to drain relatively rapidly (e.g., < 72 hours) provided less suitable habitats and rarely harbored mosquitoes. Controls that do not have standing open pools of water and/or dark interiors, are considered as highly favorable, while controls that depend on pools of water and/or have dark interiors are less favored.

3.4.1.1 Aesthetics

Some decentralized controls such as biofilters are unobtrusive and generally tend to look more natural and are more easily disguised than non-vegetated practices. In general, vegetated practices are more likely to positively impact aesthetics. Subsurface controls are typically the most unobtrusive controls simply because they are often almost completely out-of-sight, leaving low profile maintenance access structures as the only evidence of their existence. As such, subsurface controls generally do not impact aesthetics - positively or negatively. However, some underground BMPs have been found to be unacceptable to the public due to the frequency of maintenance and the associated noise and traffic disruptions. Controls that carry standing water or trap trash and floatables can negatively impact aesthetics.

3.4.1.2 Safety

Traditional BMPs like wetlands, detention ponds, and retention ponds are more likely to cause health and safety hazards than distributed BMPs. The distributed nature of decentralized controls results in smaller, shallower facilities with a resultant decrease in the scale of the hazards associated with traditional BMPs. Families with young children are more likely to be concerned with drowning. Confined spaces associated with sub-surface BMPs such as tanks and vaults may also be a source of concern for both parents of children and maintenance workers. Hazards associated with stormwater controls are more of a concern in residential areas than commercial and industrial areas, partly because children spend more time in residential areas.

3.4.1.3 Drawdown Time

Many decentralized controls are designed to drain relatively rapidly (e.g., < 72 hours) and are highly desired. Controls that do not have standing open pools of water and/or dark interiors are considered as highly favorable, while controls that depend on pools of water and/or have dark interiors are less favored.

3.4.1.4 Standing Water on Private Property

A number of steps can be taken to ease the fears of people who may have doubts about the safety of decentralized controls including the following:

- Design open-water controls with gentle side-slopes wherever possible;
- When needed, fence open-water controls and keep access gates locked;
- Lock access hatches to underground facilities; and
- Use warning and educative signage to inform people about the benefits and potential hazards associated with controls.

3.4.1.5 Contrast with Conventional Stormwater Management Methods

Decentralized stormwater controls have additional benefits that affect the livability and economics of communities. The distributed BMPs provide a network of landscaped open space areas that increase the “green infrastructure” of a neighborhood. These vegetated BMPs can be a contributing factor in minimizing the urban heat island effect, which potentially affects overall urban climates and energy consumption. The increased trees, shrubs, and perennials assist with absorption of air pollutants as well as provide shade. The distributed placement of BMPs allows for accessible outreach programs that educate residents on environmental issues and stewardship of their community resources. The BMPs are a manageable scale for businesses, volunteer organizations, residents, or public entities to participate in their design, construction, and maintenance.

3.4.2 Maintenance

Maintenance is required for the long-term performance of decentralized controls. Maintenance considerations must not be left until after a project is constructed; rather, maintenance considerations should be thought of and incorporated into the design. Maintenance requirements for decentralized controls typically consist of the following activities:

- Landscaping and vegetation management;
- Sediment and accumulated pollutant removal;
- Structural repairs to BMP components;
- Regular inspections;
- Restoration and/or rejuvenation of BMP components (i.e., scarifying infiltration beds);
- Repair of inlet and outlet structures and other BMP amenities and flow control structures; and
- Waterproofing and/or BMP liner replacement/repair.

The parties responsible for maintenance, the level of effort required, and the frequency of maintenance required, should be investigated during the BMP selection stage to ensure that the available resources for maintenance are adequate for the successful operation of the selected BMP. It is important to consider that, if the BMP area is going to be a managed landscape area, some of these maintenance activities would be necessary anyway and therefore they are not really additional maintenance.

3.4.2.1 Vegetation

The vegetation that is critical to the performance of rain gardens, vegetated roofs, vegetated swales, and pocket wetlands must be maintained regularly. Periodically these BMPs will have to be cleared and replanted.

3.4.2.2 Mulching and Other Landscaping Requirements

Mulch is a critical element of the pollutant removal process in rain gardens and similar BMPs because it intercepts gross solids (e.g., sediment) and removes metals and other pollutants through adsorption. New mulch should be added as needed on a yearly basis to maintain a minimum 3” depth.

3.4.2.3 Waterproofing

Care must be taken in the installation of vegetated roofs. Most designs of vegetated roofs require a minimum of three layers and a separate drainage layer that then drains to the street. Protection of the integrity of the building from leaks is critical in the design of the roof system.

3.4.2.4 Responsible Parties

Many watersheds encompass areas within more than one jurisdictional area. In these instances, installation, operation, and maintenance agreements between more than one agency, department, and even state may need to be developed. In such cases, a committee would likely be established early in the planning process. The committee should include key members representing each agency and department to ensure that stormwater management planning is conducted in the spirit of cooperation and good faith. The priorities of each participating agency should be fully disclosed, in advance, so that they are incorporated in the planning objectives. The maintenance of BMPs in areas controlled by one jurisdiction may still require maintenance agreements between the controlling agency and a property owner or a homeowner’s association.

Most municipalities often find it easier to have the property owners be responsible for the maintenance of BMPs on their properties, while other municipalities take over maintenance responsibility upon project completion. It is prudent to investigate maintenance responsibilities with the governing agency during the planning stages of stormwater control design, since agencies may require stormwater controls to be built according to certain standards in order to be adopted by the agency for maintenance after construction.

Table 3-1. Maintenance Factors Affecting the Feasibility of Implementing Decentralized Controls.

BMP	Responsibility	Level of Effort	Frequency
Downspout Disconnection	Owner	Minimal: No vegetation management; no removal of captured pollutants.	Low: Provide few water quality benefits.
Filter Strips	Owner	Moderate: Management of vegetation; occasional removal of captured pollutants.	Moderate: Need vegetation management.
Infiltration Practices	Owner	Moderate to High: Rejuvenation may be needed (scarifying surface/raking); possible removal of vegetation; removal of captured materials; media may have to be completely changed.	Low: Need removal of accumulated pollutants. Need occasional vegetation management. Pre-treatment is very important.
Pocket Wetlands	Owner	Moderate to High: Management of vegetation; removal of floating debris and trash; sediment and vegetation removal.	Low: Need removal of accumulated pollutants. Need occasional vegetation management. Sediment forebay.
Porous Pavement	Owner/Municipality	Moderate to High: Rejuvenation may be needed (vacuum sweeper/power washing); vegetation management; pavement may have to be completely changed.	Low: May need vegetation management.
Rain Barrels/Cisterns	Owner	Minimal: No vegetation management; no removal of captured pollutants. Requires periodic emptying. Treatment for mosquitoes may be necessary.	Low: Provide little or no water quality benefits .
Rain Gardens	Owner	Minimal to Moderate: Vegetation management required.	Moderate: Need vegetation management.
Rooftop Storage	Owner	Minimal: No vegetation removal; minimal removal of captured pollutants.	Low: Provides little pollutant removal.
Tree Box Filters	Owner	Moderate: Minimal removal of debris.	Low: May require vegetation management.
Planter Boxes	Owner	Low: Underdrains may need to be replaced if clogged.	Low: Periodic removal of weeds for aesthetics.
Vegetated Roofs	Owner/Municipality	Moderate: Vegetation management	Moderate: Require vegetation management.
Vegetated Swales	Owner	Low to Moderate: Minimal removal of captured pollutants; vegetation management.	Moderate: Require vegetation management; may require removal of accumulated material.

3.4.2.5 Level of Effort

The level of effort required for the maintenance of a BMP is a measure of the amount of work that is needed for the successful completion of a single maintenance event. A measure of the level of effort required, combined with the frequency of maintenance required, can be used to estimate the maintenance burden of a particular control. Controls that require no replacement of media, no vegetation maintenance, and no removal of accumulated pollutants are considered as low level maintenance effort controls. Examples of such controls include disconnected roof downspouts, rain barrels, and cisterns.

The highest level of maintenance effort is assigned to controls such as infiltration practices that may require vegetation maintenance, removal of captured materials, and occasional rejuvenation or complete replacement of media. The level of effort required for the rest of the BMPs fall somewhere between the two extremes, as outlined in Table 3-1.

3.4.2.6 Frequency

The frequency of maintenance required for the efficient operation of decentralized controls depends on a variety of factors, including pollutant loads, vegetation properties, and pollutant holding capacities of the controls in question. Effective pre-treatment and/or source controls can lessen the frequency of maintenance needed. In general, controls that trap gross solids and floatables (such as catch basin filters) tend to require more frequent maintenance during wet weather than during dry weather. Conversely, controls that support vegetation such as swales and filter strips may require more frequent maintenance during dry weather than during wet weather. However, this is also highly dependent on the climate and type of vegetation. Controls that provide little or no water quality benefits, such as rain barrels and disconnected roof downspouts, require the least frequent maintenance. Finally, source controls such as street sweeping, pavement cleaning, and limiting exposed soils in tributary areas, will reduce maintenance needs.

3.4.3 Structural Concerns

Primary factors to consider when evaluating decentralized controls for implementation are structural concerns such as flooding of basements, undermining nearby buildings, utility conflicts, and roof integrity. These factors assist in the “fatal flaw” analysis of decentralized controls given a particular urban environment. In other words, if the engineering parameters for a particular BMP are not achievable or are not achievable cost-effectively, given the physical conditions of the area of interest, then that particular BMP should be removed from consideration. It should be noted that in some cases the key driver and/or goal may not be 100% achievement of control through BMPs, and therefore, although there may be constraints to full achievement, partial achievement with a practice may still be considered cost-effective.

Spatial factors and engineering requirements for those decentralized controls previously selected is discussed in detail below. These requirements should be evaluated against the characteristics of the area of interest and any fatal flaws should be identified.

3.4.3.1 Flooding Basements

Basement flooding is an understandable concern regarding on-lot storage of stormwater. However, the proper use of setbacks, liners, and underdrains will prevent basement flooding from occurring. By providing small-scale stormwater management, distributed controls may potentially alleviate flooding problems.

3.4.3.2 Undermining Foundations

For practices that rely on infiltration, undermining foundations and roadways is a major concern that is usually addressed by requiring a set back away from the structure. Since porous pavements are designed to infiltrate stormwater directly beneath or adjacent to the roadway, they must be designed with a well-drained sub-base. In climates where freezing occurs, this requirement is essential to avoid frost-heave caused by ice expansion beneath the road surface. There are also structural implications with the intentional voids of porous pavement since these voids can collapse under high weight loadings. To address this issue, some porous asphalt designs have begun including polymer-modified asphalt binders to improve the life and durability of pavements.

3.4.3.3 Conflicts with Utilities

Utilities such as gas lines, water lines, electricity, telephone, and optical cables are often located underground. In some areas telecommunication and electricity lines are located overhead. Construction activities that involve excavation and/or the use of large construction equipment must be carefully planned and executed to avoid costly damage to overhead or underground utilities. Damage to overhead utilities can occur irrespective of the BMP being implemented. However, damage to underground controls may be associated with decentralized controls that require some amount of excavation. Therefore, infiltration facilities and other facilities that require significant excavation are considered to be highly susceptible to utility conflicts. Other controls that only require minor grading or can be sited above the utility (such as vegetated swales) are considered to have a medium susceptibility to utility conflicts, while controls that do not require grading or excavation are considered to have a low susceptibility.

3.4.3.4 Roof Integrity

Roof practices, including vegetated roofs, roof gardens, and rooftop storage, must have sufficient structural support to hold the weight of retained water and/or vegetation and soil. Roof retrofits may require the additional decking, trusses, joists, columns, or even foundations. To protect from leaks, the roof must include a waterproof membrane and possibly a root barrier. An architect or structural engineer should be consulted prior to any stormwater control retrofit of an existing roof.

3.5 Construction Practices

Typical construction activities impact the use of decentralized controls in urban environments by disrupting business activities, causing traffic delays, limiting access to facilities, and potentially exposing existing structures and people to safety hazards. Due to the distributed nature of most decentralized controls, construction activities are not expected to be as disruptive as the construction of building structures and roads. The implementation of decentralized controls associated with roads and buildings such as vegetated roofs and porous pavement are likely to be the most disruptive.

3.5.1 Pre-Construction

Pre-construction impacts to traffic and businesses are typically minimal in most cases; however the relocation or the provision of alternate sources of goods and services may be required in some cases. For instance, if a vegetated roof is being installed on a municipal services building, then those services may need to be moved to an alternative location prior to construction. Post-construction impacts are typically related to maintenance activities and public perceptions. Public perceptions may improve with time as users become more familiar with the changes and learn to adapt to the new restrictions or liberties resulting from the construction of decentralized controls.

3.5.1.1 Utility Location

Utility location must account both for physical conflicts as well as any adverse interactions between infiltrating stormwater and existing utilities. In infiltration BMPs such as rain gardens, the vertical profile must be clear of utilities through the entire depth and surface area. The cross-section of a BMP may be modified to account for the presence of utilities. For instance, the soil profile or ponding depth in a rain garden can be shortened.

3.5.1.2 Construction Sequencing

Timing of seasons (weather, agricultural, political, cultural, and economic) enables contractors to schedule construction activities for a time that minimizes impacts to the livelihood of stakeholders. In addition to timing, sequencing of construction activities can also be structured to further minimize impacts that are not seasonal.

As previously mentioned, surrounding land use types impact construction activities in many ways. Construction activities in crowded commercial and industrial areas may take longer than similar activities in residential areas due to potential space constraints, pedestrian and traffic control issues, and possible restrictions on specific construction activities at certain times of the day.

3.5.1.3 Construction Duration

The duration of construction activities required to implement decentralized controls, must also be taken into account, since construction timing and sequencing can only go so far to limit construction impacts. More complex BMPs such as porous pavement and vegetated roofs are expected to require relatively longer construction times, while controls such as catch basin and vault inserts are expected to take comparatively short amounts of time for implementation.

3.5.2 During Construction

3.5.2.1 Construction Complexity

Decentralized controls that are easy to construct, require no design, or are very simple in design, are preferred over controls that require more precise engineering and complex construction methods. Metrics of construction complexity include the size and availability of the equipment needed, the price and availability of the materials used, and the complexity and availability of the skills required for project completion. Due to increasing availability of guidance documents and competition from vendors, most BMPs are becoming easier to design and construct. Some decentralized controls require little or no construction activities at all. Controls such as tree box filters can often be installed fairly easily. Other BMPs such as infiltration facilities, vegetated swales, and pocket wetlands may require a moderate to large amount of earthwork which adds a level of complexity. At the top of the complexity scale are media filters, vegetated roofs, and porous pavement, which may require earthwork in addition to a level of technical expertise and the use of proprietary components that may have to be installed according to manufacturer’s instructions. The types of controls selected and the environment in which construction activities will occur influence construction complexity.

The environment in which the construction takes place influences the level of complexity of construction activities by introducing additional obstacles and constraints. Commercial and industrial land use areas may add additional levels of complexity, as compared to residential construction. For instance, the use of large equipment in crowded commercial areas with narrow streets and the possibility of causing damage to existing aged structures are issues that have to be considered.

Commercial and industrial areas may also be more prone to post-construction impacts from decentralized controls such as vegetated roofs, narrower streets, porous pavement, and street trees. Careful planning is recommended at the design and selection stage to avoid the implementation of controls that severely hinder or limit commercial and industrial activities.

3.5.2.2 Traffic Control

The majority of the traffic and business disruption impacts occur during construction rather than during maintenance activities. The severity of traffic impacts during construction depends on the following factors:

- Average daily traffic (ADT) and the peak hour volume on obstructed roadways;
- The length of the duration of construction activities;
- The availability of alternate routes and the provision of detours; and
- The construction practices employed.

Traffic disruption during construction can be minimized if necessary by scheduling construction activities during off-peak hours such as after midnight or after the regular working hours in busy areas. Announcing alternate routes in the newspapers, radio, and television and using proper signage to direct traffic onto alternate routes can significantly reduce traffic impacts. Traffic impacts typically decrease as motorists become more aware of construction schedules and detour routes. In summary, the following activities may minimize traffic disruption during construction:

- Schedule construction activities during off-peak hours;
- Publish detours and alternate routes;
- Plan for quick response to accidents and removal of disabled vehicles;
- Place proper signage to direct traffic onto alternate routes and provide information and warning updates of traffic conditions; and
- Plan for emergency vehicle access to and from the site.

Business disruptions from construction impacts include the restricted use of entrances and exits, relocation of personnel and equipment, and the closure and unavailability of services and facilities. Business impacts are often site specific and should be addressed on a case-by-case basis. However, in general, the following practices will alleviate some of the impacts to business activities during construction:

- Schedule construction activities during off-peak hours or, at a minimum, restrict noisier, dustier, more noticeable construction activities to off-peak hours;
- Minimize air and water pollution via proper use of construction site BMPs;
- Avoid simultaneous obstruction of multiple entrances and exits to a building or a facility;
- Barricade, isolate, contain, and cover active construction regions as much as possible;
- Follow health and safety practices and use proper signage;
- Keep pedestrian accessible areas as clean and as free of obstruction as possible;
- Provide alternative locations for goods, services, and facilities wherever possible; and

- Plan extra security measures to protect sensitive buildings such as banks, federal buildings, historic buildings, and other sensitive areas.
- Recommended post-construction practices to minimize traffic and business activity impacts include:
- Prompt and efficient removal of all construction related signage;
- Prompt removal of scaffolding, forms, construction equipment, and other construction aids;
- Clean up of construction spoils, including dust and debris, and the restoration of all disturbed surfaces to preconstruction conditions or better; and
- Prompt announcement of the completion of construction and the restoration of the flow of traffic, pedestrians, and business activities.

The land use type surrounding the construction site can amplify the impacts resulting from BMP implementation. For instance, vegetated roof construction in a multi-family residential area is likely to cause less impact than a similar project in a busy commercial area. Construction of BMPs in commercial and industrial parking lots may impact more people than construction in multi-family residential parking lots. Similarly, post-construction impacts in commercial areas may be more pronounced than in residential areas since those that use commercial areas are typically more varied and less habitual users than those encountered in residential neighborhoods.

3.5.3 Other Construction Impacts

Gauging planning community acceptance of BMP implementation is essential. The urban planning process is typically the catalyst for all major urban development and redevelopment initiatives, and the Comprehensive Plans, Downtown Plans, and Corridor Plans, which are developed during the urban planning process, establish the framework and guiding principles for any future development and redevelopment projects.

A vision for streetscapes, street layout, and utility corridors that includes landscaping features that can be used for decentralized controls is critical. The ability to influence development of these plans must be evaluated, in addition to determining if retrofitting an area with BMPs would dramatically modify the vision and intent of any approved urban plans.

CHAPTER 4.0

IMPLEMENTATION STRATEGIES, INCENTIVES, AND DISINCENTIVES

4.1 Introduction

The extent of impervious surfaces in the urban environment creates a clear need for decentralized controls but also presents significant challenges to their implementation. BMP size directly correlates to the amount of imperviousness in its drainage area, yet urban areas often have relatively little open space available for BMP construction. Also, BMPs must be incorporated into the site development or redevelopment plan early in the planning process to maximize their effectiveness. For both of these reasons, it is critical to follow a BMP implementation strategy that will optimize BMP selection, size, and placement based on the site constraints. This chapter presents a typical framework for an implementation strategy.

4.1.1 Planning and Design Challenges in Urban Areas

Implementation of decentralized controls in urban areas is potentially a more iterative process than for standard end-of-pipe controls. Stormwater quality and quantity benefits must be balanced with the planning goals and site constraints. Urbanized areas have a broad mix of land uses, distinctive community characteristics, complex environmental and design regulations, and a wide range of community and economic goals. Also, competing interests can change the land uses within a short period of time.

As discussed in Chapter 3.0, physical factors affecting implementation of decentralized controls in the urban environment include the proportion of directly connected impervious surface in the drainage area, proximity of pervious areas to impervious surfaces, availability of open space that is suitable for BMP construction, degree of soil compaction, presence of contaminated soils, effectiveness of existing infrastructure, and site topography. Community and economic factors may include overall community acceptance of decentralized controls, the roles of various public and private stakeholders, cost/benefit ratios, property ownership, and economic and development goals.

4.2 Implementation Strategies

The five basic steps in a decentralized control implementation strategy are:

1. Identify and prioritize drivers and watershed goals;
2. Characterize site and evaluate constraints;
3. Evaluate candidate practices;
4. Determine cost-effectiveness in context of goals and site characteristics; and
5. Select BMPs.

The process is illustrated graphically in Figure 4-1 below. This section will discuss each step in detail.

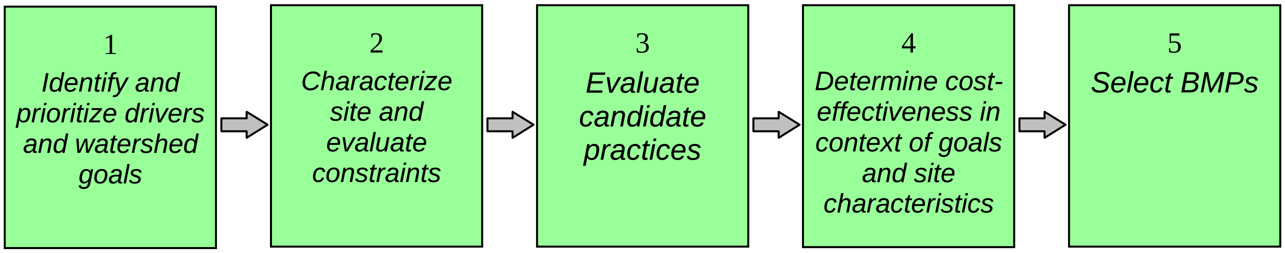


Figure 4-1. Implementation Strategy for Decentralized Controls.

4.2.1 Identify and Prioritize Drivers and Watershed Goals

The first step in defining the problem to be solved is to clarify the reason(s) *why* the retrofit is occurring. The impetus to mitigate CSOs may arise from a specific driver, such as a regulation, a court order, or a construction project. Whether or not such a driver exists, CSO mitigation must also consider the primary and secondary watershed goals, which may be long-term and independent of the CSO mitigation effort. Typical primary goals are the reduction of runoff volume and peak discharge rates. Secondary goals may include ecological, economic, and community development benefits.

4.2.1.1 Drivers

Drivers promoting the implementation of decentralized controls are typically direct or indirect responses to regulatory requirements. For instance, a requirement to reduce CSOs would lead to a direct response. An indirect response would be triggered by the requirement to implement a stormwater management plan that integrates stormwater BMPs into an urban redevelopment or construction plan. This distinction is important because even though certain BMPs may optimize stormwater flow reductions for CSO control, they may not fit within the architectural and community context of a redevelopment/construction plan, thus necessitating the consideration of alternative BMPs.

Since the selection of decentralized controls depends on these drivers of implementation, it is essential that they are identified and prioritized. Two key drivers, CSO mitigation and urban improvements, are discussed in more detail below. However, any other drivers promoting the implementation of decentralized controls should also be identified and incorporated into the selection and design process.

CSO Mitigation Considering the use of decentralized controls in an urban environment for CSO mitigation is fundamental to the preparation of this report and is assumed to be a key driver in reducing stormwater flows to the combined sewer system. However, whether it is the sole driver needs to be determined by the owner/operator of the combined sewer system.

Other Urban Improvements Many urban communities are realizing the benefits of implementing decentralized controls and are incorporating them into urban improvement projects. These techniques may be further promoted in design guidelines for the development and engineering communities. Public works projects provide another opportunity to incorporate the use of decentralized controls, especially if design guidelines have already been established. Even if such guidance is not available for the specific project area, construction projects such as retrofitting a utility corridor could provide an excellent opportunity to incorporate decentralized controls because the effort is already being made to excavate, mobilize equipment, and control traffic. While CSO mitigation may not be the main purpose of any urban improvement project, the projects may be executed so that they help to mitigate CSOs. Whenever possible, opportunities to implement decentralized controls should be linked to potential incentives for the owner/developer to use them. Several examples of urban improvements are given below.

- **Redevelopment** of an already urbanized area may range in scope from district-wide renewal to parcel-level construction, and may present opportunities to incorporate decentralized controls at the site or on adjacent roadways.
- **Brownfields** are abandoned, idle, or underused commercial and industrial sites with known or suspected environmental contamination caused primarily by past land use practices. Their redevelopment is a complicated process well beyond the scope of this document, but Brownfields may nevertheless provide significant opportunities to incorporate decentralized controls. However, depending on the existing conditions and degree of remediation, several types of decentralized controls may not be feasible to implement because of concern for offsite migration of contaminants.
- **Utility upgrades**, with careful planning, may allow stormwater improvements to be incorporated into the project. The linear nature of utilities and their typical proximity to roads may provide opportunities to treat roadway runoff using linear decentralized controls such as vegetated swales.
- **Street and road improvements** may present opportunities for decentralized controls to be incorporated into the right-of-way. This may be especially significant if the road is being widened, creating new impervious surface area.
- **New development** is rare in highly urbanized areas, but often presents the best opportunity to incorporate decentralized controls into the site design. If these practices are considered early in the planning process, prior to grading and the placement of storm drains, the site may be contoured and designed for the maximum control of stormwater. If properly planned, new development's contribution to the frequency and magnitude of combined sewer overflows may be reduced or eliminated.

4.2.1.2 Watershed Goals

Any quantitative goals (if feasible) and qualitative goals should be identified in order to guide the type, size, and placement of chosen BMPs. Quantitative evaluations of the combined sewer system (e.g., reduction in stormwater volume necessary to reduce or eliminate storage tunnels), including any permit requirements, should be recognized. This evaluation process will allow the owner/operator to determine the feasibility of individual practices as well as their effect on quantitative goals. Three main categories of watershed planning goals are hydrologic, ecological, and community and economic development. Hydrologic goals are closely related to the stormwater management objectives presented in Section 2.2. For the purposes of CSO mitigation, hydrologic goals will have primary importance, but ecological and community goals may be important secondary considerations, and these considerations may, in fact, have the greatest impact on the community on a day-to-day basis. Examples are given for each category of planning goals.

Hydrologic Hydrologic goals are related to the objectives of conventional stormwater management, but may also impact the ability of BMPs to meet ecological and community goals.

- **Runoff volume:** Volume control may be a critical component of CSO mitigation, especially in heavily urbanized areas with high imperviousness.
- **Peak discharge rate:** Peak discharge control is also an important factor in CSO mitigation. Adequately reducing peak discharge, even in the absence of volume reductions, may positively impact the frequency and volume of CSO discharges.
- **Flood control:** If applied throughout a neighborhood or watershed, decentralized controls may assist with flood control by reducing or mitigating for impervious surfaces. Flooding may be alleviated by pursuing the two preceding hydrologic goals.
- **Water reuse:** Storage of stormwater in rain barrels and cisterns for reuse in landscaping or non-potable domestic applications (e.g., toilets) can prevent relatively large volumes of stormwater from leaving the site as runoff.

Ecological Ecological goals may apply at the site, downstream of the site, or both. They may involve specific criteria, such as not exceeding a specific pollutant concentration, or may be more comprehensive, such as maintaining or enhancing the site's ecological function. Note that the first two items below have much more importance in areas draining to separate sewers.

- **Water quality:** Total Maximum Daily Loads (TMDL) or other water quality regulations may apply to the watershed in question. Decentralized controls will help to reduce the loading of non-point source pollutants (e.g., oil and grease, metals, sediment, and nutrients) leaving a site.
- **Stream health:** Stream health is a function of both water quality and hydrologic (e.g., runoff volume) criteria. Mitigating stormwater impacts on receiving streams, whether from uncontrolled runoff or from existing stormwater facilities, is a frequent management goal.
- **Habitat creation:** Open space can be enhanced by using decentralized controls to provide habitat (e.g., for birds) in addition to providing other functions.
- **Antidegradation:** When antidegradation standards apply, the quality of receiving waters must be maintained at a level sufficient to support a designated use, such as "fishable/swimmable."

Community and Economic Development Decentralized controls can also be used to address a variety of community and economic planning goals, examples of which are given below. These goals may change, or become more apparent, as the planning process proceeds and more stakeholders become involved. The planning process must be flexible enough to adapt to new concerns that arise.

- **"Green Infrastructure" or "Green City":** Decentralized controls may be incorporated as part of a larger sustainability or beautification initiative.
- **LEED (Leadership in Energy and Environmental Design) Certification:** Use of decentralized controls may contribute to a property's LEED rating.

- **Job creation:** The need for regular maintenance of BMPs may help to create a market for locally-based "green collar" jobs.
- **User fees:** The most common example is a stormwater fee. By reducing or eliminating the volume of stormwater leaving a site, landowners can reduce or eliminate the fee that is assessed. See Section 4.3 below for more on user fees.
- **Historic preservation:** In historically significant areas, decentralized controls provide an alternative to invasive conventional stormwater management techniques if new measures such as CSO mitigation are required. However, the review process may still be lengthy.
- **Disturbance:** It is important to manage the magnitude and duration of disturbance to the community from the construction of new infrastructure. In some retrofit scenarios, decentralized controls may result in less economic disturbance during construction because of their inherently small scale.

4.2.2 Characterize Site and Evaluate Constraints

The practicability and effectiveness of decentralized controls is highly dependent on the existing characteristics of the urbanized area under consideration. Four frameworks for characterizing the site are presented below with examples.

4.2.2.1 Redevelopment or Retrofit Project

The type of project, whether redevelopment or retrofit, will influence the range of available decentralized control options. Redevelopment involves a significant change to the site design. The extreme case is rebuilding a site from the ground up. A retrofit is a more limited project to achieve specific goals such as CSO mitigation or neighborhood greening. Typically most or all of the existing buildings and infrastructure are left in place.

Redevelopment There will be a relatively high degree of flexibility in the placement of buildings, roads, or utilities, which can help to achieve the planning goals. Decentralized controls can be made an intrinsic part of the site design.

Retrofit With the site design largely fixed, there may be less flexibility in the selection, design, and placement of BMPs. Structural modifications (e.g., to accommodate a vegetated roof) or minor site modifications (e.g., curb removal) may be needed.

4.2.2.2 Land Cover

A successful decentralized control project depends on the detailed analysis of land cover characteristics such as the general land uses (e.g., commercial, residential), the site-specific activities that occur, and the distribution of land cover types.

Land use Pollutant loadings from high density commercial surfaces versus medium density residential surfaces, or arterial streets versus driveways, may be quite different. If ecological goals are a concern, the water quality treatment abilities of the selected BMPs must be appropriate to the pollutant loadings from the site's land use(s). From a maintenance perspective, a given BMP may be more likely to be maintained when constructed in one land use than another.

Type of activity It is often insufficient to describe a portion of the site simply as, for example, "medium density residential pervious." The activity that occurs in both the pervious and impervious space may affect the desirability of a given BMP and may be unique to a given site. For instance, rain gardens are less appropriate in open space used for active recreation and more appropriate in landscaped areas. Permeable pavement is typically suitable for areas with low traffic volumes where acute pollutant spills (e.g., motor oil) have a low likelihood of occurring.

Pervious/impervious area distribution The proportion and distribution of pervious and impervious cover will affect the selection of BMPs. If infiltration BMPs such as rain gardens are to be used to treat impervious runoff, there must be a sufficient amount of open space in which to construct them. In sites with little or no open space, or when there is open space only in one portion of the site, there may be a greater need to distribute BMPs across the impervious surfaces (for instance, by using vegetated roofs and permeable pavement).

Stability Determine whether, and how, the site configuration may change in the future, in order to develop site and BMP designs that can adapt to future changes in the land use.

Site topography Steep slopes make the construction of infiltration BMPs more complicated, but not impossible (for instance, they can be terraced). Also, runoff from large areas should not drain to a single point, but should be distributed across the site.

Underground clearance High water tables or the presence of underground utilities may pose special challenges for the construction of infiltration BMPs. Jurisdictions may stipulate a required depth between the water table and the BMP.

Time scale Predictability of change in the watershed or modifications in land use may result in extending or preventing attainment of the water goals.

4.2.2.3 Soils

Many decentralized controls, such as rain gardens and permeable pavement, infiltrate stormwater into the soil to reduce runoff volume and improve water quality. Evaluating the soils at a site is an important factor for determining which BMPs are most appropriate for achieving the planning goals.

Compacted soils The site should be evaluated to determine the degree of soil compaction. Urban soils are often heavily compacted, impeding or preventing plant growth and infiltration. Soils with low or no infiltration capacity will decrease the effectiveness of infiltration BMPs at reducing runoff volume. In this case, other BMPs such as vegetated roofs may be a more suitable option, if runoff volume reduction is a goal. Amending compacted urban soils with compost or other soil conditioners has been shown to increase their permeability.

Infiltration capacity Infiltration capacity is strongly influenced by soil compaction, but also by the type of soil. Soils with a relatively high clay content have lower infiltration rates, and soils with a relatively high sand content have higher infiltration rates. Hydraulic Soil Group A and B soils have a high infiltration capacity, and Group C and D soils have a low capacity.

Contaminated soils It may be inadvisable to allow stormwater to infiltrate into the soil if the site has contaminated soils. Excavation of contaminated soils may pose environmental or public health risks.

4.2.2.4 Hot Spots

Areas with flooding or accumulation of debris or other pollutants should be given a relatively high priority for the use of decentralized controls, whether at the hotspot or “upstream” in the contributing drainage area. Examples include industrial districts, commercial loading docks, and areas with frequent trash storage.

4.2.3 Evaluate Candidate Practices

Once the drivers, watershed planning goals, and site characteristics are well understood, specific decentralized controls can be evaluated for their suitability. In general, BMP selection must be tailored to meet the primary and secondary drivers and watershed planning goals. BMPs must also be compatible with the land use and activity, blend into the community fabric, and be accepted by the residents in order to become a community asset and to ensure long-term effectiveness. The BMP criteria and guidelines offered below are common examples of planning and design considerations, but do not constitute an exhaustive list.

4.2.3.1 Feasibility

Feasibility considerations are screening criteria for the BMP based on the site characteristics. If the criteria cannot be met, the site characteristics and layout must be modified, if possible, or another BMP must be selected.

Land use (macro scale) The predominant land use should guide BMP selection. For instance:

- If rooftops are the predominant land use at a site, then vegetated roofs may need to be used extensively.
- If sufficient pervious space is available, rain gardens may be a more suitable option.
- If the site is largely paved, a combination of rain gardens and permeable pavement may be most appropriate.

Land use (micro scale) The intended use of the BMP should be compatible with the specific activity occurring in the area in which it will be located. For instance:

- Vegetated roofs should not be constructed in roof areas designated for roof patios or HVAC units.
- Rain gardens should not be constructed in areas intended for active recreation.
- Residential landowners will each have different priorities for the open space on their property, so the feasibility of rain garden construction may need to be considered on a case-by-case basis.
- For permeable pavement, surfaces subjected to high traffic volumes (e.g., roadways) are not appropriate.

Structural considerations The structural capacity of buildings and site infrastructure must be taken into account. For instance:

- The existing or planned roof structure must be able to support the additional loading from a saturated vegetated roof. In residential areas, the load-bearing capacity of roofs may vary between properties.
- Unlined bioretention cells should not be placed where slope stability is a concern.

- There must be sufficient space and structural capacity in buildings in which cisterns are to be used.

Utilities If utilities cannot feasibly be relocated from the area in which the BMP is to be placed, and the BMP cannot be designed around the utilities (e.g., changing its dimensions), then another type of BMP may need to be chosen.

Infiltration potential As discussed in Section 4.2.2.3, the ability of existing soils to infiltrate runoff may play an important role in BMP selection if volume reduction is a primary stormwater management objective.

- If volume reduction is important and infiltration is impractical or not advisable, infiltration BMPs such as rain gardens may not provide sufficient volume reduction. BMP selection may be tilted toward other choices such as vegetated roofs and cisterns.
- Infiltration BMPs constructed in functionally impervious soils may still provide modest volume reductions. Reductions in peak discharge and pollutant loadings should not vary significantly from BMPs constructed in pervious soils.
- Underdrains must be used wherever the permeability of existing soils is low.
- Use of soil amendments such as lime or compost may be able to restore the permeability of compacted urban soils, although improvement may take several months to a year.

Local pollution sources High loadings of pollutants, especially sediment and oil and grease, can potentially greatly decrease the performance of infiltration BMPs over time. If future acute pollutant releases are probable, then pretreatment (e.g., filter strips, compost blankets) should be provided or the BMP should not be used in that area. An infiltration BMP should not be constructed until other construction activity in its drainage area has been completed.

Table 4-1. Spatial Factors Affecting the Feasibility of Decentralized Controls.

BMP	Space Requirements	Significance of Proximity to Drainage System	Importance of Available Pervious Area and/or Space
Downspout Disconnection	May require no additional surface or subsurface space to disconnect. However, requires pervious area or cistern to infiltrate or store roof runoff. For residential applications this space is usually available, but for commercial and industrial buildings space may be limited.	It is desirable to keep these controls disconnected from the drainage system	Pervious conditions complement the operation of these controls.
Filter Strips	May require some surface space depending on the site, but can often be incorporated into road side landscaping. Subsurface space requirements are negligible, unless designed with underdrains.	Effluent and influent may have to be piped to and from drainage system. Negligible impact if influent and/or effluent not piped.	Pervious conditions complement the operation of these controls.
Infiltration Practices	May require a significant amount of surface space depending on soils and design storm intensity, but can often be incorporated into existing landscaping. A significant amount of subsurface space may be required to allow for vertical percolation and set back from structures.	Minimal impact if influent has to be piped. Negligible impact if influent is not piped.	High Impact. These controls depend on infiltration.
Planter Boxes	Usually placed next to buildings beneath downspouts; surface area requirements may be high, but can be easily integrated into landscaping	Underdrains are often routed to storm drain system, but can be designed to percolate into subsurface soils.	Some designs incorporate infiltration, so pervious areas may be important.
Pocket Wetlands	Both surface and subsurface space requirements can be significant to hold the permanent pool and surcharge volume.	Influent and effluent often have to be piped to and from the control.	Overly pervious conditions may increase costs since a liner may be needed to maintain permanent pools.
Porous Pavement	Can replace conventional pavement. Subsurface space requirements may slightly exceed conventional alternatives. In retrofit situations, additional surface and subsurface space requirements may be insignificant.	Negligible impact since influent and effluent typically do not need to be piped.	High Impact. These controls depend on infiltration.
Rain Barrels/ Cisterns	Surface space requirements are comparable to the footprint of the individual structures and subsurface requirements are moderate to low, depending on design variations (e.g., if tank is placed below ground). However, several will be needed to capture significant volumes.	Negligible impact since it is desirable to keep these controls disconnected from the drainage system.	Pervious conditions complement the operation of these controls.
Rain Gardens	Surface space requirements may be significant to allow for ponding, and subsurface space requirements may be low.	May be important if an underdrain is used.	Pervious conditions complement the operation of these controls.
Rooftop Storage	Surface area requirements are limited to the available area since existing structures are utilized. Subsurface area requirements are typically not required.	Negligible impact since it is desirable to keep these controls disconnected from the drainage system.	These controls do not depend on infiltration.
Tree Box Filters	Surface area requirements are often comparable to the foot print of the individual structures. Subsurface area requirements range from very low to negligible.	Negligible impact since it is desirable to keep these controls disconnected from the drainage system.	Pervious conditions complement the operation of these controls.
Vegetated Swales	Surface area requirements are often significant and subsurface area requirements are often minimal.	Influent and effluent may have to be piped to and from the drainage system. Negligible impact if influent and/or effluent not piped.	Pervious conditions complement the operation of these controls.
Vegetated Roofs	Surface area requirements are often significant; however, no new areas are required since existing structures are used. Subsurface area requirements are typically negligible.	Influent and effluent may have to be piped to and from the drainage system. Negligible impact if influent and/or effluent not piped.	These controls do not depend on infiltration.

Table 4-2. Additional Spatial Factors Affecting the Feasibility of Decentralized Controls.

BMP	Significance of Proximity to Existing Structures and Infrastructure	Susceptibility to Utility Conflicts	Concern for Groundwater Contamination	Concern Related to Shallow Groundwater Table
Downspout Disconnection	May impact building foundations if poorly implemented.	Little or no excavation is typically involved.	Minimal impacts due to typically low volumes.	Minimal impacts due to typically low volumes and minimal excavation.
Filter Strips	Impacts comparable to lawns and other landscape features.	Little or no excavation is typically involved.	Minimal impact, since infiltration is typically not the primary drainage mechanism.	Some amount of excavation may be required.
Infiltration Practices	May impact building foundations if poorly implemented.	Significant excavation is often required.	High Impact, since these conditions primarily depend on infiltration.	Significant excavation is often required.
Planter Boxes	May impact building foundations if poorly implemented.	Excavation may be needed.	Minimal impacts due to typically low volumes.	Negligible for designs with underdrains.
Pocket Wetlands	Minimal impacts, however some airports may not approve of wetlands built too close for fear of increase in bird populations.	Excavation may be needed.	Some amount of infiltration may occur, however, liners can be used.	Some amount of excavation may be required.
Porous Pavement	Roadside structures less likely to be damaged by infiltration practices.	In retrofit situations, additional excavation required may be minimal or not required. New installations more susceptible.	High Impact, since these conditions primarily depend on infiltration.	High water table may damage roadway sub-grade.
Rain Barrels/ Cisterns	When located close to a building, must ensure that overflow does not affect building foundation.	Little or no excavation is typically involved.	Minimal impacts due to typically low volumes.	Little or no excavation is typically involved.
Rain Gardens	When located close to a building, must ensure that overflow does not affect building foundation.	Little or no excavation is typically involved.	Minimal impacts due to typically low volumes.	Little or no excavation is typically involved.
Rooftop Storage	Minimal impacts, however poorly designed practices can cause roof leaks and structural damage.	Little or no excavation is typically involved.	It is desirable to keep these controls disconnected from the drainage system.	Little or no excavation is typically involved.
Tree Box Filters	When located close to a building must ensure that overflow does not affect building foundation.	Little or no excavation is typically involved.	Minimal impacts due to typically low volumes.	Little or no excavation is typically involved.
Vegetated Roofs	Minimal, however poorly designed controls can cause roof leaks and structural damage.	Excavation is typically not needed.	It is desirable to keep these controls disconnected from the drainage system.	Little or no excavation is typically involved.
Vegetated Swales	When located close to a building, must ensure that overflow does not affect building foundation.	Some excavation may be required.	Some amount infiltration may occur, however, liners can be used.	Some excavation may be required.

Table 4-3. Engineering Factors Affecting the Feasibility of Implementing Decentralized Controls.

BMP	Structural Concerns	Hydraulic and Hydrologic Design Parameters	Slope and Vertical Relief
Downspout Disconnection	Foundation undermining; flooding.	Infiltration rate or storage volume of receiving area/facility.	Must have enough vertical relief from disconnect point to receiving area/facility.
Filter Strips	Erosion; berm/bank stability.	Hydraulic retention time; minimum length; longitudinal slope; design flow rate/velocity/depth.	Contributing drainage area should typically be no more than 5% slope unless energy dissipation and flow spreading provided. The strip should have slopes of 1-15%.
Infiltration Practices	Foundation/ roadway undermining	Min/max infiltration rate; emptying time.	Not to be placed on steep slopes (~25% or greater). Only minimal slopes needed to route flow to infiltration area. Energy dissipator may be needed with large inlet slopes.
Planter Boxes	Foundation undermining.	Design volume; media depth and porosity.	Usually placed below downspouts near buildings, so influent vertical relief often not a concern. Energy dissipators needed below downspout. If underdrains are present, must have enough vertical relief to convey water to storm drain.
Pocket Wetlands	Berm/bank stability.	Design volume; base flow; hydraulic retention time; infiltration capacity.	Minimal needed to route flow into wetland. Energy dissipater may be needed if large inlet slopes.
Porous Pavement	Traffic loading.	Min/max infiltration rate.	Should be sloped away from travel lanes at about 1.5-2%.
Rain Barrels/ Cisterns	Negligible.	Design/reuse volume.	Adequate relief necessary to route runoff to device and then to area of application during reuse.
Rain Gardens	Foundation undermining; flooding.	Design volume; media depth and porosity.	Minimal needed to route flow into bioretention area. Energy dissipator may be needed with large inlet slopes. If underdrains are installed, about 3-5 feet of drop is needed.
Rooftop Storage	Roof integrity; leaks.	Design volume.	Flat or very mildly sloping roofs necessary to allow ponding.
Tree Box Filters	Roadway undermining.	Treatment flow rate; infiltration rate.	Same as catch basin/vault filters.
Vegetated Roofs	Roof integrity; leaks.	Design volume; media depth and porosity.	Flat or pitched roofs are possible, but not to be placed on roofs with greater than 40% pitch.
Vegetated Swales	Same as filter strip.	Same as filter strip.	Sufficient longitudinal slope to avoid ponding, but too much causes scour. Recommended 1-6%.

Table 4-4. Additional Engineering Factors Affecting the Feasibility of Implementing Decentralized Controls.

BMP	Reliability/Confidence in Fundamental Design	Design Flexibility
Downspout Disconnection	Potential for large reduction in DCIA, but must infiltrate or provide storage.	May be used with many other BMPs.
Filter Strips	Provide hydrologic control depending on design. Sediment can be re-suspended during large storms.	Many options for incorporating into landscaped environment. Higher WQ performance associated with check dams, shallow slopes, and low velocities. Soil amendments can be used to improve infiltration and retention capacity.
Infiltration Practices	Prone to clogging and bypass if not maintained frequently or sedimentation pretreatment not provided.	Trenches more amenable to urban environment than basins. Various soil amendments possible to improve pollutant adsorption capacity. Can be used in conjunction with detention.
Planter Boxes	Low potential for clogging. Provides volume reduction and peak discharge control.	Can be integrated into most building landscape designs and practically any shape or configuration is possible.
Pocket Wetlands	Effluent quality generally good for most parameters. May release nutrients during dormant periods. Some detention provided, but negligible volume reduction.	More difficult than some practices to incorporate into the ultra-urban environment.
Porous Pavement	Clogging common; requires vacuum sweeping or power washing to restore hydraulic capacity. Moderate volume losses possible when properly maintained.	Not very flexible. Should be designed to infiltrate incident rainfall only; however, porous shoulders may receive runoff from the primary travel lanes.
Rain Barrels/ Cisterns	Typically small storage volumes so minimal hydrologic benefits.	Installed above or below ground, as well as on rooftops. Below ground may require pumping for reuse.
Rain Gardens	Substantial hydrologic benefits possible due to retention, infiltration, and evapotranspiration. Pollutant reductions may also be high due to plant uptake and microbial degradation.	Very flexible in that practically any shape is possible. Many options for incorporating into landscaped environment. Underdrains may be installed for low permeable soils.
Rooftop Storage	Provide good peak control for small storm events, but no water quality benefits.	Not many options for design alternatives, but easy to incorporate into urban environment. Innovative outlet controls possible.
Tree Box Filters	Similar to rain gardens, with underdrain.	Similar to rain gardens, with underdrain.
Vegetated Roofs	Substantial hydrologic benefits possible due to retention and evapotranspiration, but benefits are realized primarily for small, frequently-occurring storm events.	Many options for design and configuration of vegetation. Roof gardens where plants are placed in pots and planter boxes are one design variation.
Vegetated Swales	Same as filter strips.	Same as filter strips.

4.2.3.2 Design Variables

Design variables provide guidelines to help determine the most appropriate or effective use for the BMP. They apply once the screening criteria for overall feasibility, described above, are met.

BMP sizing BMP surface area and depth are a function of stormwater management goals and site constraints.

- In general, the ratio of a rain garden area to its drainage area will be small, at approximately 10%. The drainage area for an individual rain garden should be less than 0.5 acres.
- If the underlying soils are permeable, increasing the surface area of infiltration BMPs will increase the annual volume reduction because more infiltration can occur. Avoid creating vast, pond-like rain gardens, but consider, for instance, lengthening or slightly widening rain garden strips when possible.

Proximity to impervious areas Infiltration BMPs should be located in the near vicinity of the impervious area they are intended to treat, and runoff should enter infiltration BMPs as sheet flow. If the flow is concentrated as a result of channelization, level spreaders and energy dissipators (e.g., rock aprons) may be able to sufficiently spread out and slow down the flow. Otherwise, other BMPs such as vegetated roofs and permeable pavement may need to be located closer to the runoff source.

Curb and gutter Curbs and gutters are a staple of conventional urban stormwater management. However, they do not necessarily have to be a hindrance to the use of decentralized controls. Curb cuts can be used to direct street runoff into infiltration BMPs. In parking lots, curb removal may be another option.

Downspouts The ability to disconnect downspouts may affect BMP size, design, or placement.

- If downspouts cannot be disconnected, any reduction of roof runoff volume will necessarily result from the use of vegetated roofs or cisterns. If disconnection is not possible, the size or extent of these BMPs may need to be increased in order to meet the stormwater management goals.
- If downspouts can be disconnected, volume control on the roof or in the building may become less critical if infiltration BMPs are able to be used. If measures are taken to dissipate the energy of downspout flow (e.g., through the use of a rock apron), then roof runoff can be directed into a rain garden or other infiltration BMPs.

Lined rain gardens If the water table is high or the soils are contaminated, a rain garden can be constructed with an impermeable liner and underdrain. Volume reduction may be limited, but a lined rain garden will still reduce the peak discharge rate and pollutant loading. A lined rain garden will function similarly to a rain garden constructed in compacted soils.

4.2.4 Determine Cost-Effectiveness in Context of Goals and Site Characteristics

A key characteristic of decentralized controls is that different BMPs may have similar stormwater management capabilities. Although several BMPs may have different space requirements, aesthetic attributes, and ancillary functions, they may be used to meet the stormwater management objectives. For example, a vegetated roof and a rain garden may reduce the annual runoff volume by a comparable amount. The designer has greater flexibility, but the selection process is less clear-cut and may often be non-linear.

The evaluation process described above may produce only one type of BMP that is appropriate for a given portion of the site, based on the selection criteria. In some cases, however, two BMPs may be approximately equal in suitability. For example, the annual runoff volume captured by a series of rain gardens around the perimeter of a building may be equivalent to that captured by a cistern in the building.

Additional evaluation criteria can be used to select the most appropriate decentralized controls. In the above example, the annual value of water conservation could be compared with the aesthetic and community benefits of the plant material in the rain gardens. Additional selection criteria such as groundwater recharge or habitat development could also be incorporated into the final decision.

If a design strategy provides only minimal modifications to accommodate decentralized controls, an initial evaluation (either qualitative or quantitative) may indicate that the stormwater management objectives or resource protection goals may not be met. Additional controls may be required that more significantly alter the site design. This may include a higher degree of site-specific customization of BMP design, a higher density of BMPs, additional maintenance measures, additional pollution prevention, or the use of off-site controls to meet the objectives.

4.2.5 Select BMPs

Select a suite of BMPs most suitable for meeting the overall watershed requirements and provide site-specific solutions to planning goals. The suite may incorporate a single BMP, a combination of BMPs (e.g., vegetated roofs and cisterns), or may use no BMPs (i.e., no-build option) depending on the watershed and natural resource protection goals.

4.3 Incentives

4.3.1 Economic and Policy Incentives

A number of incentive programs encouraging the use of decentralized controls are being used in municipalities across the country. While the focus of these programs differs, all attempt to provide economic benefit to those who install decentralized controls and manage stormwater on site. As stormwater utilities are being created in municipalities to fund stormwater control programs, some jurisdictions are incorporating provisions designed to encourage alternate stormwater controls. The stormwater utility in Portland, Oregon, for instance, will allow up to a 35% rate reduction for commercial rate payers who manage stormwater on site beginning in 2006. In addition, since its inception in 1988, the City of Orlando, Stormwater Utility, has given a 40% credit to commercial properties with on-site stormwater management.

In addition to creating a stormwater utility, the city of Portland has also offered other economic incentives. The city subsidizes a downspout disconnection program, in which they either disconnect homeowners from the combined sewer system free of charge or provide up to $53 dollars for each downspout the homeowner disconnects up to a maximum of two downspouts. Subsidized downspout disconnection programs are also offered in other municipalities with combined sewer system. The City of Portland also offers a zoning bonus in the downtown combined sewer area, allowing additional building square footage for buildings that install vegetated roofs.

4.3.2 Codes and Regulations

Municipalities should review applicable codes and regulations for opportunities to encourage the use of decentralized controls. Streamlining the permit process by allowing a waiver for the small land disturbances typical of decentralized controls is a regulatory option available in many jurisdictions. Applicable guidelines should also be reviewed to confirm that they allow for on-lot stormwater management and do not prohibit such practices.

4.4 Disincentives

Some of the largest impediments to the implementation of decentralized controls are the often unintentional zoning and code barriers. Zoning or architectural regulations (e.g., those explicitly requiring curb and gutter or prohibiting open channel conveyances) discourage decentralized controls. At the very least they require obtaining a waiver which lengthens the development and construction process, an undesirable delay for many potential users of decentralized controls. Additionally, local plumbing codes, written to enhance centralized stormwater collection systems, can discourage decentralized controls. Ordinances requiring downspouts to be directly connected to the combined sewer system unintentionally prevent downspout disconnection efforts and the use of on-site stormwater management.

CHAPTER 5.0

SIMULATION AND COST-EFFECTIVENESS ANALYSIS FOR DECENTRALIZED CSO CONTROLS

5.1 Introduction

The purpose of this chapter is to describe progress in simulating and providing cost-effectiveness comparisons for *decentralized* CSO controls. The U.S. EPA Storm Water Management Model (SWMM) was developed 35 years ago to simulate *centralized* CSO control options. The most complex modeling question for CSO evaluations is how to predict surcharging that occurs when the capacities of the collection, storage, and/or treatment system are exceeded. Surcharging in the collection system leads to CSOs into basements, streets, and receiving waters. The Extran part of SWMM was designed to handle these cases. Other early complex CSS simulation problems included how to incorporate real-time control options such as inflatable dams into the simulators. These additional features have been added to U.S. EPA SWMM and related models over the years. Recently, SWMM has been completely rewritten and updated. The new version is called SWMM 5.0. Rossman (2004) has prepared a detailed User's Manual for SWMM 5.0.

Until recently, stormwater modeling efforts focused on simulating larger, centralized controls. Runoff and its associated water quality from the subcatchments were taken as exogenous variables that could not be controlled. Hence, the only available options were centralized downstream controls. During the past several years, attention has shifted from centralized to decentralized CSO controls. The modeling question was to determine whether simulators that were developed to evaluate large central systems could be downscaled to evaluate micro-scale processes such as rainfall and runoff at the individual parcel level. The first part of this chapter addresses this question. The other part of this chapter addresses the issue of how to perform cost-effectiveness analysis on these decentralized systems.

5.2 Simulation Modeling of CSOs and Decentralized Controls

5.2.1 Background

Huber and Cannon (2002) describe how they modeled upstream CSO options by modifying SWMM. This section examines the potential impact of disconnecting impervious rooftops and other areas on individual lots as a means to reduce runoff into a combined sewer system in Portland, Oregon. The modeling methods used to evaluate the concepts are relatively new. This paper emphasizes modeling results for the purpose of evaluating decentralized control concepts in dense neighborhoods.

5.2.2 Portland Study Area

The large Sullivan combined sewer basin in Portland, Oregon is a 1,700 ac (690 ha) area located on both sides of the Banfield Freeway (Interstate 84), from about NE 25th to NE

55th Avenue in northeast Portland. The land use is primarily single-family residential with localized zones of commercial properties. The overall basin imperviousness is about 46%. Detailed information on the Sullivan area and neighboring Stark and Holladay areas is provided by Carollo Engineers (1999). Additional information is provided by Adderley and Mandilag (2000a, 2000b) and Hoffman and Crawford (2000). A portion of the Sullivan Basin is shown in Figure 5-1.

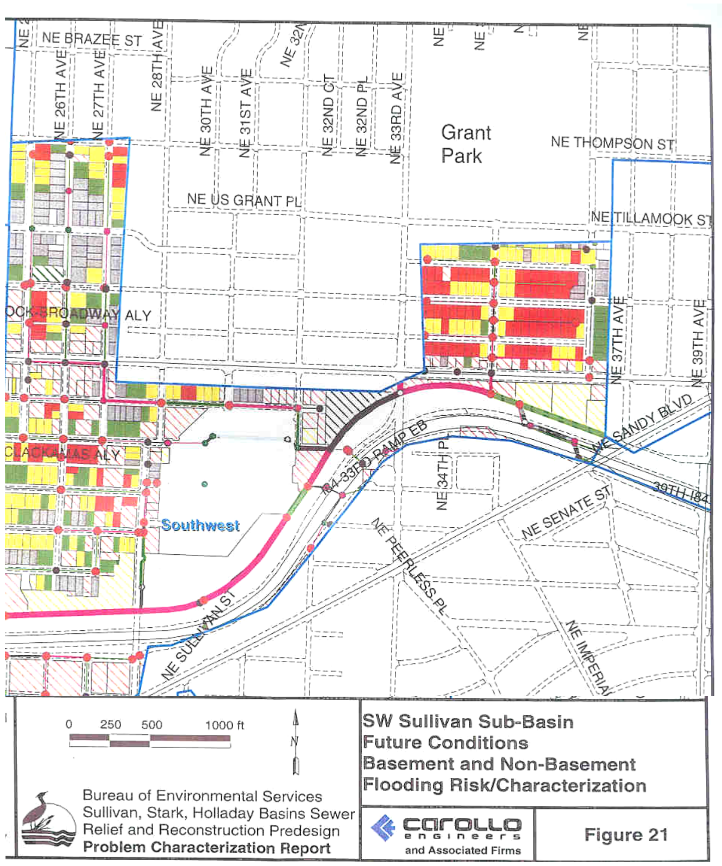


Figure 5-1. Sullivan Area (Carollo Engineers, 1999). The Sub-area Used for this Study is Just South of Grant Park.

The City of Portland's Bureau of Environmental Services (BES) has been modeling this area since the late 1990s. The area has been targeted for the city's Downspout Disconnection Program, and very detailed information is available on percentages of roof area that are currently disconnected, including a complete description of each parcel. The detailed study area for the project described in this paper uses a subset of BES data, including ArcView spatial coverages.

The detailed study area is between 33rd Ave. and 37th Ave. (west and east boundaries) and between the Banfield Freeway (I-84) on the south and Grant Park on the north. A six-block area of 115 single-family residential lots (parcels or tax lots) totaling 16.9 ac (6.8 ha) with 35% impervious area is being modeled (Figure 5-2). Average lot size is just over 0.10 ac (400 m^2).

This area has been monitored extensively because of basement flooding. There is a flow monitor in the study area and a tipping bucket rain gage less than 500 ft from the center of the study area (Figure 5-2). The ArcView layer in Figure 5-2 also shows the roof density of the neighborhood and the main sewer laterals. Monitoring data are available at the location indicated in Figure 5-2 from November 1998 – May 1999 at 5-minute intervals. Measured flow data were used for all model comparisons.

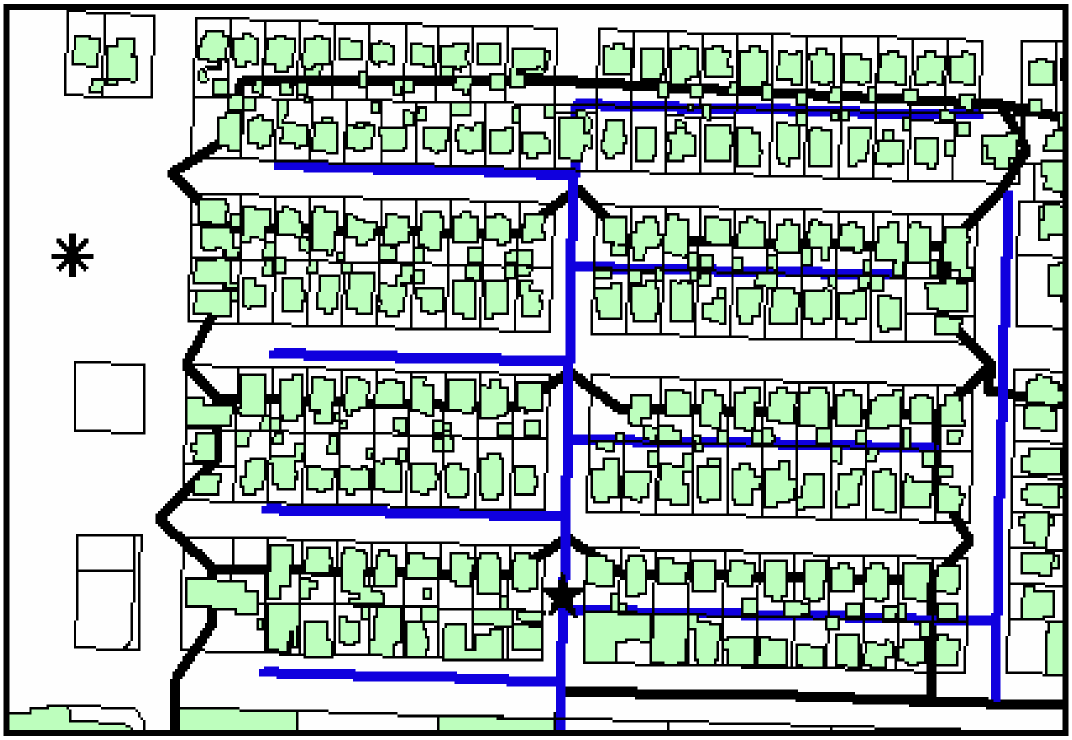


Figure 5-2. Study Area Showing Individual House Parcels and Rooftop Imperviousness. Aggregated subcatchments used by BES are shown in heavy black. The sewer network is shown in heavy blue. The monitoring station on 35th Street is shown with a star and the rain gage with an asterisk (*). Dimensions of the figure border are approximately 1050 ft (320 m) wide by 590 ft (180 m) high.

5.2.2.1 Model Data Preparation Methods

5.2.2.1.1 Required Parameters

The SWMM Runoff Block converts rainfall into runoff using a nonlinear reservoir technique (Huber and Dickinson, 1988). Each subcatchment is characterized by the following parameters:

- Area;
- Imperviousness;
- Width;
- Slope;
- Depression storage (pervious and impervious subareas);
- Manning's roughness (pervious and impervious subareas); and
- Three (3) Green-Ampt (G-A) infiltration parameters.

These parameters were developed for both an aggregated and a disaggregated model representation of the 16.9 acre basin, as described in the following sections. However, the same values for depression storage, roughness, and infiltration parameters were used for all subcatchments, as indicated in Table 5-1. Subcatchment slopes were taken from BES digital terrain models. Parcel widths (widths of subcatchments representing individual lots) were 50 ft for single parcels and 100 ft for two double-width parcels. These values are based on BES simulations and data. *All model runs shown are uncalibrated.* The reason for this is twofold: 1) BES had already performed a preliminary calibration, and 2) one objective was to investigate how well the model would perform without calibration data, since such data are often missing. Although the modeling team relied upon BES estimates for baseflow, there was no attempt to improve upon the parameter estimates described below to obtain better fits. However, all model-monitor comparisons are generally good, due in part to the relatively high imperviousness of the overall basin. The goodness of fit will be seen below; model performance in general is not an issue in this paper.

Table 5-1. Constant Model Parameters.

Parameter	Impervious Area	Pervious Area
Depression storage, in.	0.03	0.25
Manning roughness	0.013	0.25
G-A suction, in.	n/a	2.56
G-A hydraulic conductivity, K_s, in./hr	n/a	1.1
G-A initial moisture deficit	n/a	0.08

The SWMM Runoff Block was used only for surface runoff simulation; the sewer network was simulated in the Extran Block of SWMM (Roesner et al., 1988). Hence, while most of the discussion that follows deals with the Runoff Block, simulated vs. monitored flows rely upon Extran Block output at the monitor location. Pipes in the system are generally small, ranging from 8 in. (200 mm) diameter in the upstream laterals to a maximum of 16 in. (406 mm) at the monitor location. Slopes were determined by BES from field surveys. A value of Manning's n = 0.013 was used for all pipes. A five-minute time step was used in the Runoff Block and a 10-second time step was used for flow routing in the Extran Block.

5.2.2.1.2 Subcatchments and Conduits

Directly connected impervious area (DCIA) consists of the impervious area of each subcatchment that is directly connected to the sewer through laterals. The impervious roof and parking areas for each parcel were obtained from photogrammetric maps of the city by BES. The model was based on actual impervious areas only. No impervious area assumptions were made based on land use.

Initial modeling by BES aggregated all DCIA for each service lateral and treated it as one 100%-impervious subcatchment. Eleven subcatchments were used to simulate the parcel impervious area draining into six laterals and five inlets along the north-south trunk sewer. These eleven DCIA subcatchments are identified by the sewer segment into which they drain, as shown in Figure 5-3. For the aggregated subcatchment model, streets, sidewalks and all pervious areas are lumped into three additional surface subcatchments (Figure 5-4). The aggregated model runs are called "A-model" runs in descriptions that follow. The main purpose of these runs was to compare Oregon State University's efforts with prior BES efforts, and to compare aggregated vs. disaggregated simulation results.

A disaggregated model representation was created using one subcatchment for each of 115 house parcels. These "I-model" runs were used to predict flows for both current and decentralized control situations (disconnected roof and driveway areas). The parcels and roof areas are shown in Figure 5-2. This method makes it quite simple to simulate decentralized control rerouting of DCIA to pervious areas on the individual parcels through the ability of the Runoff Block to route from impervious to pervious subcatchment subareas (Huber, 2001a). Three street subcatchments (Figure 5-4) were used to account for all area not included in the parcels, both impervious (streets and sidewalks) and pervious (green strips). All impervious area in these three subcatchments is assumed to be directly connected, even though some sidewalk runoff might flow over grassed strips between the sidewalk and the street.

Each sub-basin has a north-south sewer main line and two east-west service laterals on either side of the main line (Figure 5-3). The same Extran pipe network was used for both the aggregated (14 subcatchments) model runs and for runs that simulate every house parcel. Runoff from the DCIA and parcel areas is typically inserted into the Extran pipe simulation at the upstream manhole of each segment. The street subcatchments drain to the north-south sewer mainline for the basin.

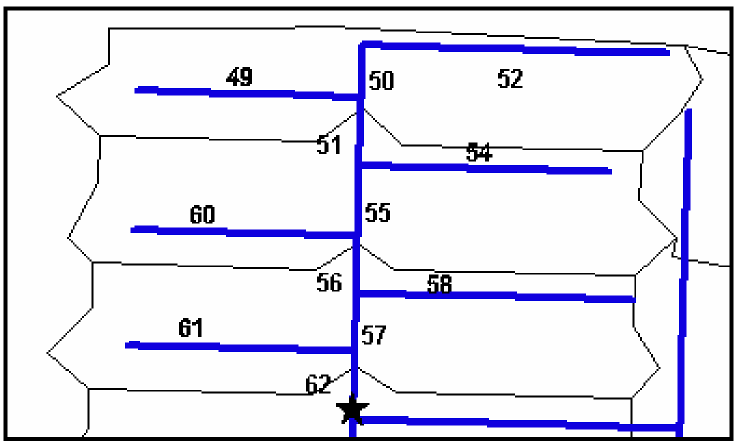


Figure 5-3. Pipe Segment ID for the Study Area, as Simulated in Extran. The aggregated subcatchment model (A-model) includes the DCIA in parcels in the six areas draining to laterals 49, 52, 54, 58, 60. and 61. Five smaller DCIA areas (not shown) drain to north-south trunk sewer segments 51, 55, 56, 57, and 62. For the aggregated subcatchment model, streets, sidewalks and all pervious areas are lumped into three surface subcatchments. The street and sidewalk components of these surface subcatchments are shown in Figure 5-4.

Since the basin is a combined sewer area, baseflow (dry-weather flow) must be considered. BES data indicate an average of about 0.032 cfs (0.91 L/s) at the monitor. BES provided baseflow estimates distributed in time for each sub-basin, and these were added to the upstream end of each lateral in the Extran simulation.

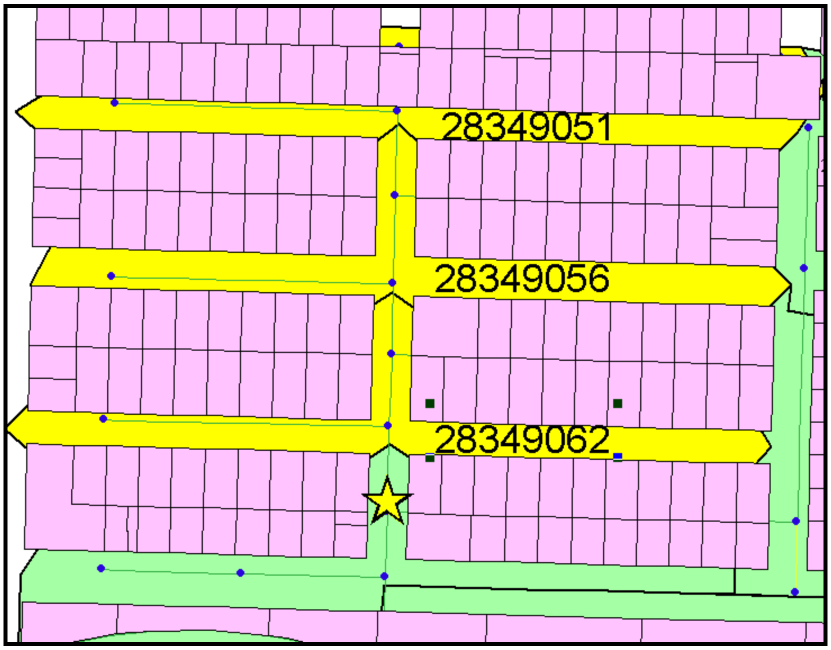


Figure 5-4. Aggregated Areas for Three Street Subcatchments Include Roads, Sidewalks, and Grass Strips. The three areas shown are the actual areas used for the disaggregated modeling and conceptual areas for the aggregated modeling, since the aggregated modeling adds all pervious area from house parcels into the three surface subcatchments. Subcatchment 28349051 drains to pipe 51 (Figure 5-3), etc.

5.2.2.2 Modeling Results

5.2.2.2.1 Simulation Descriptions

Three simulations from the overall study are shown in this paper:

1. A-model: eleven (11) aggregated subcatchments (Figure 5-3);
2. I-model: simulation of 115 house parcels (Figure 5-2) as individual, disaggregated subcatchments, plus three street subcatchments, assuming all parcel imperviousness is directly connected; and
3. I-LID: same as 2 above, but assuming all parcel imperviousness has been disconnected (i.e., roofs and driveways drain onto lawns).

Simulation outputs show the comparison between simulated and measured hydrographs at the monitoring location for both the aggregated and disaggregated model representations and show the results of a hypothetical impervious area disconnect program, the I-LID option described above. With a saturated hydraulic conductivity, K_s, of 1.1 in./hr (28 mm/hr), as estimated by BES, almost no parcel runoff would be expected for the I-LID option since the soil in this neighborhood can be expected to absorb almost all runoff placed on top of it. This, in fact, is the result that was obtained, as shown below.

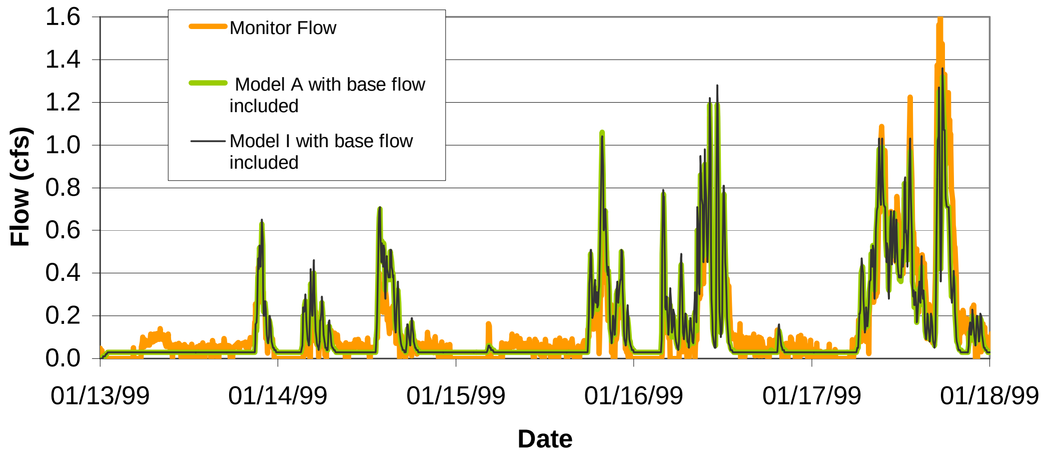


Figure 5-5. Five-day Comparison of Simulated and Measured Flows at the Monitoring Site. A Visual Comparison is Difficult Because of the Crowded Scale.

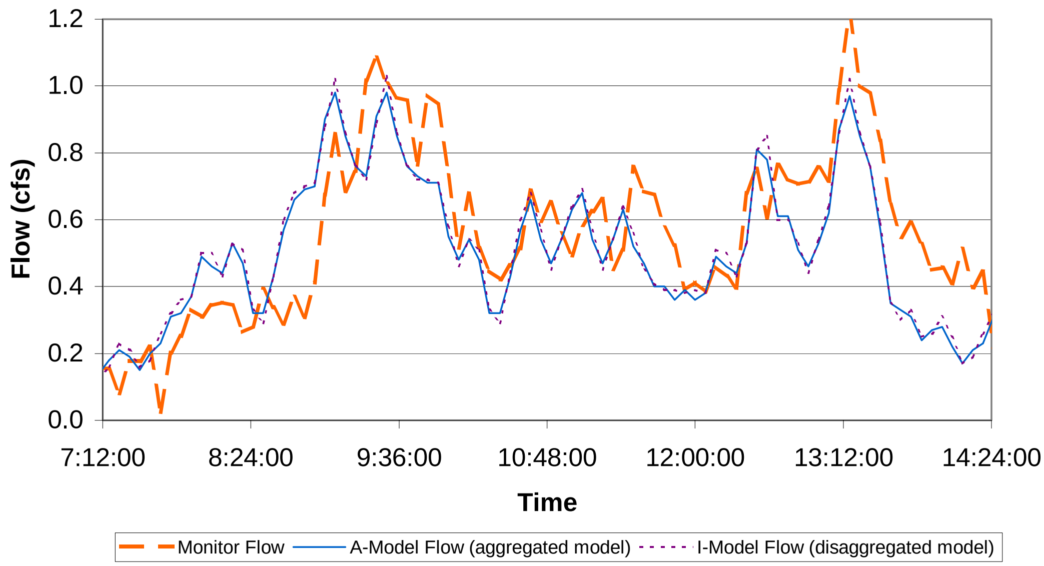


Figure 5-6. Simulated and Measured Flows for Seven-hour Period on January 17, 1999. The Aggregated and Disaggregated Models Show Very Little Difference.

5.2.2.2.2 Aggregated vs. Disaggregated Model Representations

Uncalibrated SWMM output, including baseflows, for January 13-18, 1999 for the aggregated and disaggregated model representations, is shown in Figure 5-5. This time period corresponds to a high five-day rainfall total of 2.42 in. (61 mm) and was used because BES focused strongly on this time period during their modeling efforts. There is good correlation with monitor flow data, but the comparison is difficult to make visually when the five days are compressed into just one plot. Hence, the event of January 17 is considered in more detail in Figure 5-6, wherein it may be seen that there is practically no difference between the aggregated and disaggregated model simulations. This is good news for continuous modelers, for whom an aggregated model representation will require much less computer time.

Generally, the model vs. monitor comparison is good with regard to shape, but the rising limb of the modeled hydrographs is somewhat high, and the modeled recession limb is somewhat low. This might be better simulated by detaining a little more water on the land surface prior to letting it run off. Recall that no calibration or adjustment has been attempted. Extran continuity is very good for all runs, on the order of 0.4%.

Another method for comparison is total runoff volume; these values are shown in Table 5-2. Baseflow is necessary in order to obtain close to the monitored runoff volume. Runoff volumes are comparable for the aggregated and disaggregated models, as would be expected from the inspection of the hydrographs. This confirms the utility of aggregated simulations for long-term simulation.

Table 5-2. Model Total Flow Comparison for Five-day Event, Jan 13-Jan 18, 1999. In bottom row, Ks is the saturated hydraulic conductivity.

	Total flow comparison for five day event, Jan 13-Jan 18, 1999		**Seven-hour interval, 7:00 am to 2:00 pm, January 17, 1999**	
	(cubic feet)	(inches)	(cubic feet)	(inches)
Rainfall for event	148,987	2.42	37,555	0.61
Monitored flow	58,130	0.94	14,082	0.23
Baseflow volume, @ 0.032 cfs	13,0000824	0.22	806	0.01
Model A (aggregated catchments)				
No baseflow	47,244	0.77	12,492	0.20
With baseflow included	60,459	0.98	13,365	0.22
Model I (disaggregated, separate subcatchment for each parcel)				
With baseflow included	60,492	1.02	13,416	0.23
Model I-LID (re-routing impervious runoff over pervious area)				
With baseflow included	26,829	0.45	4,494	0.076
Same as above but with K_s = 1/10 previous value	27,762	0.47	4,872	0.082

How are subcatchments aggregated? Past experience with SWMM (Huber and Dickinson, 1988) indicates that an aggregated subcatchment scheme may be used that gives nearly equivalent results to a disaggregated scheme by proper adjustment of the subcatchment width. “Nearly equivalent” means a hydrograph volume, peak and time of peak within about 10% of the disaggregated scheme. An aggregated scheme typically means a loss of storage in the simulation because fewer conduits are simulated. Hence, reducing the width of subcatchments provides for more storage on the land surface in an “equivalent” manner.

An aggregated scheme is appropriate when the primary goal is to reproduce the hydrograph at the outlet of the overall catchment. For the Portland catchment, it was important to retain the flow routing along the trunk sewer within the catchment, i.e., segments 50, 55, and 57 in Figure 5-3, this to ensure that capacity was not exceeded during the simulations. Capacity of trunks and laterals often dictate the degree of aggregation that should be employed. That is, the minimum number of subcatchments is often set by the need to provide inlet hydrographs to the minimum number of conduits to be simulated. For the Portland scheme, it was also convenient to aggregate in a way that corresponds with the main laterals shown in Figure 5-2. Fortunately, as computer processor speeds increase, the need to aggregate in order to reduce run times decreases, and the aggregation question can sometimes be avoided as unnecessary from a computational point of view. However, for the Portland example, a reduction in the number of subcatchments from 118 total subcatchments for the disaggregated scheme to 14 for the aggregated scheme can indeed represent a convenient saving in computer time for continuous simulations, especially when the Extran Block is used ("dynamic routing" in the current SWMM 5.0 model).

5.2.2.2.3 Decentralized Control Simulation

The essence of decentralized controls is to retain as much water on site as possible at the parcel level (Prince George's County, 2000; Wright et al., 2000). One essential technique is to minimize direct connections to the drainage system by routing runoff from roofs, driveways, etc. over pervious areas to promote infiltration. The SWMM Runoff Block has been adapted for this purpose by Huber (2001a). As indicated in Figure 5-7, overland flow can be rerouted internally within subcatchment subareas (i.e., from pervious to impervious and vice versa) and also may be routed from one subcatchment onto another. The simulation shown below simply routes the impervious area runoff from each of 115 parcels over the pervious area within the same parcels: in essence, a massive, hypothetical decentralized control effort for the neighborhood.

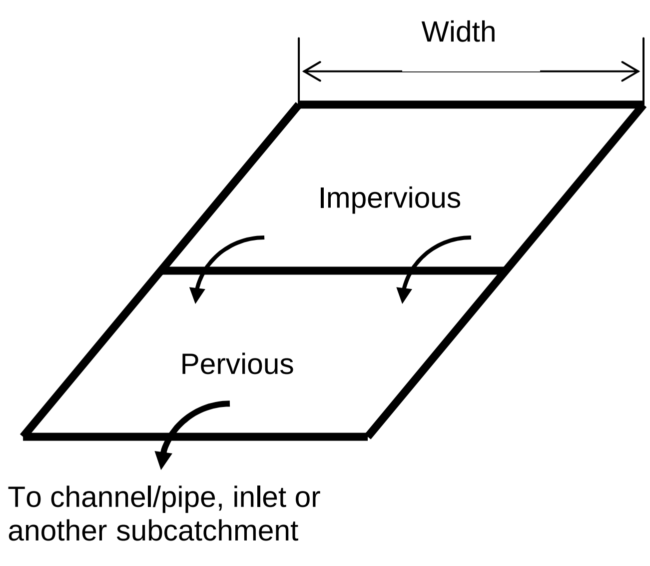


Figure 5-7. Conceptual Routing from the Impervious Sub-area of a Subcatchment to the Pervious Sub-area of a Subcatchment (Huber, 2001a). The scheme is similar for flow from pervious to impervious. Subcatchment outflow can also be directed to another subcatchment.

The I-LID simulation uses the I-Model as the base and reroutes 4.0 ac (1.6 ha) of impervious area runoff from rooftops and driveways over 7.9 ac (3.2 ha) the pervious areas of each parcel. Street surface runoff (and sidewalk and grass strip runoff from the three street subcatchments is unaffected. A drastic reduction in the runoff hydrograph (Figure 5-8) and runoff volume (Table 5-2) is produced by the decentralized control option. The five-day runoff volume is reduced by 56% and the seven-hour runoff volume by 67% (Table 5-2). This is to be expected for this hypothetical simulation for which the saturated pervious area hydraulic conductivity of 1.1 in./hr (28 mm/hr) will accept any intensity of runoff associated with typical western Oregon rainfall, including the additional non-DCIA runoff from the roofs, etc.

Soil is often compacted in urban developments, with a lower hydraulic conductivity than for pre-development conditions (Pitt, 1999). An additional run was made with a value of saturated hydraulic conductivity, K_s, equal to one-tenth of the value used for the rest of the modeling. That is, the new value of K_s = 0.11 in./hr (2.8 mm/hr) compared to the previous value of K_s = 1.1 in./hr (28 mm/hr). The much lower hydraulic conductivity resulted in only slightly higher runoff volumes (Table 5-2) for the five-day and seven-hr duration events. (The hydrograph is also a little higher but very close to the I-LID hydrograph shown in Figure 5-8 and has not been plotted.) This reflects generally low rainfall intensities in western Oregon (typically less than 0.11 in./hr, but of long duration). Thus, an even lower infiltration rate would be necessary to reduce the effectiveness of the decentralized control option simulated. This decentralized control option is likely to be even more effective in climatological regions with rainfall (and runoff) intensities that are characteristically low in magnitude.

Portland has had a downspout disconnection program for this area (Adderley and Mandilag, 2000b). The disconnected flows are directed to dry wells. Although this program mostly affects rooftop runoff, its impact could be significant if implemented over a large area.

Infiltration is assumed to remove quality constituents as well, either through advection of dissolved constituents into the soil, or by sedimentation of particulates as water enters the soil. Hence, infiltration is effective in cleaning up *surface* water. There may be concern, however, at the impact of infiltration on groundwater.

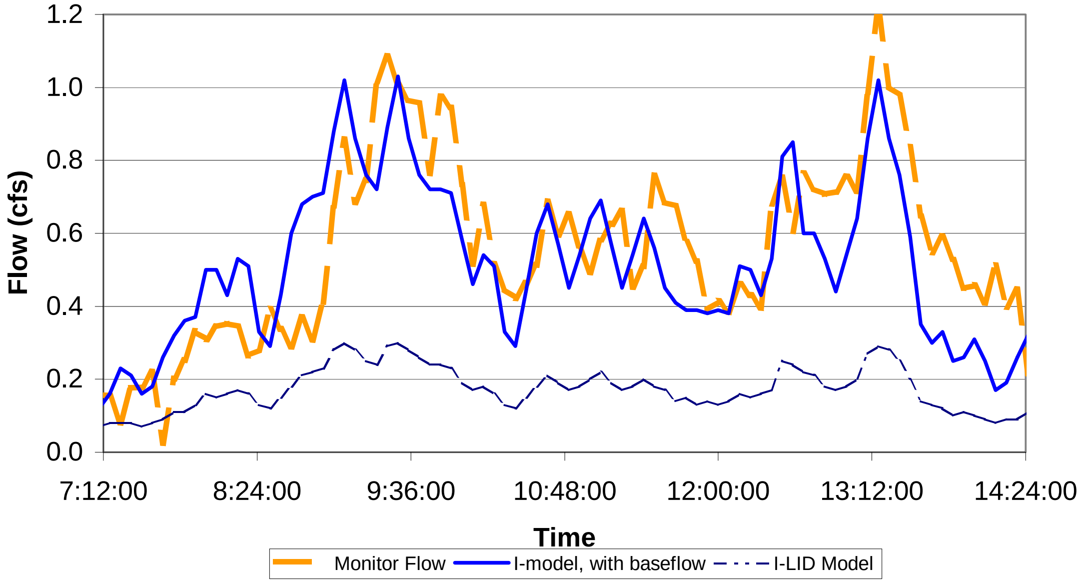


Figure 5-8. Comparison Between Model I and Model I-LID Simulations for a Seven-hour Interval, January 17, 1999.

5.2.2.3 Summary and Conclusions

SWMM has been applied to a 16.9 ac combined sewer catchment in the Sullivan Basin in northeast Portland, Oregon. With the aid of prior modeling work performed by the Portland Bureau of Environmental Services (BES), the SWMM Runoff and Extran Block simulation of the area compares well with monitoring data for a 118-subcatchment disaggregated simulation (I-Model) of every tax lot (house parcel). The simulations are uncalibrated and could easily be improved through additional effort, including a better definition of baseflow in the combined sewers. In addition, the disaggregated simulation of every individual house parcel compares well with an aggregated simulation that uses only 14 subcatchments to simulate all the parcels, pervious areas and street surfaces. This suggests that long-term modeling (i.e., continuous simulation, if performed) can conveniently be done with a less detailed model representation.

When a typical decentralized control option of routing non-directly connected impervious area runoff over pervious areas is simulated, the hypothetical SWMM Runoff Block output indicates an expected reduction in discharge. Although no hypothetical quality simulation was performed for this study area, quantity reductions by infiltration induce corresponding quality improvements (Huber, 2001a, b).

Key points of this section are:

- SWMM may be used to simulate decentralized control options that involve routing of runoff from non-directly connected impervious area (non-DCIA) over pervious areas, e.g., roof and driveway runoff over lawn surfaces;
- SWMM may also be used to direct surface runoff from one subcatchment over another;
- Simulation of an aggregated model representation (14 subcatchments) performed about as well as a disaggregated model representation (118 subcatchments) for the Portland, Oregon test area; and

- ♦ A hypothetical decentralized control option that infiltrates all roof and driveway runoff in the dense Portland study area is predicted to result in over a 50% reduction in runoff volumes and peak flows in the combined sewer system. Although a reduction would be expected, the modeling allows a better quantification of the potential results.

5.3 Spreadsheet Simulators for CSOs and Decentralized Controls

Process simulators such as SWMM 5.0 can model much of the complexities of decentralized controls and CSO systems. However, the number of parameters in the process simulation model can get unwieldy as one shifts from centralized downstream controls to decentralized upstream controls. Simulations of centralized controls require only a few subcatchments and one or two downstream controls. However, simulation of decentralized controls can require hundreds of subcatchments and controls.

A variety of spreadsheet techniques can be used to simulate the behavior of decentralized systems including CSSs. Wright and Heaney (2001) outline design procedures for decentralized stormwater systems. In the simplest situations, conventional design methods can be used for decentralized systems by simply varying input parameters that are typically accepted as fixed inputs. For example, the runoff coefficient is usually assumed to be constant in rainfall-runoff calculations. Implementation of decentralized control approaches can be represented as decreasing the runoff coefficient. Unfortunately, the net effect of a variety of decentralized controls is not easy to determine and convert into a single runoff coefficient.

The increased complexity in evaluating decentralized controls for CSSs comes from multiple sources including:

1. The presence of a large number of controls in a relatively small area;
2. The reliance on infiltration as an important control; and
3. The utilization of “soft” controls that attempt to mimic the natural hydrologic cycle.

Thus, within a single block in which decentralized controls were implemented, there may be well over 100 individual controls linked by vegetated waterways and complex infiltration patterns.

Geographic Information Systems (GIS) is a vital tool in order to capture the spatial complexity. Sample et al. (2001) describe how to set up a decision support system that incorporates GIS along with other modeling tools. Lee and Heaney (2003) show how detailed GIS coverage can be used for decentralized control analysis at the individual parcel level. Heaney and Lee (2005) have developed a suite of spreadsheet-based tools for simulating and optimizing wet-weather systems including CSSs. Sample and Heaney (2005) show how irrigation and stormwater infiltration can be integrated into a more cost-effective control program. This section will describe the results of other recent efforts to simulate these decentralized systems.

This section focuses on presenting a general method to analyze and optimize distributed urban stormwater quantity and quality control alternatives and sustainable urban land development strategies such as decentralized controls. Dynamic process simulation models that can evaluate the performance of distributed wet-weather control (WWC) alternatives and/or decentralized control options have been developed using spatial databases and long-term precipitation data. Two functional land development optimization models are presented for finding the combination of on-site functional land development options and/or off-site storage-treatment facilities that minimizes the total cost of providing the required level of wet-weather flow control.

5.3.1 General Description of Decentralized Controls

A conventional lot consists of about 20% impervious area and 80% grass area (Prince George's County 1999). In a conventional lot arrangement, most of impervious areas are directly connected to the storm drainage system and curb and gutter is the main runoff conveyance device to release excess stormwater as rapidly as possible out of the site. In decentralized control lot arrangement, some of grass area is replaced by woods and bioretention area to enhance on-site depression storage. Most impervious areas drain to adjacent pervious areas and a grass swale is the main flow conveyance device in the decentralized control arrangement. If necessary, a small-scale on-site detention area can be installed in the front or back yard of the lot.

5.3.2 Significance of Detailed Spatial Information

The performance of decentralized controls for both water quantity and quality controls is strongly dependent upon the site's arrangement and its hydrologic properties. A number of lumped analyses, such as land use based runoff coefficient applications, calibrated flow lengths and slopes for a limited number of subcatchments in a large drainage area, land use based seasonal or annual pollutant loadings, etc., have been applied to understand wet-weather flow responses basically using land use zoning maps. Those kinds of analyses have usually been used for traditional and/or centralized approaches such as flood control, regional retention pond design, and pollutant loadings for the entire city. However, they are not appropriate to analyze the process dynamics of urban runoff throughout the entire system because of their lumped spatial and hydrologic information. Urban surfaces can be modeled in a distributed manner using raster-based spatial data such as a digital elevation model (DEM), but this approach may not be applicable to urban hydrology because urban surfaces are much more complex than undeveloped natural areas. Surface properties may change significantly within a very short distance. High-resolution raster data that can reasonably represent complex urban surfaces are not available in most cases. Thus, vector data that are mostly available from local public agencies are appropriate for evaluating urban wet-weather flows.

The best way to resolve problems related to urban stormwater runoff is to control runoff as close to the source as possible (Dunne and Leopold, 1978; ASCE-WEF, 1992) using distributed patterns of WWC alternatives. These alternatives include minimizing DCIA, increasing flow paths or the time of concentration, and/or maximizing on-site depression storage at lot-level scale. These are the most important options in applying decentralized controls. Using conventional lumped spatial information, it is impossible to understand wet-weather flow response dynamics and to evaluate the physical performance of decentralized controls in a distributed manner. Detailed spatial information that can represent complex urban surfaces is critically important in order to analyze and optimize new approaches of WWCs using decentralized control strategies.

Shamsi (1996; 2002), Heaney et al. (1999b) and Sample et al. (2001) summarize GIS applications to urban stormwater problems. Sample et al. (2001) also describe the applicability of a parcel-level detail GIS database for urban stormwater management purposes. Functional spatial information that can represent complex urban surfaces is critically important for the analysis and optimization of urban stormwater management options, especially distributed decentralized control alternatives. It is necessary to develop a functional spatial database based on different stormwater response functions for a number of hydrologic functional sub-areas. For example, a residential lot can be divided into several hydrologic functional sub-areas such as rooftop, driveway, patio, grass, and woods as shown in Figure 5-9. Excess stormwater can be treated on-site mainly by depression storage (DS) and infiltration. Stormwater captured by DS is eventually removed by ET and infiltration.

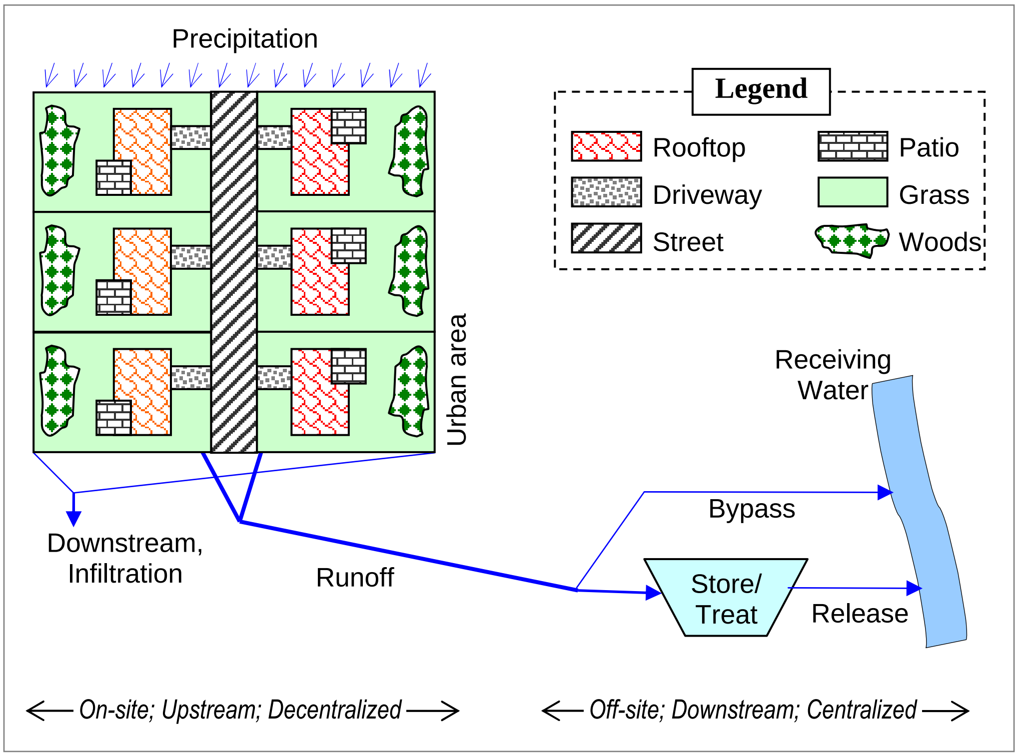


Figure 5-9. Functional Breakdowns for Urban Residential Area and On-site and Off-site Stormwater Control Devices.

Lee (2003) shows how a functional spatial database can be used to analyze wet-weather flow dynamics and control effectiveness. Modeling techniques and reliability of the modeling results can be improved using a functional spatial database. Lee and Heaney (2003) show potential errors and significance of applying spatial information in urban stormwater analysis. Performance of distributed WWCs and decentralized control scenarios can also be analyzed using a functional spatial database with reasonably high accuracy. Lee et al. (2003, 2005) present how to evaluate the overall performance of on-site upstream and/or off-site downstream stormwater controls using spreadsheet-based simulation/optimization models. These models integrate spreadsheet process simulators with spreadsheet optimization tools to find the least-cost optimal option for upstream and/or downstream controls.

5.3.3 Simulation/Optimization Framework

The traditional formulation for a constrained optimization problem is: max. or min. $Z = f(x)$; subject to $g(x) \leq, =, or \geq b$. The constraint set, $g(x) \leq = \geq b$, includes the process characterization relationships and performance criteria. If classical programming techniques are used, then the objective function and the constraint set must be well behaved in the mathematical sense, meaning that the relationships are linear, nonlinear but convex, etc. If the problem can be formulated as a coupled system, the optimization methods work quite well and the optimal solution can be found quickly. However, if the objective function and/or the constraint set violate the conditions for solving a classical optimization problem, then more flexible evolutionary solvers need to be used (Heaney and Lee, 2005). State-of-the-art meta-heuristic (MH) optimization techniques represent a substantial departure from traditional methods in how physical processes and optimization are considered. MH techniques allow for independent process simulation. This decoupled optimization procedure is fundamentally different from the traditional approach. The optimizer no longer constrains the nature of the functional relationships that are allowed in the process model. A key computational question is how to write an interface program that links the optimizer and the simulator. If the simulator is in a spreadsheet, then it is very simple to link the optimizer and no interface program is needed.

5.3.4 Optimization of Functional Land Development Strategies

5.3.4.1 Time-Area Concept Runoff Routing Model

A few process models are available to evaluate distributed wet-weather flow control (WWC) alternatives. If an optimization was based on an inaccurate process model and/or information, the results would not be reliable. To develop the entire hydrograph, Ross (1921) described the time-area (TA) method using isochrones, i.e., lines of equal travel time of a drainage area. The areas between adjacent isochrones are measured to create the time-area histogram, and the rainfall intensities within successive time increments are averaged. The Rational Method is then applied for each area and each time increment to develop the entire combined hydrograph. The time-area method has been applied to several models in analyzing urban hydrology – e.g., TRRL (Watkins 1962), ILLUDAS (Terstriep and Stall 1974), ILLUDAS-SA (Watson 1981), and ILSAX (O'Loughlin 1986).

The TA method does not account for storage and dispersion effects. As a result, hydrographs calculated by the TA method show higher peaks than those that consider storage. This is the main reason that TA related techniques are considered to be applicable only for small to mid-sized catchments (Stall and Terstriep, 1974; Ponce, 1989). Whether a catchment is small can be determined by its physical size and the relationship between time of concentration and rainfall duration. Ponce (1989) characterized a small catchment as follows:

- A catchment with a concentration time of 1 hour or less, or a catchment with an area of less than 2.5 km^2 (about 1 mi^2 or 640 acres);
- Storm duration (t_r) exceeds time of concentration (t_e): $t_r \geq t_e$;
- Rainfall can be assumed to be uniformly distributed in time and space;
- Runoff is primarily by overland flow; and
- Channel storage processes are negligible.

Storage and dispersion effects may occur more significantly within a channel rather than overland sheet flow. In order to model those effects, some flow routing models use a storage concept, such as level pool or linear reservoir routing technique, to perform flow simulation in channel or storm sewer systems along with the TA method for overland flow simulation. The Muskingum-Cunge method (Cunge, 1969), one of the most popular methods in channel or stream flow routing techniques, can also be applied to either catchment or channel flow routing to account for storage and dispersion effects.

A more critical limitation of the time-area method is the time stationary problem due to a unique time-invariant flow transfer function. This limitation originated from one of the fundamental assumptions in the original TA concept. The unit hydrograph (UH) method, which was originally developed based on the TA concept and a hypothetical linear reservoir routing to account for storage effects (Clark, 1945; ASCE-WEF, 1992), has been applied to distributed runoff routing models using a raster-based DEM (Maidment 1993; Muzik 1996; Kull and Feldman,1998; Olivera and Maidment, 1999). Those models, however, have the same time stationary problem and cannot account for time-variable rainfall intensity dynamics. Saghafian et al. (2002) present a runoff hydrograph simulation model based on the time variable isochrone technique. They describe it as a distributed model in space and time. It includes spatial and temporal variations of rainfall intensity and spatially variable catchment characteristics using raster-based GIS, mainly a DEM. A number of time-area histograms were derived based on excess rainfall intensities, and then applied separately to derive individual outflow hydrographs for each rainfall pulse. For derivation of the overall hydrograph, individual hydrographs are overlapped and integrated throughout time. This time variable isochrone technique alleviates a major constraint from the conventional TA method.

In applying the time-area method, the estimation of time of concentration or subcatchment flow travel time is the most critical procedure. In small catchments, overland flow can be assumed to be an outflow from a rectangular plane with averaged flow length, slope, and width. Travel time is a function of surface roughness, slope, overland flow length, and rainfall intensity. If high-resolution spatial and rainfall data are available, then travel time can be confidently estimated. Several empirical equations have been introduced to estimate travel time and/or time of concentration. The kinematic wave equation that was introduced by Morgali and Linsley (1965) has been widely used to estimate overland flow travel time (Aron and Erborge 1973; Chow et al., 1988; Muzik, 1996; Molnár and Julien, 2000). It can be obtained from the Saint-Venant equations and the Manning resistance equation (Woolhiser, 1977; Saghafian and Julien, 1995). It is applied to this study and can be expressed as follows (ASCE-WEF 1992):

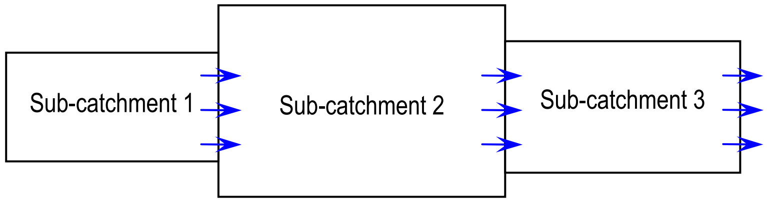
$$t_e = C_t \frac{L^{0.6} n^{0.6}}{i^{0.4} S_o^{0.3}} \qquad (5.1)$$

where t_e = time of concentration (min); C_t = unit constant (6.99 for SI units and 0.938 for U.S. customary units); L = overland flow length (m or ft); n = Manning's roughness coefficient; i = rainfall intensity (mm/hr or in/hr); and S_o = average overland slope.

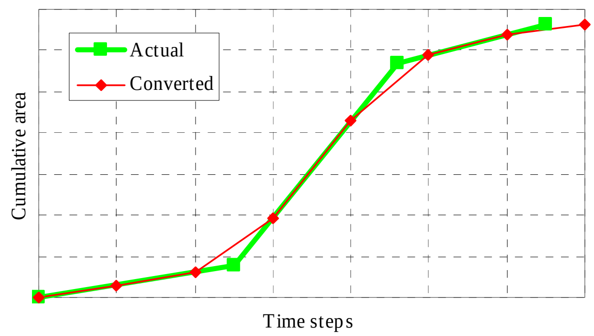
A time-area histogram can be developed using isochronal lines that are placed on a catchment map. Placing accurate isochronal lines is the most critical procedure in the conventional TA, but it is not an easy task. It can be performed more accurately and easily using GIS techniques, but most of the applications have been developed using raster-based data. In this study, a time-area histogram is developed based on a cumulative time-area relationship instead of using physical isochronal lines or distributed grids. Flow travel time for each sub-catchment is estimated by the kinematic wave equation. The start time of runoff contributing from a sub-catchment is estimated from the sequence of cascading planes. The start time is the sum of all travel times of the planes between the sub-catchment and the connected storm inlet. If the flow travel time of the sub-catchment is added to this start time, it becomes the end of runoff contributing time for the sub-catchment. Based on these start and end times of contributing runoff for cascading sub-catchments, a cumulative time-area diagram can be developed for the entire catchment. A time-area histogram for any isochronal time increments (Δt) can be derived from this cumulative TA diagram. This procedure is described in Figure 5-10 and a net runoff contributing area for each isochronal time step can be calculated as follows:

$$A_i = \sum_0^i A - \sum_0^{i-1} A \qquad (5.2)$$

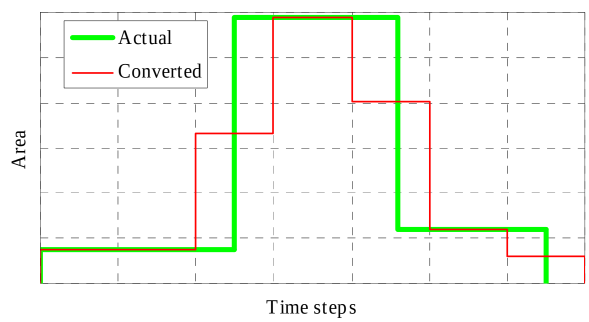
where A_i = net runoff contributing area for the time step i; and $\sum A$ = cumulative runoff contributing area.



(a) Cascading sub-catchments



(b) Cumulative time-area diagram



Actual: based on the actual time of concentration for each sub-catchment
Converted: converted for every time step
(c) Time-area histogram with equal time increments

Figure 5-10. Development of a Time-area Histogram Using Cascading Planes.

5.3.4.2 Optimization Model for Urban Land Development

Sample et al. (2001) presented a linear programming (LP) model to find the combination of functional land use options that minimizes the total cost of providing the required amount of roof, driveway, yard, and patio while satisfying the requirements for on-site depression storage at a residential lot. However, this model is not able to handle other hydrologic functions that can represent the performance of various distributed wet-weather flow control alternatives such as peak discharge, total runoff volume, and flow travel time or time of concentration. These criteria are important for designing urban stormwater management systems and need to be included in optimization models to represent process constraints more accurately.

To include them, a stormwater rainfall-runoff simulation needs to be performed within the optimization procedure.

Maximizing on-site stormwater management is the key concept of decentralized controls. Using a lumped simulation model and/or spatial information, it would be very difficult to evaluate their physical performance. An alternative optimization system is developed based on a lot-level functional spatial database and time-area concept flow routing techniques. Functional land development options can be evaluated using multiple constraints for rainfall-runoff parameters within distributed WWCs: depression storage, peak discharge, runoff volume, and time of concentration. Depression storage is modeled linearly, as in Sample et al. (2001). To estimate peak discharge, the Rational Method is applied with a new approach of estimating a runoff coefficient. It is based on depression storage and infiltration rate for each functional land use option as follows:

$$Q_p = C\, i\, A \tag{5.3}$$

$$C = \frac{\sum C_j A_j}{A} \tag{5.4}$$

$$C_j = \frac{(i - f_j)\, t_e - DS_j}{i\, t_e} \tag{5.5}$$

where Q_p = peak discharge [L^3T^{-1}]; C = area-weighted runoff coefficient; i = total rainfall intensity [L T^{-1}]; A = catchment area [L^2]; j = functional sub-areas; f = infiltration rate [L T^{-1}]; t_e = time of concentration [T]; and DS = depression storage [L]. (Note: DS = 0 in the worst-case scenario.)

The time-area method is able to develop the entire hydrograph and estimate the peak discharge and time of concentration. Travel time for each sub-area is estimated using a kinematic wave equation (ASCE-WEF, 1992) and area-weighted roughness coefficients as follows:

$$t_e = C_t \frac{L^{0.6} n^{0.6}}{i_e^{0.4} S_o^{0.3}} \tag{5.6}$$

$$n = \frac{\sum n_k A_k}{A} \tag{5.7}$$

where t_e = time of concentration (min); C_t = unit constant (6.99 for SI units and 0.938 for U.S. customary units); L = overland flow length (m or ft); n = Manning's roughness coefficient; i_e = excess rainfall intensity ($i_e = i - f$) (mm/hr or in/hr); S_o = average overland slope; and k = land use option for the functional sub-area.

Using the above process models, a distributed land development optimization model is organized as follows:

$$\text{Minimize } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} C_i^j A_i^j \tag{5.8}$$

$$\text{Subject to } \sum_{j=1}^{n} A_i^j = A_i \tag{5.9}$$

$$\sum DS_i^j A_i^j \geq S \tag{5.10}$$

$$Q_p^{estimated} \leq Q_p^{target} \tag{5.11}$$

$$t_e^{estimated} \geq t_e^{target} \tag{5.12}$$

where Z = total cost; i = functional sub-areas; j = functional land development options; C_i^j = unit cost of option j for sub-area i; A_i^j = area of option j for sub-area i; DS_i^j = depression storage of option j for sub-area i; S = required on-site depression storage; *estimated* = model estimated value; and *target* = design target value.

Two more process constraints are added to the existing model (Sample et al., 2001). Other design criteria can also be added to the above model. A reasonable value of target time of concentration needs to be arranged based on a general intensity-duration relationship as follows:

$$i = \frac{a}{t_r^b + c} \tag{5.13}$$

Solving equation (5.13) for t_r yields:

$$t_r = \left(\frac{a}{i} - c\right)^{1/b} \tag{5.14}$$

where i = design rainfall intensity; t_r = rainfall duration (min); a = constant varying with location and return period; and b and c = constants varying with location but independent of return period.

The framework of this optimization model for functional land development strategies is shown in Figure 5-11. It consists of functional land use information from spatial analysis, design storms from the intensity-duration-frequency (IDF) analysis, time-area concept flow routing, and cost estimation. It includes modeling depression storage, roughness coefficient (*C*), runoff coefficient (*n*), time-area method flow routing, intensity-duration relationship, resulting peak discharge, and time of concentration. Process characterization relationships and performance criteria throughout the optimization procedure are significantly improved compared to the existing LP model, which only considered initial depression storage (Sample et al., 2001). These modeling components can be assembled and integrated with optimization tools within a spreadsheet.

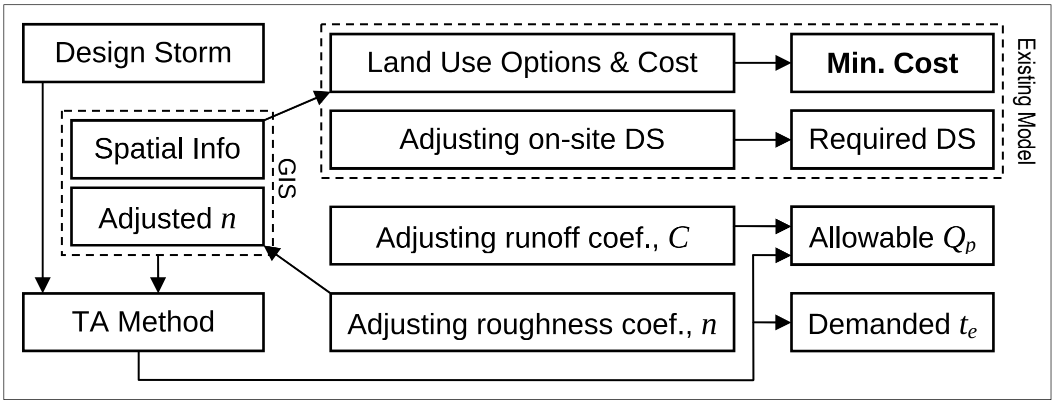
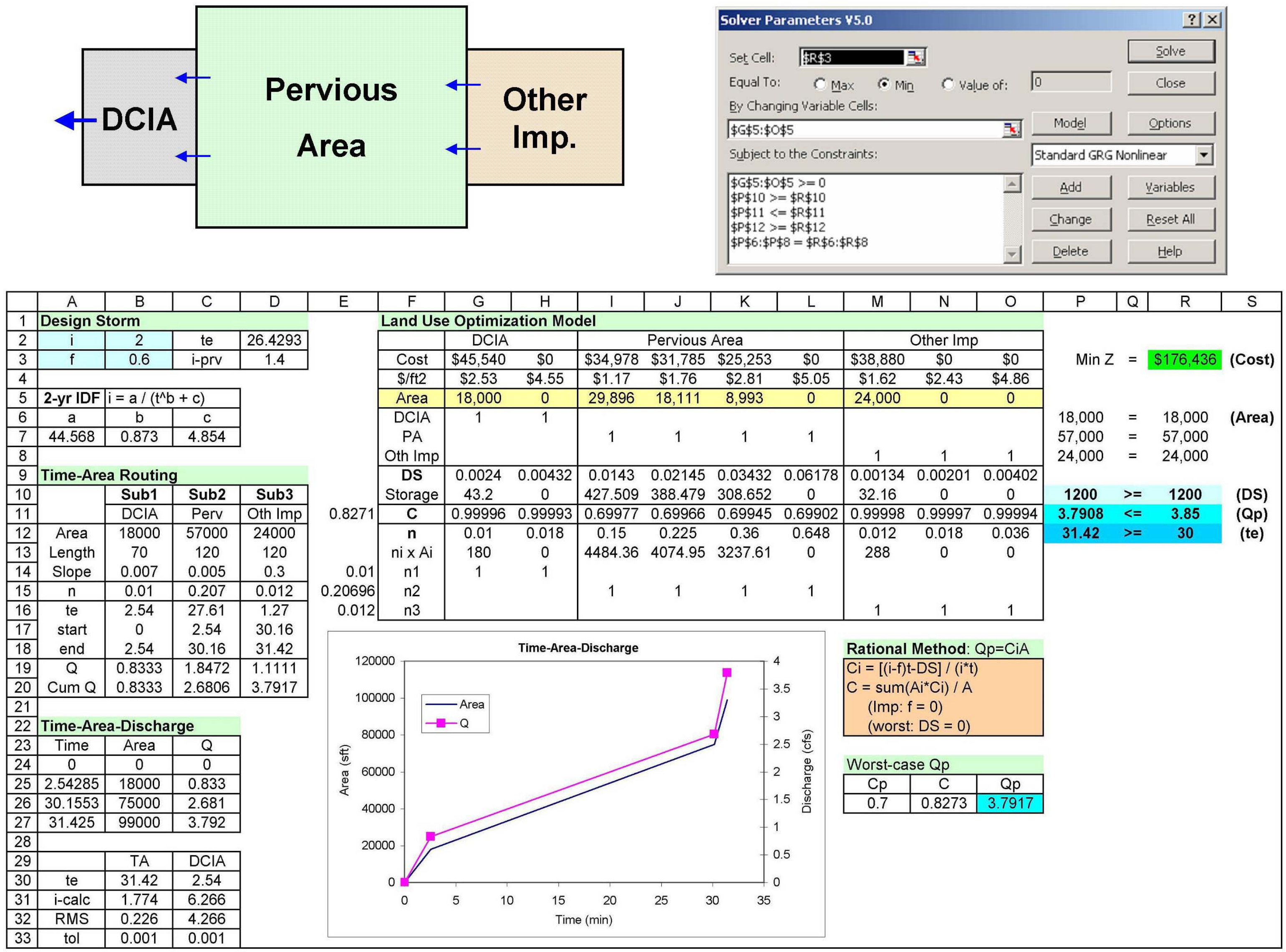


Figure 5-11. Optimization Framework for Functional Land Development Strategies.

An example of the developed spreadsheet optimization model is presented in Figure 5-12. This model was solved by the standard nonlinear programming generalized reduced gradient solver in Excel to find the most cost-effective solution. The existing simple land use optimization model is extended to include two more important process constraints: peak discharge and time of concentration for evaluating the performance of distributed stormwater management strategies.

As described in equations (5-3) through (5-5), the peak discharge can be estimated using an area-weighted runoff coefficient. In this model, the runoff coefficient is derived directly from the surface physical parameters: infiltration rate and depression storage of every functional sub-area. Depression storage can be assumed as zero to estimate the worst-case peak discharge. Time of concentration is estimated using the time-area concept process simulator (see the upper left part of Figure 5-12). Flow travel time for each sub-area is adjusted by different surface roughness options. An adjusted roughness coefficient for each sub-area is obtained directly from the functional land use simulation model through an area-weighted approach (see the upper right part of Figure 5-12). Time of concentration can also be changed by adjusting flow directions from one sub-area to other sub-areas. It is easily modeled using the time-area process simulator by adjusting outflow directions and/or bottom slopes. This kind of implementation for urban wet-weather flow control is one of the most important directions in the decentralized control concept for urban development. If necessary, the time-area simulator can create the entire hydrograph to evaluate a comprehensive performance, including the peak discharge, the total runoff volume, and detailed temporal responses. It can be done with reasonable effort and still in an explicit manner.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Design Storm					Land Use Optimization Model													
2	i	2	te	26.4293			DCIA			Pervious Area				Other Imp					
3	f	0.6	i-prv	1.4		Cost	$45,540	$0	$34,978	$31,785	$25,253	$0	$38,880	$0	$0	Min Z	=	$176,436	(Cost)
4						$/ft2	$2.53	$4.55	$1.17	$1.76	$2.81	$5.05	$1.62	$2.43	$4.86				
5	2-yr IDF	i = a / (t^b + c)				Area	18,000	0	29,896	18,111	8,993	0	24,000	0	0				
6	a	b	c			DCIA	1	1								18,000	=	18,000	(Area)
7	44.568	0.873	4.854			PA			1	1	1	1				57,000	=	57,000	
8						Oth Imp							1	1	1	24,000	=	24,000	
9	Time-Area Routing					DS	0.0024	0.00432	0.0143	0.02145	0.03432	0.06178	0.00134	0.00201	0.00402				
10		Sub1	Sub2	Sub3		Storage	43.2	0	427.509	388.479	308.652	0	32.16	0	0	1200	>=	1200	(DS)
11		DCIA	Perv	Oth Imp	0.8271	C	0.99996	0.99993	0.69977	0.69966	0.69945	0.69902	0.99998	0.99997	0.99994	3.7908	<=	3.85	(Qp)
12	Area	18000	57000	24000		n	0.01	0.018	0.15	0.225	0.36	0.648	0.012	0.018	0.036	31.42	>=	30	(te)
13	Length	70	120	120		ni x Ai	180	0	4484.36	4074.95	3237.61	0	288	0	0				
14	Slope	0.007	0.005	0.3	0.01	n1	1	1											
15	n	0.01	0.207	0.012	0.20696	n2			1	1	1	1							
16	te	2.54	27.61	1.27	0.012	n3							1	1	1				
17	start	0	2.54	30.16															
18	end	2.54	30.16	31.42															
19	Q	0.8333	1.8472	1.1111															
20	Cum Q	0.8333	2.6806	3.7917															
21																			
22	Time-Area-Discharge																		
23	Time	Area	Q																
24	0	0	0																
25	2.54285	18000	0.833																
26	30.1553	75000	2.681																
27	31.425	99000	3.792																
28																			
29		TA	DCIA																
30	te	31.42	2.54																
31	i-calc	1.774	6.266																
32	RMS	0.226	4.266																
33	tol	0.001	0.001																

Figure 5-12. Distributed Land Development Optimization Model Based on a Design Storm Approach.

5.3.5 Optimization of Integrated Urban Wet-weather Controls

5.3.5.1 Distributed Land Use Optimization Model

The effectiveness of distributed land use options for urban WWCs can be estimated using on-site depression storage. Depression storage (or initial abstraction), which must be filled prior to the occurrence of runoff, is caused by interception, surface wetting and ponding, and instant evaporation (Huber and Dickinson, 1988). Some of the precipitation will be stored in depressions during the wet period, and then the stored water will be depleted by ET during a subsequent dry period. An existing parcel-level land use optimization model based on on-site depression storage (Heaney et al., 1999; Sample et al., 2001) was extended in this study to incorporate the recovery of depression storage capacity using the estimated average monthly ET rate.

5.3.5.2 Continuous Stormwater Rainfall-runoff and Storage-release Simulation Model

Developing a physically sound process simulator is critically important for estimating the performance of WWC alternatives. Based on the Storage, Treatment, Overflow, Runoff Model (STORM) (Hydrologic Engineering Center, 1977), a continuous rainfall-runoff model was developed using spreadsheets. Urban stormwater quality control systems can be evaluated using the storage-release system shown in Figure 5-13. Stormwater flow may be captured and treated by a storage facility or bypassed after its storage capacity is reached.

Runoff occurs after satisfying available land surface depression storage and deducting infiltration loss. Released surface runoff flows to the storage facility up to its maximum capacity, and then is bypassed to the receiving water. Water in the storage facility is released at a fixed rate. Runoff, storage, release, bypassed stormwater, and capture rate are calculated using equations (5.15) to (5.19) respectively.

$$Rff^{j} = \min(0,\ Prcp^{j} - DS^{j} - f^{j}\Delta t) \tag{5.15}$$

$$S_{av}^{j} = \min(S_{max},\ \max(0,\ S_{av}^{j-1} - Q_{rls}t_{Dry}^{j}) + Rff^{j}) - Q_{rls} \tag{5.16}$$

$$Trt^{j} = \min(Rff^{j},\ S_{av}^{j}) \tag{5.17}$$

$$Bp^{j} = Rff^{j} - Trt^{j} \tag{5.18}$$

$$Cpt = \frac{\sum Trt}{\sum Rff} \tag{5.19}$$

where Rff = runoff depth during a time step [L]; $Prcp$ = precipitation pulse [L]; DS = available depression storage [L]; f = infiltration rate [LT^{-1}]; Δt = precipitation data time step size [T]; S_{av} = available storage [L]; S_{max} = maximum storage [L]; Q_{rls} = release rate [LT^{-1}]; t_{Dry} = dry period after the previous precipitation pulse [T]; Trt = treated stormwater [L]; Bp = bypassed stormwater [L]; Cpt = captured or treated rate; and j = temporal steps in simulation.

Stormwater volume is normalized as the equivalent depth over the entire catchment area. Pollutants will be removed in the storage facility through various physical, chemical and biological processes. Pollutant removal is simulated using a first-order plug-flow model as follows:

$$C_{out} = C_{in} e^{-k\,t_d} \tag{5.20}$$

$$t_d = \frac{S_{max} - S_{av}}{Q_{rls}} + 0.5\frac{Trt}{Q_{rls}} \tag{5.21}$$

$$M_{rv}^{\,j} = Trt^{\,j}\,(C_{in} - C_{out}) \tag{5.22}$$

where C_{out} = outflow concentration [ML^{-3}]; C_{in} = inflow concentration [ML^{-3}]; k = first-order reaction constant [T^{-1}]; t_d = hydraulic detention time for each plug [T]; and M_{rv} = pollutant mass removal normalized by catchment area [ML^{-2}].

Equation (5.20) could be adjusted for manipulating various types of pollutants and also including their background concentrations. Equation (5.21) shows how to calculate a hydraulic detention time for each plug: the release time of the existing stored stormwater before the current plug and the average release time of the current plug.

5.3.5.3 Cost Functions

Linear cost functions of distributed land use options, which are described by Sample et al. (2001), are adapted in this study. Power functions summarized by Heaney et al. (1999a) are applied to estimate the overall cost of storage-release systems. The cost analysis study on urban BMPs, presented by Sample et al. (2003), can be used to select a mathematical representation of cost function for several urban WWC alternatives (See Table 1).

5.3.5.4 Optimization Tools

The entire process simulation models were developed using spreadsheet functionalities in this study. A decoupled optimization procedure was designed using spatial and temporal process simulation models and spreadsheet-based optimization tools. An add-in to the basic Excel package called Premium Solver Platform (Frontline Systems, 2005) was used for this study. In addition to much more powerful linear and nonlinear programming software, it includes an evolutionary solver (ES) for cases where the problem cannot be solved using classical optimization techniques.

Table 5-3. Capital Cost Functions for Selected WWCs (Sample et al. 2003).

Item	Equation	Explanatory variable	Source
CMP drainage pipe	$C = 0.5262\ D^{1.3024}\ L$	D = diameter (cm) L = length (m)	Means (1996)
RCP pipe	$C = 0.1368\ D^{1.6259}\ L$	D = diameter (cm) L = length (m)	Means (1996)
Manholes	$C = 1458\ H^{0.9317}$	H = manhole height (m)	Means (1996)
Surface storage	$C = 1.515 \times 10^6\ V^{0.826}$	V = volume of storage (mL)	U.S. EPA (1993)
Deep tunnels	$C = 2.162 \times 10^6\ V^{0.795}$	V = volume of storage (mL)	U.S. EPA (1993)
Detention basins	$C = 2.195 \times 10^4\ V^{0.69}$	V = volume of storage (mL)	Young et al. (1995)
Retention basins	$C = 2.247 \times 10^4\ V^{0.75}$	V = volume of storage (mL)	Young et al. (1995)
Infiltration trenches	$C = 1482.864\ V^{0.63}$	V = volume of voids (m^3)	Young et al. (1995)
Infiltration basins	$C = 178.967\ V^{0.69}$	V = volume of basin (m^3)	Young et al. (1995)
Sand filters[a]	$C = K_1\ A$	A = impervious surface (ha)	ASCE (2001)
Grass swales[b]	$C = K_2\ L$	L = length of swale (m)	ASCE (2001)

[a]K_1 is a constant ranging from 27,700 to 53,300.

[b]K_2 is a constant ranging from 16.4 to 45.9.

Note: Costs in January 1999 dollars. Does not include cost of land acquisition. Significant figures are necessary due to metric conversion and do not imply the equivalent accuracy in the result.

5.3.5.5 Framework of Optimization Model

An integrated stormwater management optimization model has been developed using a functional land use simulator and a continuous stormwater process simulation model. The developed optimization model consists of two core system components: simulating functional land development options and modeling continuous rainfall-runoff and storage-release responses. Functional distributed land development options are evaluated using on-site depression storage. Long-term continuous rainfall-runoff and storage-release responses are simulated using one year of hourly precipitation data, on-site depression storages for each land use option, a fixed infiltration rate for pervious area, average monthly ET rates, an area-normalized catchment runoff model based on the STORM model, a fixed stormwater pollutant concentration or an event-mean pollutant concentration (EMC), and a first-order plug-flow pollutant treatment model. The functional land development evaluation model, based on a detailed spatial database, is able to represent spatial reality for a variety of distributed WWCs in lot level detail. The continuous stormwater rainfall-runoff and storage-release model simulates rainfall-runoff responses and evaluates overall pollutant removal performance as well as volume-based stormwater capture rate based on a long-term continuous simulation. In this case study, one year of precipitation data were applied to show how to perform long-term continuous simulation in spreadsheet environment. Thus, the developed spreadsheet model can be used to perform truly long-term continuous simulation with many years of precipitation records. The framework of the developed spreadsheet optimization model is presented in Figure 5-13.

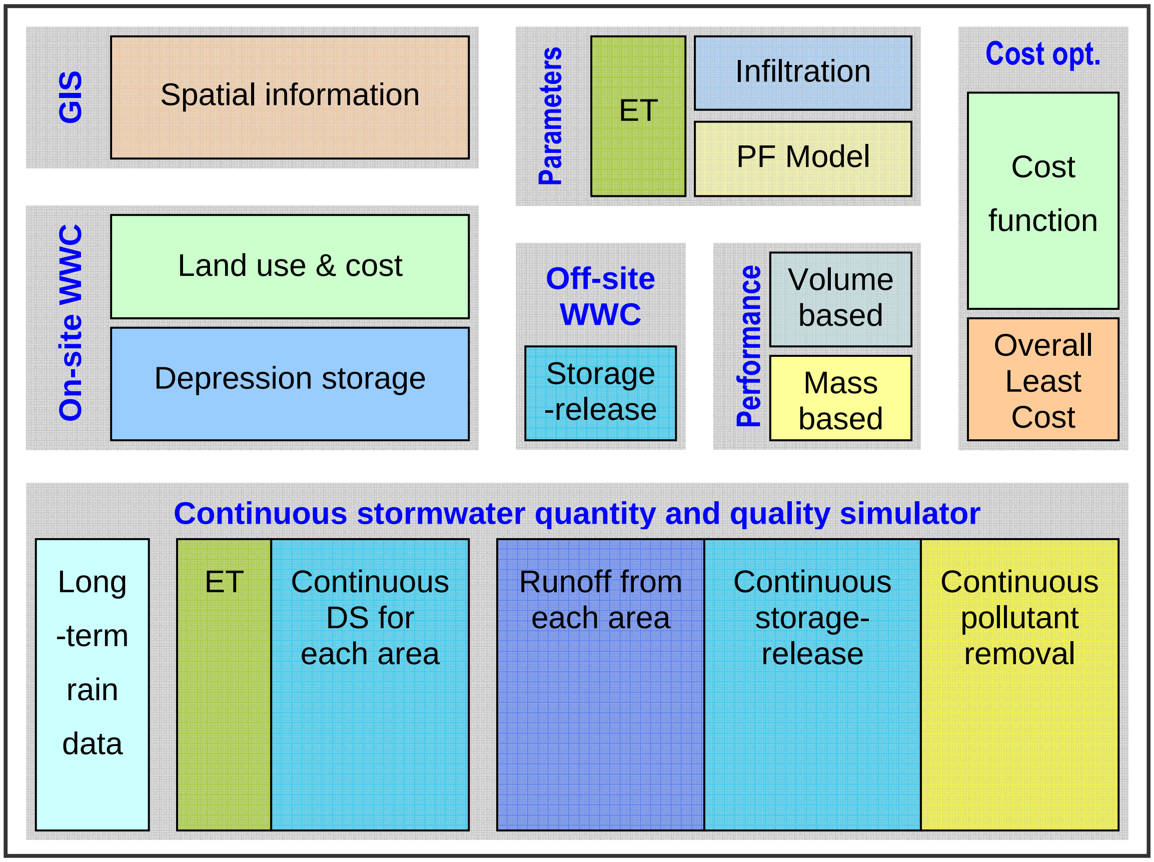


Figure 5-13. Spreadsheet Layout of Optimization Model for Integrated Urban WWC Strategies

5.3.5.6 Developed Optimization Model

This integrated optimization model with a functional land development simulator and a continuous stormwater rainfall-runoff and storage-release simulation model can be summarized as follows:

$$\text{Minimize } Z = f(Land) + f(Trt) \text{ (total cost)} \tag{5.23}$$

$$\text{Subject to } \sum_{k=1}^{n} A_i^k = A_i \text{ (each functional land use)} \tag{5.24}$$

$$\sum S_i^{onsite} \geq S_{target}^{onsite} \text{ (minimum on-site depression storage)} \tag{5.25}$$

$$Trt \geq Trt_{target} \text{ (minimum stormwater volume capture)} \tag{5.26}$$

$$P \geq P_{target} \text{ (minimum pollutant treatment)} \tag{5.27}$$

where Z = total cost; $f(Land)$ = cost function for land development options; $f(Trt)$ = cost function for storage-treatment systems; A = area of a functional land use segment; S_i^{onsite} = on-site storage; S_{target}^{onsite} = design target of on-site storage; Trt = volume-based treatment rate; Trt_{target} = volume-based target treatment rate; P = pollutant removal rate; P_{target} = target pollutant removal rate; k = land use options for each functional sub-areas; and i = functional spatial segments in land use simulation.

To estimate potential pollutant removal performance, the plug-flow model described in equations (5.20) through (5.22) is applied for each inflow pulse and the overall pollutant removal efficiency is estimated as follows:

$$P = \frac{\sum M_{rv}}{\sum M_{in}} \tag{5.28}$$

$$M_{in} = C_{in} Rff \tag{5.29}$$

where P = mass-based long-term pollutant removal rate; M_{rv} = pollutant mass removal normalized by catchment area [ML^{-2}]; M_{in} = pollutant mass inflow normalized by catchment area [ML^{-2}]; C_{in} = runoff inflow pollutant concentration [ML^{-3}]; and Rff = inflow runoff volume normalized by catchment area [L].

The spreadsheet optimization model is presented in Figure 5-14. It includes spatial representation of the conceptual rainfall-runoff and storage-release system (see the upper left part of Figure 5-14), the entire spreadsheet optimization model, and the spreadsheet optimization tool (see the upper right part of Figure 5-14). The spreadsheet optimization model simulates depression storage and infiltration, runoff from rainfall, an off-site storage-treatment-release system, and system performance based on both runoff volume capture and pollutant removal.

The model shown in Figure 5-14 describes an integrated optimization approach for estimating the overall performance of the off-site stormwater storage-release system and the distributed on-site WWCs implemented in lot-level detail functional sub-areas. Detailed spatial information shown in the upper left part of the spreadsheet in Figure 5-14 was obtained from a functional spatial database. It can represent a single residential lot or an urban catchment. Each functional sub-area within a catchment can be integrated for representing the entire catchment based on their stormwater response characteristics. Thus, a spatial database can be used as-is or in an integrated format after aggregating spatial elements based on each functional sub-area.

Using this functional spatial information, the performance of distributed land development options for urban WWCs can be evaluated. In this study, on-site depression storage was used for this evaluation, as shown in the upper left part of Figure 5-14. Monthly average ET rates are used to model the recovery of depression storage. Monitored ET data are presented in the upper center part of Figure 5-14. The long-term continuous stormwater process simulator is integrated with the land use model for simulating rainfall-runoff, storage-release, and pollutant removal phenomena throughout the entire stormwater management system (see the lower part of Figure 5-14).

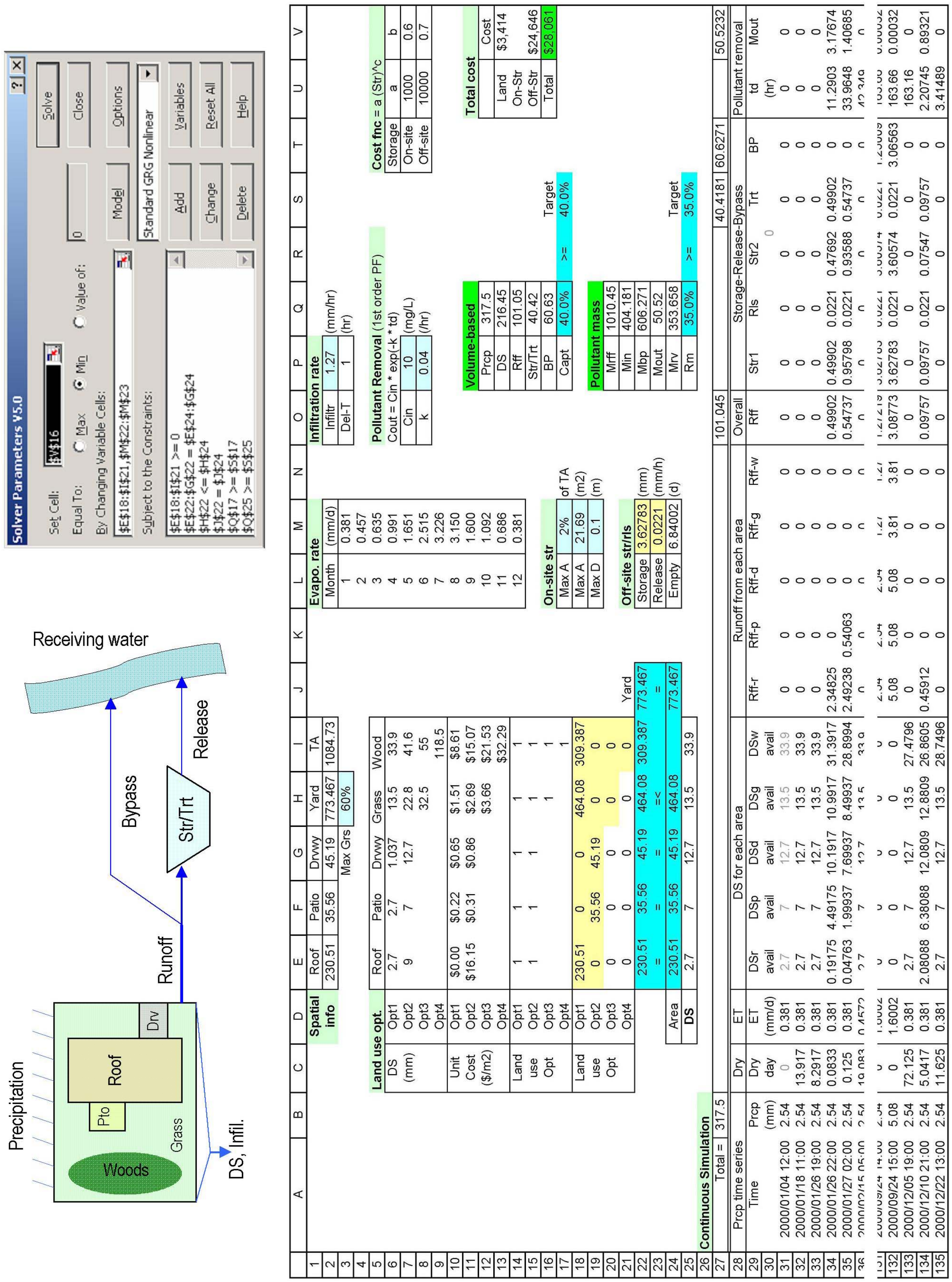


Figure 5-14. Integrated Optimization Model for On-site and Off-site Urban WWCs.

Fundamental modeling parameters for stormwater quantity and quality simulation, which are infiltration rate (f), long-term precipitation data time increment (Δt), runoff inflow pollutant concentration (C_{in}), and the first-order pollutant reaction constant (k), can be adjusted using appropriate available data (see the upper but slightly right part of Figure 5-14). The performance of the overall stormwater management facilities can be evaluated as an off-site storage system in this model. The long-term continuous storage-release model is shown in the right side of the continuous simulator and storage capacity and release rate is modeled in the upper middle part of Figure 5-14.

Two performance constraints for evaluating off-site stormwater storage facilities are installed in this model: volume capture rate and pollutant removal rate (see the right center part of the spreadsheet in Figure 5-14). On-site small detention storage can also be simulated with a recovery function implemented by evaporation and infiltration (see the center of Figure 5-14). Cost functions for on-site and off-site storage-release systems are added in the model (see the upper right part of Figure 5-14). Based on this cost function for the off-site storage-release system and the on-site distributed land development cost functions (see the upper right part of Figure 5-14), the overall least cost can be found. The least cost solution is shown in the upper right part of Figure 5-14. This decoupled optimization model in Figure 5-14 uses 15 decision variables and seven design constraints. The model could be solved by the standard NLP Solver but the solution depends on the initial guess. Premium Solver Platform has a multi-start option for NLP optimization that reduces the problem of local optima (Frontline Systems, 2005). Alternatively, the evolutionary solver (ES) can be used to find the cost-effective solution in most cases. The applied Solver parameters are shown in the upper right part of Figure 5-14.

5.3.6 Conclusions

The purpose of this section is to present simulation/optimization methods for finding cost-effective solutions to decentralized control options for CSO control. Micro-scale functional land development options for stormwater controls are jointly optimized with decentralized on-site and/or centralized downstream controls by linking the optimizers to developed simulation models. The developed optimization models can be used to determine the most cost-effective strategies at any range of performance for the combination of storage-release systems and/or distributed on-site WWC alternatives based on peak discharge, total runoff volume, and flow travel time or time of concentration. The models were developed using decision support systems that include functional spatial databases, a single storm or a continuous stormwater process simulation models, cost functions for distributed land use options and a storage-release system, and a spreadsheet optimization tool. The entire optimization procedure – process simulation and optimization – has been implemented in a spreadsheet environment so that it is understandable to the large group of professionals who use spreadsheets routinely.

Major advances in our ability to evaluate urban wet-weather flow systems have come about because of having high quality GIS and associated database information that allows us to evaluate and optimize a variety of decentralized control options. Data resolution, physical process models, and optimization approaches need to be matched with each other based on wet-weather flow response dynamics in space and time. The time-area concept modeling techniques with a functional spatial database showed excellent performance to evaluate distributed WWC alternatives. Accurate benefits of distributed WWCs need to be included in the conventional design procedures to obtain better performance and cost-effectiveness of stormwater management strategies.

5.4 Case Studies

The previous sections described simulation and optimization procedures that can help prioritize CSO controls. This section presents case studies of how various cities have implemented CSO controls over the years.

5.4.1 Boston

The CSO control program in Boston illustrates the variety of controls that cities have deployed to reduce overflows as shown in Table 5-4. The estimated cost of this program is $650 million.

Table 5-4. Massachusetts Water Resources Authority CSO Plan 1998-2008.

Period	CSO Control	Performance
1988-1992	Add CSO treatment facilities. Improve Deer Island Treatment Plant's ability to pump wet weather sewage flows.	A reduction of CSO volume by 55% (over 1988 levels). Treatment of 50% of remaining CSO flows.
1992-2000	Upgrade CSO treatment facilities. Further increase the Deer Island Treatment Plant's ability to achieve full planned pumping and treatment capacity.	A reduction of CSO volume by 70% (over 1988 levels). Treatment of 60% of remaining CSO flows.
2000-2008	Separate combined sewers in some areas. Increase hydraulic capacity of the system in certain areas. Screening/ disinfection/ dechlorination for Reserved Channel. Construct storage facilities. Upgrade CSO facilities to improve treatment performance. Close 36 of 84 CSOs. Eliminate CSO discharges to swimming and shellfishing areas.	Reduce CSO volumes by 88% of 1988 levels. Minimize untreated discharges. Treat 95% of remaining flow.

source: http://www.mwra.state.ma.us/03sewer/html/sewcso.htm

5.4.2 Portland

In 1991, the city of Portland was sued by the state of Oregon's Department of Environmental Quality (DEQ) for violating the Clean Water Act due to CSOs which occurred when combined stormwater and sanitary sewers would overflow during periods of wet weather, discharging untreated sewage into the Willamette River and Columbia Slough. As a result of this lawsuit, the City was mandated to take significant steps to reduce the frequency of CSOs by whatever means could be shown to be appropriate.

A major component of the CSO control plan is to construct two tunnels to handle discharges into the Willamette River, one for the east side and one for the west side. This section discusses how Portland's Bureau of Environmental Services (BES) constructed simulation models of the city to determine what tunnel size would be required to handle the Eastside CSOs, and also how they investigated the effectiveness of decentralized control measures to reduce the volume of stormwater entering the combined sewer system. Section 5.2 described how SWMM was used to evaluate the potential impact of disconnecting downspouts in Portland.

5.4.2.1 Model Development

To address this issue, BES created the CSO Sizing and Flow Management Pre-design (FMP) Project. The general purpose of this project was to determine the appropriate size of the Eastside CSO (ESCSO) tunnel. Additionally, they investigated how to create a cost-effective balance between the CSO tunnel sizing, stormwater separation projects, and decentralized controls. An example of a stormwater separation project is stream diversion, which is the removal of a natural stream from the combined sewer system.

BES developed and calibrated 19 different "explicit" models of the Willamette River basin CSO system for existing and projected future conditions. The projected future condition models were called "future-base" models. The explicit modeling approach used was a very detailed technique which simulates all of the features, such as pipes, manholes, and diversion structures which exist in the conveyance system as individual, or "explicit" objects. Additionally, pervious and impervious surface areas are defined as individual objects for each tax lot parcel. This provides a very detailed representation of the actual stormwater hydrology and impacts of various stormwater controls. Four different design storms were used as input into the various models. The XP-SWMM and DHI's MOUSE modeling programs were used by BES.

5.4.2.2 Tunnel Sizing

An effort was undertaken to identify the range of Eastside tunnel diameters which would be necessary to capture the water volume generated from different models which incorporated different system configurations and assumptions. Examples of factors examined were the separation from the sewer system of streams currently discharging into the combined sewer, onsite treatment of some highway runoff, and also future development assumptions. As can be seen in Table 5-5, taken from BES Technical Memorandum 3.8, the range of necessary tunnel diameters found from the modeling results was approximately 18-28 feet.

Table 5-5. Tunnel Diameter as Computed Based on Results from Various Modeling Assumption Scenarios (BES Technical Memorandum 3.8).

Model Configuration	Description	Tunnel Diameter
2011 CSO-only (existing zoning)	No separated stormwater enters the tunnels. Tanner A, Carolina Stream separation and Taggart D separation projects assumed constructed and discharged to the Willamette. New separation added in NW, and in fringe areas	18-ft
2011 CSO-only with NW industrial and Fringe Areas (existing zoning)	2011 CSO-only configuration plus all stormwater from 735 acres in NW Industrial area and 46 acres of fringe area.	19-ft
Current Design Configuration for eastside tunnel (existing zoning)	CSO plus 735 acres from NW Industrial area and 46 acres of fringe area plus water quality flows from Mill/Jefferson, Tanner A, and Taggart D.	20-ft
CSO-only (full Comp Plan future zoning)	Comparable to existing zoning 2011 CSO-only configuration (18-ft), but assumes future zoning	26-ft
Current Design Configuration for Eastside Tunnel (full Comp Plan future zoning)	Comparable to existing zoning 2011 CSO-only configuration (18-ft), but assumes future zoning	28-ft

Two CSO-only configurations were developed which assume that the Tanner stream separation, Carolina stream separation, and Taggart D separation projects are complete, and all separated stormwater flows are directed to the Willamette River. The two configurations differ only in that one is sized to handle only the Year 2011 existing condition CSO-only flows while the other is designed to handle future CSO-only flows.

The last two configurations analyzed include the combined sewer areas described above along with an additional 735 acres of NW Industrial Area, 46 acres of fringe area, and the water quality flows from major separation projects. The two configurations differ in that one is based on existing conditions and the other is based on the estimated future land use conditions.

A tunnel size sensitivity analysis was performed in order to observe the sensitivity of the Eastside CSO Tunnel diameter to system-wide increases in flow. The “2011 CSO with NW industrial and Fringe Areas (existing zoning)” configuration was the baseline. Table 5-6, taken from BES TM 3.8, summarizes the results of the analysis. One important conclusion is that a 5% increase in flows results in a 1-foot increase in Eastside CSO tunnel diameter.

Table 5-6. Tunnel Sizing Sensitivity Analysis Results (BES Technical Memorandum 3.8).

Sensitivity Configuration	Description	Tunnel Diameter	Increase in inflow to the Tunnels relative to 2011 CSO-only (existing zoning)
CSO Plus Policy Areas – This Configuration in comparable to the 19-ft. CSO plus 735 acres from the NW Industrial areas and the 46 acres of fringe area. The configuration does <u>not</u> include water quality flow from Mill/Jefferson, Tanner A, or Taggart D.	Existing Flows x 1.05	20-ft	12%
	Existing Flows x 1.10	22-ft	15%
	Existing Flows x 1.20	25-ft	27%

Figure 5-15 shows the relationship between Eastside Tunnel diameter and additional impervious area and model inflow. This figure combines the results of the five system configurations and the tunnel size sensitivity analysis. Assuming a linear relationship between tunnel diameter and impervious area acreage, the following conclusions can be made: A 3% increase in impervious area results in a 1-foot increase in Eastside CSO Tunnel diameter. A 5% increase in model inflow results in a 1-foot increase in Eastside CSO Tunnel diameter. Zoning changes from existing to the original future-base conditions result in an 8-foot increase in Eastside CSO tunnel diameter.

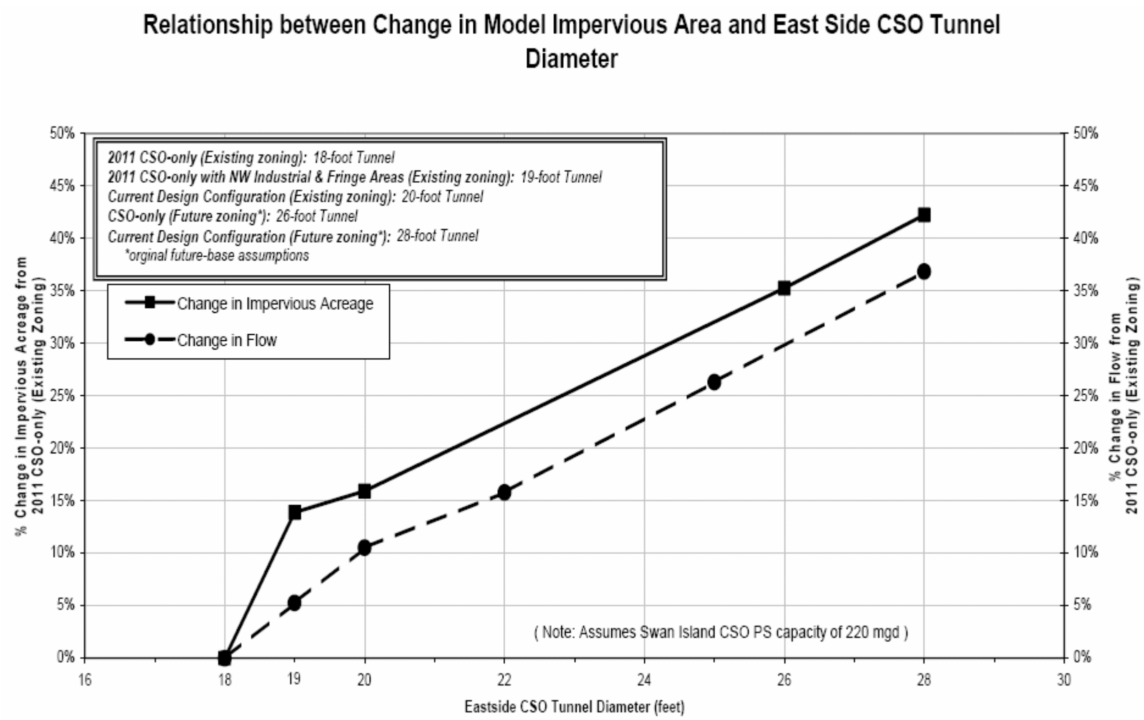


Figure 5-15. Summary of Tunnel Diameters Found from Different Model Configurations.

5.4.2.3 Modified Current Design Configuration (re-examining assumptions)

After the development of the future-base models, new data and information was discovered that resulted in revision of some of the original future-base modeling assumptions. One of these changes focused on definition of future-base impervious area. A decrease in effective impervious area between the original and the revised future-base assumptions was found, due to decreased growth predictions in certain industrial and residential areas. BES created a revised future-base model which incorporated these revised assumptions. This new model was named the Modified Current Design Configuration.

The original model, which was called the "Current Design Configuration," assumed that future roof and parking area of every tax lot in the Willamette River CSO area would eventually become developed to the maximum possible extent allowed by the 1999 City of Portland Comprehensive Plan (Comp Plan) zoning. This assumption was revised for the Modified Current Design Configuration as a result of data provided by the city of Portland Bureau of Planning. The revised assumptions limited the areas that were expected to be fully developed out to the impervious area allowed under Comp Plan zoning to certain areas deemed most likely to develop further, such as those near main arteries. This change in assumptions was estimated to have the largest impact on tax lots zoned Single Family Residential, since a large portion of these tax lots are currently not developed to the fullest extent allowed by existing zoning. Table 5-7 summarizes these current and future-base impervious area assumptions:

Table 5-7. Relative Change of Assumed Future-base Model Impervious Areas Between Different Model Assumptions (BES Technical Memorandum 3.8).

Basins	Original Future-base Assumptions	Revised Future-base Assumptions	% Change
Westside Basins			
Balch/Fredment/Nicola/TannerB	1411	1305	-8%
California	98	87	-11%
Carolina/Lowell/Sheridan/Woods	912	762	-16%
Central Business District (CBD)	145	135	-7%
Mill-Jefferson	392	246	-12%
Tanner A	455	384	-16%
Eastside Basins			
Alder	619	592	-4%
Division	93	88	-5%
Insley	764	504	-34%
Lents 1	45	41	-9%
Lents 2	693	345	-50%
Oak	335	305	-9%
Sellwood	121	69	-43%
Taggart A	455	300	-34%
Taggart B,C, & D	1217	1132	-20%
Northside Basins			
Beech-Essex	723	465	-36%
Holladay/Stark/Sullivan	2339	1755	-25%
Riverside	218	130	130%
Wheeler	415	281	-32%

The total revised future-base effective impervious area estimated for use in the Modified Current Design Configuration is a 22% increase from the total existing conditions effective impervious area. This is significantly less than the 56% increase predicted by the original Current Design Configuration future-base modeling assumptions. The new tunnel diameter estimates are shown in Table 5-8.

Table 5-8. Tunnel Diameters Determined Using the Modified Current Design Configuration Model (BES Technical Memorandum 3.8).

Model Configuration	Description	Tunnel Diameter
2011 CSO-only (existing zoning)	No separated stormwater enters the tunnels. Tanner A, Carolina Stream separation and Taggart D separation projects assumed constructed and discharged to the Willamette. New separation added in NW, and in fringe areas	18-ft
2011 CSO-only with NW industrial and Fringe Areas (existing zoning)	2011 CSO-only configuration plus all stormwater from 735 acres in NW Industrial area and 46 acres of fringe area.	19-ft
Modified Current Design Configuration for Eastside Tunnel (existing zoning)	CSO plus 735 acres from NW Industrial area and 46 acres of fringe area, the Beech-Essex OF44A Stormwater Separation, plus water quality flows from Mill/Jefferson	20-ft
Modified Current Design Configuration for Eastside Tunnel (revised future-base assumptions)	Comparable to existing zoning 2011 CSO-only configuration (18-ft), but assumes future zoning	23-ft

5.4.2.4 Eastside CSO Tunnel Size Selection Criteria

These simulation results indicated that the tunnel size necessary was about 23 feet. In order to assess the feasibility of building such a large tunnel, factors such as constructability and cost needed to be considered.

A group of BES staff and also design and construction consultants considered the issues involved with building a tunnel in the 20-24 foot diameter range. They determined that a tunnel diameter of about 24 feet was large enough to approach high constructability risk levels, as opposed to medium risk levels associated with smaller sizes.

As the diameter increases in this range, the tunnel segments become more expensive to build because they are too large to be built using hand labor, and more costly machines must instead be used. Furthermore, the cost to transport the segments also increases because trucks can only handle one part of a ring per load, rather than several rings per load.

To summarize, the conclusion reached was that there was no significant difference in the risk of constructing tunnel sizes in the range of 20-24 feet in diameter. However, the affordability of the tunnel becomes an essential factor, because the costs increase sharply as the tunnel diameter increases in this range.

Because every increase in tunnel diameter in this range is associated with a large increase in cost, options for reducing the size of the tunnel by controlling combined sewer inflows were investigated by BES. Methods of achieving this goal are discussed in the next section.

5.4.2.5 Stormwater Reduction Opportunities

Reducing the amount of stormwater which enters the combined sewer system, and the separation of natural streams from the combined sewer system, are two examples of ways in which the amount of sewer volume reaching the Willamette CSO tunnel system can be reduced. BES spent considerable time identifying opportunities for implementation of this type of stormwater reduction to the combined sewer system.

Projects were implemented to separate streams such as Tanner Creek and Carolina Stream from the combined sewer system. These streams contain natural uncontaminated water, and so therefore can be discharged directly into the Willamette River without detrimentally affecting its water quality.

In addition to such separation projects, several decentralized control options were examined by BES. These include projects such as downspout disconnection, inflow reduction projects, green roofs, and modifications to development requirements to reduce effective impervious area. A summary of these projects and programs is provided below, as taken from BES TM 3.8:

- **Expanded Eastside Downspout Disconnection**: This project expands the current Downspout Disconnection Program to target the Eastside homes zoned single-family residential (SFR) and duplexes zoned multi-family residential (MFR) that were not part of the original Program areas and those which have not yet been disconnected through BES' existing program.
- **Inflow reduction projects**: The Eastside Inflow Control Pre-design Project (CIP No. 6907) will identify a series of facilities to reduce and control stormwater from rooftops, parking lots, and streets within most combined sewer basins east of the Willamette River. Curb extensions, vegetated infiltration basins, and stormwater planters are example facilities that reduce inflow to the ESCSO Tunnel for storms at or below the three-year, 24-hour summer storm event.
- **Green Roof Legacy Project**: The objective of this project is to identify a targeted portion of the City and determine the extent to which property owners can be encouraged to construct ecoroofs on their buildings. This project is part of a larger effort undertaken by BES Sustainable Stormwater Program as part of the 2nd Annual International Green Roof Infrastructure Conference held in June 2004.
- **School and Church Disconnection Program**: The BES Planning Group is interested in expanding its current program to disconnect impervious areas at schools and churches throughout the east side of the Willamette River. A combination of downspout disconnection techniques and drywells for limited vegetated areas is proposed to remove this runoff.
- **Existing Impervious Area Reduction**: The BES Planning Group is interested in mitigating effective impervious area on existing property to reduce its runoff into the city's combined sewer system. One option posed is to reduce existing

impervious area by 5% for those commercial or industrial areas that apply to develop or redevelop their land.

5.4.2.6 Simulation Results and Conclusion

Many different simulations of those decentralized options were done by BES. The modeling results provided them with an estimate of the volume of water controlled for each modeling scheme. Estimated costs of implementing the schemes were also computed, and so the estimated cost per volume controlled could be determined. This cost per volume amount was used as the final criterion for deciding which schemes to implement. As it turned out, the majority of the most cost-effective solutions were the downspout disconnection options.

Furthermore, it was found that enough volume was mitigated by the downspout disconnection options so that if they were enacted, then a tunnel with about a 20-21 foot diameter would be sufficient to capture the required volume of water. Eventually, it was decided to construct a tunnel with an approximate diameter of 22 feet. This diameter is less than the value of 23 feet which was earlier deemed to be necessary, due to the inclusion of the decentralized control source control options. Essentially, decentralized control was shown to be a cost-effective method to reduce the tunnel size necessary to meet the mandated CSO control requirements. Additional details and updates on this case study are available at: http://www.portlandonline.com/cso/.

5.4.3 Seattle

Seattle and King County, Washington have had a long-term program to control its CSOs that began in the early 1960s as shown in Figure 5-16. A regional wastewater agency was formed in 1961. At that time, annual CSOs ranged from 20-30 billion gallons. The first significant improvement came as a result of constructing the South and West Treatment Plants in 1965. A combination of CSO controls, installed between 1968 and 1976, resulted in a major improvement, lowering the annual overflow volumes to 5-10 billion gallons. These major reductions were the result of installation of new interceptors, sewer separation, and real-time control of the flows through the collection, storage, and treatment system. These initial controls over a 15-year period reduced the annual CSOs by about 70% relative to their 1961 level. Between 1976 and 2005, another 15 projects were implemented. They included refinements of the control system, improved regulators, more storage, and additional sewer separation. These additional controls reduced the annual overflows to about 2 billion gallons per year, about 8% of their 1961 level. When completed, an estimated $600 million will have been spent to control CSOs in this area.

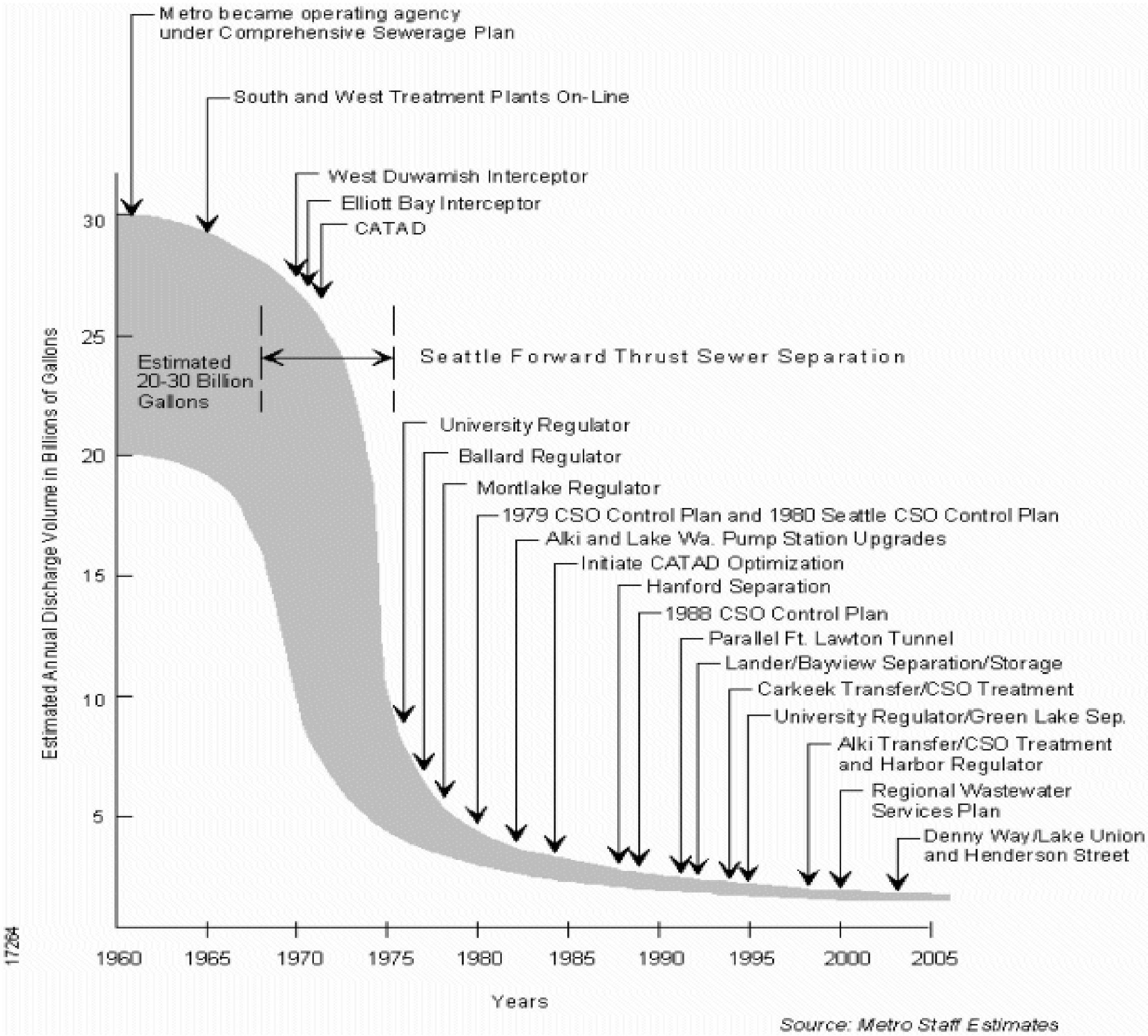


Figure 5-16. King County CSO Reduction Over Time (http://dnr.metrokc.gov/wtd/cso/page02graph.htm).

5.4.4 Upstream CSO Controls

While decentralized controls are a relatively new idea, source control of CSOs has been practiced for a number of years as described in the following sections.

5.4.4.1 Inflow Reduction Options

Inflows to combined sewers can be reduced in a number of ways as described by U.S. EPA (1999) and summarized below.

- Roof drain redirection;
- Basement sump pump redirection;
- Flow restriction and flow slipping;
- Stormwater infiltration sumps; and
- Stream diversion.

Each of these options is discussed in more detail in the following sections. Most of this information is taken from the U.S. EPA report (1999).

5.4.4.2 Roof Drain Redirection

Roof drains are disconnected from the sewer and the water is directed to pervious areas on the property such as lawns. In St. Paul, Minnesota, about 20% of CSO volume came from roof drains. As a result of a $40 rebate for voluntary redirection and other outreach efforts, roof drains were redirected in approximately 18,000 homes. Presently, 99% of all residential properties are disconnected. The general range of rebates in CSO cities has ranged from $40-$75 to homeowners and businesses participating in voluntary redirection programs to offset typical costs for redirection.

5.4.4.3 Basement Sump Pump Redirection

Sump pumps are used to remove excess water that would otherwise enter basements and other low-lying areas. They are typically connected directly to sewers. The outflow from these sump pumps can be redirected onto the local pervious areas as is done for roof drains. Some effort is required to locate houses that use sump pumps. South Portland, Maine, used a visual survey of 6,000 residential buildings and found 380 homes with roof drains and 300 homes with sump pumps discharging directly into the CSS. The city reimbursed each property owner $75 for each redirected roof gutter and $400 for each redirected sump pump. The program has redirected more than 379 roof drains and 304 basement sump pumps. The resulting reduction is approximately 58 million gallons of water per year. The city has not determined a direct correlation between these programs and CSO events; however, overall flow to the city's wastewater treatment plant has been reduced by 2% through these efforts. Typical costs for basement sump pump regulations are $300-$500 per home. Full rebates can be used to encourage homeowners to participate.

5.4.4.4 Flow Restriction and Flow Slipping

Flow restriction and flow slipping methods use roads and overland flow routes to temporarily store stormwater on the surface, or to convey stormwater away from the CSS. Flow restriction is accomplished by installing static flow or "braking" devices in catch basins to limit the rate at which surface runoff can enter the CSS. Excess storm flow is retained on the surface and enters the system at a controlled rate. The volume of on-street storage is governed by the capacity of the static flow device, or orifice, used for restriction, as well as surface drainage patterns. Flow slipping refers to the intentional blocking of stormwater from entering the CSS at catch basins for the purpose of routing, or "slipping", it elsewhere. Flow slipping is accomplished by partially or completely blocking the entry of surface runoff at catch basin inlets and letting the runoff follow overland flow routes.

In Skokie, Illinois, a fully developed suburb of Chicago served by a CSS that covers 8.6 square miles, an integrated program was developed that emphasized berms and flow restrictors to both increase on-street storage and to reduce the peak rate of flow entering the CSS. A total of 2,900 flow restricting devices were installed at catch basins, and 871 berms were constructed on streets. In addition, all of the roof drains previously connected to the CSS were disconnected.

South Portland, Maine, conducted a detailed evaluation of 750 catch basins within the CSS and determined that 30 catch basins could be eliminated without any adverse safety or flood damage consequences. Solid covers were placed on these catch basins to direct flow to separate storm sewers or natural drainage. Flow slipping in this manner has reduced flow in the CSS by approximately 12 million gallons per year.

Flow restricting orifice devices for catch basins cost $500-1,200 each. Detailed engineering studies to evaluate the collection system and catch basins require substantial in-house expertise or consultant assistance for modeling and related evaluations of effectiveness.

5.4.4.5 Stormwater Infiltration Sumps

Stormwater infiltration sumps are below-ground structures used to collect storm runoff and pass it into the soil. The infiltration sumps collect runoff in standard stormwater inlet structures at the ground surface and route it to a two-chambered system consisting of a manhole structure and an attached sump chamber. The manhole chamber serves as a sedimentation basin.

Infiltration sumps can be retrofitted within combined sewer areas, usually beneath the street system. In Portland, Oregon, much of the combined sewer area has highly permeable soils with a high hydraulic capacity. Portland has installed approximately 4,000 infiltration sumps. Combined with other CSO control programs, including a successful roof drain disconnection program, sewer separation, and stream diversion, it is predicted that the total CSO volume will be reduced by 3 billion gallons per year (approximately half of the total CSO volume).

Costs are closely related to the type of soil, the density of the sumps, and the desired amount of inflow reduction. Depending upon site specific conditions, total costs are expected to range from $2-8 per 1,000 gallons per year.

5.4.4.6 Stream Diversion

In early CSSs, many small streams were routed into pipes to facilitate development. Rerouting natural streams and surface runoff away from the CSS and back to their original watercourse or to other receiving waters can have a significant impact on CSS capacity. Portland, Oregon's Ramsey Lake Wetland Project involved completely separating an urban stream from the CSS, creating a wetland to treat the separated stormwater flow prior to discharge into a receiving stream. Portland has six additional stream diversion projects planned. Costs for the Ramsey Lake Wetland Project included $500,000 for purchasing the 29.75-acre wetland area; $2.6 million for wetland planning and construction costs; $10 million for sewer separation and $3 million for new storm sewer trunk lines; and $1.3 million for sump disconnection. This wetland drains 640 acres.

5.5 Summary and Conclusions

The purpose of this section is to describe how contemporary simulation and optimization software can be used to evaluate decentralized control options for CSO control. Evaluations of decentralized controls are more complex than the traditional centralized controls because there are a larger number of them and many decentralized controls rely on infiltration that is more complex to evaluate. The availability of GIS and associated databases makes it much more feasible to evaluate decentralized controls. While the more refined models described in this section can provide fairly accurate estimates of decentralized control performance, it is unlikely that these models will be used in routine evaluations. Rather, local regulatory agencies will still rely on the existing design event approaches that only calculate a required water quality capture volume and release rate. Even these simple methods can be improved to better incorporate decentralized controls by making several refinements including:

- Explicit recognition that directly connected impervious area contributes far more annual runoff than unconnected impervious area;
- Partitioning land uses into functional categories such as roofs, driveways, etc. instead of the more aggregate approaches such as low density residential; and
- Explicitly including event mean concentrations by functional land uses and estimating pollutant load and concentration reduction, not just volume controlled. For example, rooftops would not be expected to generate as much pollution as streets even though both are impervious areas.

CHAPTER 6.0

ANCILLARY BENEFITS

6.1 Introduction

The use of decentralized stormwater controls in urban areas introduces ancillary benefits into the community that extend beyond the stormwater management benefits. The two broad categories of ancillary benefits, discussed in Sections 6.2 and 6.3, respectively, are:

- environmental benefits not directly related to stormwater management; and
- community, educational, and economic benefits.

Many of the ancillary benefits described in this chapter stem from the fact that BMPs, especially vegetated BMPs, reintroduce natural processes and functions into highly urbanized environments. In other words, they serve as environmental amenities in areas where such amenities may be lacking. Benefits may include open spaces that are more hydrologically functional, aesthetically pleasing, and useful as habitat. As stormwater controls become integrated into communities, especially private properties, BMPs can become educational tools, facilitate awareness of the environment, and encourage stewardship. They also present opportunities for collaboration between the public and private sectors. Social benefits tied to the ecological characteristics of decentralized controls include community building, an enhanced sense of place, and job creation. Additional information on ancillary benefits can be found in Appendix C.

6.2 Ancillary Environmental Benefits

In addition to meeting the stormwater management objectives described in Section 2.2, there are secondary environmental benefits of decentralized stormwater practices as shown in Table 6-1. A BMP that uses vegetation and soil to reduce runoff volume, achieving its primary goal through detention and retention, may also reduce air pollution and air temperature (through evapotranspiration), helping to minimize the urban heat island effect while at the same time providing landscaped areas that serve as habitat.

Table 6-1. Environmental Benefits of BMPs.

BMP	Water Conservation	Heat Island Reduction	Energy Conservation	Air Pollution Reduction	Habitat
Downspout Disconnection	✓				
Filter Strips		✓			
Infiltration Practices					
Pocket Wetland		✓	✓	✓	✓
Porous Pavement					
Rain Barrels/Cisterns	✓				
Rain Gardens	✓	✓	✓	✓	✓
Soil Amendments					
Tree Box Filters		✓		✓	✓
Vegetated Roofs		✓	✓	✓	✓
Vegetated Swales		✓		✓	✓

BMPs were indicated as providing an environmental benefit when available research showed a direct contribution to the identified ancillary benefit.

6.2.1 Definition of Categories

6.2.1.1 Water Conservation

Water conservation has been divided into two categories. One is potential use by other processes, such as non-potable water use, and the other is reduction of irrigation.

Downspout disconnections and rain barrels/cisterns are designed to direct and store rainwater to irrigate the landscape, thus reducing the need to use potable water. Rain gardens detain and retain stormwater, are planted with native or site-appropriate plantings that tolerate extended drought and saturated soils (for 24 hours), and do not require additional irrigation.

6.2.1.2 Heat Island Effect Reduction

The urban heat island effect is the warming of cities resulting from the lack of natural vegetation and soil moisture. Evapotranspiration (ET) naturally cools the surrounding air because evaporation absorbs heat. As a result of the preponderance of impervious surfaces in urban areas, heat tends to be absorbed and retained in roofs and paved surfaces rather than be dissipated through ET. Research by the U.S. EPA indicates that urban areas are approximately 2-10ºF hotter than surrounding suburban and rural areas.[1]

The vegetated BMPs in this technical review contribute to lowering ambient air temperatures by promoting ET and also by reducing absorption of heat into the ground surface. The vegetation in rain gardens, tree box filters, vegetated swales, and vegetated roofs cools the air through ET and provides opportunities to infiltrate stormwater into the soils and re-establish the urban tree canopy. Light colored, reflective porous paving reduces the thermal heat index by decreasing the absorption of solar radiation.

The heat island effect has numerous impacts on urban areas including elevated temperatures that put residents at risk of heat stroke and death according to the National Aeronautics and Space Administration. If enough decentralized BMPs are used, they potentially reduce the severity of the problems.

[1] United States Environmental Protection Agency, 2003.
http://yosemite.epa.gov/oar/globalwarming.nsf/content/ActionsLocalHeatIslandEffect.html

6.2.1.3 Energy Conservation

There is a direct correlation between the urban heat island effect and energy costs and electrical demand. Energy requirements are reduced as urban temperatures are decreased and stabilized by vegetated roofs, porous paving, increased infiltration, and increased shade from trees and vegetation. Vegetated roofs are found to reduce energy costs by 20-30%. Roofs constructed with lightly colored, reflective materials use 40% less energy for cooling. Strategically placed shade trees can reduce heating and cooling costs by 10-20%[2].

6.2.1.4 Air Pollution Reduction

Air pollution is also associated with the heat island effect because pollutant levels, specifically concentrations of ground level ozone (smog), increase with ambient temperature. Elevated temperatures also increase energy consumption, which results in heightened pollution levels and energy costs resulting from the burning of fossil fuels. The installation of vegetated BMPs such as vegetated roofs and rain gardens not only reduce urban temperatures but also absorb carbon dioxide, filter air, and capture airborne particles.

6.2.1.5 Habitat

In the urban environment, habitat corridors are typically sparse and fragmented; thus, it is necessary to maximize the habitat potential of open space, conservation areas, rights-of-way, and transportation easements and reconnect them when possible. In the urban setting, many landscaped areas are covered with turf grass and provide meager habitat for wildlife. However, vegetated BMPs such as rain gardens encourage native flora and fauna to repopulate urban areas. Numerous land uses commonly found in urban communities are prime locations for large- and small-scale BMPs. These sites, such as large linear rights-of-way, small linear strips, unused intermediate easements, and open space, can be used both for stormwater management and to create a green network that provides habitat functions.

6.3 Ancillary Community, Educational, and Economic Benefits

Decentralized stormwater controls also have community, cultural, educational, and economic benefits in addition to the hydrologic and secondary environmental benefits discussed previously. Rain gardens, for example, significantly meet water quality and water quantity objectives, assist in mitigating extreme urban temperatures, are planted with water-conserving plants, and as Table 6-2 shows, beautify the physical environment, facilitate opportunities for education and outreach, and increase property values.

[2] Lawrence Berkeley National Laboratory - Heat Island Group http://eetd.lbl.gov/HeatIsland/

Table 6-2. Community, Education, and Economic Benefits of BMPs.

BMP	Beautification	Environmental Stewardship and Education	Public / Private Collaboration	Increased Property Values
Downspout Disconnection		✓	✓	✓
Filter Strips				
Infiltration Practices				
Pocket Wetland	✓	✓	✓	
Porous Pavement	✓			
Rain Barrels/Cisterns		✓	✓	
Rain Gardens	✓	✓	✓	✓
Soil Amendments	✓	✓	✓	✓
Tree Box Filters	✓	✓		
Vegetated Roofs	✓	✓	✓	✓
Vegetated Swales	✓			

BMPs were indicated as contributing to community, education, or economic benefits based upon the reasonable expectation of enhancing the benefit. Typically, the landscaped BMPs have demonstrated a direct link to the enrichment of communities and an increase in property values.

6.3.1 Definition of Categories

6.3.1.1 Beautification

Decentralized stormwater controls enhance the quality of life in urban areas by increasing the amount of vegetation and green space throughout the community. The BMPs alter the expanse of concrete and buildings by softening the surroundings with landscaped areas and networks of stormwater collection devices that double as gardens. Close proximity to natural spaces, such as rain gardens that resemble perennial cutting gardens, can attract birds and butterflies, improve the physical environment, provide places for gathering and recreation, create a unique sense of place, and enrich the lives of residents.

6.3.1.2 Environmental Stewardship

Rain gardens, vegetated swales, and vegetated roofs provide unique venues in which to educate the public about their immediate environment, the multiple benefits of the stormwater controls, and a wide range of environmental issues, including their watershed. The BMPs also provide "ownership" opportunities as citizens become stewards of their physical environment, and ensure the attractiveness and effectiveness of the BMPs.

6.3.1.3 Public/Private Collaboration

As discussed in Section 2.4, urban BMPs may be constructed in areas outside of what is normally considered to be publicly maintained stormwater infrastructure (for example, the roof or yard of a private residence). In other words, while BMPs provide a public good (i.e., the benefits discussed in this chapter and in Chapter 2.0), they may be located on private property. Distributed stormwater controls therefore provide opportunities for collaboration between the public and private sectors in terms of design, construction, monitoring, and maintenance. Community-based organizations that may assume partial or full responsibility for these tasks include:

- "green collar" programs that provide education, job training, and employment;
- existing neighborhood garden clubs;

- small for-profit landscaping businesses;
- volunteer organizations; and
- business improvement groups.

Additionally, numerous opportunities exist for funding the installation of the BMPs described in this technical review, such as federal grants for “sustainable” construction. The localized nature of decentralized controls and the multiple community benefits they provide create opportunities for non-profit organizations and community volunteer groups to collectively coordinate and secure funding from businesses that have economic investment in the community.

6.3.1.4 Increased Property Values

Developers are beginning to recognize that landscaped spaces with mature trees and native vegetation are highly desirable, especially in the urban environment. Properties adjacent to parks and conservation easements typically have higher real estate values. Landscaped areas intertwined and networked throughout communities increase lot and community marketability. The installation of BMPs such as rain gardens and vegetated roofs provides a significant benefit to the “green infrastructure” of the community.

APPENDIX A

LITERATURE CATALOG

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APPENDIX B

DESCRIPTION OF BEST MANAGEMENT PRACTICES

Decentralized BMPs appropriate for use in urban environments and for CSO management and the criteria used for their selection are described in Chapter 2.0. This appendix provides more detailed information on the selected BMPs. Details provided for each BMP include a definition, design variations, and a description of how stormwater management objectives are addressed. This information is provided in support of the tabular data in Chapter 2.0.

B.1 Downspout Disconnection

B.1.1 Definition

In urban areas, downspouts are commonly connected to drain tiles that feed the sewer system, and the cumulative effect of thousands of connected downspouts can greatly increase the annual number, magnitude, and duration of CSO events. Downspout disconnection is the process of separating roof downspouts from the sewer system and redirecting roof runoff onto pervious surfaces, most commonly a lawn. This reduces the amount of directly connected impervious area (DCIA) in a drainage area.

B.1.2 Design Variations

Ideally, a downspout disconnection plan will work with the existing downspouts on a building. In some cases, however, downspouts can be relocated if the new position would drain to a more appropriate receiving area (e.g., a hedge). Re-pitching the gutters in order to direct the flow to another corner of the roof is another option. For buildings with internal drainage, disconnecting internal downspouts may be difficult or impractical. Other BMPs such as cisterns or vegetated roofs may be more appropriate in such a case.

For disconnection to be safe and effective, each downspout must discharge into a suitable receiving area. Runoff must not flow toward building foundations or onto adjacent property. Typical receiving areas for disconnected roof runoff include lawns, gardens, and other existing landscaping such as shrubs. Soil amendments can be used to increase soil permeability if necessary. However, site constraints such as small or non-existent lawns may dictate that runoff be directed into a rain garden or, most commonly, an infiltration practice (see Section B.4).

B.1.3 Stormwater Management Objectives

B.1.3.1 Volume

Volume reductions occur through infiltration and evapotranspiration in the receiving area. The potential exists for disconnected roof runoff to be completely taken “out of the system” by spreading out and infiltrating over pervious surfaces and BMPs. Stormwater that eventually flows onto an impervious surface and then into the sewer will at least be initially detained by flowing over rough, pervious surfaces such as grass.

B.1.3.2 Peak Discharge

Downspout disconnection decreases the peak discharge by reducing the volume of roof runoff that enters the sewer and by increasing the discharge time over which it enters. Also, roofs are inherently distributed over a drainage area. Connected downspouts concentrate and centralize roof runoff, causing peak discharges from individual roofs to accumulate in a relatively small number of manmade conveyances. By contrast, downspout disconnection helps to keep separate the peak discharge from each individual roof.

B.1.3.3 Water Quality

Roof runoff contains deposited atmospheric pollutants, particles of roofing material, and nutrients and BOD loading from bird droppings. The concentrations of these pollutants will be reduced as the stormwater infiltrates and is taken up into plant roots. Also, receiving water quality will improve because CSOs will occur less frequently and with less magnitude as a result of the water quantity benefits of downspout disconnection.

B.1.4 Images

Downspout Disconnection into Vegetated Area
Source: LID Center

Downspout Disconnection into Vegetated Area
Source: PGDER

B.1.5 References

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B.2 Filter Strips

B.2.1 Definition

Filter strips are bands of dense, permanent vegetation with a uniform slope, primarily designed to provide water quality pretreatment between a runoff source (i.e., impervious area) and another BMP. Filter strips are important components of a BMP treatment train.

B.2.2 Design Variations

A filter strip may be constructed with or without a permeable berm at the downstream end. The maximum berm height is one (1) foot and may be used to contain the water quality volume (WQ_v). Because it increases the contact time with runoff, a berm will reduce the required filter strip width.

B.2.3 Stormwater Management Objectives

B.2.3.1 Volume

Filter strips can significantly reduce the volume of runoff from small, frequently-occurring storms if:

- the soils are sufficiently pervious;
- sheet flow is maintained through the entire length and width of the strip; and
- contact time is long enough for infiltration to occur.

Infiltration and evapotranspiration are the means by which water is retained. A berm can be used to lengthen the contact time and increase the retention volume, and soil amendments can be used to enhance permeability if the existing soils are compacted.

B.2.3.2 Peak Discharge

Filter strips decrease the peak discharge by reducing the volume of runoff through ponding and infiltration and by reducing the velocity because of surface roughness.

B.2.3.3 Water Quality

As a general guideline, a filter strip can be expected to reduce TSS concentrations by 50%, total Phosphorus by 20%, total Nitrogen by 20%, and heavy metals by 40%. Essentially, filter strips are designed to fill with sediment. Filter strips achieve water quality improvements through infiltration and vegetative filtering and their effectiveness increases with runoff contact time and density of vegetation.

B.2.4 Images

Filter Strip and Grassed Swale.
Source: LID Center

B.2.5 References

Atlanta Regional Commission, *Georgia Stormwater Management Manual – Volume 2: Technical Handbook*, AMEC Earth and Environmental, Center for Watershed Protection, Debo and Associates, Jordan Jones and Goulding, Atlanta Regional Commission, Atlanta, GA (2001).

B.3 Infiltration Practices

B.3.1 Definition

Designs that enhance water percolation through a media matrix that slows and partially holds stormwater runoff and facilitates pollutant removal.

B.3.2 Design Variations

B.3.2.1 Infiltration Trench

Infiltration trenches are stone-filled excavated trenches that allow stormwater runoff to infiltrate into surrounding soils through the bottom and sides of the trench. Captured stormwater generally exfiltrates to surrounding soils within 48 hours and serves to recharge groundwater. Designs must include filter strips or other filtering mechanisms to prevent sediment from reaching and clogging the trench.

B.3.2.2 Dry Well

Dry wells typically are gravel or stone aggregate-filled pits located to catch stormwater from roof downspouts or paved areas. Most often used to treat stormwater from small impervious surfaces, dry wells act as an alternative to infiltration trenches and can be used on steep slopes where other infiltration practices are not as well suited. Dry wells should not be installed in areas of high sediment loading.

B.3.3 Stormwater Management Objectives

B.3.3.1 Volume

Diverting runoff to the soil and encouraging infiltration has the ability to largely control volume from small storm events and reduce the overall volume of larger events. Infiltration retention volumes are typically equal to the first flush stormwater volume. The captured volume serves to recharge groundwater and help to maintain regional baseflows.

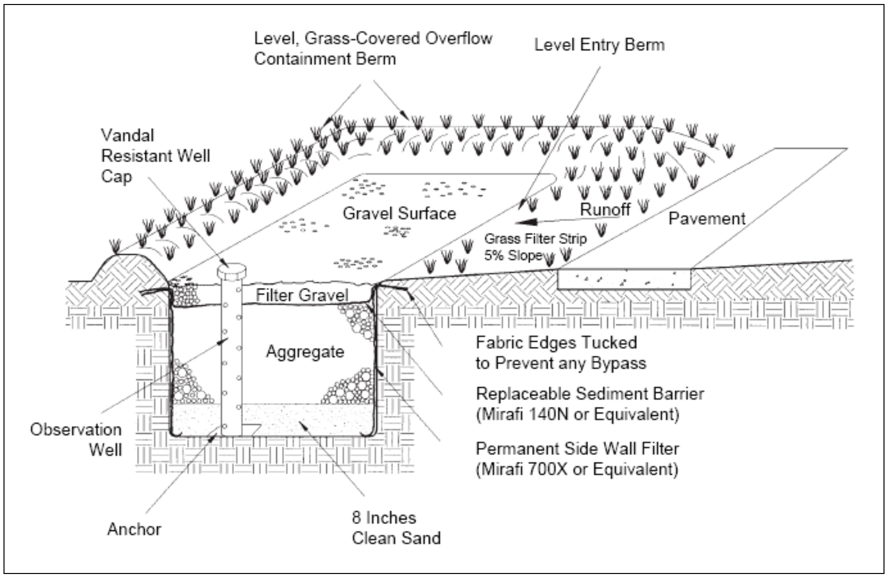
B.3.3.2 Peak Discharge

Infiltration practices have a small effect on peak discharge. Dependent upon the storage volume of the infiltration area and the porosity of surrounding soils, discharge stormwater flow rates will be modestly diminished with the use of infiltration techniques.

B.3.3.3 Water Quality

The filtering properties of the media and surrounding soils allow infiltration techniques to improve water quality. A wide suite of pollutants may be removed by various mechanisms: sorption, precipitation, filtering, and bacterial and chemical degradation. Estimated pollutant removals are 60% for nitrogen and phosphorus, 80 percent for TSS, and 90 percent for metals and pathogens.

B.3.4 Images



Infiltration Trench Schematic
Source: Northern Virginia BMP Handbook

B.3.5 References

Atlanta Regional Commission, *Georgia Stormwater Management Manual – Volume 2: Technical Handbook*, AMEC Earth and Environmental, Center for Watershed Protection, Debo and Associates, Jordan Jones and Goulding, Atlanta Regional Commission, Atlanta, GA (2001).

B.4 Pocket Wetlands

B.4.1 Definition

Pocket wetlands are constructed shallow marsh systems designed and placed to control stormwater volume and facilitate pollutant removal. As engineered constructed facilities, pocket wetlands have less biodiversity than natural wetlands but still require a base flow to support the aquatic vegetation present. Pollutant removal in these systems occurs through the settling of larger solids and course organic material and also by uptake in the aquatic vegetation. Pocket wetlands are designed with three distinct zones: a forebay immediately after the inlet to receive stormwater, the wetland area, and a micropool immediately prior to the outfall. The forebay and micropool allow for sediment control.

B.4.2 Design Variations

Several design variations exist for stormwater wetland systems, with the differences occurring in the amount of storage volume provided, pond depth, and dry storage. While other design variations exist, including shallow wetlands, extended detention shallow wetlands, and pond/wetland systems, only pocket wetlands have realistic application in urban environments. The other design variants require a large drainage area to sustain wetland water levels. Pocket wetlands may be supported by drainage areas of 5-10 acres. Pretreatment of stormwater prior to its introduction into the wetland may be used to prevent sediment and grit loading. Pretreatment options include filter strips, swales, catch basins, and oil and grit separators.

B.4.3 Stormwater Management Objectives

B.4.3.1 Volume

Pocket wetlands are designed to treat stormwater runoff from a 5–10 acre drainage area. Hydraulic detention of stormwater is achieved through an increase in the water depth of the wetland. Detention times are 24 hours or less and the water depth increase is no more than 3 feet. The wetland should also be designed to contain the runoff volume of 90% of the annual storm events.

B.4.3.2 Peak Discharge

Increasing the duration of discharge and controlling stormwater volume enables pocket wetlands to significantly reduce peak discharge. Detaining and extending runoff times reduces the total energy of the runoff event.

B.4.3.3 Water Quality

Improving water quality is a primary focus of pocket wetland design. Settling and vegetative uptake are the primary mechanisms of pollutant removal with removal rates anticipated to be 80% for TSS, 40% for phosphorous, 30% for nitrogen, and 50% for metals.

B.4.4 References

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B.5 Porous Pavement

B.5.1 Definition

Porous pavement allows stormwater and snow melt to pass through voids in the paved surface and infiltrate into the subbase. In open (unlined) systems, infiltration into the underlying soil may also be possible.

B.5.2 Design Variations

Porous pavements may be constructed of four (4) basic material types:

- porous asphalt;
- porous concrete;
- interlocking paver blocks; and
- plastic grid.

Porous asphalt and concrete often look the same as their conventional counterparts but are mixed with a low proportion of fine aggregates, leaving void spaces that allow for infiltration. Interlocking paver blocks themselves are impervious, but gravel- or grass-filled voids in between the blocks allow stormwater to enter the subbase. Plastic grid systems provide a stable structure in which each cell in the grid contains grass or gravel.

Drainage in porous pavements may be one of three types:

- full exfiltration;
- partial exfiltration; and
- no exfiltration or tanked systems.

The amount of exfiltration depends on the permeability of the existing soil. Regardless of which approach is used, overflow devices are usually provided to prevent ponding. In full exfiltration systems, all stormwater is expected to exfiltrate into the underlying subsoil. Pipes at the top of the subbase provide overflow and secondary drainage in case the base becomes clogged or loses capacity over time. Partial exfiltration systems are designed so that some water exfiltrates into the underlying soil while the remainder is drained by the overflow devices. No exfiltration occurs when the subbase is lined with an impermeable membrane and water is removed at a controlled rate through the overflow device. Tanked systems are essentially underground detention systems and are used in cases where the underlying soil has low permeability and low strength, there is a high water table, or there are water quality limitations.

B.5.3 Stormwater Management Objectives

B.5.3.1 Volume

Potentially 70-80% of the annual rainfall can be returned to groundwater through the use of porous pavement if underlying soils have a permeability of between 0.5 and 3.0 inches per hour. In lined systems, stormwater will be detained in the subbase and slowly pass through the underdrains into the sewer.

B.5.3.2 Peak Discharge

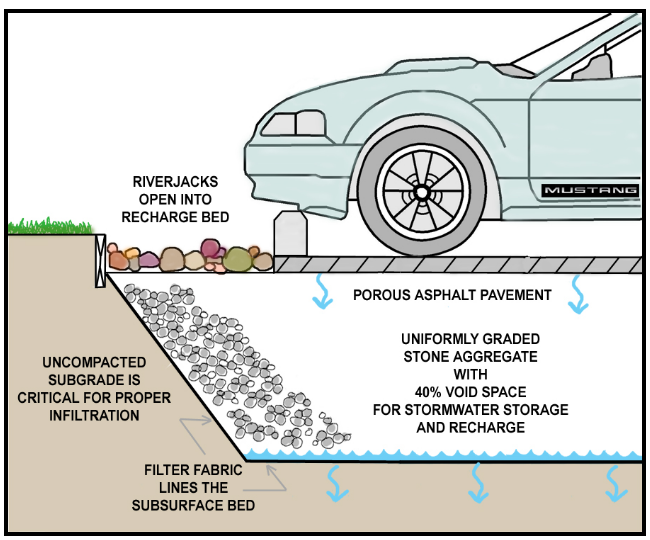
As a design rule, if the subbase can provide a storage volume equal to the volume of increased runoff during a local two-year storm event (that is, the difference between the pre- and post-development runoff volumes), this will provide sufficient storage to mitigate the peak rate of runoff during larger storm events (25-year to 100-year). For small events, the peak discharge is attenuated by stormwater movement through the subbase.

B.5.3.3 Water Quality

Porous pavements intercept TSS and larger sediment particles in the pavement structure and the subbase; annual vacuuming is required to preserve permeability. Brattebo and Booth (2003) compared the quality of infiltrated water from two (2) paver block systems and two (2) grid systems with that of surface runoff from conventional asphalt. Copper concentrations in the infiltrated runoff were 83-89% lower than in the surface runoff from the conventional asphalt. Zinc concentrations were reduced 39-69%. Motor oil concentrations were reduced to below detection limits.

In open systems, pollutants that are not easily trapped or adsorbed, such as nitrates and chlorides, may continue to move through the soil profile and into groundwater. Further scientific data is necessary before porous pavement is constructed near drinking water supplies. Porous pavements simultaneously serve as hardscape and as stormwater infrastructure, and are therefore especially practicable where space constraints preclude the use of other water quality BMPs.

B.5.4 Images



Permeable Pavement Cross-section
Source: Cahill Associates

B.5.5 References

United States Environmental Protection Agency, *Stormwater Technology Fact Sheet – Porous Pavement*, Office of Water, Washington, D.C. (1999). U.S. EPA 832-F-99-023.

Brattebo, B.O., and D.B. Booth, *Long-Term Stormwater Quantity and Quality Performance of Permeable Pavement Systems*, University of Washington, Seattle, WA (2003).

B.6 Rain Barrels/Cisterns

B.6.1 Definition

Rain barrels are placed outside of a building at roof downspouts to store rooftop runoff for later reuse in lawn and garden watering.

B.6.2 Design Variations

Rain barrels and cisterns are low-cost water conservation devices that reduce runoff volume and, for very small storm events, delay and reduce the peak runoff flow rates.

B.6.3 Stormwater Management Objectives

Rain barrels are most often used for individual residences while cisterns have both residential and commercial applications. Both storage devices act to decrease the volume and flow rate of rooftop generated stormwater runoff. Rain barrels and cisterns can provide a source of chemically untreated 'soft water' for gardens and compost, free of most sediment and dissolved salts.

B.6.3.1 Volume

Rain barrels and cisterns are low-cost water conservation devices that reduce runoff volume and, for very small storm events, delay and reduce the peak runoff flow rates. Rain barrels are most effective when collected rainwater is emptied from the barrel prior to the next storm event. Rain barrel water is most commonly used for residential landscaping purposes.

B.6.3.2 Peak Discharge

Peak discharge is minimally impacted by the use of rain barrels and cisterns. An initial runoff volume is retained by the storage devices, ranging from approximately 50 gallons to several thousand for each device, prior to the remaining runoff bypassing the systems. When used throughout a watershed or stormwater collection basin, rain barrels and cisterns will modestly impact the peak stormwater flow rate.

B.6.3.3 Water Quality

Modest water quality improvements will be gained by using rain barrels and cisterns to reduce the volume of stormwater available to convey pollutants.

B.6.4 Images

Residential Rain Barrel
Source: LID Center

B.7 Rain Gardens

B.7.1 Definition

Rain gardens, also known as bioretention cells, are vegetated depressions that store and infiltrate runoff. Uptake into plants reduces runoff volume and pollutant concentrations. The soil media is engineered to maximize infiltration and pollutant removal. Rain gardens are typically designed to avoid ponding for longer than 24 hours.

B.7.2 Design Variations

Rain gardens function as soil and plant-based filtration devices that remove pollutants through a variety of physical, biological, and chemical treatment processes. They can resemble miniature ponds or long strips, and may be lined or unlined, depending on site requirements. Rain gardens are used to treat stormwater that has run over impervious surfaces in commercial, residential, and industrial areas. Use of rain gardens for stormwater management is ideal for median strips, parking lot islands, and swales.

B.7.3 Stormwater Management Objectives

Rain gardens provide stormwater treatment and enhance the quality of downstream water bodies. Runoff is temporarily stored in the rain garden and released over a period of four days to the receiving water.

B.7.3.1 Volume

Rain gardens allow for high-rate infiltration of stormwater runoff and provide storage and exfiltration capacity to surrounding soils. These mechanisms result in substantial volume reduction of generated stormwater. Volume reductions are also realized through plant uptake and evapotranspiration facilitated by the rain gardens.

B.7.3.2 Peak Discharge

Rain gardens effectively both reduce stormwater volume and increase the duration of stormwater discharge. Controlling these two hydrologic functions serves to diminish the peak discharge of the storm event. Volume reduction decreases the total amount of stormwater discharged and duration extension decreases the energy of the discharge.

B.7.3.3 Water Quality

Rain Gardens are among the best BMPs for stormwater quality control incorporating physical and microbiological remediation processes. The removal effectiveness of rain gardens has been studied during field and laboratory studies conducted at the University of Maryland (Davis et al., 1998). Bioretention has been shown to be effective at removing 90% of bacteria, 90% of organics, 90% of total suspended solids, 70-80% of Total Kjeldahl nitrogen, 93-98% of metals, and 70-83% of total phosphorus.

B.7.4 Images

Rain Garden
Source: LID Center

B.7.5 References

Davis, A.P., M. Shokouhian, H. Sharma, and C. Minani, *Optimization of Bioretention Design for Water Quality and Hydrologic Characteristics*, University of Maryland, College Park, MD (1998).

Prince George's County Department of Environmental Resources, *Design Manual for Use of Bioretention in Stormwater Management*, Division of Environmental Management, Watershed Protection Branch, Landover, MD (2000).

B.8 Soil Amendments

B.8.1 Definition

Including the use of both soil conditioners and fertilizers, soil amendments make the soil more suitable for the growth of plants and increase water retention capabilities. The use of soil amendments is conditional on their compatibility with existing vegetation.

B.8.2 Design Variations

A variety of techniques are included as potential soil amendments including aerating, fertilizing, and adding compost, other organic matter, or lime to the soil.

B.8.3 Stormwater Management Objectives

B.8.3.1 Volume

Soil amendments increase a soil's infiltration capacity and thereby add storage volume to a site. Allowing more stormwater to infiltrate on-site decreases the total volume of runoff; good control of small storm events is achieved with the possibility of eliminating runoff. A reduction in total runoff of large storm events is also obtained.

B.8.3.2 Peak Discharge

By effectively controlling volume and extending runoff duration, soil amendments also diminish the peak discharge from the site. The maximum stormwater flow rate is reduced by the enhanced infiltration capability of the site and the additional storage volume that is realized in the amended soils.

B.8.3.3 Water Quality

Amended soils have the ability to remove pollutants through sorption, precipitation, filtering, and bacterial and chemical degradation. Water quality improvements in compost-amended soils are realized because surface runoff volumes are significantly lower from compost-amended soils than conventional soils, and compost materials are less prone to erosion than topsoil or compacted subsoil. As a result, while pollutant concentrations in many compost materials are far higher than in topsoil or compacted subsoil, the mass discharge of most soluble and adsorbed pollutants in surface runoff is far lower in amended soils than in conventional soils. Subsurface mass discharges of many nutrients are expected to increase in amended soils; the concentrations decrease significantly after six (6) months, however.

B.8.4 Images

Soil Amending Process
Source: U.S. EPA

B.8.5 References

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B.9 Tree Box Filters

B.9.1 Definition

Tree box filters are in-ground containers typically containing street trees in urban areas. Runoff is directed to the tree box, where it is filtered by vegetation and soil before entering a catch basin. Tree box filters adapt bioretention principles used in rain gardens to enhance pollutant removal, improve reliability, standardize and increase ease of construction, and reduce maintenance costs.

B.9.2 Design Variations

The number and dimensions of tree box filters are adjusted according to the stormwater management objectives of a given subwatershed (i.e., stretch of road).

B.9.3 Stormwater Management Objectives

B.9.3.1 Volume

Individual tree box filters hold a relatively small volume of stormwater (100-300 gallons), but concerted use throughout a stormwater drainage area will decrease the total volume of discharged stormwater.

B.9.3.2 Peak Discharge

Tree box filters decrease peak discharge by detaining stormwater volume and by increasing discharge duration. Use of numerous tree box filters in a stormwater drainage area can have an impact on total discharge energy and flow rates.

B.9.3.3 Water Quality

Tree box filters have a high removal rate of pollutants in stormwater, as they have similar mechanisms and pollutant removal capabilities as rain gardens and vegetated roofs. They also provide the added value of aesthetics while making efficient use of available land for stormwater management.

B.9.4 Images

Tree box filter
Source: LID Center

B.10 Vegetated Roofs

B.10.1 Definition

Vegetated roofs, also known as green roofs, eco-roofs, or nature roofs, are structural components that help to mitigate the effects of urbanization on water quality by filtering, absorbing, or detaining rainfall.

B.10.2 Design Variations

Modern vegetated roofs can be categorized as "intensive" or "extensive" systems depending on the plant material and planned usage for the roof area. Intensive vegetated roofs utilize a wide variety of plant species that may include trees and shrubs, require deeper substrate layers (usually > 10 cm (4 in)), are generally limited to flat roofs, require 'intense' maintenance, and are often park-like areas accessible to the general public. In contrast, extensive roofs are limited to herbs, grasses, mosses, and drought tolerant succulents such as Sedum, and can be sustained in a shallow substrate layer (< 10 cm (4 in)), require minimal maintenance, and are generally not accessible to the public.

B.10.3 Stormwater Management Objectives

Through a variety of physical, biological and chemical treatment processes that filter pollutants and reduce the volume of runoff, vegetated roofs reduce the amount of pollution delivered to the local drainage system and, ultimately, to receiving waters. In addition, vegetated roofs have a longer life-span than standard roofs because they protect the roof structure from ultraviolet radiation and the extreme fluctuations in temperature that cause roof membranes to deteriorate. Furthermore, the construction and maintenance of vegetated roofs provide business opportunities for nurseries, landscape contractors, irrigation specialists, and other green industry members while addressing the issues of environmental stewardship.

B.10.3.1 Volume

A major benefit of vegetated roofs is their ability to absorb stormwater and release it slowly over a period of several hours. Vegetated roof systems have been shown to retain 60-100% of the stormwater they receive. Generally vegetated roofs treat only the rainfall that falls directly on that particular surface area.

B.10.3.2 Peak Discharge

Peak flow reductions of as much as 80% have been observed in the U.S. from extensively vegetated roofs. Much more work has been done in Europe, particularly Germany. Water retention rates are known to be higher in the summer than in the winter due to higher evapotranspiration rates.

B.10.3.3 Water Quality

Current research on concentrations of non-point source pollutants in vegetated roof effluent is inconclusive. The selection of the soil material will impact the effluent quality. While materials such as compost will provide excellent volume reduction, the concentrations of nutrients in vegetated roof effluent may increase because of nutrients present in the soil. From a CSO perspective, however, green roofs will provide water quality improvements in receiving waters by reducing the volume and peak rate of stormwater entering the sewer system. Further study is needed before the water quality benefits of green roofs can be generalized.

B.10.4 Images

Extensive Green Roof
Source: Katrin Scholz-Barth Consulting.

B.10.5 References

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B.11 Vegetated Swales

B.11.1 Definition

Vegetated swales are broad, shallow channels designed to convey and infiltrate stormwater runoff. The swales are vegetated along the bottom and sides of the channel, with side vegetation at a height greater than the maximum design stormwater volume. The design of swales seeks to reduce stormwater volume through infiltration, improve water quality through infiltration and vegetative filtering, and reduce runoff velocity by increasing flow path lengths and channel roughness.

B.11.2 Design Variations

Two primary vegetated swale design variations exist. Dry swales are designed with highly permeable soils and an underdrain to allow the entire stormwater volume to convey or infiltrate away from the surface of the swale shortly after storm events. Dry swales may be designed with check dams that act as flow spreaders and encourage sheet flow along the swale. Check dams also retain stormwater. Wet swales are designed to retain water and maintain marshy conditions for the support of aquatic vegetation. Because of their highly permeable soil and conveyance capability, dry swales are more applicable for urban environments.

B.11.3 Stormwater Hydrologic Characteristics

B.11.3.1 Volume

Infiltration into the underlying and surrounding soils is the mechanism through which vegetated swales reduce stormwater volume. Evapotranspiration further reduces the stormwater volume. Reductions in discharge volume will be most apparent in moderate to small storms. Soils in vegetated swales can be amended to enhance permeability and increase volume reductions.

B.11.3.2 Peak Discharge

Peak discharge is decreased because of a decrease in volume and an increase in runoff duration. Dry swales should be sized to store and infiltrate the determined water quality volume of runoff within 24–48 hours.

B.11.3.3 Water Quality

Vegetated swales improve water quality through two main mechanisms. The vegetation in the channel removes large and course particulate matter from stormwater. Pollutant removal is also facilitated by the infiltration process encouraged through the use of swales. Estimated removal efficiencies are 80% for TSS, 50% for phosphorus and nitrogen, and 40% for metals.

B.11.4 Images

Vegetated Swale.
Source: Portland BES

B.11.5 References

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APPENDIX C

Ancillary Benefits of Best Management Practices

Decentralized stormwater controls have additional benefits that affect the livability and economics of communities. The distributed BMPs provide a network of landscaped open space areas that increase the "green infrastructure" of a neighborhood. These vegetated BMPs can be a contributing factor in minimizing the urban heat island effect, which potentially affects overall urban climates and energy consumption. The increased trees, shrubs, and perennials assist with absorption of air pollutants as well as provide shade. The distributed placement of BMPs allows for accessible outreach programs that educate residents on environmental issues and stewardship of their community resources. The BMPs are a manageable scale for businesses, volunteer organizations, residents, or public entities to participate in their design, construction, and maintenance.

C.1 Environmental Benefits

Each of the identified BMPs was evaluated to determine its impact on five environmental criteria other than stormwater management: water conservation, heat island reduction, energy conservation, air pollution reduction, and habitat. The following section describes how these benefits are realized. Discussions are provided only for environmental criteria for which the BMP provides a benefit; criteria not affected by a BMP are not discussed.

C.1.1 Downspout Disconnection

C.1.1.1 Water Conservation

Disconnecting roof downspouts can reduce potable municipal water usage if the downspouts are routed to collection devices such as rain barrels or cisterns. The collected rainwater can then be used for landscape irrigation and other non-potable water uses.

C.1.2 Filter Strips

C.1.2.1 Heat Island Reduction

Filter strips potentially temper urban climates by introducing green space. For the benefit to be realized, a number of filter strips would need to be installed in conjunction with other vegetated BMPs as part of a comprehensive stormwater program that resulted in a significant increase in urban green space. The introduced green space reduces the amount of man-made radiation absorbing and heat radiating material in the urban space and increases the amount of moisture introduced into the atmosphere by evapotranspiration.

C.1.3 Infiltration Practices

Infiltration practices do not impact any ancillary environmental criteria.

C.1.4 Pocket Wetlands

C.1.4.1 Heat Island Reduction

Pocket wetlands potentially reduce the urban heat island effect by introducing permanent water bodies and increasing the amount of evapotranspiration with the introduction of wetland plants.

C.1.4.2 Energy Conservation

Pocket wetlands potentially assist with energy conservation by influencing ambient temperatures with water and vegetation.

C.1.4.3 Air Pollution Reduction

The vegetation in pocket wetlands potentially decreases air pollution as the wetland plants filter and absorb airborne chemicals and particles.

C.1.4.4 Habitat

Pocket wetlands provide a habitat for a diversity of native species. Facultative and obligate wetland plants provide shelter, breeding grounds, and foraging areas for fish and other wildlife.

C.1.5 Porous Pavement

Porous pavement does not impact any ancillary environmental criteria.

C.1.6 Rain Barrels/Cisterns

C.1.6.1 Water Conservation

Rain barrels and cisterns capture and store rainwater from roof downspouts for irrigation and other non-potable uses, thus reducing the use of potable water needed from municipal water supplies.

C.1.7 Rain Gardens

C.1.7.1 Water Conservation

Rain gardens receive stormwater from downspouts or from adjacent surface areas and do not require supplemental irrigation between storms provided that they are planted with native vegetation that is suitable to the site and microclimate.

C.1.7.2 Heat Island Reduction

Rain gardens assist with the reduction of ambient air temperatures in urban areas as they contribute to the infiltration of stormwater into the soil and are planted with vegetation that cools the environment through evapotranspiration. A network of rain gardens throughout a community can effectively stabilize temperatures through the introduction of urban green space and the collective increase in evapotranspiration.

C.1.7.3 Energy Conservation

Rain gardens may contribute to reduced energy use when used as part of a comprehensive green infrastructure program that reduces urban ambient temperatures.

C.1.7.4 Air Pollution Reduction

The vegetation in rain gardens helps to improve urban air as the root systems and leaves absorb carbon dioxide, filter air, and capture airborne particles.

C.1.7.5 Habitat

Rain gardens provide shelter, nesting, foraging, and breeding areas for birds, butterflies, and animals. Rain gardens planted with vegetation that is indigenous to the area and adapted to the local ecosystem, soil, and weather flourish and provide essential habitat for local wildlife. Networks of rain gardens in yards and easements establish a green corridor essential for plant and animal species.

C.1.8 Soil Amendments

Soil amendments do not impact any ancillary environmental criteria.

C.1.9 Tree Box Filters

C.1.9.1 Heat Island Reduction

If implemented widely, the trees and vegetation introduced with the installation of tree box filters could impact heat island effects. For the effect to be observable, the introduction of tree box filters would likely have to complement an urban forestry initiative aimed at increasing the percentage of urban tree canopy.

C.1.9.2 Air Pollution Reduction

The vegetation in tree box filters reduces air pollution by filtering and absorbing common urban pollutants. Many tree box installations would have an observable effect on air quality.

C.1.9.3 Habitat

The shrubs, small trees, ornamental grasses, and flowers in tree box filters provide habitat for birds and other urban wildlife.

C.1.10 Vegetated Roofs

C.1.10.1 Heat Island Reduction

Vegetated roofs have a significant impact on reducing the urban heat island effect as the vegetation reduces rooftop temperatures by replacing traditional roofing materials that absorb radiation and reach high temperatures with vegetation. Vegetated roods also provide a source of moisture for evapotranspiration.

C.1.10.2 Energy Conservation

Vegetated roofs reduce energy consumption due to the cooling effects and the insulation provided by the vegetated rooftop surfaces. Cooler rooftops contribute to cooler building interiors which require less energy to cool in the summer months. Vegetated roofs also dampen the large fluctuations in temperature normally observed during a diurnal cycle, also reducing energy demand.

C.1.10.3 Air Pollution Reduction

Vegetated roofs absorb carbon dioxide, filter air, and capture airborne particles.

C.1.10.4 Habitat

Vegetated roofs have the potential of providing essential habitat for urban birds, insects, and butterflies.

C.1.11 Vegetated Swales

C.1.11.1 Heat Island Reduction

Vegetated swales have the potential to help reduce ambient air temperatures as part of a comprehensive green infrastructure program.

C.1.11.2 Air Pollution Reduction

Vegetated swales help absorb carbon dioxide, filter air, and capture airborne particles.

C.1.11.3 Habitat

Vegetated swales provide an environment for insects and worms that are essential components of the urban ecosystem.

C.2 Community, Educational, and Economic Benefits

Each of the identified BMPs was evaluated to determine its impact on four community, educational, and economic benefits: beautification, environmental stewardship and education, public/private collaboration, and increased property values. The following section describes how these benefits are realized. Discussions are provided only for benefits for which the BMP has an impact; benefits not affected by a BMP are not discussed.

C.2.1 Downspout Disconnection

C.2.1.1 Environmental Stewardship and Education

Downspout disconnection programs present an opportunity to educate the public on the value of water as a reusable resource in the urban environment and the impact that the redirection of rainwater can have on a metropolitan area and the local watershed. Outreach and education programs can guide residents to understand their role in conserving and reusing rainwater on their properties, and how disconnected drain pipes can reduce the volume of stormwater that enters storm drains while improving the quality of streams and rivers in their neighborhood and surrounding areas.

C.2.1.2 Public/Private Collaboration

Downspout disconnection programs are an excellent opportunity for public institutions to collaborate with private entities to install BMPs at a local level. Numerous municipalities have established incentives, such as “finder’s fees” for organizations that identify properties that have not been disconnected and who assist with disconnections. Additionally, EPA (319) grants are available to non-profit organizations with interest and expertise in downspout disconnections and rain barrel connections.

C.2.2 Filter Strips

Filter strips do not provide any benefits in addition to environmental improvements.

C.2.3 Infiltration Practices

Infiltration practices do not provide benefits other than stormwater control.

C.2.4 Pocket Wetlands

C.2.4.1 Beautification

Pocket wetlands have the potential to provide scenic areas and vistas in the urban environment such as in transportation easements and corridors.

C.2.4.2 Environmental Stewardship and Education

Pocket wetlands in easements and adjacent to greenways have the potential to increase the public's understanding of the value of marshes, bogs, and fens. Wetlands provide a unique habitat in which to study diverse plant and wildlife species.

C.2.4.3 Public/Private Collaboration

Pocket wetlands can potentially generate economic development opportunities in local communities by promoting conservation education, training, and employment. There are possibilities for partnership and collaboration for organizations and agencies to demonstrate the value of wetlands, develop interpretive trails, and care and maintain for the wetlands to remove invasive plants and trash to enhance the wildlife habitat value.

C.2.5 Porous Pavement

C.2.5.1 Beautification

Porous pavement can potentially enhance the physical environment through the use of various colors and textures of materials.

C.2.5.2 Environmental Stewardship and Education

Porous pavement can provide an opportunity to increase awareness on the impact of permeable pavement in the urban environment as well as the value of infiltration.

C.2.6 Rain Barrels/Cisterns

C.2.6.1 Environmental Stewardship and Education

Rain barrels and cisterns have great potential to increase awareness of stormwater controls and rainwater as a renewable resource, particularly in residential areas. The small-scale BMP allows residents of all ages to discover how to be stewards of rainwater. Rain barrels and cisterns also can potentially educate the public on large-scale watershed issues.

C.2.6.2 Public/Private Collaboration

There are numerous opportunities for public and private collaboration associated with the manufacturing, training, and distribution of rain barrels and cisterns in the urban setting. These BMPs provide countless opportunities for the involvement of volunteer organizations and businesses in the identification of disconnection opportunities, in training citizens, and in the installation of rain barrels and cisterns on residential and commercial properties.

C.2.7 Rain Gardens

C.2.7.1 Beautification

Rain gardens beautify the urban environment with native trees, shrubs, and perennials. The variations of size and configurations of rain gardens allow for interconnected backyard habitats and community gardens that enhance the livability of the urban environment.

C.2.7.2 Environmental Stewardship and Education

Rain gardens can be used to educate the public on the benefits of distributed stormwater controls, native landscaping, and wildlife in the urban community. These local environmental concerns can be tied to the larger watershed as well as regional/national environmental issues and challenges. Rain gardens can be used to facilitate environmental stewardship and provide an opportunity for the community to come together, take care of, and beautify their properties, the surrounding environs, and the greater community.

C.2.7.3 Public/Private Collaboration

Rain gardens provide a unique opportunity for small businesses, volunteer organizations, private investors, and public agencies to unite and collaborate. Rain gardens have the potential to generate economic development opportunities in design, installation, training, and maintenance in commercial, industrial, and residential areas. Rain gardens are a fitting BMP for community and economic partnerships due to their size, scale, and simplicity.

C.2.7.4 Increased Property Values

Rain gardens have the potential to increase property values as mature landscaping increases appreciation.

C.2.8 Soil Amendments

Soil amendments do not provide any benefits in addition to environmental improvements.

C.2.9 Tree Box Filters

C.2.9.1 Beautification

Tree box filters improve and enhance commercial, industrial, and residential areas because they increase vegetation along streetscapes in the urban environment.

C.2.9.2 Environmental Stewardship and Education

Tree box filters are installed and maintained by local agencies; however, they can be used to educate the public on the stormwater benefits, native landscaping, and stewardship of engineered controls.

C.2.10 Vegetated Roofs

C.2.10.1 Beautification

Vegetated roofs enhance the urban setting by contributing to the greening of the environment. Buildings and offices adjacent to vegetated roofs are provided with views of flowers and bird habitats.

C.2.10.2 Environmental Stewardship and Education

Vegetated roofs can be used to educate the public on the importance of minimizing stormwater runoff in the urban environment as well as the impact that the reduction has on local waterways and the region. They can be used to facilitate community involvement and stewardship.

C.2.10.3 Public/Private Collaboration

Vegetated roofs provide opportunities for volunteer organizations, private investors, public agencies, and small businesses to collaborate on the design, installation, training, and maintenance.

C.2.10.4 Increased Property Values

Vegetated roofs do not increase or decrease property value; however, they reduce costs in energy consumption by keeping rooftops cooler in the warmer months and insulated in the cooler months. The roof membrane, the lightweight growth media, and the sedum plantings protect the roof from ultraviolet radiation and minimize the expansion and contraction, thus extending the life of the roof installation and reducing life-cycle costs.

C.2.11 Vegetated Swales

C.2.11.1 Beautification

The use of vegetated swales increases the amount of green space, thus enhancing the urban environment.

C.2.11.2 Environmental Stewardship and Education

Vegetated swales are an easily accessible teaching tool that can be used to demonstrate the importance of vegetated BMPs to distribute stormwater, filter runoff, and help increase infiltration.

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WASTEWATER UTILITY

Alabama
Montgomery Water Works & Sanitary Sewer Board

Alaska
Anchorage Water & Wastewater Utility

Arizona
Gila Resources
Glendale, City of, Utilities Department
Mesa, City of
Peoria, City of
Phoenix Water Services Department
Pima County Wastewater Management

Arkansas
Little Rock Wastewater Utility

California
Calaveras County Water District
Central Contra Costa Sanitary District
Corona, City of
Crestline Sanitation District
Delta Diablo Sanitation District
Dublin San Ramon Services District
East Bay Dischargers Authority
East Bay Municipal Utility District
Eastern Municipal Water District
El Dorado Irrigation District
Fairfield-Suisun Sewer District
Fresno Department of Public Utilities
Inland Empire Utilities Agency
Irvine Ranch Water District
Las Virgenes Municipal Water District
Livermore, City of
Lodi, City of
Los Angeles, City of
Napa Sanitation District
Orange County Sanitation District
Palo Alto, City of
Riverside, City of
Sacramento Regional County Sanitation District
San Diego Metropolitan Wastewater Department, City of
San Francisco, City & County of
Sanitation Districts of Los Angeles County
San Jose, City of
Santa Barbara, City of
Santa Cruz, City of
Santa Rosa, City of
South Bayside System Authority
South Coast Water District
South Orange County Wastewater Authority
Stege Sanitary District
Sunnyvale, City of
Union Sanitary District
West Valley Sanitation District

Colorado
Aurora, City of
Boulder, City of
Colorado Springs Utilities
Greeley, City of
Littleton/Englewood Water Pollution Control Plant
Metro Wastewater Reclamation District, Denver

Connecticut
The Mattabassett District
New Haven, City of, WPCA

District of Columbia
District of Columbia Water & Sewer Authority

Florida
Broward, County of
Fort Lauderdale, City of
JEA
Miami-Dade Water & Sewer Authority
Orange County Utilities Department
Reedy Creek Improvement District
Seminole County Environmental Services
St. Petersburg, City of
Stuart Public Utilities
Tallahassee, City of
Tampa, City of
Toho Water Authority
West Palm Beach, City of

Georgia
Atlanta Department of Watershed Management
Augusta, City of
Clayton County Water Authority
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Des Moines, City of

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