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Report on Enhanced Framework (SUSTAIN) and Field Applications for Placement of BMPs in Urban Watersheds

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Report on Enhanced Framework (*SUSTAIN*) and Field Applications for Placement of BMPs in Urban Watersheds

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Disclaimer

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building the science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and sub-surface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments, and groundwater; prevention and control of indoor air pollution; and restoration of eco-systems. NRMRL collaborates with both public- and private-sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

Abstract

The System for Urban Stormwater Treatment and Analysis Integration (*SUSTAIN*) was developed by the U.S. Environmental Protection Agency (EPA) to provide stormwater managers with a decision support system for the cost-efficient selection and placement of stormwater best management practices (BMPs) in urban watersheds. The *SUSTAIN* modeling system integrates simulation based on sound science and engineering principles, with cost estimation tools, and optimization to support users in selecting the best solutions on the basis of cost and effectiveness. This report documents the enhancements to the system since the initial release of version 1.0 in October 2009 (Shoemaker et al., 2009; http://www.epa.gov/nrmrl/wswrd/wq/models/sustain). Two case studies also provide insight into the application of the system, and demonstrate the utility of *SUSTAIN* in evaluating the use of green infrastructure (GI) in communities addressing the mitigation of combined sewer overflows (CSOs).

SUSTAIN's innovative integration of optimization and simulation of BMP performance in a watershed setting provides significant capabilities to support the evaluation of various configurations of BMPs, the impact of local site conditions on BMP placement, and the types and relative costs of the BMPs available. At the same time, the flexibility and range of application complexity available within *SUSTAIN* provide choices for users in developing the appropriate configuration for a specific watershed application.

Through the use of case studies in Kansas City, MO, and Louisville, KY, the implications of assumptions in the application of *SUSTAIN* are evaluated. The *SUSTAIN* model including recent enhancements was demonstrated to perform well in predicting the hydrologic response and matched previous applications using other modeling systems. In particular, the addition of a sub-hourly time step improved the ability of *SUSTAIN* to predict hydrologic response and peak flow from design storms used as a basis for planning many CSO and stormwater programs. The addition of aggregate BMP tools facilitated the use of the model in Louisville and other regions where users want to evaluate the benefits of many, in some cases hundreds or thousands of smaller BMPs across a large catchment. The optimization process applied in the case studies was also shown to be highly sensitive to BMP cost data in selecting the most efficient solutions.

Executive Summary

The System for Urban Stormwater Treatment and Analysis Integration (*SUSTAIN*) was developed by the U.S. Environmental Protection Agency (EPA) to provide stormwater managers with a decision support system for the cost-efficient selection and placement of stormwater best management practices (BMPs) in urban watersheds. The *SUSTAIN* modeling system integrates simulation based on sound science and engineering principles with cost estimation tools and optimization to support users in selecting the best solutions on the basis of cost and effectiveness. This report demonstrates the utility of *SUSTAIN* and showcases its power and flexibility as a decision making platform both for evaluating current management decisions and for future expansion of the science.

The report provides an overview of the system and documents the system enhancements made since the initial release of version 1.0 in October 2009 (Shoemaker et al. 2009; http://www.epa.gov/nrmrl/wswrd/wq/models/sustain). Two regional case studies explore the use of *SUSTAIN* in evaluating green infrastructure (GI) management alternatives for mitigation of combined sewer overflows (CSOs) in Kansas City, Missouri, and Louisville, Kentucky. The case study applications provide an overview of the user application process from start to finish, including problem formulation, data collection, calibrating a baseline condition, BMP parameterization, and optimization. Through the case study application process the common themes and recommendations for how *SUSTAIN* can be applied and interpreted are presented.

SUSTAIN has seven components, including: (1) Framework Manager, (2) BMP Siting Tool, (3) Watershed/Conveyance Module, (4) BMP Module, (5) Cost Module, (6) Optimization Module, and (7) Post-Processor. The modular components are integrated under a common ArcGIS platform, which performs hydrologic and water quality modeling in watersheds and urban streams and searches for optimal management solutions at multiple-scale watersheds to achieve desired water quality objectives based on cost effectiveness. *SUSTAIN*'s unique system design provides significant capabilities to support the evaluation of various configurations of BMPs, the impact of local site conditions on BMP placement, and the types and relative costs of the BMPs available. At the same time, the flexibility and range of application complexity available within *SUSTAIN* provide choices for users in developing the appropriate configuration for a specific watershed application.

Several enhancements to *SUSTAIN* were identified earlier in the current phase of the system development during workshops of invited national experts in July 2010 and through development of the two case studies. The list of planned enhancements were selected on the basis of their ability to fulfill the goal of improving *SUSTAIN* by (1) enhancing existing functionality, (2) developing additional system capabilities, (3) increasing simulation accuracy, and (4) promoting the use of *SUSTAIN* through regional case studies. Enhancements were prioritized based on their potential to advance the applicability, accuracy, and functionality of *SUSTAIN* and based on the needs for application to the case study areas that emphasize CSOs. The updates to *SUSTAIN* included both operational and technical enhancements affecting most of *SUSTAIN*'s core modules: Framework Manager (ArcGIS), BMP Siting Tool, and the BMP, Watershed/Conveyance, and Optimization Modules. The first set of completed *SUSTAIN* enhancements include:

Enhancement	Description
Siting Tool functionality	More functionality for selection, placement, and prioritization of suitable BMP sites
Sub-hourly time step simulation	Improved performance for hydrologic and hydraulic peak flow prediction
Horton infiltration method	Method added to Watershed and BMP modules as a third option for calculating infiltration
Soil recovery and initial conditions	Evapotranspiration multiplier and initial moisture conditions added to the BMP module to provide more flexibility for model configuration and "hot" simulation
Pump curve	A user-specified option (besides the available weir, orifice, or underdrain outlets) for dewatering a storage element
Area BMP	New option for representing practices such as disconnected imperviousness
Groundwater system	Accounting module for tracking and releasing infiltrated water from a BMP into a conveyance segment
Point source time series	New option that allows for a user-specified inflow to a node in the routing network (e.g. dry weather sewer flow and pollutant loads to a CSO regulator)

The case study application of *SUSTAIN* in Kansas City, Missouri, demonstrates the use of GI for CSO control through two general sets of goals: (1) management goals to inform the decision-making process and (2) modeling goals to test system functionality and provide application guidance for the user community. The case study examines a 480-acre sewershed in the Middle Blue River watershed. This sewershed includes a planned 100-acre BMP implementation/monitoring site in the Battleflood Heights neighborhood and 86 acres of an adjacent control area where only monitoring is planned. The case study application combines a number of key outcomes from local and regional efforts, including elements of an Overflow Control Plan and an accepted GI design plan that was being constructed in the watershed at the time of the case study.

The model application established an existing condition baseline by using an existing model and updating it based on more recently collected monitoring data that spanned a wider range of storms and included larger events that were more representative of the CSO critical condition. Because of the size and complexity of the study area, selective simplifications where used to streamline the model application while preserving the physical responses, including: (1) grouping similar areas into Hydrologic Response Units (HRUs), (2) consolidating the subcatchment delineation, and (3) aggregating the hydraulic network representation. For a portion of the pilot area, *SUSTAIN*'s "aggregated BMP" approach, which represents a coarser version of a detailed routing network, was tested against an articulated network to understand the effects that those simplifications have on predicted storm response. Comparison of aggregated and articulated networks showed that even though there were notable attenuation differences for small storms, the larger critical condition storm response was well maintained. The optimization objective was to fully contain a critical condition design storm runoff response at the lowest cost, using a mix of GI and gray management options. Controlling the critical condition design storm achieves the regional allowable exceedance frequency criteria for CSO.

The case study in Louisville, Kentucky also demonstrates the use of GI for CSO control. However, there are some differences from the Kansas City case study in the specific goals and, consequently, the application sequence. For example, one of the goals for the Louisville case study was to conduct sensitivity tests of key BMP model parameters. The focus area for this case study is the Lousiville-Jefferson County Metropolitan Sewer District (MSD) CSO 019 sewershed, located west of downtown

Louisville. The sewershed drains 1,094 acres of mixed land use dominated by single-family residential neighborhoods. The existing CSO 019 outfall is on the north edge of the sewershed and discharges directly into the Ohio River. Because MSD already has a preferred model for the sewershed, another goal of the case study is to use *SUSTAIN* to replicate the critical condition response of that model. The MSD model estimates that the sewershed produces overflow volumes for a certain number of discrete events based on a 2001 typical year precipitation record. Instead of controlling a design storm, the optimization objective of this case study is to achieve the regional allowable exceedance frequency criteria for CSO at the lowest cost, using continuous simulation for the 2001 typical year. Available options include a mix of GI and gray management activities.

These case studies provide users with an overview of two urban settings and demonstrate how *SUSTAIN* was used to support a cost-benefit evaluation of CSO management alternatives. The two case studies have also shown how *SUSTAIN* was used to analyze, streamline, and extrapolate BMP representation throughout the respective study areas and demonstrated how to evaluate various combinations of green and gray management alternatives. The case study applications led to the follow general observations and conclusions:

- *SUSTAIN* is a comprehensive decision support tool with many useful features and functions. Successful and meaningful application largely depends on accurate representation of the baseline, BMP alternatives, and the associated BMP costs.
- *SUSTAIN* application process is iterative and adaptive, meaning that once the *SUSTAIN* modeling framework is established, it can be adapted to answer various management questions and test underlying assumptions.
- Model simplification becomes critical when optimization is applied to a larger area or when multiple smaller BMPs are distributed widely across a catchment. The aggregate BMP concept and utility provided in *SUSTAIN* is proven to be a viable and useful technique in the evaluation of the benefit of stormwater management practices, especially smaller GI practices, across a large area. When the aggregate BMP tools are used, the appropriate aggregation spatial scale should be carefully selected to maintain reasonable predictive capability and accuracy.
- The optimization process is highly sensitive to BMP cost data used in selecting solutions for each application. As a result, performance of sensitivity analysis and evaluation of cost control measures or economies of scale are recommended wherever *SUSTAIN* is applied.

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Abbreviations and Acronyms

BMP	Best Management Practice
CIP	Capital Improvement Plan
CSO	Combined Sewer Overflow
CWP	Center for Watershed Protection
CSS	Combined Sewer System
DCIA	Directly Connected Impervious Area
ENR	Engineering News-Record
EPA	United States Environmental Protection Agency
ET	Evapotranspiration
GI	Green Infrastructure
GIS	Geographic Information System
HRU	Hydrologic Response Unit
HSPF	Hydrologic Simulation Program—FORTRAN
IOAP	Integrated Overflow Abatement Plan
LTCP	Long-Term Control Plan
MG	Million Gallons
MSD	Louisville-Jefferson County Metropolitan Sewer District
NCDC	National Climatic Data Center
NRMRL	National Risk Management Research Laboratory
O&M	Operation and Maintenance
OCP	Overflow Control Plan
ORD	Office of Research and Development
PEVT	Potential Evapotranspiration
SCS	Soil Conservation Services
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
SWMM	Storm Water Management Model
UMKC	The University of Missouri-Kansas City
WaPUG	Wastewater Planning Users Group
WinSLAMM	Source Loading and Management Model for Windows
WSD	Kansas City, Missouri, Water Services Department

Chapter 1. Introduction

The U.S. Environmental Protection Agency (EPA) initiated a research project in 2002 to develop a decision support system for selection and placement of stormwater best management practices (BMPs) at strategic locations in mixed land use urban watersheds. The primary objective of the system is to provide stormwater management professionals with a BMP assessment tool based on sound science and engineering principles that helps develop, evaluate, select, and place BMP options on the basis of cost and effectiveness. Phases 1 and 2 of this effort culminated in the release of the System for Urban Stormwater Treatment and Analysis Integration (*SUSTAIN*) version 1.0 in October 2009 (Shoemaker et al., 2009) and is publicly available on the EPA *SUSTAIN* web site (http://www.epa.gov/nrmrl/wswrd/wq/models/sustain).

Since the release of *SUSTAIN* version 1.0, EPA has initiated Phase 3, to further enhance *SUSTAIN's* functionality, capabilities, and accuracy with the goal of releasing *SUSTAIN* version 2.0 in 2012 (Lai et al., 2010). In addition to improving and enhancing the modeling system, the scope of Phase 3 includes continued support for the use of *SUSTAIN* by user groups through ongoing technical support, training and workshops, and the development of regional case studies to further demonstrate and test the model.

This report documents the enhancements and updates to the system since the release of Version 1.0, and the results of two case study applications. Chapter 1 provides detailed documentation of the system enhancements and their role in creating a richer, more productive tool for the user community. Chapter 2 and Chapter 3 present two regional case studies for combined sewer overflow (CSO) communities in Kansas City, Missouri and Louisville, Kentucky, respectively. The case study applications provide an overview of the user application process from start to finish, and the critical steps in the process including problem formulation, data collection, calibrating a baseline condition, BMP parameterization, and optimization. Chapter 4 discusses common themes and insights derived from the case study applications on how *SUSTAIN* can be applied and interpreted when used to support decision-making in CSO and stormwater communities. Chapter 5 provides concluding remarks and recommendations for future research and analysis.

1.1. *SUSTAIN* Enhancements

Several enhancements to *SUSTAIN* were identified in the Phase 3 scope, during expert workshops in July 2010, and through development of case studies in Kansas City, Missouri (Chapter 2) and Louisville, Kentucky (Chapter 3). The list of planned enhancements were selected on the basis of their ability to fulfill the goal of improving *SUSTAIN* by (1) enhancing existing functionality; (2) developing additional system capabilities; (3) increasing simulation accuracy; and (4) promoting the wide use of *SUSTAIN* through regional case studies. Enhancements were prioritized based on their potential to advance the applicability, accuracy, and functionality of *SUSTAIN,* consistent with the Phase 3 objectives; and based on the needs for application to the case study areas that emphasize CSOs.

The updates to *SUSTAIN* under Phase 3 included both operational and technical enhancements affecting most of *SUSTAIN's* core modules: Framework Manager (ArcGIS), BMP Siting tool, BMP, Watershed, and Optimization. These enhancements, as implemented, provided improved support for the application of the model to the case studies as demonstrated in Chapter 2 and Chapter 3. Figure 1-1 and Table 1-1 provide an overview of the modules and the specific enhancements described in the following sections. Table 1-1 identifies both planned and completed enhancements to each of the core modules.

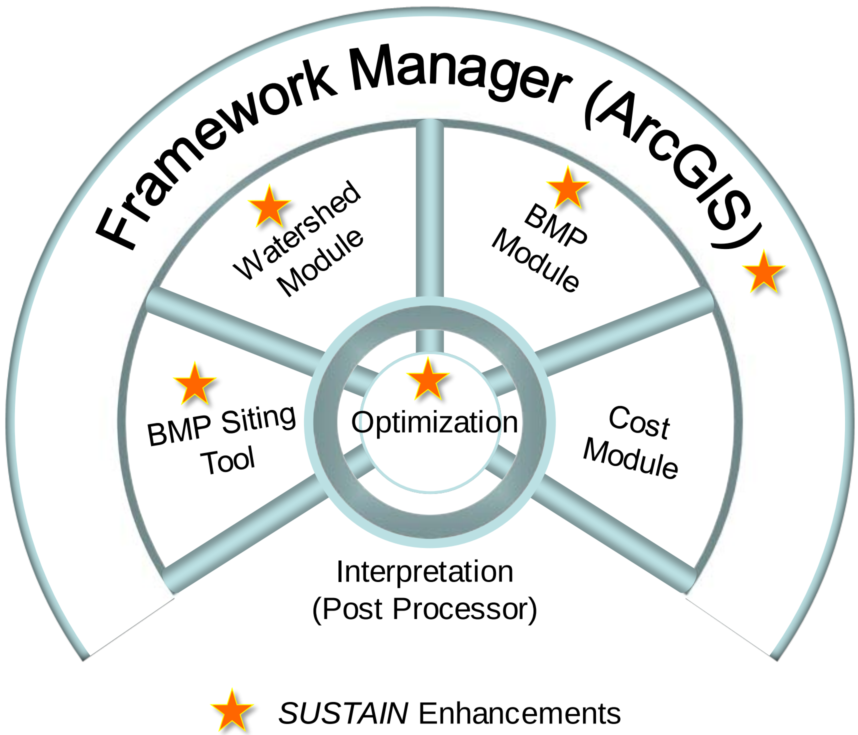

Figure 1-1. Diagram highlighting the modules to be enhanced in *SUSTAIN*

Table 1-1. Summary of enhancements to the core modules in *SUSTAIN*

Description ● = Enhancement completed ⊙ = Enhancement under development -- = Enhancement does not address	**Framework Manager (ArcGIS)**	**BMP Siting Tool**	**BMP Module**	**Watershed Module**	**Optimization Module**
Public or private land constraint for suitable site selection of BMPs	●	●	--	--	--
Proximity to land features for suitable site selection of BMPs	●	●	--	--	--
Rank suitable sites based on slope and infiltration rate	●	●	--	--	--
Enhanced suitable site selection and placement of BMPs on the map	●	●	--	--	--
Horton infiltration method	●	--	●	●	--
Evapotranspiration (ET) multiplier	●	--	●	--	--
BMP initial moisture conditions	●	--	●	--	--
Pump curve	●	--	●	●	--
Sub-hourly time step	●	--	●	●	--
Area BMP (new BMP)	⊙	--	●	--	●

Description ● = Enhancement completed ⦿ = Enhancement under development -- = Enhancement does not address	Framework Manager (ArcGIS)	BMP Siting Tool	BMP Module	Watershed Module	Optimization Module
Groundwater system	●	--	--	●	--
Point source time series	●	--	●	●	--
Variable time step (dry/wet)	⦿	--	⦿	⦿	⦿
Improved simulation process to address sediment and pollutant trapping in BMP	--	--	⦿	--	--
Develop templates for selection of permeable pavement technologies	⦿	--	⦿	--	--
Operation and maintenance (O&M) factors	--	--	⦿	--	⦿
Check dams (new BMP)	⦿	--	⦿	--	⦿
Variable number of sediment classes	--	--	⦿	⦿	--
Infiltration temperature correction factor (viscosity)	--	--	⦿	--	--
Plug flow method	⦿	--	⦿	--	--
Enhanced BMP templates (interfaces)	⦿	--	⦿	--	--
Update sediment associated pollutant loading algorithms for internal land simulation option	--	--	--	⦿	--
Develop a user interface with CSO models for evaluation of green versus gray infrastructure options	⦿	--	--	⦿	--
Street sweeping (new BMP)	⦿	--	⦿	⦿	⦿
Improve infiltration recovery factor	--	--	⦿	⦿	--
Curve number method	⦿	--	--	⦿	--
Dynamic wave routing in conduits	⦿	--	--	⦿	--

1.1.1. *Enhancements to the Framework Manager (ArcGIS)*

The framework manager includes the user interface and the linkage to all the core modules of the system and is based on the ArcGIS system. The framework manager is essential to the overall operation and application of the model. Table 1-1 shows the list of enhancements to the framework manager in Phase 3 of the project. Each change or enhancement to the various system modules, documented in this chapter, also include related updates to system interfaces in the framework manager to link the relevant model input parameters and data management. In this version, the framework manager was also enhanced to provide additional support to the user in the application of the model's BMP placement function, by alerting if the BMP placement location on the map is not suitable. The testing of suitability is based on the information provided by the siting tool, which evaluates BMP placement based on site constraints such as soil, slope, and land use. The siting tool is heavily dependent on ArcGIS to perform the needed analysis on multiple geographic information system (GIS) data layers based on the user selected site suitability criteria for the selected BMP type.

1.1.2. *Enhancements to the BMP Siting Tool*

The BMP siting tool was developed to help users in selecting suitable locations for different types of low impact development techniques or conventional BMPs. Site suitability is the dominant factor in identifying potential site locations (USEPA, 1999). The siting tool provides guidance on where to place a selected BMP on the watershed on the basis of the site suitability criteria. The BMP siting tool is for guidance purposes only because it is highly data-driven tool. It requires field verification beyond the GIS exercise to validate the suitable locations before using them in *SUSTAIN* for BMP placement.

The following enhancements were made to the publicly released version 1.0.

- Land ownership (public or private land): The user has option to limit the selection criteria to public or private land for different selected BMP types.
- Proximity to land features (i.e., roads, streams, and buildings): The user has option to specify a buffer size (i.e., less than, greater than, lower and upper limit) for the suitable locations.
- Prioritize the suitable locations by adding a weighting factor to the suitability criteria for slope and hydrologic soil group. For example, a bioretention basin is best suited in areas with hydrologic soil group A as compared to D.
- Efficient selection of appropriate sites by enhancing the code. The code logic is improved to minimize the run-time overhead and more robust performance of the tool.
- An increased level of automation for siting and placement of BMPs on the map.

Version 1.0 of the BMP siting tool was released in September 2009, which requires ESRI's ArcView 9.3 and the Spatial Analyst extension. Version 1.1 which will be released in September 2011 is made compatible with ArcGIS 10.0 (Service Pack 2) and is backward compatible with ArcGIS 9.3.1 (Service Pack 2).

1.1.3. *Enhancements to the BMP Simulation Module*

The BMP simulation module performs process simulation of flow and water quality through BMPs. It uses a combination of process-based algorithms, including weir and orifice control structures, flow routing and pollutant transport, infiltration, ET, and pollutant loss/decay simulation. BMPs supported by *SUSTAIN* include, but not limited to, bioretention, cistern, constructed wetland, dry pond, grassed swale, green roof, infiltration basin, infiltration trench, porous pavement, rain barrel, sand filter, vegetated filter strip, and wet pond. Sediment (sand, silt, and clay) settling and routing is computed using the processed based algorithms adopted from the Hydrologic Simulation Program—FORTRAN (HSPF) (Bicknell et al., 2001). Table 1-2 summarizes the completed enhancements to *SUSTAIN*'s BMP module so far as part of Phase 3 of the project.

Table 1-2. Summary of completed BMP module enhancements

Description ● = Enhancement addresses -- = Enhancement does not address	Support regional case studies	Develop additional capabilities	Enhance existing functionality	Increase simulation accuracy
Sub-hourly time step	●	--	●	●
Horton infiltration method	●	--	●	●
ET multiplier	●	--	●	●
BMP initial moisture conditions	●	●	●	●
Pump curve	●	●	●	●
Area BMP	●	●	●	●

Horton Infiltration

The *SUSTAIN* BMP module previously included the Green-Ampt and Holtan infiltration methods. The Horton infiltration method is implemented in *SUSTAIN* using the Storm Water Management Model (SWMM) formulation (Rossman, 2005). The Horton infiltration method is an empirically based model parameterized by specifying an initial (maximum) infiltration rate and a final, saturated infiltration rate. The model assumes that infiltration begins at a constant, maximum rate that decreases exponentially over time. The shape of the curve as the infiltration rate changes from initial to final is controlled by a decay rate specific to the type of soil (USEPA, 1998). The equation follows:

$$f_t = f_c + (f_o - f_c)e^{-kt}$$

where f_t is the infiltration rate at time t, f_o is the maximum infiltration rate, f_c is the saturated infiltration rate, and k is the decay constant.

Evapotranspiration (ET) Multiplier

ET rates in *SUSTAIN* version 1.0 were set globally for the system meaning that all BMPs used the same evaporation rates regardless of the type of practice. A global approach requires that the same ET rates apply to all BMPs regardless of the type of density of vegetative cover.

An evaporation multiplier was added allowing a unique multiplier value to be set for each BMP instance *in a SUSTAIN model. The multiplier is applied to the global evaporation rate (e.g., constant monthly,* time series, and so on) to account for unique evaporation conditions that are BMP specific. For example, a multiplier greater than one can be used to parameterize an individual BMP with more abundant vegetation to account for higher ET rates expected with that type of condition.

BMP Initial Moisture Conditions

Previously, *SUSTAIN* had been presented in the context of long-term, continuous simulation modeling using months or years of runoff and pollutant time series data where optimization objectives are set on the basis of annual flow or water quality targets. Traditional CSO applications commonly use a design storm approach where a synthetic precipitation event is generated on the basis of a critical condition peak intensity or rainfall depth. When performing a long-term simulation, the initial BMP conditions do not typically affect the average annual results; however, initial conditions become critical when implementing a design storm approach. For single storm events, it is expected that a BMP at field capacity will perform differently from a BMP still saturated from a recent storm. Figure 1-2 illustrates the two BMP initial condition parameters.

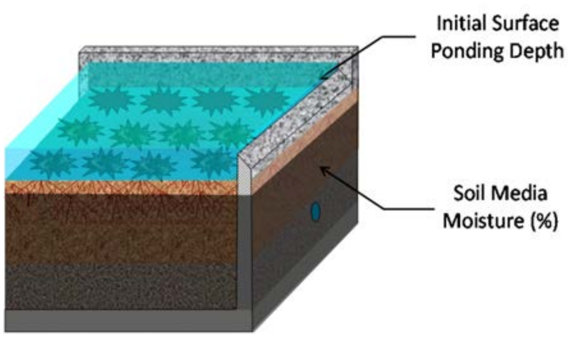

Figure 1-2. Conceptual illustration of user-defined BMP initial soil moisture parameters.

The initial water depth is the depth of water ponding on the surface of the BMP at the start of the simulation. The initial soil moisture (%) is the fraction of void space in the soil media occupied by moisture. Typically that value could be set at field capacity or the wilting point.

Area BMP

While *SUSTAIN* provided an option to model directly connected impervious area (DCIA) and disconnected impervious area using the internal land simulation option, no feature was available in the system to model it using the external land simulation option. In order to model disconnection of downspouts as a BMP in the case studies, a new practice, the Area BMP, was added to the BMP module. The Area BMP is a pervious land segment over which a portion of impervious runoff, from disconnected impervious areas like rooftops, is routed. The BMP simulation occurs only when there is no runoff from the BMP area otherwise the total inflow to the BMP is bypassed. The Area BMP simulation is an approximation to the reality where the runoff from the disconnected impervious area is routed to and simulated on the pervious area. The runoff from the disconnected impervious area is captured by the Area BMP through the infiltration (under saturated soil condition) and the surface storage. The runoff from the BMP area (i.e., pervious area) is not simulated by the Area BMP and is always bypassed. Figure 1-3 shows the conceptual flow diagram of Area BMP simulation.

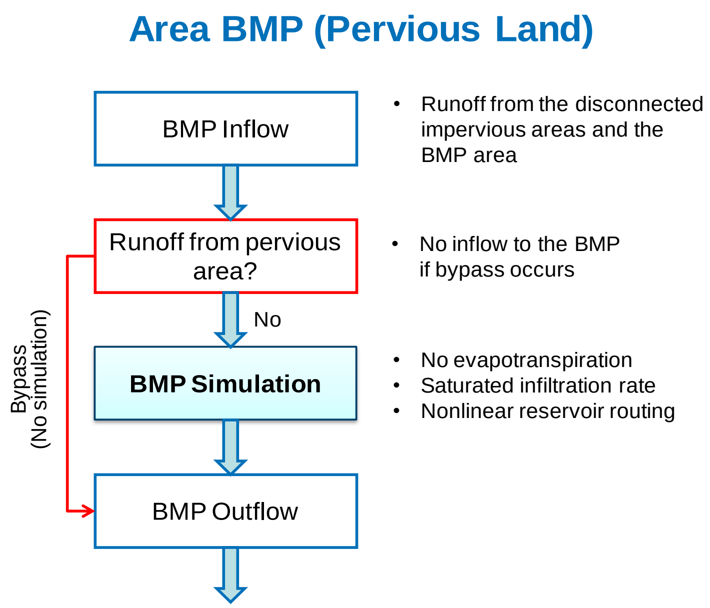

Figure 1-3. Conceptual flow diagram of Area BMP simulation.

A nonlinear reservoir routing algorithm is applied to route the surface runoff from the impervious area to the Area BMP (i.e., pervious area). This BMP does not simulate ET assuming that surface runoff already accounts for it on both pervious and impervious land. Also because runoff occurs under saturated soil conditions, saturated infiltration rate is used as a background infiltration rate. Surface runoff, Q, occurs only when the surface water depth, d, exceeds the maximum surface storage depth, d_p, in which case the outflow is given by Manning's equation:

$$Q = W\frac{1.49}{n}(d - d_p)^{5/3}S^{1/2}$$

where

Q = outflow rate (cfs),
W = pervious area width (ft),
n = Manning's roughness coefficient,
d = water depth (ft),
d_p = depth of surface storage (ft), and
S = pervious area slope (ft/ft).

The pervious area width (W) can be estimated by dividing the BMP area by the length of the representative flow path in the Area BMP.

The calibration parameters are surface storage, flow length, and slope to attenuate the flow peaks. The feature was added to model the disconnected downspouts and to optimize the percent DCIAs as a decision variable in the model. The option is available only to the external land simulation option in *SUSTAIN*.

Pump Curve

Certain management practices require an external pump to convey flow out of the BMP. In CSO applications, storage tanks are often implemented to temporarily store excess volume until the treatment plant has sufficient capacity and to which the volume can be pumped. *SUSTAIN* includes the ability to specify unique pump curves for each BMP. Pump curves define the numeric relationship between BMP water depth and pump flow rate, similar to the Type 4 pump curve available in SWMM (Rossman, 2005). Figure 1-4 presents a conceptual illustration of a pump implemented in a storage tank.

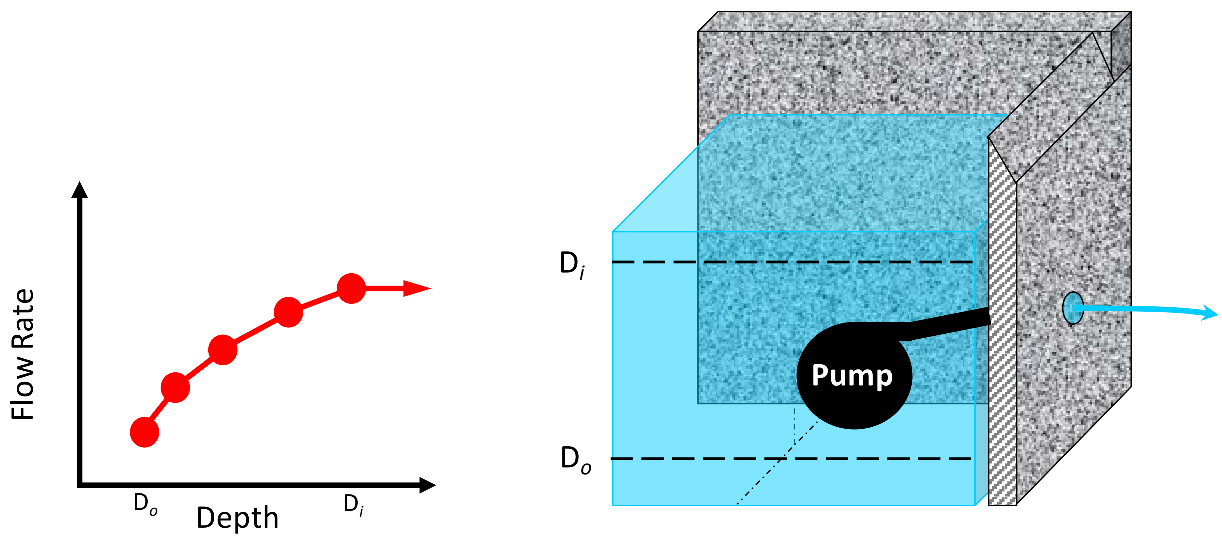

Figure 1-4. Conceptual illustration of the BMP pump curve.

The curve is represented as a table of paired water depth and flow rate values. The water depths represent the pump's operating bounds where D_o is the depth of the pump's minimum operating capacity and D_i is the depth of the pump's maximum operating capacity after which flow rate becomes constant. The pump can be implemented in a BMP that also has orifice, weir, or underdrain; however, the pump will take priority over the outlets.

1.1.4. Enhancements to the Watershed Module

The watershed module generates runoff and pollutant loads from the land through internal land simulation or importing calibrated land simulation time series. In the internal land simulation, surface runoff and water quality components are provided through an internal application of EPA's SWMM (version 5) (Huber and Dickinson, 1988) or from an external linkage to a previously calibrated watershed model. The sediment erosion process is simulated using HSPF (Bicknell et al., 2001); the particle size distribution for the eroded sediments is represented as fractional distribution of sand, silt, and clay. Table 1-3 summarizes the completed enhancements to the *SUSTAIN*'s watershed module so far as part of Phase 3 of the project.

Table 1-3. Summary of completed watershed module enhancement

Description ● = **Enhancement addresses** -- **= Enhancement does not address**	**Support regional case studies**	**Develop additional capabilities**	**Enhance existing functionality**	**Increase simulation accuracy**
Groundwater system	--	●	●	--
Horton infiltration method	●	--	●	●
Point source time series	●	●	●	●
Sub-hourly time step	●	--	●	●

Groundwater System

A subsurface aquifer component in *SUSTAIN* allows tracking water infiltrated through BMPs to the shallow groundwater system. Each subwatershed can be linked with an aquifer, the basic delineation unit of the shallow groundwater system. As in Haan (1972), the shallow groundwater is modeled as a simple linear reservoir. Groundwater discharge $G(t)$ and deep seepage $D(t)$ from the shallow groundwater storage $S(t)$ at time t are calculated as

$$G(t) = r \times S(t)$$

$$D(t) = s \times S(t)$$

where r and s are groundwater recession and seepage constants, respectively (per hour).

A recession constant can be estimated from two stream flows $F(t_1)$, $F(t_2)$ measured on hour t_1 and t_2 ($t_2 > t_1$) during the hydrograph recession as

$$r = \frac{ln[F(t_1)/F(t_2)]}{t_2 - t_1}$$

Recession constants are measured for a number of hydrographs, and an average value is used for the simulation. No standard techniques are available for estimating the rate constant for deep seepage loss. The most conservative approach is to assume that s = 0 otherwise the constant must be determined by calibration.

Horton Infiltration

The *SUSTAIN* watershed module previously included the Green-Ampt infiltration method. The Horton infiltration method is incorporated in *SUSTAIN*, as an alternative method for land simulation module, using the SWMM formulation (Rossman, 2005). This method is based on empirical observations showing that infiltration decreases exponentially from an initial maximum rate to some minimum rate over the course of a long rainfall event. The equation and the input parameters are shown under the Horton Infiltration method for BMP simulation in the previous section 1.1.3.

Point Source Time Series

While the primary boundary conditions in *SUSTAIN* are represented as runoff time series from the land, specialized applications could require the representation of other flow or pollutant time series such as flow and pollutant loading from a wastewater treatment plant. In CSO applications, dry-weather flow can account for a significant portion of the annual flow volume and, in some cases, could affect overflow events. *SUSTIAN* provides the ability to link an external time series of flow and pollutant loading to a BMP, junction, or conduit. Figure 1-5 provides an example of the required data format for external time series files.

```
154954  2001    1   1   0   0   2.88E-04    0.00E+00
154954  2001    1   1   0   15  3.05E-04    0.00E+00
154954  2001    1   1   0   30  2.46E-04    0.00E+00
154954  2001    1   1   0   45  3.37E-04    0.00E+00
154954  2001    1   1   1   0   2.35E-04    0.00E+00
154954  2001    1   1   1   15  3.33E-04    0.00E+00
154954  2001    1   1   1   30  2.82E-04    0.00E+00
```

Figure 1-5. Sample data format for point source time series.

The first column represents a station identification number and is not used by *SUSTAIN*. The following five columns represent the year, month, day, hour, and minute respectively. The seventh column represents point source flow data with units of in.-acre per time step. Subsequent columns are optional and can be used to represent corresponding pollutant loading with units of pounds per time step.

Sub-Hourly Time Step

To improve simulations accuracy for predicting peak flows and time of concentration, a sub-hourly (1 to 60 minutes) time step option was added to input the external time series with data at temporal scales finer than 60 minutes. Comparison of both watershed and BMP simulations using 60 minute and a smaller 15 minute time step were reviewed and are presented in the case study for Kansas City (Chapter 2).

1.1.5. *Enhancements for Optimization Efficiency*

Enhancements that benefit *SUSTAIN's* optimization module build credibility and increase computation efficiency in the search for cost-effective solutions. Although the proposed enhancements do not change the optimization module, they help to improve its performance and efficiency. For example, implementing a sub-hourly time step discussed in Section 1.1.4 provides increased accuracy for predicting time of concentration. It is expected that improved simulation accuracy will improve the effectiveness of the optimization module. Further improvement in system application efficiency, without a significant reduction in predicative accuracy, can also be achieved by implementing a variable time step. In a variable time step application, during the dry periods the simulation time step is increased, while during wet periods the time step is reduced, significantly reducing the number of operations that need to be performed to simulate the hydrologic response over the application period of the model. This enhancement is planned for completion as part of Phase 3 of this project.

1.2. Release of *SUSTAIN* 1.2

An updated *SUSTAIN* version 1.1 compatible with ArcGIS 10.0 with an enhanced BMP siting tool will be released in September 2011. The Version 1.1 release also includes two specific updates: (1) removing the comma delimiter from the number format (e.g., ***1,000*** is modified to ***1000***); and (2) converting the subcatchment ID for the internal land simulation input file to be unique by adding ***SC*** before the catchment ID (e.g., the subcatchment ID ***1*** is modified to ***SC1***). Version 1.1 also includes an updated copy of the step-by-step user's guide which provides guidance for users in setting up the example applications. An additional release of *SUSTAIN* version 1.2 is planned for the fall of 2011, which will include the completed system enhancements discussed in Table 1-2 and Table 1-3. The release of version 1.2 will further support adoption of *SUSTAIN* by the user community by providing additional functionality and will coincide with publications related to the case study applications in Kansas City and Louisville.

Chapter 2. Case Study: Kansas City, Missouri

EPA's Office of Research and Development (ORD) has conducted a pilot project to demonstrate the use of green infrastructure (GI) for CSO control in Kansas City, Missouri. This case study effort includes two general sets of goals: (1) management goals to inform the decision-making process; and (2) modeling goals to test system functionality and provide application guidance for the user community. The management goals of the case study were two-fold: (1) to quantify the benefit of a planned GI design in a portion of the CSO basin toward overflow reduction goals; and (2) to estimate how much additional GI, if implemented in a similar way, would be required to achieve CSO reduction goals for the basin. Likewise, the modeling goals of this effort were to (1) highlight some of the key steps associated with problem formulation and setup of a *SUSTAIN* application; (2) test the sensitivity of new *SUSTAIN* features and functions; and (3) present the lessons learned through the application process to serve as guidance for the *SUSTAIN* user community.

The focus area for this case study was the Middle Blue River watershed in Kansas City, Missouri, which includes a planned 100-acre BMP implementation/monitoring site in the Battleflood Heights neighborhood, and 86 acres of an adjacent control area where only monitoring is planned. Figure 2-1 is a map showing the pilot and control study areas in Kansas City, Missouri, and is within the combined sewer service area. Both pilot and control areas are tributary to CSO 069. The approximate location of the pilot study area is between East 74th Street and East 79th Street and is generally bounded by Paseo Boulevard to the east and Holmes Road to the west. The project combined local and regional efforts that were aimed at collecting performance data for GI practices, assessing management performance at the sewershed scale, and gathering stakeholder input into selection, design, and O&M of GI systems. This chapter first provides a brief overview of past or ongoing complementary efforts and explains how those efforts were used to inform *SUSTAIN* modeling. Second, it outlines the specific objectives of the study including steps for how the *SUSTAIN* modeling framework was applied to the selected CSO project areas to achieve each objective. The report also describes how *SUSTAIN* was used to analyze the physical system, evaluate alternatives for BMP placement, and ultimately, refine the current knowledge and understanding of the effectiveness of the selected management practices under certain conditions. The case study findings provide regional insights for GI planning and implementation for CSO mitigation. Through the case study application process, some of the key lessons learned were also summarized to provide guidance for *SUSTAIN* application for the broader user community.

2.1. Background

Parallel and complementary research efforts have been conducted in Kansas City's Middle Blue River watershed in the time leading up to this effort. This section provides (1) a brief background description of those efforts; (2) highlighted aspects of each project that was incorporated into this analysis; and (3) identification of areas where additional effort or information was needed. These efforts consist of the following:

- An *Overflow Control Plan* (OCP) (WSD, 2009) which includes an XP-SWMM sewershed model that was reviewed and refined to represent baseline stormwater runoff conditions;
- Project-specific monitoring data for a range of storm events flowing through the sewer network;
- Desktop analysis conducted to highlight BMP opportunity and cost estimates within the study area;
- A siting analysis and approved design plan of a BMP implementation strategy for the 100-acre study area; and

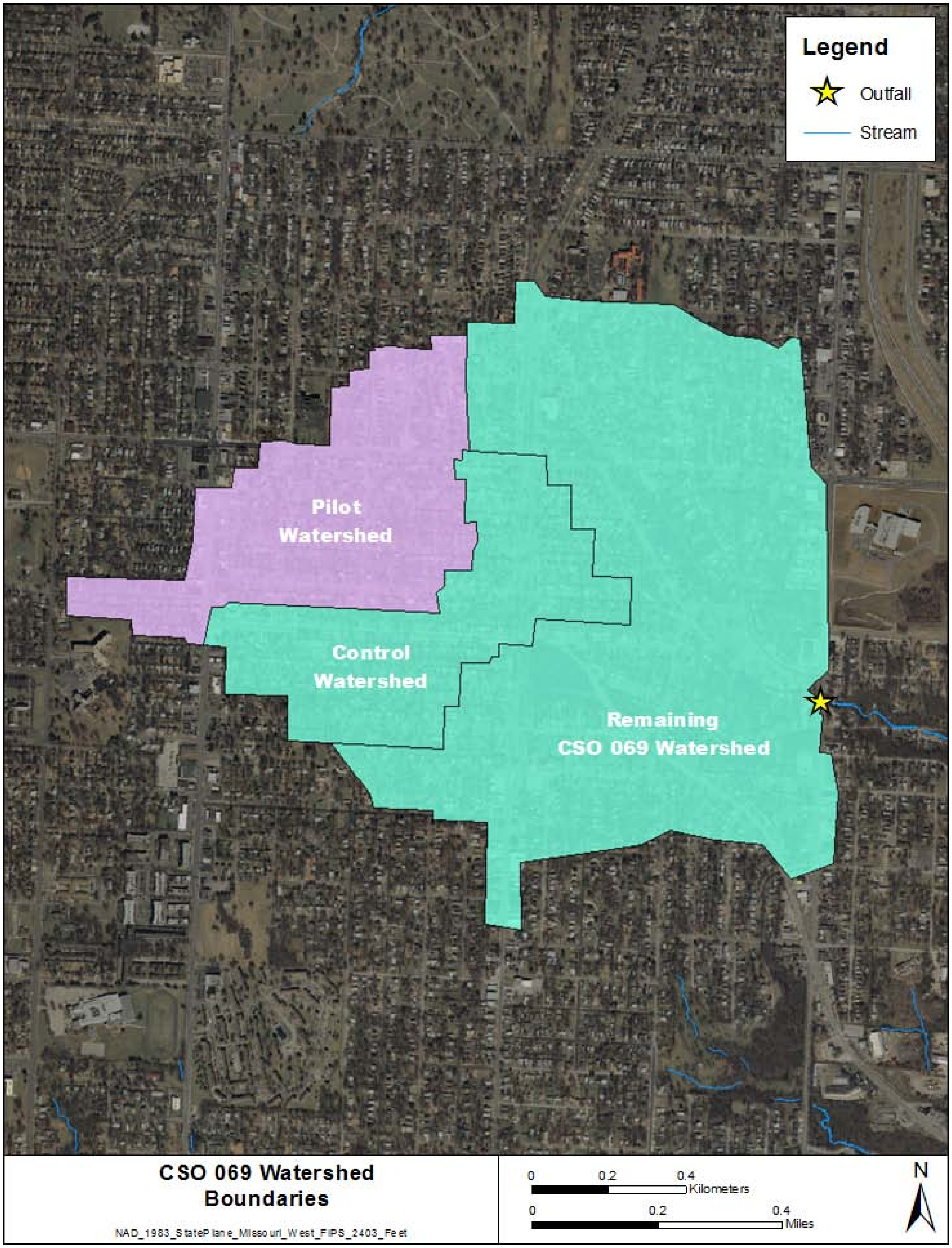

Figure 2-1. Location of pilot study area within the CSO 069 sewershed boundaries.

- Site-specific BMP performance modeling of private land areas using Source Loading and Management Model for Windows (WinSLAMM).

Each of those complementary research efforts is further described in the subsections below. After summarizing the efforts, specific objectives and outcomes were formulated for this case study as outlined in Section 2.2.

2.1.1 Overflow Control Plan: XP-SWMM Model

The Kansas City, Missouri, Water Services Department (WSD) developed an OCP to provide guidance for managing CSOs (WSD, 2009). As part of that effort, an XP-SWMM model was developed as an evaluation tool. The primary objective of the model was to quantify the storage capacity required to mitigate CSOs. The XP-SWMM model was configured for the pilot study area within the CSO 069 sewershed. It was developed as an event-based model and was not intended for long-term continuous simulation.

Synoptic statistical analyses were performed on precipitation data at (1) Kansas City International Airport—Coop ID: 234358; and (2) Kansas City Downtown Airport—Coop ID: 234359 to characterize the storm distribution for a typical meteorological year in the study area (WSD, 2009). A combined precipitation time series for long-term analysis was developed for this study using the Kansas City Downtown Airport data from January 1949 through October 1972 and Kansas City International Airport data from November 1972 through December 2004. Long-term annual average precipitation was calculated using the combined time series data from 1949 through 2004. This case study extended the record through December 2009 using the Kansas City International Airport gage data. Figure 2-2 shows variations in annual average precipitation, as well as the mean, 25^{th}, and 75^{th} percentiles.

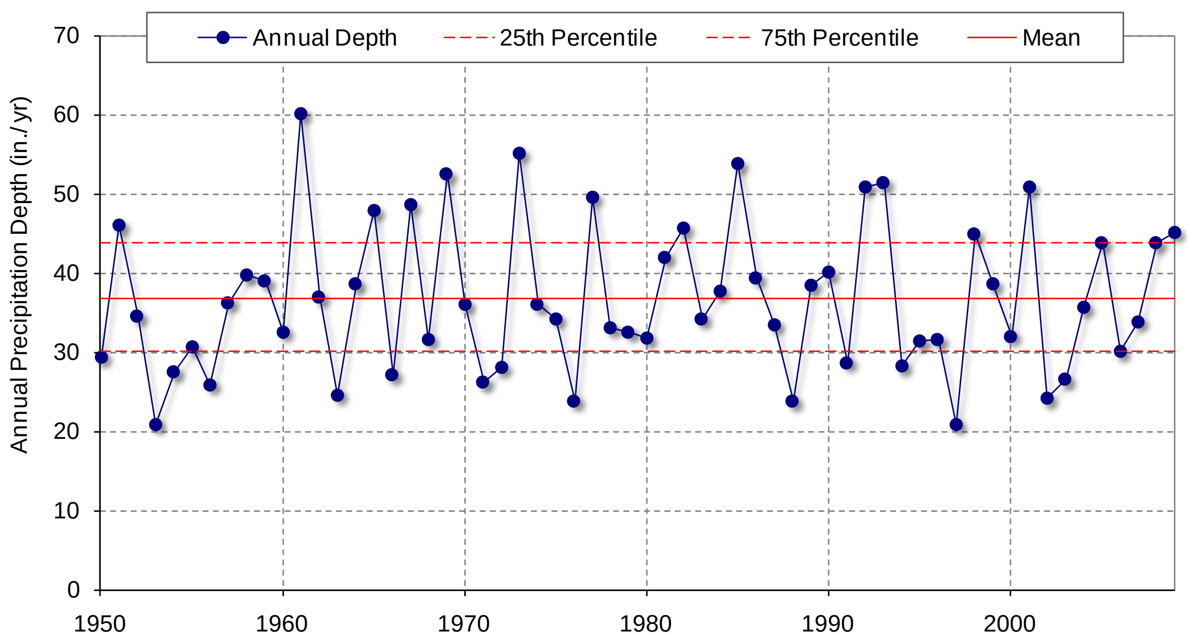

Figure 2-2. Annual precipitation for Kansas City

A set of eight types of design rainfall events was constructed to characterize Kansas City rainfall for a typical year. Table 2-1 presents a summary of the design storm characteristics that were determined as part of the rainfall analysis (WSD, 2006). The design storms total volume and duration were based on a statistical analysis of precipitation events that occurred in the recreation season (April 1 – October 30) assuming 12 hour inter-event spacing. A SCS (soil conservation service) type II distribution was applied to the overall events, with some adjustments made to ensure that peak intensity matched historic records (WSD, 2006). The table corresponds to the information shown in Figure 2-3. Those design storms were used with the XP-SWMM model to predict CSO response and identify the critical condition storm size. WSD has stipulated an allowable overflow frequency criteria of 6 events per year at CSO 069, which corresponds to the type D design storm (D-storm: 1.4 in. depth, 0.6 peak in./hr intensity, 16.75 hr duration).

Table 2-1. Summary of design storms used for CSO control plan

Return period	Type	Depth (in.)	Peak (in.)	Duration (hr)	Annual exceedance frequency[a]	Annual number of events[b]
0.33 month	A	0.28	0.16	6.00	36	18
0.67 month	B	0.52	0.25	8.75	18	6
1 month	C	0.86	0.38	12.25	12	6
2 months	D	1.40	0.60	16.75	6	2
3 months	E	1.80	0.73	19.75	4	1
4 months	F	2.00	0.82	21.00	3	1
6 months	G	2.40	0.95	23.75	2	1
12 months	H	2.90	1.20	26.75	1	1

Source: WSD 2006

a. Average number of events per year with total depth and peak intensity equal to or exceeding the design storm.

b. Average number of events per year with similar depth, intensity, and duration characteristics to the design storm.

A synthetic storm distribution (Table 2-1) for a typical year indicates that on average, Kansas City experiences 78 rainfall annual events. Of those events, those with depths greater than 0.28 in. were shown to result in overflows at the 069 outfall (WSD, 2006). Figure 2-3 is a histogram of a typical annual storm distribution.

2.1.2. *Site-Specific Monitoring Data*

Additional data were collected after the development of the XP-SWMM model, which was originally done as part of the OCP. In 2009 and 2010, a total of 20 runoff events were monitored at the outfall of the 100-acre pilot study area in addition to the original four events from 2008. Of the 20 new events, some showed very minimal response at the outlet (i.e., flow was less than 5 cfs), and some of the events had no coincident precipitation data at the local gage. Nevertheless, 10 events were identified between 2008 and 2010 for which (1) coincident precipitation data existed; and (2) which generated flows greater than 5 cfs at the monitoring site. The observed precipitation associated with the monitored events were compared against the long-term historical precipitation record at the nearby Kansas City International Airport gage to get an idea of how representative the monitored events were of the larger, critical condition events associated with overflow. A storm event separation analysis was performed on the long-term precipitation data recorded between 1949 and 2009. Storm separation assumed a 12 hr inter-event time consistent with WSD's design storm analysis, and a minimum storm size of 0.1 in (WSD, 2006). After storm separation, 10 equal percentile bins were established for the storms in the historical record, according to ranges of the resulting storm event volumes. Figure 2-4 is a histogram of the rainfall associated with the 10 monitored events against the long-term historical precipitation record at Kansas

City International Airport. The graph suggests that the monitored storms (and associated pipe flow) between 2008 and 2010 are representative of larger storm events that cause CSO in the 069 sewershed. The data were used to calibrate and establish a model baseline, as further described in Section 2.2.1.

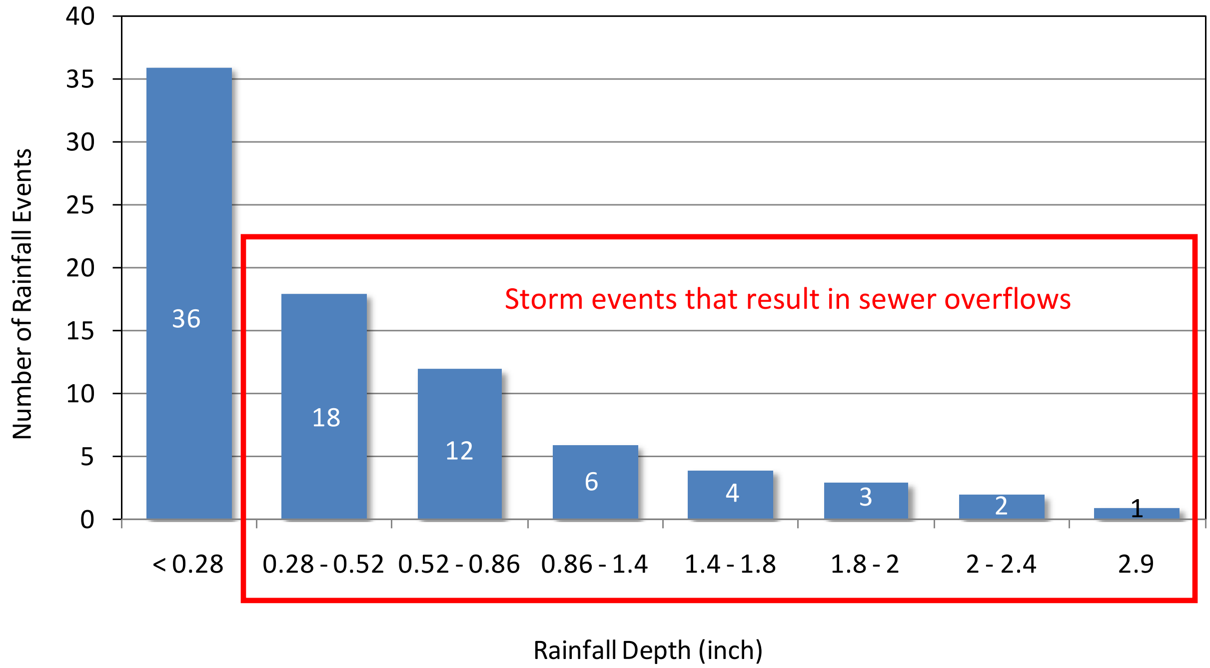

Figure 2-3. Storm size distributions for a typical Kansas City meteorological year.

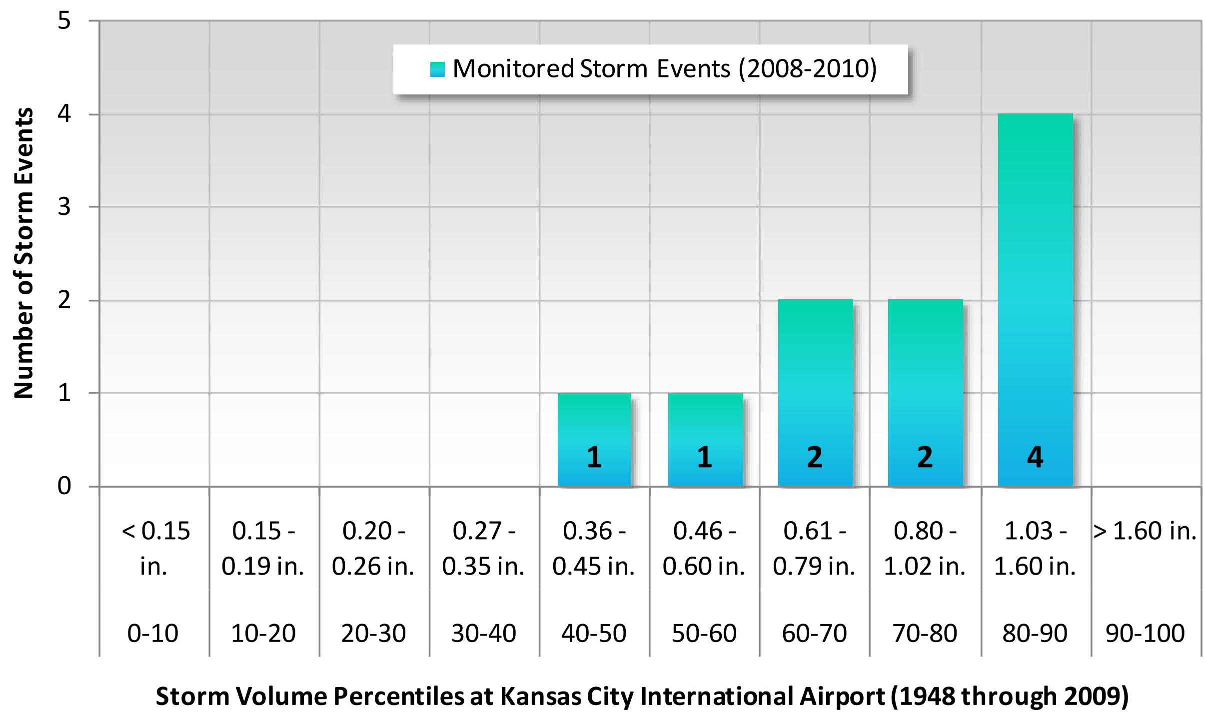

Figure 2-4. Histogram of monitored against the long-term historical precipitation record.

2.1.3. *Green Alternatives for Sewershed 059 & 069 Technical Memorandum and Overflow Control Plan*

The Kansas City, Missouri WSD conducted a desktop analysis and subsequently published a technical memorandum, *Green Infrastructure Alternatives for Outfalls 059 & 069* (WSD, 2008), which quantifies the costs associated with modifying the CSO controls presented in the May 6, 2008, draft *OCP Summary* for two outfalls in the Middle Blue River basin. That study included considerations for incorporating both conventional *gray* infrastructure (i.e., intermediate underground storage) and conservational GI technologies for mitigating CSO. Areas tributary to the two outfalls were identified as most likely to be improved through implementing a combination of green and gray solutions.

Approximately 744 acres of the Middle Blue River Basin tributary were selected for the desktop analysis. The desktop analysis area encompasses outfalls 059 and 069; however, the 069 drainage area was selected as the focus of this case study. The desktop study made the assumption that a gallon of stormwater storage was sufficient to control a gallon of CSO discharge for the selected event. The analysis did not include modeling of the BMP and drainage network, but rather evaluated opportunities to place BMPs on either public or private property. The desktop screening analysis included some basic volume estimates to approximate storage requirements for the catchment, its simplified flow-accounting approach did not attempt to represent cumulative impacts and benefits. A collection of well-distributed GI management practices throughout the sewershed was envisioned to provide some additional storage requirements. The desktop analysis included a basic evaluation of specific GI storage technologies that are expected to be used in the study area, which consisted of the following:

- Inlet retrofits in road and street rights of way;
- Curb extension bioretention;
- Replacing sidewalks in road and street rights of way with permeable pavement;
- Replacing pavement outside of road and street rights of way with permeable pavement; and
- Converting roof areas to green roofs.

Gray infrastructure options included a combination of underground storage tanks with screening facilities and outflow pumping stations. Compared to the other alternatives considered, the gray infrastructure practices represent the highest overall capital cost, in terms of unit cost per gallon stored. For the 069 sewershed, the desktop analysis suggested that it would be more cost-effective to either replace or supplement the gray components with GI alternatives without adversely affecting the desired level of control at the respective outfalls. Table 2-2 is a summary of gray infrastructure controls at CSO 069.

Table 2-2. Gray infrastructure CSO controls for outfall 069

Control component	Estimated capital cost (million dollars)[a, b]	Storage provided (MG)[a]	Capital cost per gallon stored (dollars)[a]
2 MG storage tank 1.5 MG per day pumping station 51 MG per day screening 100 ft, 48 in. Sewer 500 ft, 12 in. force main Odor control	$30.6	2.0	$15.30

a. Source: WSD, 2008

b. Includes a 25 percent allowance for planning, engineering and design, and an additional 25 percent contingency.

Other considerations must be taken into account when comparing the cost-benefit of GI versus gray infrastructure. For example, the gray infrastructure solution presented in Table 2-2 requires 2.0 million gallons (MG) of storage volume, which assumes that pumping from storage occurs during the most intense 6 hours of the design storm. A GI solution must provide storage volume *greater* than 2.0 MG because of the additional pumping capacity otherwise represented in the gray storage tank. Accounting for the additional pumping capacity, the required storage volume of GI must equal that of gray infrastructure storage plus 6 hours' pumping volume (an additional 0.375 MG), which results in a total GI storage capacity of 2.375 MG (WSD, 2008). According to the original desktop analysis results, the estimated capital cost to develop 2.375 MG of GI storage in the area tributary to outfall 069 is approximately $24.6 million—a $6 million dollar (≈ 20 percent) savings (WSD, 2008). It is important to note that cost information published in this study represented capital costs only and no O&M costs were included.

In January 2009, the Kansas City, Missouri WSD released the full text of its OCP. The plan cites some uncertainty associated with the performance of GI in mitigating overflow volumes at the outfalls. As a result, the GI capital budget proposed by the desktop analysis was increased by approximately 30 percent, bringing the original desktop analysis estimate of $24.6 million up to a value of $32 million (WSD, 2009). Following the adjustment, the updated plan suggests that gray infrastructure might be a more cost-effective solution. Nevertheless, while the full cost of gray infrastructure is a public burden, GI offers the possibility for cost sharing through public-private partnerships. In addition, GI provides other benefits not offered by gray infrastructure. The OCP also proposed an annual budget of $2 million for O&M costs associated with GI upstream of outfalls 059 & 069.

Another result of the desktop study was the selection of the 100-acre pilot study catchment that services the Battleflood Heights neighborhood. The desktop study recommended further investigation of BMP placement opportunity, associated costs, and a quantification of GI benefits. In addition, the pilot study site was targeted to receive the first phase of implementation activity, for which significant pre- and post-implementation monitoring would be performed.

2.1.4. *Middle Blue River Green Solutions Pilot Project*

The design plan represents a culmination of efforts. In April 2009, WSD published a *Draft Conceptual Design Report* for the Middle Blue River Pilot Study (WSD, 2009). Those designs were based on a combination of XP-SWMM hydraulic modeling analyses performed by Burns & McDonnell Engineering Company, Inc. (for the pilot area) and HDR (for the entire Middle Blue River combined sewer area) as part of the OCP development (WSD, 2009). URS Corporation ultimately developed the final BMP designs for the 100-acre pilot study site, called the Middle Blue River Green Solutions Pilot Project. This section provides a general overview of the design plan components. Section 2.4.1 describes how these BMPs were represented in the *SUSTAIN* optimization model.

The BMP design plan for the 100-acre pilot study area includes 158 individual surface features, plus 21 supplemental underground storage pipe systems that were designed to retain BMP overflow and underdrain outflow from selected bioretention and porous pavement structures. Figure 2-5 is a map showing the locations of the surface features.

Table 2-3 summarizes the various surface and subsurface structural components from the design plan. Figure 2-6 through Figure 2-11 are example excerpts of schematic drawings from the final BMP design plan (URS, 2010). These schematic drawings are also cross-referenced in Table 2-3 for each of the unique design plan component categories.

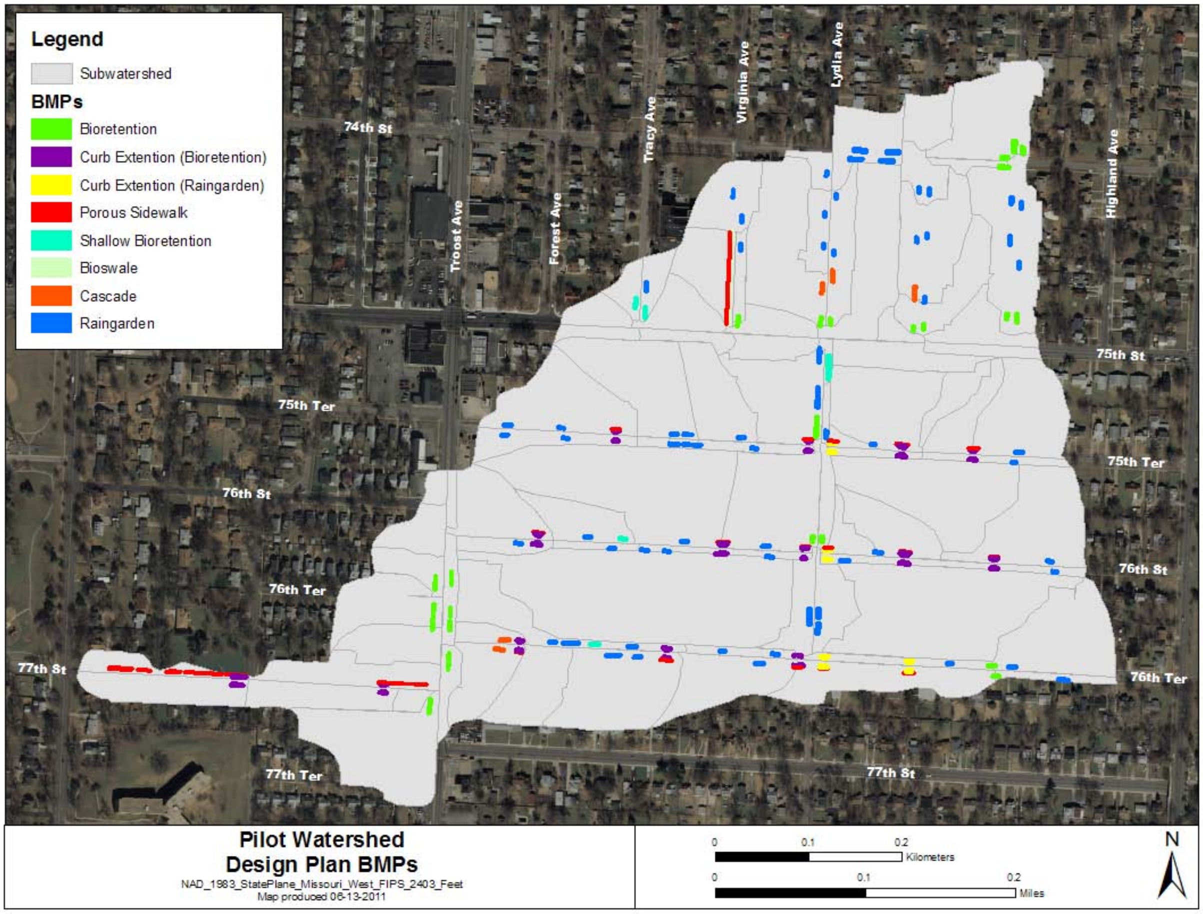

Figure 2-5. BMP layout in the 100-acre pilot study area.

Table 2-3. Summary of BMP design plan components

Design plan component	Structural description	Number of BMPs	Figure reference
Bioretention	Bioretention without curb extension	24	Figure 2-6
	Curb extensions with bioretention	28	
	Shallow bioretention	5	
Bioswale	Vegetated swale infiltrates to background soil	1	Figure 2-7
Cascade	Terraced bioretention cells in series	5	Figure 2-8
Porous sidewalk or pavement	With underdrain	18	Figure 2-9
	With underground storage cubes	5	
Rain garden	Rain garden without curb extension	64	Figure 2-10
	Curb extensions with rain gardens	8	
Below grade storage	Retains BMP overflow and underdrain outflow from selected bioretention cells or porous pavement	21	Figure 2-11

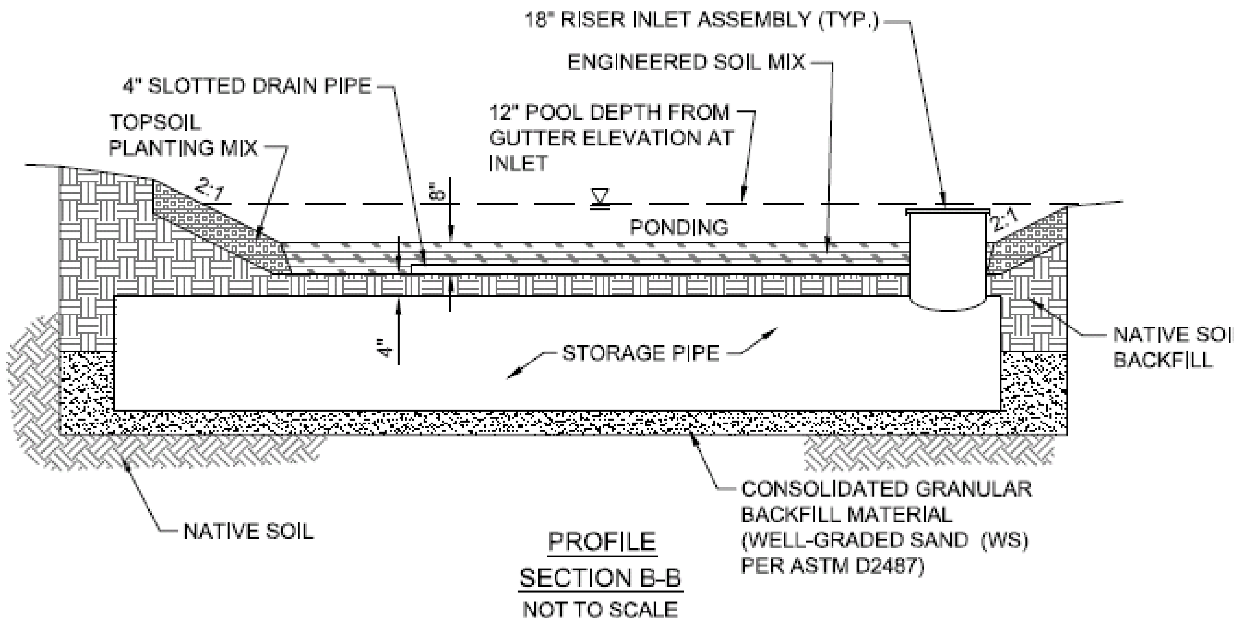

Figure 2-6. Bioretention with underground storage cross-section profile.

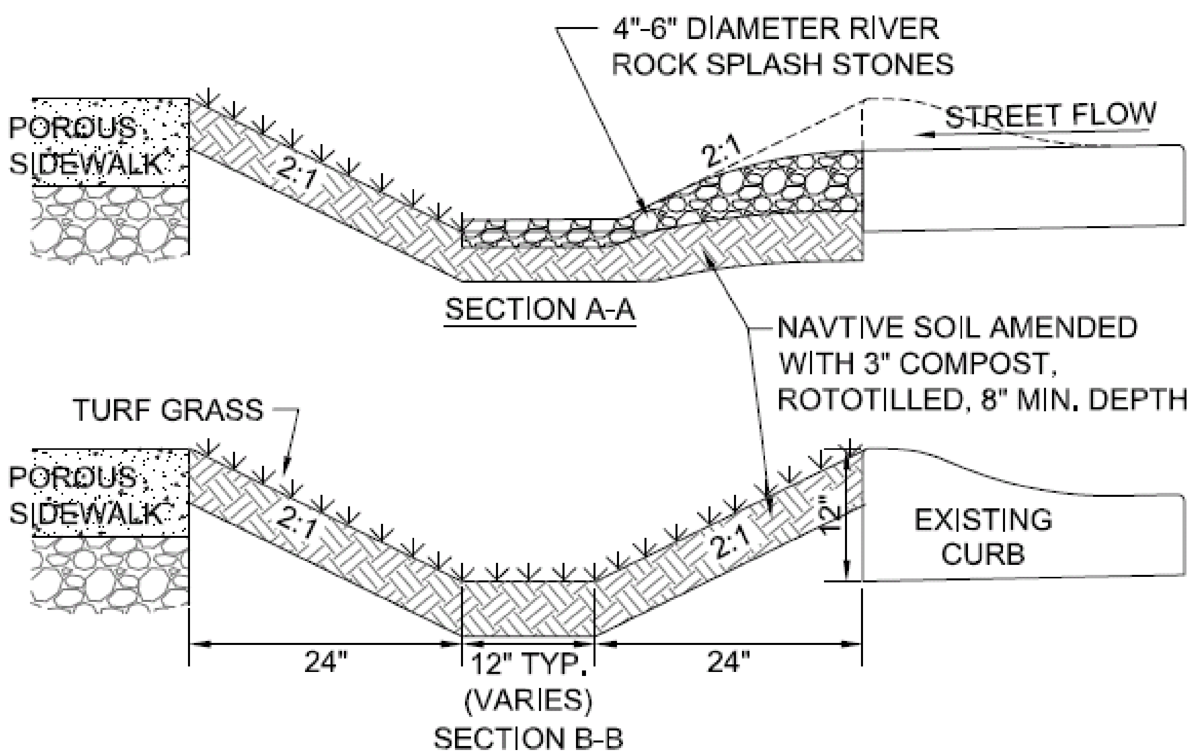

Figure 2-7. Bioswale cross-section profiles.

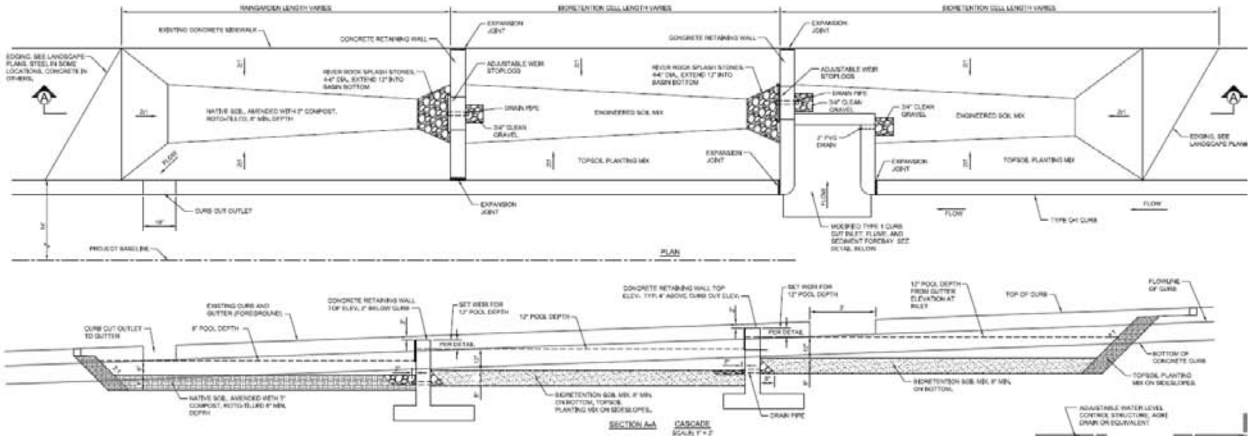

Figure 2-8. Cascade plan view and cross-section profile.

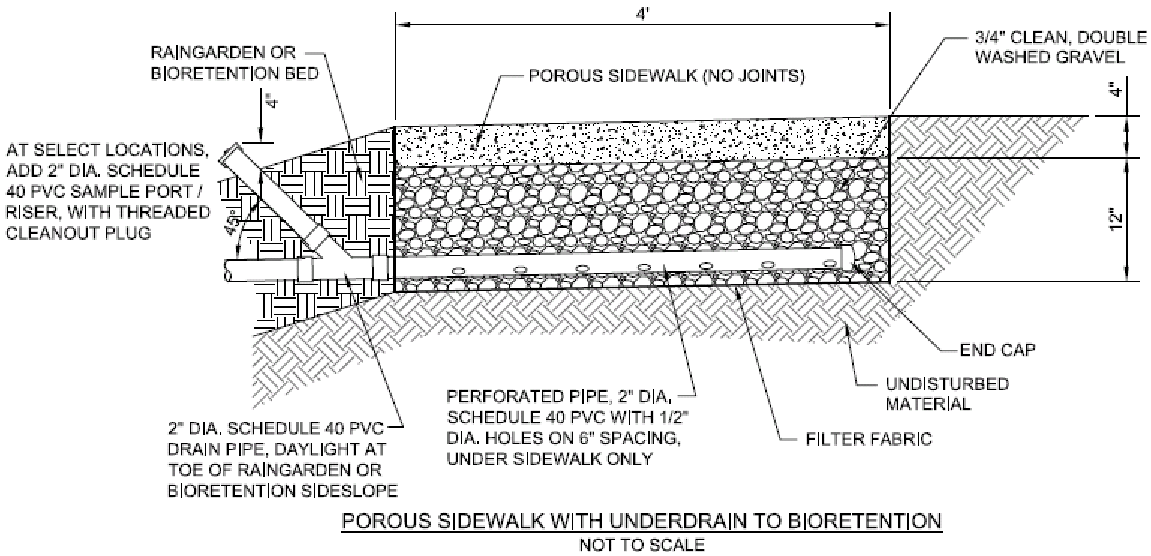

Figure 2-9. Porous sidewalk cross-section profile.

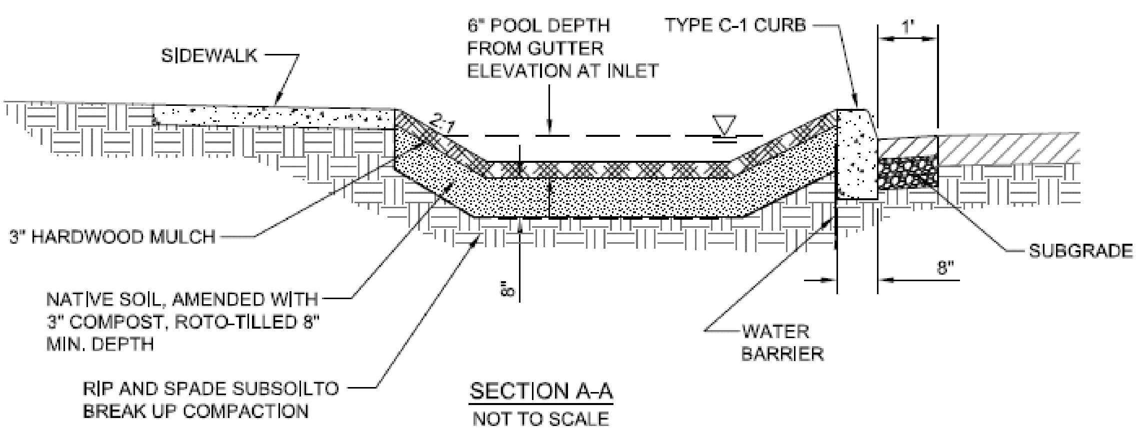

Figure 2-10. Rain garden cross-section profile

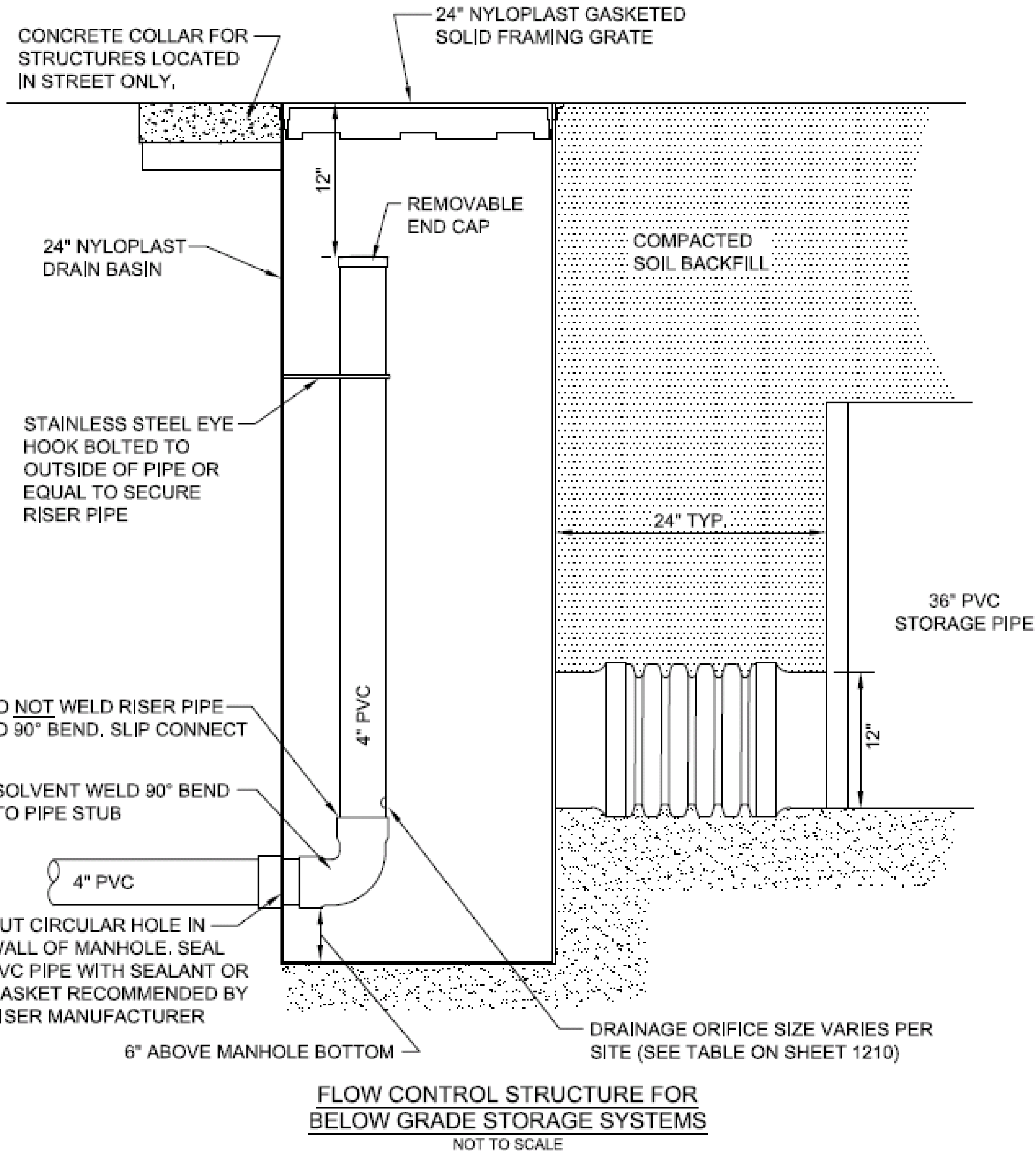

Figure 2-11. Below-grade storage outlet structure.

All the BMPs were planned for construction within the public rights of way and were developed using field surveys and feasibility assessment. The factors influencing BMP selection included the width of the right of way, slope, soils, utility lines, physical obstructions, and public acceptance. The total estimated storage capacity provided by all the BMPs is approximately 300,000 gallons, which corresponds to about 56 percent of the total D-design storm runoff volume. The BMPs receive runoff from the streets through road side curb and gutter, and release the flow back to the sewer network through underdrain and outlet structures (for treated flow) or through overflow structure (for untreated bypass flow).

It is important to note that the objective of this case study is not to evaluate the effectiveness of the proposed design. This case study recognizes that some site-specific elements of engineering design cannot be fully addressed in a modeling application alone without verification on the ground. For that reason, the proposed design is accepted as the best recommended solution within the pilot area because it has been derived from on-the-ground engineering and design surveys. Nevertheless, some of the expected outcomes of this case study are (1) to quantify the relative contribution of the proposed plan toward CSO mitigation in the context of the larger sewershed; and (2) to evaluate the CSO mitigation benefit of extrapolating similar design guidance throughout the remainder of the 069 sewershed.

2.1.5. *WinSLAMM Modeling for Private Residential BMPs*

As a parallel effort, WinSLAMM is being used to evaluate the water quality and quantity improvement benefits of a large-scale application of GI control practice retrofits in the same pilot sewershed that was identified by the desktop analysis study (the 100-acre catchment servicing the Battleflood Heights neighborhood). That effort was conducted in conjunction with the previously described Middle Blue River Pilot Study, a complementary EPA ORD demonstration project to quantify benefits associated with advanced drainage concepts using GI for CSO control in Kansas City. The difference between the WinSLAMM application and this case study is that the WinSLAMM effort focused on BMP practices for private property as supplementary management to the practices designed in the public right of way. The WinSLAMM model was used to evaluate the runoff reduction benefit from the following types of BMPs (Pitt and Voorhees, 2010):

- Residential rain gardens;
- Rain barrels for turf irrigation;
- A combination of residential rain barrels and rain gardens; and
- Disconnected residential roof runoff controls.

The WinSLAMM model was applied using a long-term, continuous simulation approach, which generated time series of flow for various types of upland controls on private parcels. The goal of the WinSLAMM study was to quantify individual private parcel BMP performance. Private parcel BMP cost information was not a part of the initial phase of that study; therefore, there was no assessment of the cost-benefit relationship of private parcel implementation of GI. For the purposes of this current case study, cost estimates were derived from other sources, as described in Section 2.5.3.

2.2. Overview of Case Study Objectives

As previously noted, this case study had two general categories of objectives: (1) CSO management objectives that inform the decision-making process; and (2) modeling objectives that test *SUSTAIN* functionality and provide application guidance for the *SUSTAIN* user community. Section 2.1 provides a summary of some of the recent research efforts in Kansas City. The most relevant information was highlighted from each of those efforts; also, key areas where additional needed information was identified. That evaluation formed the basis for the set of expected outcomes for this case study outlined in this section. This case study aims to build on previous research efforts, while avoiding overlap or redundancy of work products, in an effort to identify new information that will guide the decision-making process with regard to CSO modeling and implementation of controls. Table 2-4 summarizes key research questions and shows how the *SUSTAIN* case study application interfaces with each complementary research component.

Table 2-4. Decision-making questions and expected outcomes by study

Key research questions addressed by study: ● = Study directly addresses ⊙ = Incorporated from a previous study -- = Study does not address	**XP-SWMM model**	**Updated monitoring**	**BMP design plan**	**Desktop analysis and bid data**	**WinSLAMM application**	***SUSTAIN***
What is the regional rainfall-runoff response relationship?	●	●	--	--	--	●
What are suitable GI practices within the public rights of way for the 100-acre pilot site?	--	--	●	--	--	⊙
What are typical costs associated with different types of regional management alternatives?	--	--	--	●	--	⊙
What are the benefits of implementing GI practices on private parcel in the region?	--	--	--	--	●	⊙
What is the cost-benefit relationship associated with: (1) extrapolating the proposed pilot study BMP design plan throughout the sewershed, (2) adding GI on private parcels, and/or (3) constructing a storage tunnel at the regulator for CSO mitigation at the sewershed outlet?	--	--	--	--	--	●
At what level of management (1), (2), or (3) above, are CSO 069 mitigation objectives projected to be achievable?	--	--	--	--	--	●

Both (1) management and (2) modeling goals can be summarized into four focused objectives for this effort, as listed below:

1. Demonstrate a process for establishing and confirming a model baseline condition;
2. Evaluate the computational validity and performance efficiencies associated with different degrees of drainage network resolution and articulation;
3. Apply optimization to identify the degree(s) of management required to mitigate CSOs; and
4. Test the sensitivity of simulation time step on predicted optimization results.

The broader case study goals were first defined at the onset of the effort; but they were further refined during the model setup, application, optimization, and results interpretation process. A strong emphasis has been placed on describing the *SUSTAIN* application process, and specifically, on clearly defining the modeling application objectives. The defined objectives directly influence (1) the direction and complexity of each component of the analysis; and (2) the expected outcomes of the effort—how successful achievement of the articulated objectives will be measured. Each of the refined case study objectives is described in greater detail in the sections below.

2.2.1. *Establishing a Sewershed Model Baseline*

The sewershed model baseline represents the existing condition rainfall-runoff response. It characterizes the nature of the current physical system before any new management activities are implemented. It also represents the reference point from which any stormwater improvement will be measured, as well as the starting point for BMP selection and placement optimization. Because it forms the basis for comparative assessment of target achievement, establishing a representative baseline condition with a high degree of confidence in its applicability is a critical first step in any modeling effort. It becomes especially important where cost-benefit optimization of future management objectives is a primary focus of the modeling effort. It is necessary to ensure that the *SUSTAIN* baseline representation is:

- Reflective of existing landscape features and behavior;
- Adequately responsive to critical rainfall conditions;
- Able to reproduce observed flow data within accepted metrics (WaPUG, Nash-Sutcliffe, 2002); and
- Able to be meaningfully extrapolated to areas outside the modeled 100-acre pilot project site.

As a secondary benefit of the case study (in terms of model development objectives), documenting the step-by-step modeling process associated with establishing a *SUSTAIN* baseline sewershed model can serve as a valuable reference contribution for the broader user community.

2.2.2. *Simplifying the Network Articulation for Large-Scale Extrapolation*

SUSTAIN provides different ways of handling issues of scale in modeling. For small-scale settings, it can be both feasible and practical to use a fully articulated routing network, meaning that each pipe connection, BMP size and location, and associated drainage area is explicitly defined. For larger-scale applications, using a fully articulated approach often becomes cumbersome and impractical because of the size and complexity of the associated network. *SUSTAIN* provides an aggregated BMP option that simplifies the complexity of the specified drainage network while attempting to preserve the physical basis of the BMP components and interactions. When the aggregate BMP approach simplifies the complexity of the network, it sacrifices some detail of the model representation. This case study tests the use of a simplified aggregated approach versus the fully articulated routing network. Three natural questions arise:

- How much network simplification is tolerable without significantly compromising model accuracy or precision or both?
- What components of a fully articulated BMP and drainage network are appropriate candidates for aggregation, and to what degree can they be aggregated?
- How much computational advantage does the aggregate BMP approach provide?

Another ancillary product and objective of this case study through investigating those questions, is that it provides a reference for comparative analysis configurations and performance for varying degrees of model network articulation and complexity.

2.2.3. *Optimize BMP Opportunity for CSO Mitigation in the 069 Sewershed*

A third listed objective of this case study effort (though central for the local decision-making process), is to evaluate the degree of management required to mitigate CSO throughout the larger 069 sewershed, in which the pilot study site is located. The BMP design plan for the 100-acre pilot area focuses on suitable GI practices in the public rights of way. The design plans were developed using on-the-ground engineering for feasibility and best professional judgment, though it is recognized that additional physical opportunities for implementation of BMPs exists outside those that were included in the design plan (WSD, 2010). This case study uses the project as designed within the 100-acre pilot sewershed, as a boundary condition in the baseline model for optimization.

At this stage of the case study application is where synthesis of the previously described components occurs. After establishing an optimization model baseline condition (Objective 1) and proving the validity of a streamlined spatial representation of the proposed BMPs (Objective 2), the third case study objective builds on those efforts to quantify the degree of management that is required to mitigate CSOs for the 069 sewershed as follows:

1. Extrapolate the proposed GI design plan for public rights of way to the remainder of the sewershed, where GI design plans have not yet been developed;
2. Expand optional GI opportunity on private parcels (as defined by additional WinSLAMM application) as needed to supplement public BMPs (Pitt and Voorhees, 2010); and
3. Evaluate suggested gray infrastructure storage options at the sewershed outlet regulator.

It is important to note that the optimization process follows a predetermined step-wise sequence for this study. Some inherent constraints have already been factored into developing that sequence, including construction accessibility, O&M costs, and some of the known relative cost and implications of constructing gray versus GI opportunity. In addition, optimization will be performed using a selected target design storm for CSO mitigation. The optimized solution will be validated using continuous simulation for a representative year to see if the number of overflows predicted confirms that the proposed design objectives for the basin has been met.

2.2.4. *Evaluate the Influence of Model Time Step on Optimization Results*

While *SUSTAIN* 1.0 (USEPA, 2009) used a fixed hourly time step, version 2.0 will offer more flexibility. The selected simulation time step can have an influence on model performance and behavior. The fourth and final case study objective is to characterize the influence of model time step on model performance, and ultimately, on the selected optimization results. Such a sensitivity analysis will be performed in conjunction with the optimization modeling sequence previously outlined in Section 2.2.3, and will provide guidance to the user community in selecting a suitable simulation time step for modeling.

2.3. Establishing a Sewershed Model Baseline

In *SUSTAIN*, stormwater runoff from the sewershed model is the forcing function that drives BMP simulation. Sewershed models use site-specific spatial and temporal elements to characterize the rainfall runoff response. The sewershed model time series represent the existing condition (or baseline), which serves as the reference point from which stormwater improvement will be measured. A critical first step of a *SUSTAIN* application is to establish or confirm a representative baseline condition with a high degree of confidence in its applicability. That becomes especially important in the context of cost-benefit optimization of future management objectives, because the model baseline is foundational to results interpretation and resulting conclusions. It is important for the sewershed model baseline condition to appropriately represent variability throughout the sewershed. It needs to consider the influence of physical features associated with both surface and subsurface behavior.

An event-based modeling effort was conducted as part of the Middle Blue River Pilot Study by using the XP-SWMM modeling platform version 9.50 (WSD, 2009). Review of this effort showed the model was configured using a catchment approach where parameters like slope, flow length, and depression storage can vary for each subcatchment. The model assumes that only runoff from DCIA reached the CSO network. As a result, the model was primarily calibrated by adjusting the ratio of DCIA per subwatershed. Because the model was run for a single storm event, it used fixed initial conditions with no consideration for the influence of ET. Calibration results were presented for two storm events that occurred in fall of 2008.

SUSTAIN provides the user an option to link to an existing sewershed model using unit-area (one acre) time series for each land unit or hydrologic response unit (HRU) for representing land rainfall-runoff responses as boundary conditions. The runoff time series can be generated using any watershed model (e.g., HSPF, SWMM) that meets the temporal and spatial resolution requirements. For this application, HRUs were developed using unique combinations of select physical features: (1) impervious elements;

(2) hydrologic soil type; and (3) slope. SWMM5 was used to generate the unit-area runoff time series for each HRU type. *SUSTAIN* associates the time series with the HRU distribution in the delineated drainage area. The unit-area runoff time series for each HRU is multiplied by the HRU area within each catchment to derive the total volume and pollutant loads boundary conditions BMP simulation. A GIS representation of the unique HRU elements serves as the physical link that *SUSTAIN* uses to tabulate distributions within each catchment. For this application, one important advantage that the HRU approach offers over the traditional catchment approach is that it provides a level of consistency that carries across spatially to other areas outside the immediate 100-acre pilot study that were not otherwise explicitly monitored or modeled.

Other spatial characteristics of the baseline model representation were considered. For this application, there was a desire to simplify the size and complexity of the network within reason in a way that minimized distortion of system behavior and response. It is important to note that the level of model sophistication should match the required response and purpose of the application. In the context of sewershed optimization modeling, any reduction in the model's computational time demand for a single run will translate to potentially significant savings when thousands of runs are required for a solution; however, care should also be given to preserve required level of model accuracy for the specific application.

This section describes the steps taken to develop a baseline sewershed model condition. Those steps consist of: (1) HRU development; (2) subcatchment delineation; and (3) model calibration. The following sections describe each step in greater detail.

2.3.1. *Development of Hydrologic Response Units*

In a sewershed model, land unit representation should be sensitive to the features of the landscape that most affect hydrology, including surface cover, soils, and slope. In urban areas, it is important to estimate the division of land use into pervious and impervious components. Because the focus of this study is volume control, it is not as important to further subdivide land use beyond pervious and impervious cover; however, rooftop areas were distinguished from other impervious areas to facilitate rerouting of downspout flow as a management alternative. Because the CSO 069 sewershed contains mostly older urban soils and basic infiltration parameter guidance was available from existing XP-SWMM modes, soil type was not used as a distinguishing element for HRUs. When hydrologic soil groups are not homogenous in a sewershed, further subdividing pervious land cover according to hydrologic soil group can provide a higher degree of resolution. Slope might also be an important factor in some areas, especially where slope varies noticeably. For this case study, the combination of slope and surface cover (pervious, impervious, and rooftop) was used to define HRUs for the CSO 069 sewershed. This section details the HRU development processes.

Slope Analysis

For the slope analysis, a GIS data set of 2 ft topographic contours provided by WSD was used. The contours were interpolated into a 10 ft raster representing surface elevation. Slope for each grid cell was calculated from the digital elevation model and classified into three categories (1) low slopes less than 1.5 percent; (2) medium slopes between 1.5 and 3.5 percent; and (3) high slopes above 3.5 percent. Although slope does not vary dramatically in the study area, catchment slope was a calibration parameter that was varied spatially in the previous XP-SWMM application. Including slope in the HRU development process provided a way to capture some of the spatial variation across the sewershed. A map showing the distribution of slope categories developed for the CSO 069 sewershed is presented below as Figure 2-12. The sewershed is fairly flat, with the highest slopes occurring at ravines adjacent to tributary banks.

Surface Cover Analysis

For this analysis, GIS data sets for roads, impervious surfaces, and building rooftops provided by WSD were used. The roads layer contained the footprint of the typical road rights of way. The impervious surfaces layer included features such as sidewalks, driveways, parking lots, and other distributed impervious surfaces. The building footprint layer was used to represent rooftop area in the sewershed. Those three layers were merged into a single raster representation, with rooftops distinguished from other types of impervious cover. The disconnected areas between impervious features were treated as pervious land. A map showing the distribution of surface cover types for the CSO 069 sewershed is presented below as Figure 2-13.

Hydrologic Response Units

An overlay of slope and surface cover type was created using the two raster layers described above. This overlay resulted in a distribution of seven unique combinations of HRUs that capture both the topographic and physical texture of the sewershed. Figure 2-14 is a map showing the resulting HRU distribution within the CSO 069 sewershed.

2.3.2. *Subcatchment Delineation*

In the original XP-SWMM model configuration for the Middle Blue River Pilot Study, the pilot watershed was divided into 179 subcatchments ranging in size from 0.065 to 3.091 acres. For catchment based models such as SWMM, having more subcatchments provides more latitude for creating a spatially variable response. In other words, a higher resolution better approximates a distributed parameter response. However, increasing the number of subcatchments and connections also increases the complexity and run-time for a single model run. By implementing an HRU-based approach, some of the heterogeneity of the system gets transferred away from the catchment into the land cover distribution. As a result, the catchment resolution and the number of network connections can be judiciously aggregated without sacrificing too much of the spatial variability of the runoff response.

The 179 subcatchments were aggregated to 85 for model calibration on the basis of coincident and nested drainage areas, while the number of modeled pipe segments was reduced from 350 down to 36. Figure 2-15 illustrates how several XP-SWMM subcatchments were aggregated into one subcatchment. Much of the spatial heterogeneity within the grouped subcatchment is preserved by using an HRU representation. Note that the sewershed model boundaries provided with the XP-SWMM model were based on the topographic boundaries, while the sewershed boundaries are based on the sewer network. The percent difference in total drainage area associated with these two models is less than two percent. A comparison of the HRU distributions within each of the two different delineated boundaries was reviewed and is presented as Figure 2-16. The difference is wholly attributable to the difference in watershed versus sewershed drainage area boundaries.

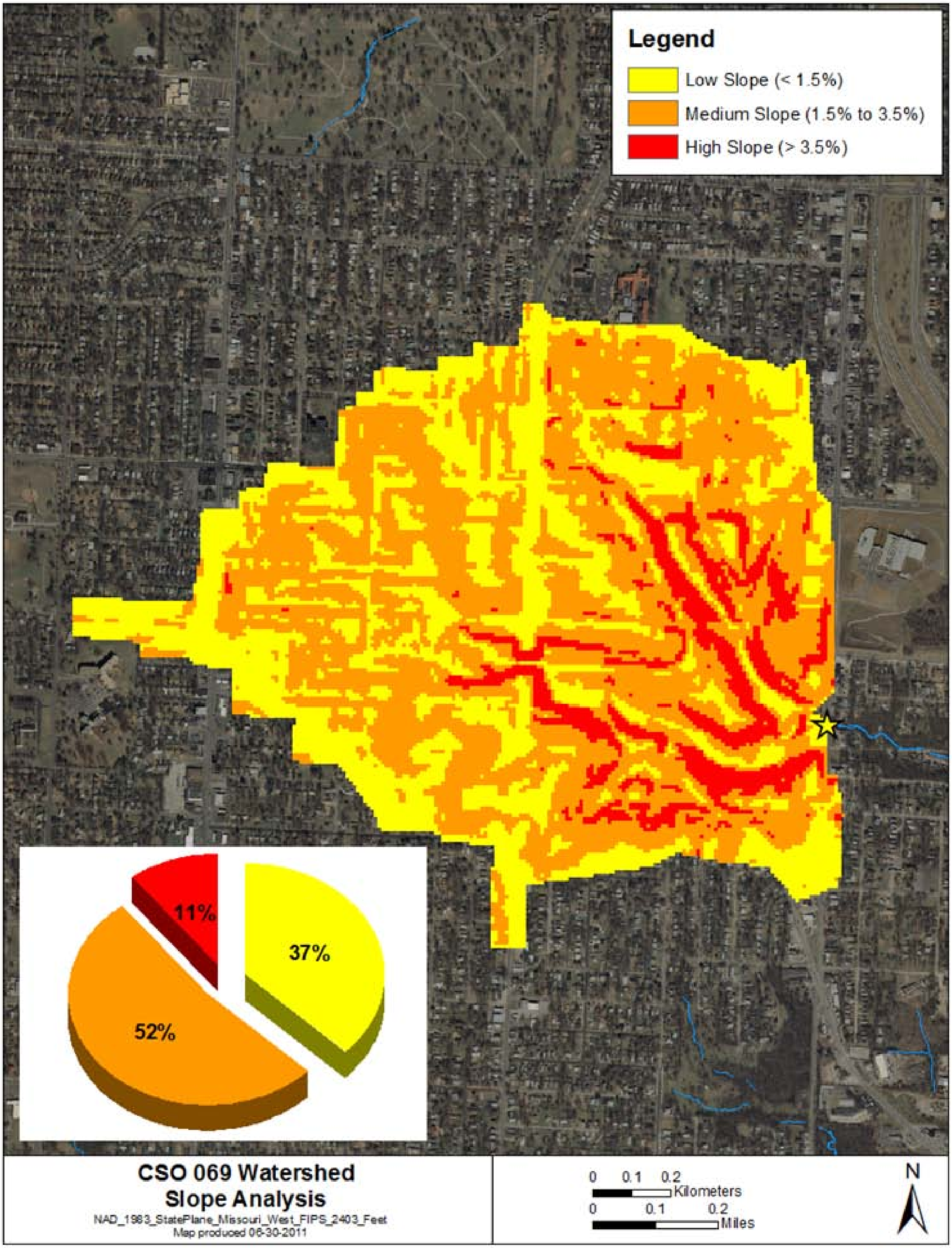

Figure 2-12. CSO 069 sewershed slope analysis.

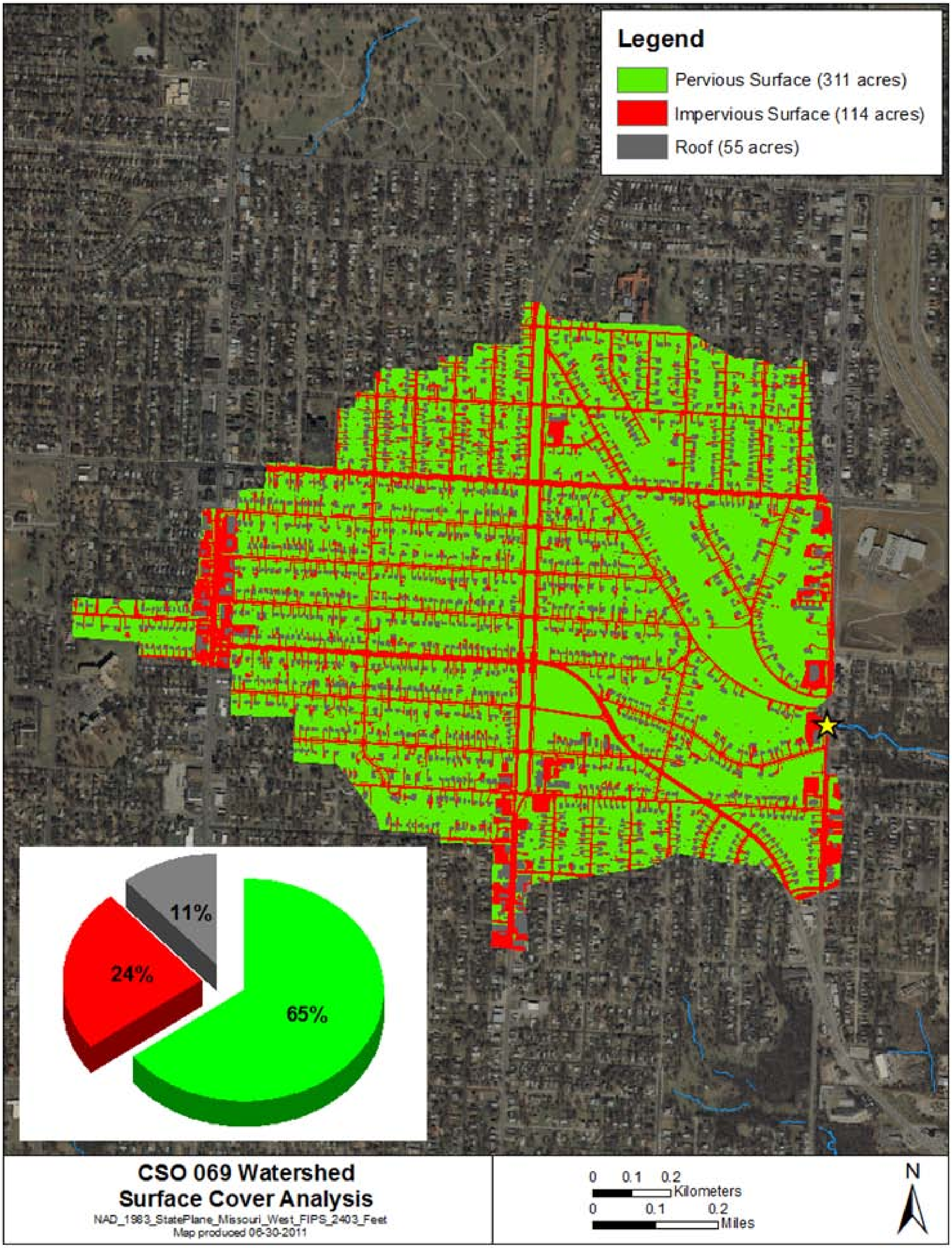

Figure 2-13. CSO 069 sewershed surface cover analysis.

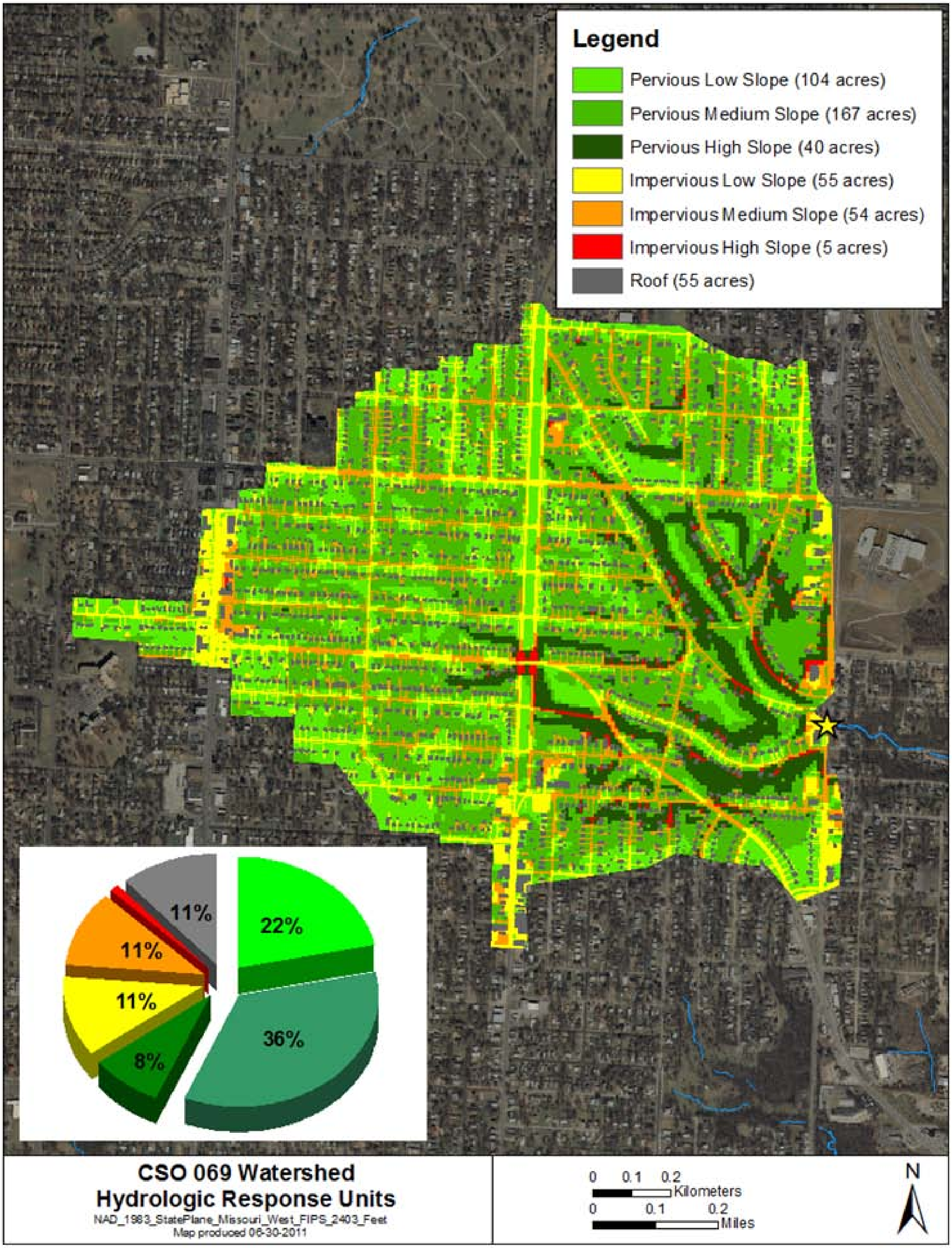

Figure 2-14. CSO 069 sewershed HRUs.

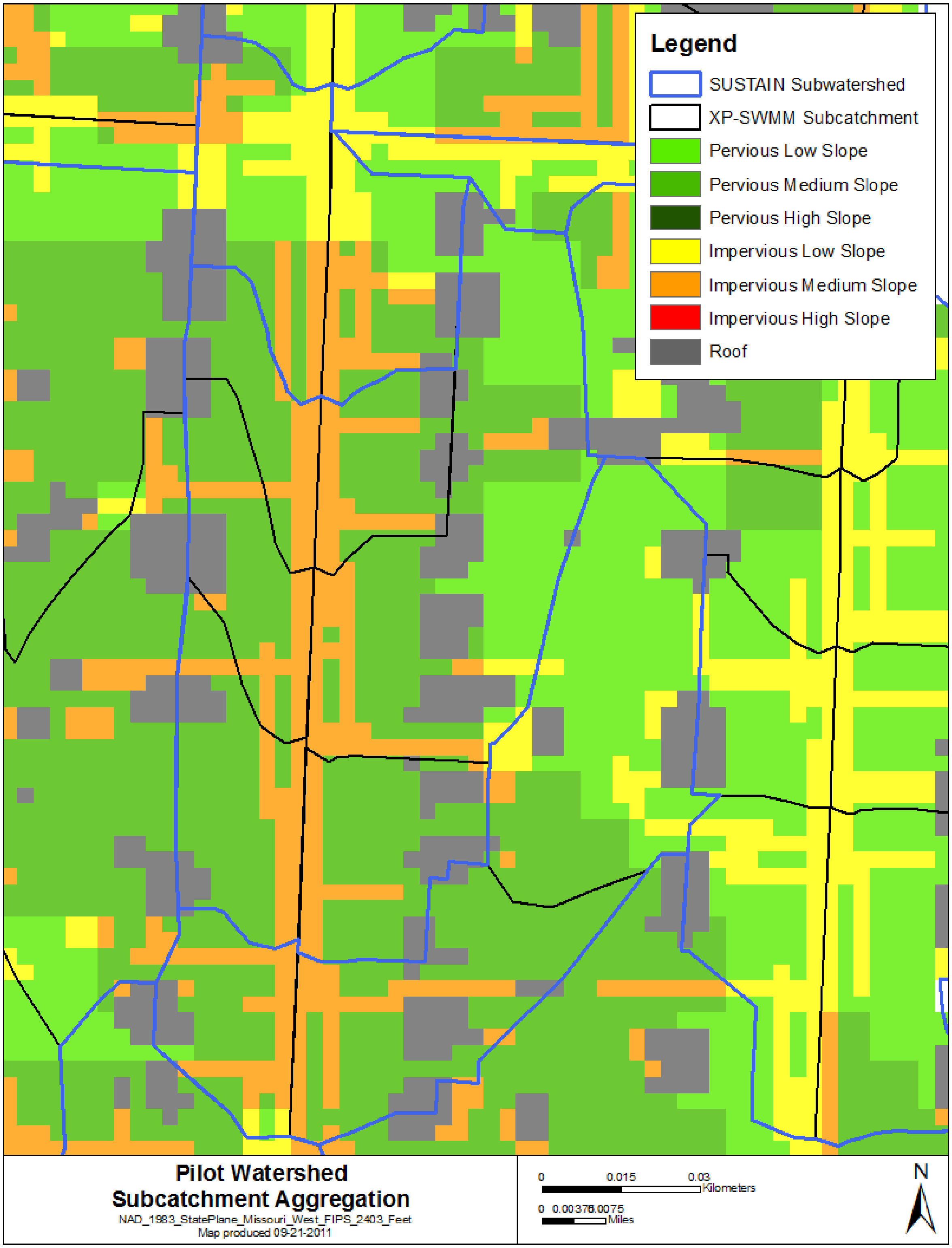

Figure 2-15. Comparison of XP-SWMM subcatchments and subcatchment aggregation in *SUSTAIN*.

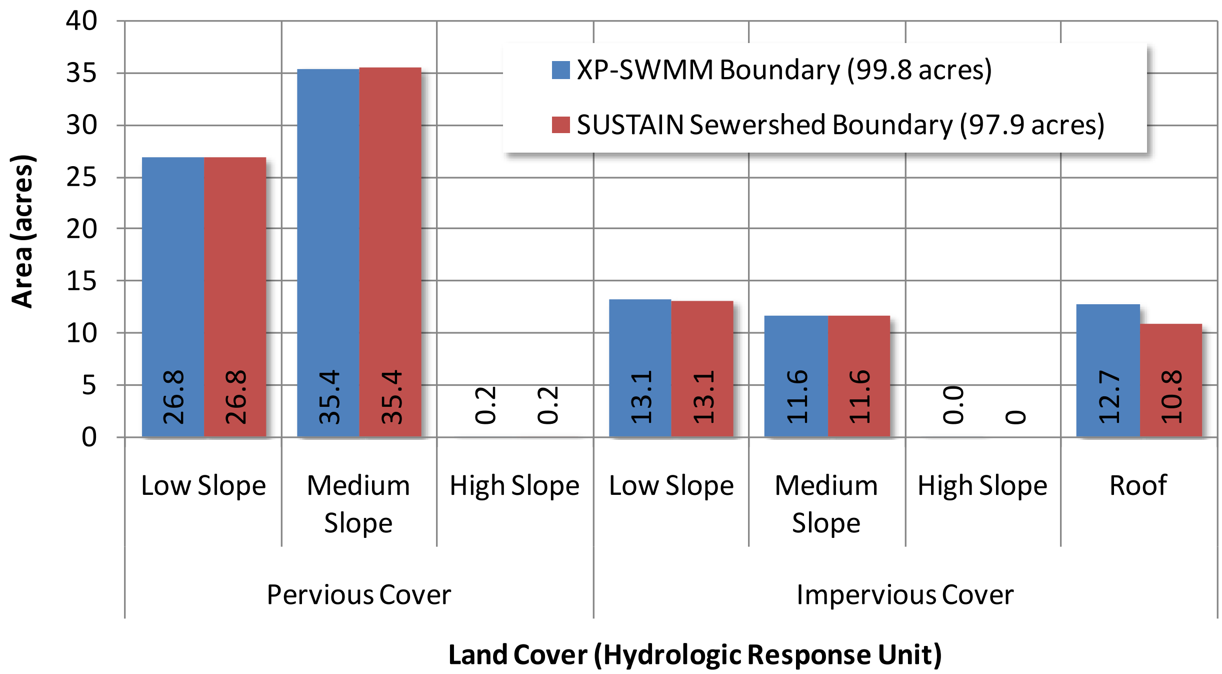

Figure 2-16. Comparison of HRU distributions within XP-SWMM and sewershed boundaries.

Even though the calibration was based on the XP-SWMM watershed boundaries, the sewershed boundary was ultimately used for optimization in the 069 sewershed. Catchment boundaries for the calibration were not changed to conform to the sewershed outline during calibration, because as suggested in Figure 2-16, doing so would only have yielded inconsequential benefits for flow calibration at the outlet of the pilot study area. Instead, selected boundaries from the XP-SWMM delineation were dissolved to form larger catchments. Figure 2-17 compares the original XP-SWMM subcatchment boundaries, the collapsed calibration boundaries used for the baseline model calibration, and the *SUSTAIN* sewershed boundary.

After collapsing some of the subcatchments, there was also no need to explicitly model pipes smaller than one foot in diameter. The contributing areas for the pipes were directly routed to the next largest pipe size in the network. Although this section describes how the model was spatially reconfigured for model calibration purposes, Section 2.4 evaluates the larger implications associated with model spatial resolution, simulation time, and predictive precision.

2.3.3. *Watershed Model Calibration*

During model calibration, parameters are expressed uniquely for each HRU. The objective of the calibration process is to identify a unique set of parameters for each HRU that remain constant for all instances of that HRU within the study area, such that the spatial variation of the watershed response becomes only a function of the HRU distribution within each subarea. Parameters from the XP-SWMM modeling effort were used as a starting point for calibration. Of the four available 2008 storm events, the previous XP-SWMM calibration presented results for two that were much smaller than the critical condition design storm. Given that new monitoring data were available for this effort, the calibration objective became to characterize model performance for the wider range of storm conditions. As previously described in Section 2.1.2, 10 storms of various sizes were selected, spanning 3 years and two different seasons: fall 2008, fall 2009, and spring 2010. Some of the calibrated storms had rainfall volumes that were higher than the critical condition design storm, while others had comparable peak intensities. Calibration parameters were adjusted during the process until an acceptable match of benchmark calibration metrics was achieved. Some of the key parameters were those associated with (1) depression storage and overland flow; (2) infiltration; and (3) DCIA. The earlier parts of this section describe the three general aspects of model parameterization and time series generation, while the later summarizes model testing, output summarization, time series comparisons, and calculation of calibration indicator metrics.

Depression Storage and Overland Flow

Depression storage describes the depth of surface ponding. The subcatchment roughness coefficient describes Manning's roughness coefficient N for overland flow. Both the roughness coefficient and depression storage parameters are set independently for pervious and impervious areas. A summary of those parameters for the CSO 069 watershed model is presented below as Table 2-5. The values of the parameters do not vary by slope, but only by land cover type.

Table 2-5. Roughness and depression storage parameters by land cover type

Land cover type	Parameter	Value
Pervious areas	Roughness coefficient (unitless)	0.1
	Depression storage (in.)	0.2
Impervious areas	Roughness coefficient (unitless)	0.02
	Depression storage (in.)	0.1

Subcatchment width was set by calculating the area-weighted average of the widths that were used in the XP-SWMM model. On the basis of that area-weighted average methodology, the subcatchment width was set to 100 ft. The percentage of impervious surfaces with zero depression storage was also set consistently with the XP-SWMM model at zero percent (USEPA, 2010).

Infiltration

The Green-Ampt infiltration method assumes that a sharp wetting front exists in the soil column, which separates the un-wetted zone of soil with some initial moisture content below and the wetted zone of soil above (Rossman, 2005). The infiltration rate is calculated as a function of soil moisture, saturated hydraulic conductivity, and average wetting front suction head, and is based on Darcy's law and the principle of mass conservation (Huber and Dickinson, 1988).

A major advantage of the Green-Ampt method is that the input parameters can be determined from physical measurements. The XP-SWMM model for much of the Middle Blue River watershed used the following parameters for the Green-Ampt infiltration method presented below in Table 2-6 (Burns & McDonnell, 2009). Those parameters were used as the starting values when developing time series for each of the seven HRUs using SWMM5, and were ultimately left unchanged.

Table 2-6. Green-Ampt infiltration parameters

Parameter	Value
Average capillary suction head (in.)	6.75
Initial soil moisture deficit (unitless)	0.37
Saturated hydraulic conductivity (in./hr)	0.134

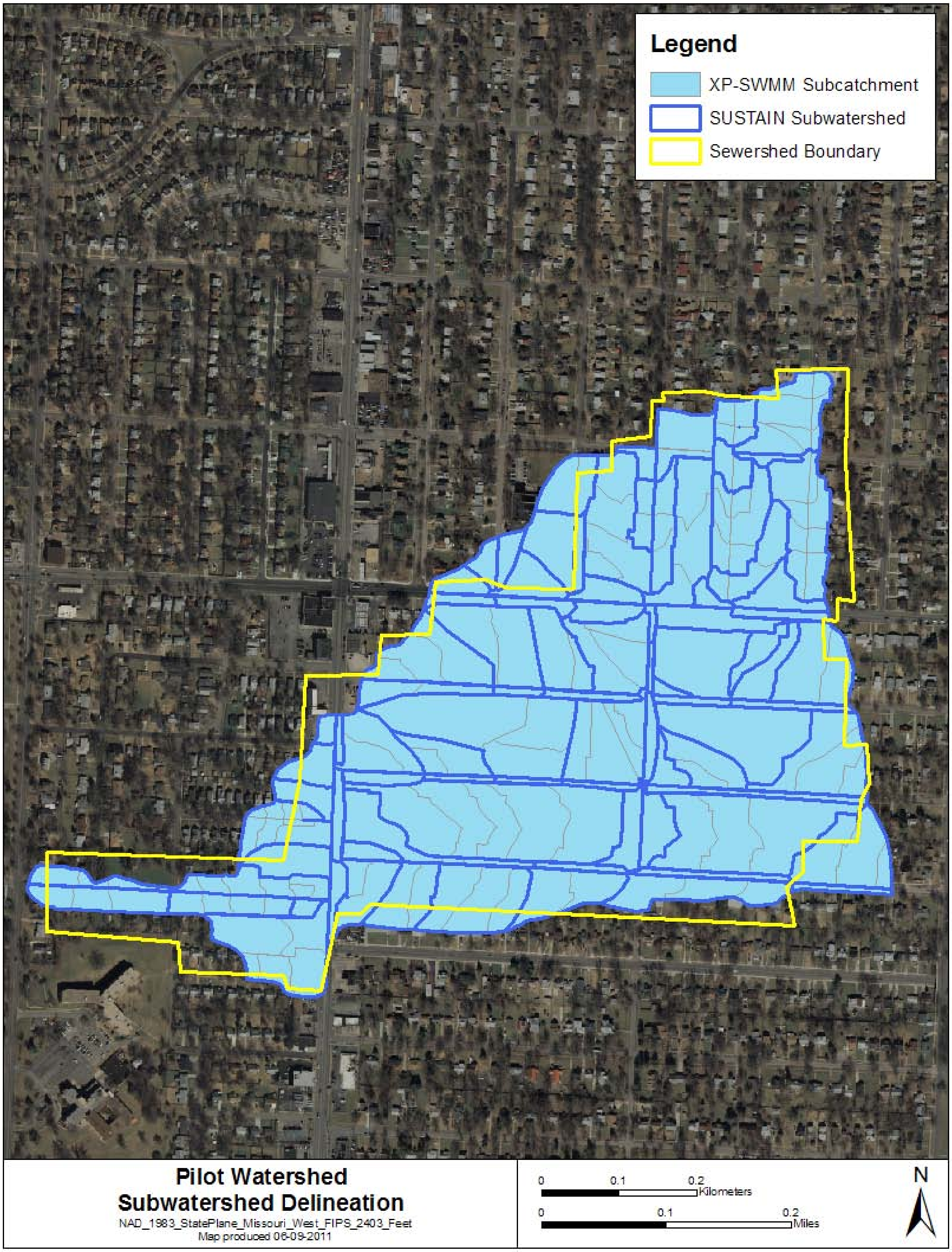

Figure 2-17. Comparison of XP-SWMM and *SUSTAIN* subwatershed delineations.

Design Storm Time Series

In its long-term control plan (LTCP) update, WSD identified the type D design storm (D-storm) as the critical event that must be controlled to achieve CSO reduction objectives. The D-storm is a 1.4 in. rainfall event with a peak intensity of 0.6 in. per hr and an event lasting 16.75 hours. Runoff time series for the D-storm were developed using the calibrated baseline model.

A single-event design storm approach like the modeling effort conducted previously must specify the initial condition of antecedent soil moisture. Another reason for testing across a range of antecedent moisture conditions is because the observed storms were only monitored between April and October, which do not fully represent all possible conditions. Recognizing the potential variability of antecedent moisture conditions, three sets of the time series were developed for the D-storm to represent low, medium, and high ET antecedent recovery conditions. The low recovery time series represents winter conditions, when evaporation is low with a 12 hr inter-event time. The medium recovery time series represents average conditions of the spring or fall, with moderate evaporation and 3 days between storm events. The high recovery time series represents dry conditions during the summer, with a high evaporation rate and a longer inter-event time of 7 days. These three conditions are meant to bracket the uncertainty associated with antecedent conditions inherent in design storm modeling. Table 2-7 presents a summary of the three recovery conditions. Three sets of time series, corresponding to the three antecedent recovery conditions, were developed for each of the seven HRUs.

Table 2-7. Summary of antecedent recovery conditions for the D-storm

Antecedent condition	Interpretation	Dry time (days)	Evaporation (in./day)
Low recovery	Most conservative	0.5	0.001
Medium recovery	Average condition	3	0.030
High recovery	Least conservative	7	0.106

Hyetographs of the three D-storm scenarios are presented as Figure 2-18 to better illustrate the antecedent recovery condition concept. The time series were developed with two consecutive D-storms, with the first serving as a *seed* to initialize system storages for recovery. In the high recovery scenario, the storms are separated by 7 dry days subject to a high evaporation rate, which would provide ample time for the BMPs to recover storage capacity. For the medium recovery scenario, dry time is decreased to 3 days, and evaporation rate decreased to 0.03 in. per day. For the low recovery scenario, the two events are separated by 12 hours with a low evaporation rate. Previous estimates calculated impervious runoff from this storm at 1.25 in. versus the total rainfall amount of 1.4 in. (WSD, 2008). The time series generated with SWMM5 for the D-storm show runoff depth from the medium slope impervious HRU at 1.23 in.

Directly Connected Impervious Area (DCIA)

DCIA refers to the fractions of impervious surfaces that are connected directly to the combined sewer system (CSS) without first draining to any pervious surfaces or buffers. In addition to primary roads, DCIA often incorporates features in the right of way such as sidewalks, private parking lots, and private driveways all of which might be continuously connected to the CSS.

As mentioned previously, the existing XP-SWMM model of the pilot study area reviewed for this case study varied DCIA by subcatchment as a calibration parameter. The new *SUSTAIN* baseline watershed model incorporated the previous DCIA parameters (% DCIA) as area-weighted values by subwatershed. Runoff from DCIAs was routed first to an area-BMP (described in Chapter 1) before being conveyed to a downstream junction.

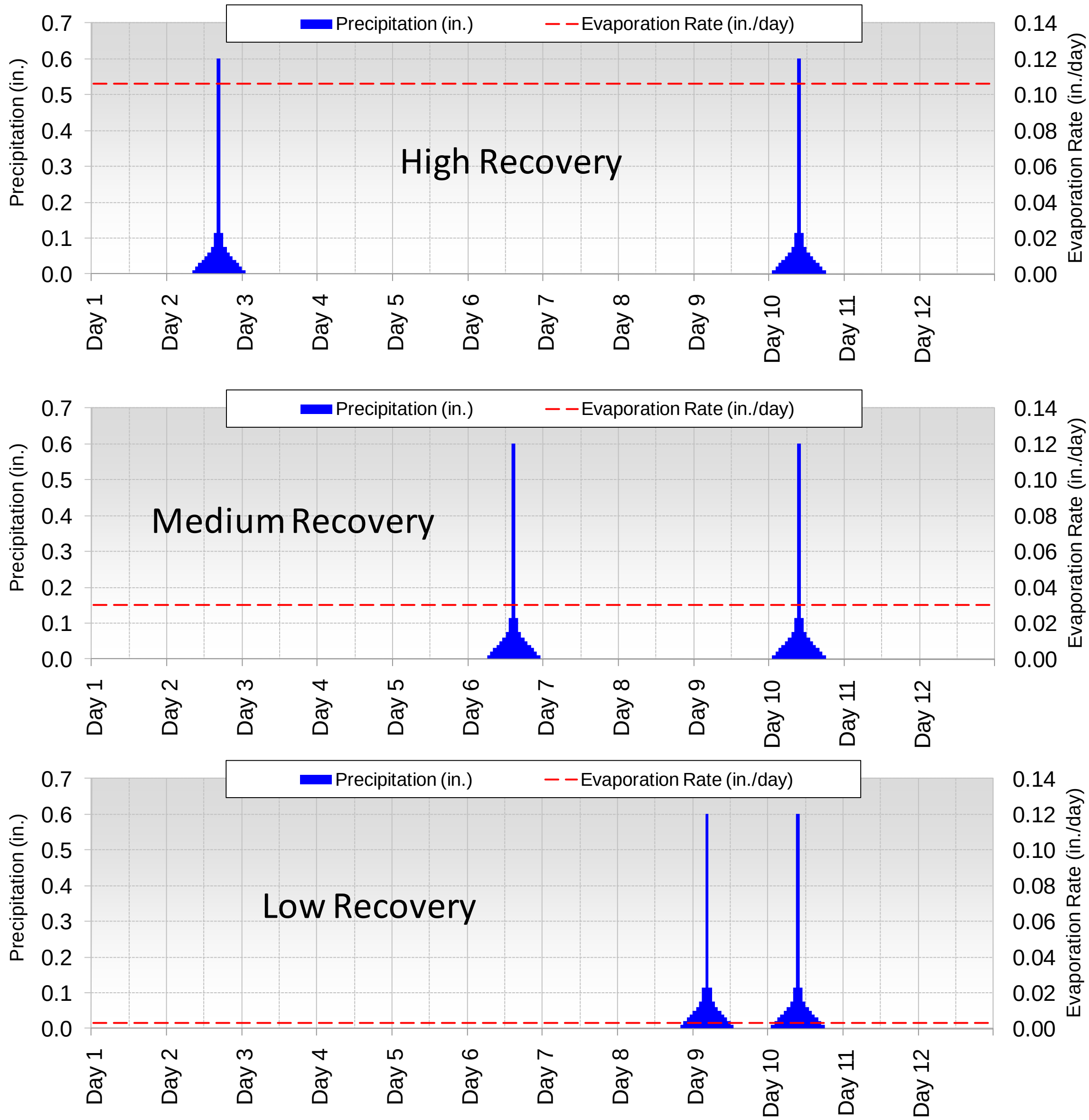

Figure 2-18. D-storm hourly hyetographs for high, medium, and low recovery scenarios.

Stormwater Runoff Calibration

Updated watershed monitoring data from the Middle Blue River Pilot Study area were used to recalibrate the SWMM5 baseline watershed model. The calibrated SWMM5 model was then used to generate unit area (one acre) HRU time series for *SUSTAIN*. *SUSTAIN* was setup to represent the BMP and pipe routing network for the entire study area; however, it was driven by the SWMM5-generated runoff boundary conditions. Because of the updated watershed monitoring data available for this effort, the newly calibrated model reflected a wider range of storms than previously. The flow meter number 01 at The University of Missouri-Kansas City (UMKC-01) was located at the outlet of the pilot watershed. The data were compared against modeled pipe outflow at the same location. Coincident 5 minute and 15 minute rainfall data collected at a locally operated precipitation gage in the watershed were used as the forcing functions to drive the watershed model. Because the model was run on a continuous simulation basis, ET data were also required to provide recovery of soil moisture between storm events. ET was computed in two steps. First, evaporation was computed as a function of temperature, solar radiation, dew point, and wind speed using the Penman energy balance method (Penman, 1948). Quality controlled National Climatic Data Center (NCDC) surface airways data from the Kansas City International Airport and Kansas City Downtown Airport were used for this computation. Second, a locally referenced crop factor for turf grass of 0.85 (KSU, 2010) was applied to convert the evaporation time series to ET.

Certain calibration benchmarks were also used to confirm *goodness of fit* for model prediction. The Wastewater Planning Users Group (WaPUG) is a technical group that operates under England's Chartered Institution of Water and Environmental Management. WaPUG is internationally recognized for its promotion of best practice standards and for publishing related technical guidance as industry standards. The WaPUG *Code of Practice* for use in hydraulic sewer system modeling provides acceptable calibration criteria for observed versus modeled time series comparison. Those criteria include acceptable percent error ranges for both peak flow and total volume. Modeled wet-weather peak flow should be no more than 15 percent below or 25 percent above metering data, while modeled wet-weather flow volume should be no more than 10 percent below or 20 percent above metering data (WaPUG, 2002). Those metrics provide acceptable ranges in recognition of the fact that a certain amount of inherent error associated with rainfall gages, model parameterization, or flow measuring gages exist, and are propagated through modeling.

Another metric that is commonly used for assessing the performance of continuous simulation hydrology models is a model efficiency metric, E, developed by Nash and Sutcliffe (1970). They interpret the model efficiency metric E as follows:

- Values below zero suggest that the mean of observed data is a better predictor than the model;
- A value of 0 indicates that the observed data mean is equally as good a predictor as the model; and
- The closer the model efficiency is to 1, the better it predicts observed data.

For example, a Nash-Sutcliffe value of 0.70 indicates that the mean square error of the difference between observed data and model prediction is 1.0–0.70, or 30 percent of the variance in the observed data. A common rule of thumb in hydrology modeling practice suggests that obtaining a value of 0.7 or better generally indicates adequate model fit. The WaPUG criteria and the Nash-Sutcliffe metric were used as the bases for evaluating model performance and confirming the watershed model calibration for the pilot watershed.

As previously noted, 10 selected storms were calibrated using observed data at the UMKC-01 flow monitoring station at the outlet of the pilot watershed. For each storm event, the observed and modeled flow in at the pilot area outlet was converted to inches of runoff by dividing the flow by the drainage area. Such normalization provided a convenient and consistent approach for comparing the modeled versus observed runoff yields for storms of different sizes. The average projected runoff volume for the CSO critical condition D-storm was also computed using the calibrated model for relative comparison. For each storm event, antecedent potential evapotranspiration (PEVT) was computed by summing the total PEVT from the end of the previous event to the start of the event. All those values were computed and plotted together during model calibration to better visualize and understand the behavior of the natural system and modeled systems versus precipitation and PEVT. Figure 2-19 shows the area-normalized observed versus modeled runoff depths, total depth antecedent PEVT, and projected runoff depth for the D-storm.

One might expect that storms with lower antecedent PEVT would generate more runoff. While that was observed in some instances, there was no clear and consistent trend between antecedent PEVT and model-predicted volume *alone* because other factors such as rainfall intensity and the spatial/temporal variability of precipitation can cloud interpretation of a perceived response. That fact further demonstrates the need to look at multiple metrics (graphical and numerical) during model calibration. A weight-of-evidence approach, comparing multiple evaluations such as time series plots, correlation plots, and a number of calculated indicator metrics, was used to confirm model calibration.

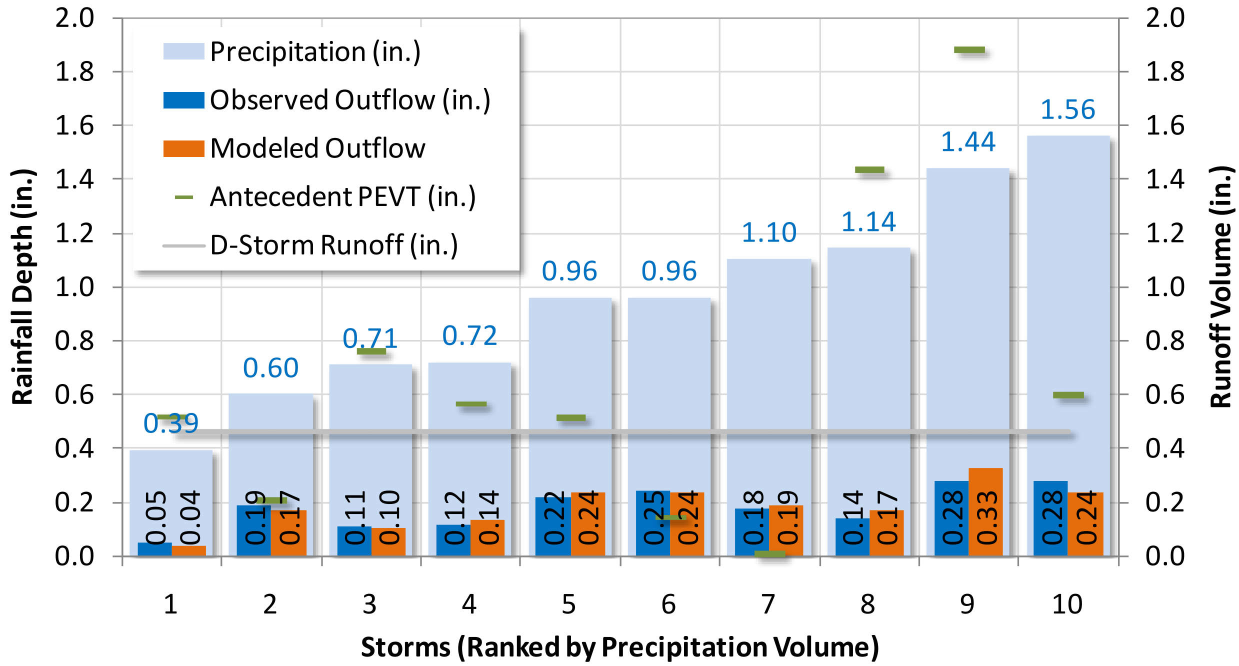

Figure 2-19. Observed versus modeled runoff at the watershed outlet for 10 selected storms.

Using the normalized outflow depths, runoff ratios for observed and modeled runoff yield was computed by dividing the normalized depth runoff by the precipitation depth for each of the ten events. The average projected runoff ratio for the D-storm was also computed using the calibrated model. Figure 2-20 shows observed versus modeled runoff ratios for each of the 10 selected storms and the average projected runoff ratio for the D-storm.

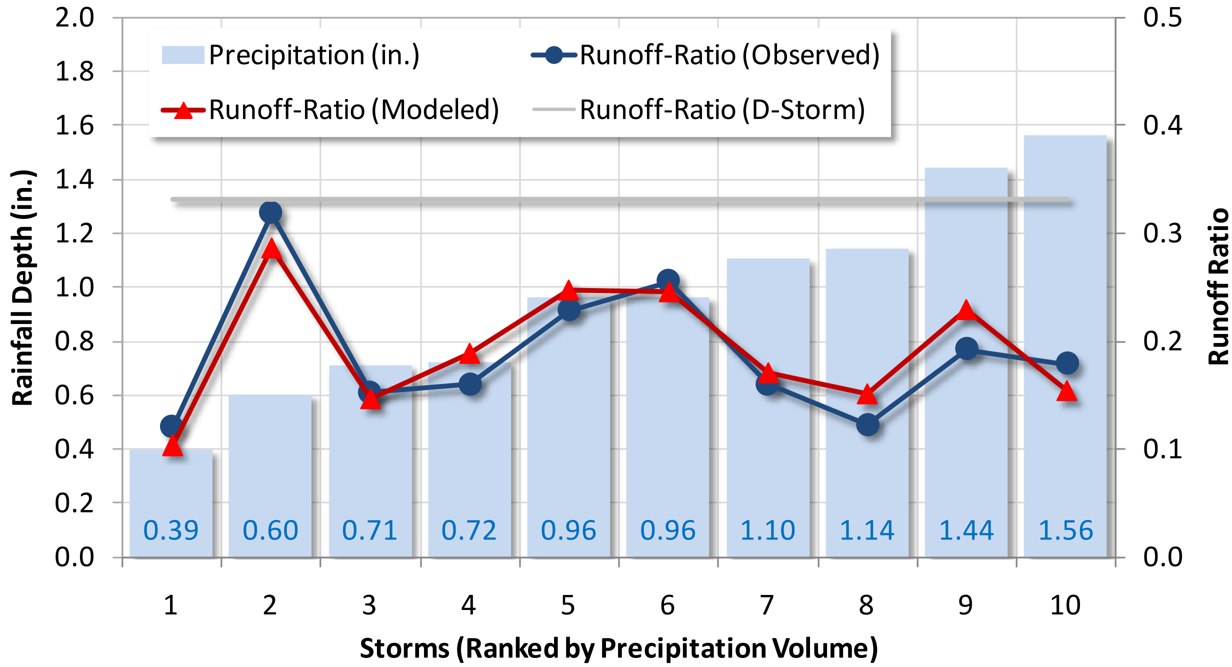

Figure 2-20. Observed versus modeled runoff at the watershed outlet for 10 selected storms.

The calibrated model predicted runoff averaged around 0.2 in. of runoff per in. of precipitation, with values ranging between 0.1 and 0.3 in. for different storms. That predicted range is corroborated by those predicted by the WinSLAMM study, which estimated an annual runoff coefficients around 0.3 for this watershed (Pitt and Voorhees, 2010). In addition to volume, the model predicted peak flow was also evaluated for goodness of fit. Modeled versus observed volume and peak flow were correlated for all 10 storms, as shown in Figure 2-21. The WaPUG criteria bands and the regression equations are also shown in both panels of the figure. Red points are storm that fell outside the targeted calibration ranges.

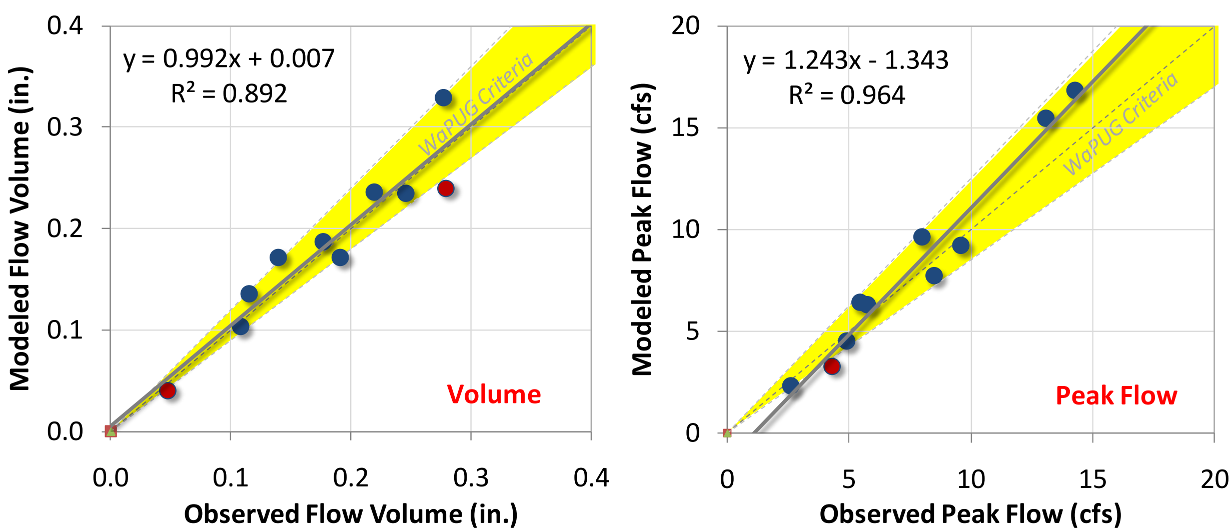

Figure 2-21. Modeled versus observed volume and peak flow correlations, with WaPUG criteria.

So what constitutes a suitable calibration? The calibration effort focuses on refining certain physical parameters of the model to characterize spatially dispersed features, processes, and responses. The computed calibration metrics provide some guidance for how much difference is acceptable between modeled and observed time series. Nevertheless, occasionally some unfactored conditions cause differences between modeled and observed responses, which might need to be either identified or reconciled. One example is localized rainfall events, which are common occurrences. Because rainfall time series are typically applied uniformly per model segment, the true heterogeneous nature of localized events cannot always be accurately represented in a model. Of the 10 selected calibration storms, 8 were relatively easy to calibrate; however, 2 events did not seem to realistically match the observed response in the pipe network. For example, initial runs for the April 22, 2010, event gave results that (1) were outside the acceptable WaPUG criteria; and (2) had a negative Nash-Sutcliffe *E* value. Figure 2-22 shows the initial hydrograph comparison and computed metrics for the April 22, 2010 storm event.

The underlying rainfall data were investigated for clues as to the source of the discrepancy. The local rainfall gage data for the storm event had a total rainfall depth of 1.76 in. Daily rainfall data for the same event at the nearby NCDC Kansas City International Airport gage (COOPID 234358, about 20 miles away from the watershed gage) was also reviewed for cross comparison. The NCDC gage reported a total rainfall of 1.13 in., compared to 1.76 at the local gage. That represented a 0.63 in. difference in rainfall volume, which is not an unusual amount of variation between localized events. The ratio of rainfall volumes was used to normalize the 5 minute rainfall distribution to conform to the NCDC measured depth. Figure 2-23 shows the resulting hydrograph and calibration metrics for the adjusted volume event.

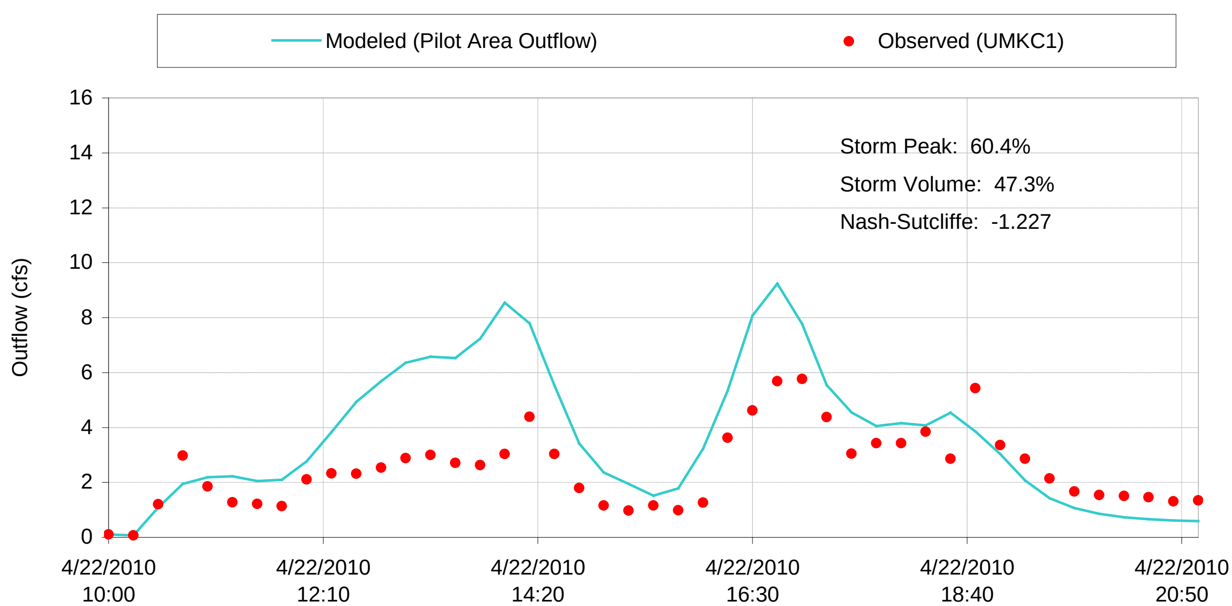

Figure 2-22. Initial calibration: UMKC-01 catchment outlet (rainfall = 1.76 in.).

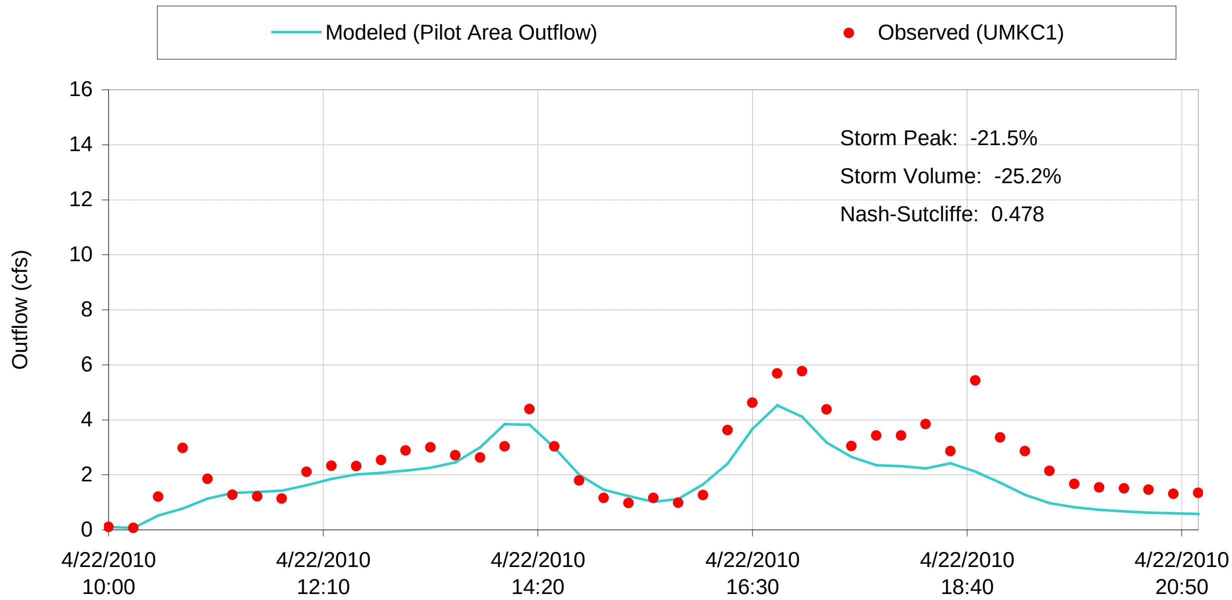

Figure 2-23. Intermediate calibration: UMKC-01 outlet (adjusted rainfall depth = 1.13 in.).

The tests revealed that the model responded dramatically to the adjusted storm depth. In fact, the adjustment resulted in an under-prediction for both peak flow and total volume, but it improved the Nash-Sutcliffe *E* value. The test confirms that a better representation of the rainfall volume lies somewhere between 1.13 and 1.76 in., and it probably follows a slightly different temporal distribution. For the sake of expediency, the two rainfall values were averaged to produce a value of 1.44 in. for this event. A straight multiplier of 0.818 (1.44/1.76) was applied to the original 1.76 in. storm distribution for a third test run for the event. Figure 2-24 shows the final calibration hydrograph comparison and associated metrics for the event.

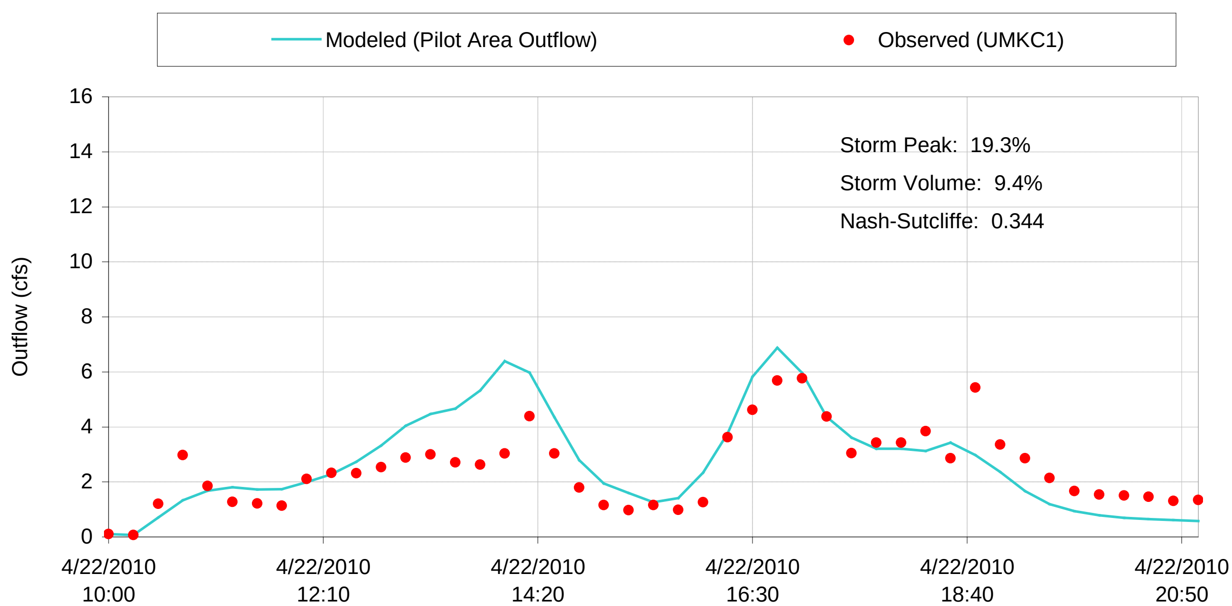

Figure 2-24. Final calibration: UMKC-01 outlet (adjusted rainfall depth = 1.44 in.).

The second adjusted storm event occurred on October 8, 2009. It also had a reported rainfall depth of 1.93 in. at the local gage, with 0.90 and 1.38 in., respectively reported at the NCDC Kansas City International Airport (20 miles away) and the Kansas City Downtown Airport gages (12 miles away). The Normal Ratio Method (Dunne and Leopold, 1978) was used to estimate a rainfall total for the watershed, resulting in a total estimated rainfall value of 1.56 in. For that storm event, there was a 30 to 40 percent difference in rainfall depths among the three measuring gages.

Table 2-8 presents a summary of model performance as defined by the selected calibration metrics for the ten selected storm events. The table, whose data are also plotted in Figure 2-19 through Figure 2-21, identifies three of the storms as having one WaPUG calibration metric that is outside the recommended range. For the October 8, 2009, event, no additional effort was spent on further adjustments because the measured rainfall distribution at the gage appeared to be fundamentally different than what probably fell throughout the watershed. That suspicion arose because model calibration would consistently cause either one metric or another to fall out of range. The event was the largest recorded storm among the selected calibration storms. The other two events with metrics that fell outside the range were the two smallest events on record. Although the peak flow criterion was not met for the October 29, 2009 event, it had the highest Nash-Sutcliffe *E* value of all the storms that were evaluated, indicating a high degree of model efficient at replicating the observed temporal runoff distribution. Because percent error for both peak flow and volume were on the lower end of acceptable, it probably would have been possible to adjust the rainfall totals to bring that metric into compliance without violating the peak flow criteria. However, model testing has already proven the variable nature of rainfall and localized event differences. Doing so would have been an exercise that did not advance the ultimate objective of establishing a model baseline. The weight-of-evidence for the remaining storms that were within the criteria was deemed to be sufficient grounds to verify good systematic model performance. No further adjustments were made to any of the other observed rainfall records. In general practice, adjusting measured data should not be done unless there is clear and corroborative justification like the body of evidence presented above.

Table 2-8. Model calibration performance metrics for 10 selected storms events

Start date	End date	Precipitation (in.)	Volume[a] (percent error)	Peak[b] (percent error)	Nash-Sutcliffe *E*
09/24/08 04:00	09/24/08 12:00	0.71	-4%	18%	0.62
10/15/08 03:00	10/15/08 12:00	1.10	6%	18%	0.50
10/21/08 16:00	10/21/08 22:00	0.39	-14% [c]	-8%	0.67
11/05/08 22:00	11/06/08 04:00	1.14	23%	-9%	0.19
10/08/09 00:00	10/09/09 00:00	1.56	-14% [c]	20%	0.51
10/21/09 23:00	10/23/09 00:00	0.96	8%	-12%	0.67
10/29/09 06:00	10/30/09 05:00	0.60	-10%	-23% [c]	0.76
04/22/10 10:00	04/22/10 21:00	1.44	19%	9%	0.34
04/30/10 07:00	04/30/10 17:00	0.72	18%	18%	0.32
05/19/10 18:00	05/20/10 03:00	0.96	-4%	-4%	0.50

a. Calibration target for percent difference in volume: +20 percent to –10 percent (WaPUG, 2002)

b. Calibration target for percent difference in peak flow: +25 percent to –15 percent (WaPUG, 2002)

c. Highlighted metrics are outside the recommended range.

2.4. Simplifying the Network Articulation for Large-Scale Extrapolation

In the context of optimization, where thousands of individual model runs are often needed as the system searches for the *optimal* solution, any amount of computational time that can be saved per model run quickly translates into significant computational time savings over the course of an optimization. *SUSTAIN* provides an aggregated BMP option that facilitates simplification of the representation of the physical system. Network simplification reduces computation time; however, it also simplifies the representation of the physical process and has an impact on the accuracy of the model prediction. The model user must consider the balance between efficiency and accuracy in the selection of the appropriate level of simplification for the particular application and decision support.

Section 2.3 describes the process of establishing a representative watershed model baseline condition. An important distinction between the model calibration baseline and the optimization baseline is that for the latter, the proposed BMP design plan is assumed to be fully deployed throughout the drainage network. The aspect of the system that is being simplified is the BMP drainage network as overlaid on the watershed or catchment areas. The aggregate BMP network was compared against a more detailed articulated network with BMPs and evaluated for predictive accuracy. Through that process, the following questions are addressed and discussed:

- How much network simplification is tolerable without significantly compromising model accuracy and/or precision?
- What components of a detailed or articulated BMP and drainage network are appropriate candidates for aggregation, and to what degree can they be aggregated?
- How much computational advantage does the aggregate BMP approach provide?

This section begins with a discussion of how BMPs were configured for both the aggregate and articulated configurations, followed by a sensitivity analysis with results and conclusions.

2.4.1. *SUSTAIN BMP Representation*

The BMP design plan consisted of 179 structural components (158 surface features and 21 subsurface storage components), as described in Section 2.1.4. All the BMPs have specific design configurations associated with the functions they provide. Figure 2-25 presents conceptual renderings of three proposed BMP project sites in the Middle Blue River Green Solutions Pilot Project: bioretention/rain garden, porous sidewalk, and porous parking on cube storage. Each of the 179 unique surface and subsurface structures was evaluated and grouped into 11 generalized categories according to similar configurations, as outlined in Table 2-9. For each BMP type, *SUSTAIN* provides three optional vertical layers—(1) surface ponding depth; (2) soil media depth; and (3) underdrain layer (as needed), to characterize the actual BMP physical response.

Figure 2-25. Example BMP renderings: Middle Blue River Green Solutions Pilot Project.

Table 2-9. BMP design dimensions and specifications

BMP categories		BMP component depths (ft)			Outlet type
		Ponding	Soil media	Underdrain	
Bioretention	type 1	0.83	0.83	0.33	weir
	type 2	0.75	1	0.33	weir
	type 3	0.167	0.83	0.33	weir
	shallow	0.83	0.83	0.1	weir
Bioswale		0.5	0.83	--	weir
Cascade		0.93	0.83	--	weir
Porous pavement	on sidewalk	0.01	1	0.33	weir
	on storage cube	0.01	0.3	0.33	weir
Rain garden	type 1	0.5	0.83	--	weir
	type 2	0.5	0.83	--	2 in. orifice
Storage pipes		3	--	--	orifice (variable)

The detailed BMP design dimensions were estimated on the basis of the 100 percent design plans. In the course of deriving the design dimensions, simplifications were made to accommodate the *SUSTAIN* BMP configuration requirements. For example, the designed bioretention, rain gardens, and bioswale have a side-slope of 2:1; however, in *SUSTAIN*, the ponding pool of BMPs were configured with vertical sides. To preserve the ponding pool volume, the ponding depth was adjusted lower while holding the surface area constant, as shown in the design plan. Another example is the representation of the subsurface storage pipes, the actual storage pipes are 3 ft in diameter with an outlet structure in a manhole. The outlet orifices of the storage pipes are at the same elevation as the invert elevation of the horizontal storage pipes. In *SUSTAIN*, the storage pipes are represented using cubical storage tanks that were 3 ft tall, with bottom orifices. The cylindrical pipe volume was maintained by calculating the surface areas of the tank equal to the pipe volume divided by the assumed depth of 3 ft. In terms of BMP subsurface soil layers, the associated properties are specified in Table 2-10.

Table 2-10. Subsurface layer properties for applicable BMP layers

Soil layer	Property	Value	Units
Engineered soil media	Porosity	0.4	--
	Field capacity	0.3	--
	Wilting point	0.1	--
	Holtan vegetation parameter	0.6	--
	Saturated infiltration rate	2	in./hr
Underdrain layer	Void fraction	0.4	--
Native background soil	Saturated infiltration rate	0.1	in./hr

A conservative background infiltration rate of 0.1 in/hr was used in this study, for consistency with the value reported in the WinSLAMM application (Pitt and Voorhees, 2010). The report states that native undisturbed soils had infiltration rate of 0.2 in./hr, and loam soil fill had an infiltration rate of 0.15 in./hr; however, in the WinSLAMM application it is noted that disturbed urban soils, such as those typical for the urbanized parts of Kansas City, can have greatly reduced infiltration rates compared to non-compacted soils (Pitt and Voorhees, 2010).

For the articulated BMP network representation, individual BMPs are simulated. The only exception applied in this application, is that if there is more than one unit of the same BMP type in a subwatershed, the unique units are simulated as a single object with an adjusted volume that accounts for the combined storage benefit of the unique components. That happened in 14 instances, bringing the number of unique BMP units in the articulated representation down from 158 to 144. For the aggregate BMP network, the same 11 BMP types listed in Table 2-9 were aggregated into a single representative volume, while preserving the relative position in the generalized BMP network. The sizes and drainage areas of each component were calculated as the total of all the individual BMPs of each type. The outlet structures of all BMP types were kept consistent. Therefore, in the aggregate representation, the unit surface areas of each BMP component are estimated as the average surface area of BMPs of the same type. In general, the outlet structure dimensions were maintained; however, for the below-grade storage pipes, the outlet orifice sizes in the articulated network of the actual design plan BMPs varied significantly, from 0.375 in. to 1.25 in. The aggregate BMP needs to assume one representative size to approximate the articulated variability. Recognizing that the release rate is largely dependent on the orifice diameter, the representative storage outlet orifice diameter was calibrated (within the 0.375 in. to 1.25 in. range) to obtain a close match of the aggregate BMP outflow hydrograph with that of the articulated representation.

For private parcel BMPs, the WinSLAMM application indicates that rain barrel and rain gardens are suitable alternatives. The BMP dimensions are listed in Table 2-11. The private BMP rain gardens were modeled with the same subsurface parameters as the public green BMPs, as summarized in Table 2-10.

Table 2-11. Private BMP design dimensions and specifications

BMP categories	BMP dimensions				Outlet type
	Surface area	Ponding (ft)	Soil media (ft)	Underdrain	
Rain garden	200 sq ft per house (1,000 sq ft roof)	1	2	No underdrain	Weir
Rain barrel	35-gallon tank				Weir and orifice

2.4.2. *Articulated versus Aggregated Network*

For this application, the baseline condition in Figure 2-26 below shows the fully articulated model representation of BMPs in the pilot watershed, where distributed collection points and conveyance segments are explicitly defined. Model configuration included 85 subwatersheds and 36 unique pipe segments. Only pipes with diameters larger than 12 in. were included in the model. Within each catchment, the amount of storage associated with each practice from the design plan was added to the network. Flow is routed from each catchment through the network to the watershed outlet.

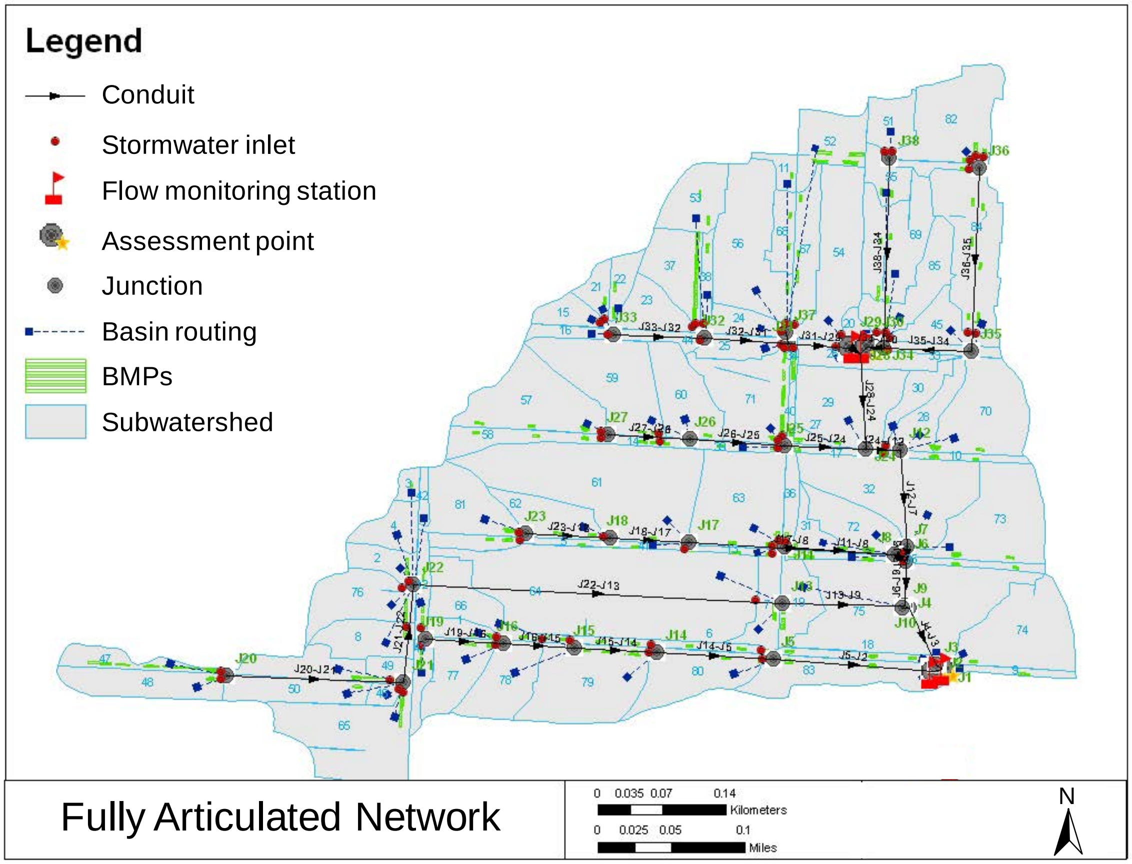

Figure 2-26. *SUSTAIN* model representation of fully articulated model network.

In this aggregate BMP network configuration, the routing network is simplified in recognition of the fact that the time of concentration for the watershed is on the order of about 15 minutes or less, which is similar to the simulation time step. The time of concentration was estimated by comparing the average amount of time between the peak of the rainfall event and the peak observed flow at the outlet gage. Figure 2-27 presents a conceptual diagram of the aggregate BMP representation of the same network presented in Figure 2-26. Each BMP component is represented as an object; however, the typical situation of that BMP relative to others within close proximity is preserved by the network. Because aggregate BMP application is intended for places with short times of concentration, it assumes that all intermediate connections are instantaneous routing elements where no pipe conveyance is simulated. Runoff generated from the 100-acre pilot is proportionally distributed among the various pathways according to the typical orientation and distribution of land cover upstream of each type of practice. The land cover distribution was surveyed and estimated using GIS spatial analysis of aerial photographs. A portion of runoff can also be assigned as untreated, which would allow it to flow directly to the outlet without passing through the BMP network.

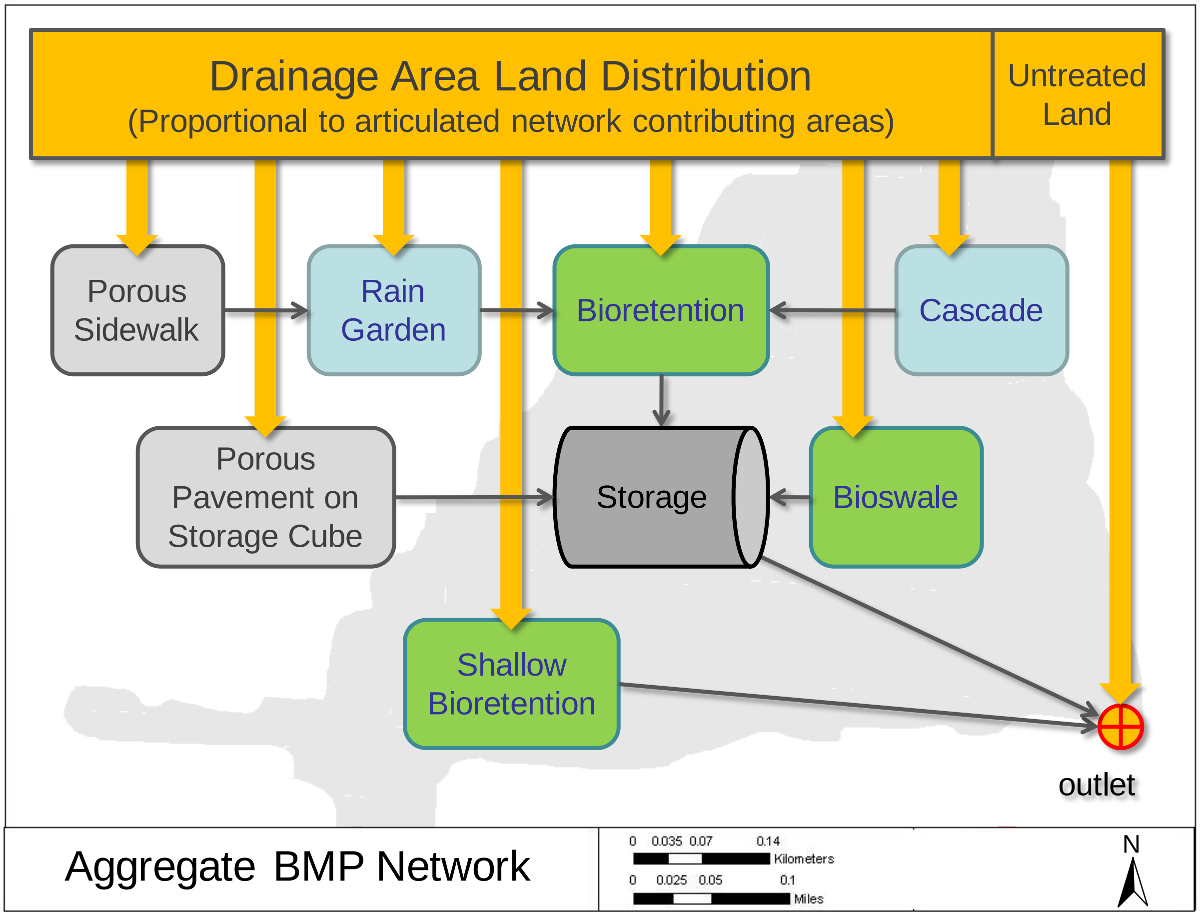

Figure 2-27. Conceptual diagram of a comparable aggregate BMP representation.

Notwithstanding the inherent simplification involved, some of the major advantages of the aggregate network representation is that it is (1) easier to implement in the modeling environment because fewer individual BMPs need to be configured; (2) scalable for other areas, allowing for extrapolation to a larger watershed; and (3) computationally less demanding because detailed simulation of all pipe segments is not necessary. Those advantages become critical when performing optimization where thousands of consecutive model runs are performed.

Although all models are simplified version of a natural system, the aggregate BMP is significantly less detailed than the network typically used to represent watershed systems with BMPs. The aggregate BMP representation assumes that the dominant function of BMPs is water storage, evaporation, and infiltration, and that the impacts of transport through a network, especially timing and attenuation are less significant. Model testing (i.e., calibration/validation), and an understanding of the local hydrologic response, can be used to evaluate to what degree that the various levels of simplification are both valid and representative of the local conditions. Four comparison simulation sets for the 100-acre pilot site were developed to test the model (1) at two different time steps; and (2) with and without BMPs. For those runs, the D-storm was applied, assuming average antecedent moisture conditions. Table 2-12 is a matrix of figure references for the comparison runs. The figures and associated observations and conclusions are subsequently presented.

Table 2-12. Reference matrix for aggregate versus articulated BMP comparison tests

Model scenario	Simulation time step	
	Hourly	15 minute
Baseline condition runs	Figure 2-28	Figure 2-29
Proposed BMP design plan	Figure 2-30	Figure 2-31

Baseline Condition Runs

Figure 2-28 shows a hydrograph comparison for the aggregate approach versus the articulated routing networks for the baseline watershed model scenario (without BMPs). Both were run on an hourly time step for this comparison. The aggregate hydrograph (solid line) shows a strong match with the fully articulated hydrograph (discrete points). Total outflow volumes show 100 percent agreement (0 percent difference), while peak flow shows a 1.4 percent higher peak for the aggregate scenario. The aggregate representation forgoes detailed routing through pipes and instead uses an instantaneous flow routing to the outlet. This is consistent with expectations since simplification of the routing reduces attenuation and associated time of concentration.

Similarly, Figure 2-29 shows a hydrograph comparison for the baseline scenario; however, the models were run with a 15 minute time step. Overall, the aggregate hydrograph (solid line) shows a strong match with the fully articulated hydrograph (discrete points). Once again, the total outflow volumes show 0 percent difference, but the peak flow for the aggregate scenario is 1.1 percent higher than for the articulated scenario. Although both the hourly and 15 minute time step simulations show good overall agreement for both the aggregate and articulated network representations, it is interesting to note the difference in shape of the hydrographs. The 15 minute hydrographs for both the aggregate and articulated networks (Figure 2-29) provide a higher resolution of the timing of the response. The timing of the peak is modeled at 9:00 a.m. for the hourly scenarios (which interpreted, means during the 9:00 hour), but is plotted at 9:45 a.m. for the 15 minute scenarios (i.e., between 9:45 a.m. and 10:00 a.m.).

Proposed BMP Design Plan

The effect of time step on model precision is even more pronounced when BMPs were incorporated into both the aggregate and articulated scenarios. Figure 2-30 shows a hydrograph comparison for the aggregate approach versus the fully articulated routing networks for the proposed BMP design plan. At an hourly time step, the aggregate BMP produces a peak flow response that is 11.4 percent lower than the articulated response; however, it gives a total flow volume that is 7.5 percent higher than the articulated network, which equals a 5 percent lower volume reduction relative to the baseline condition). The lower peak in the aggregate hydrograph in Figure 2-30 translates to more attenuation than the articulated hydrograph.

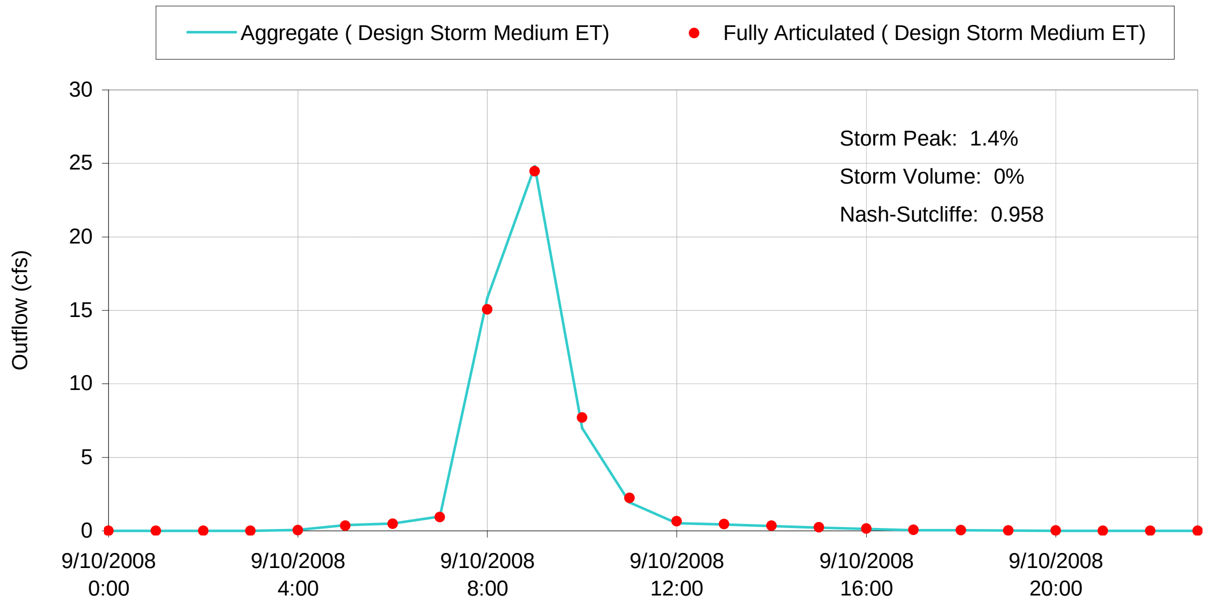

Figure 2-28. Hourly time step, aggregated versus articulated (baseline, no BMPs).

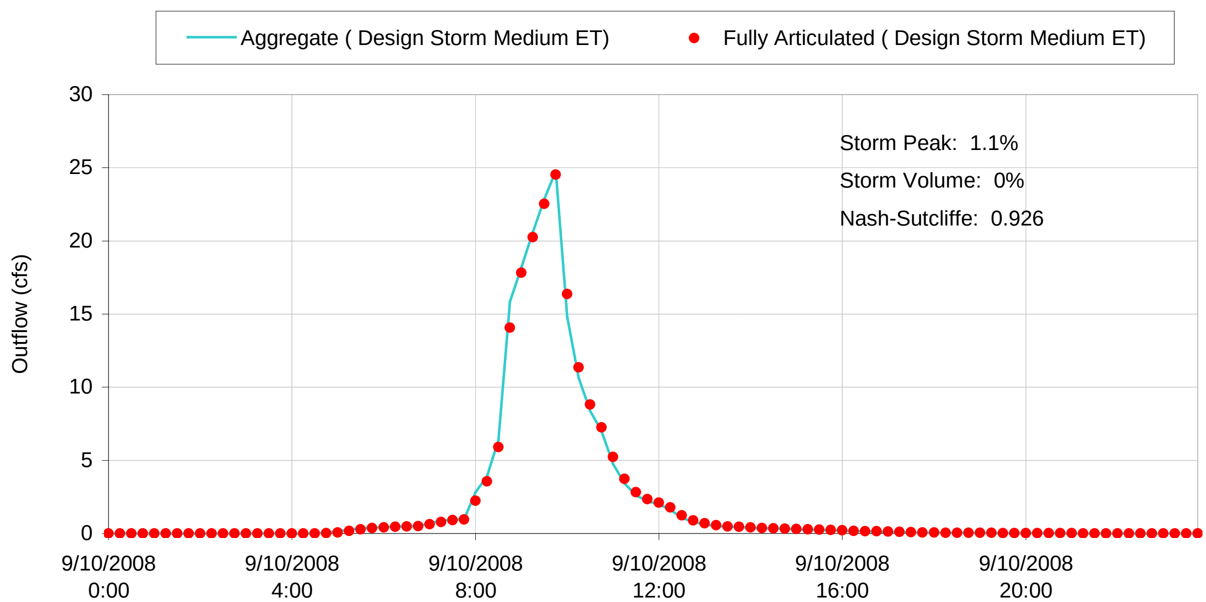

Figure 2-29. Fifteen minute time step, aggregated versus articulated (baseline, no BMPs).

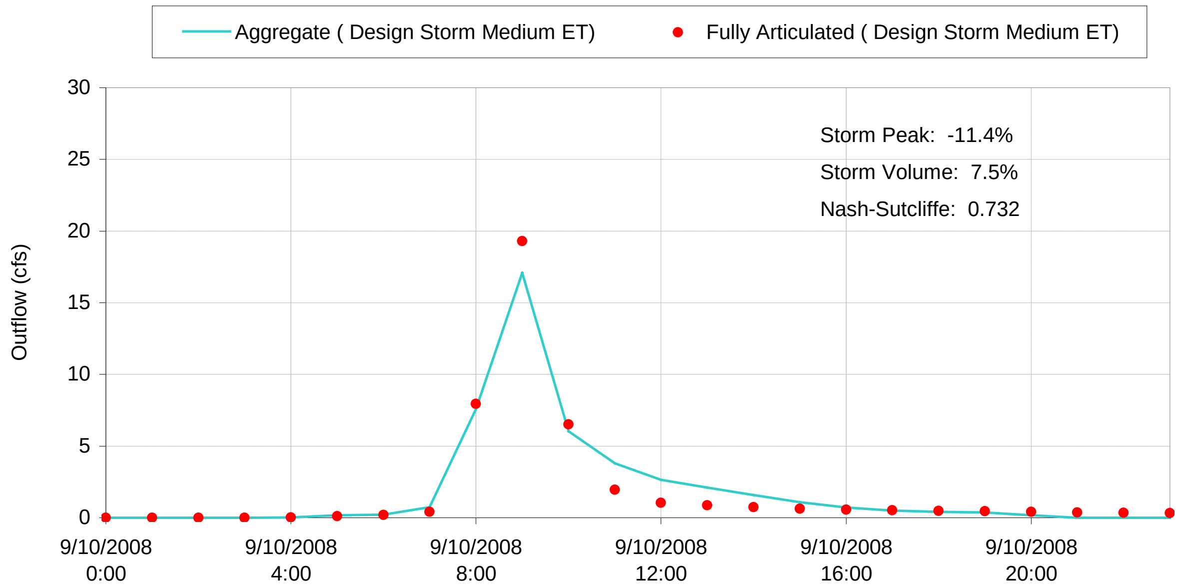

Figure 2-30. Hourly time step, aggregated versus articulated (with BMPs).

Figure 2-31 shows a hydrograph comparison for the proposed BMP design plan scenario; however, the models were run with a 15 minute time step. The aggregate hydrograph (solid line) shows a fairly good match with the fully articulated hydrograph (discrete points). For the BMP scenario, the total outflow volumes show 4.2 percent higher flow volume than the articulated, and a 0.1 percent lower peak. Once again, the shape of the hydrograph shows more attenuation of the water from the start of the storm, as seen in Figure 2-31.

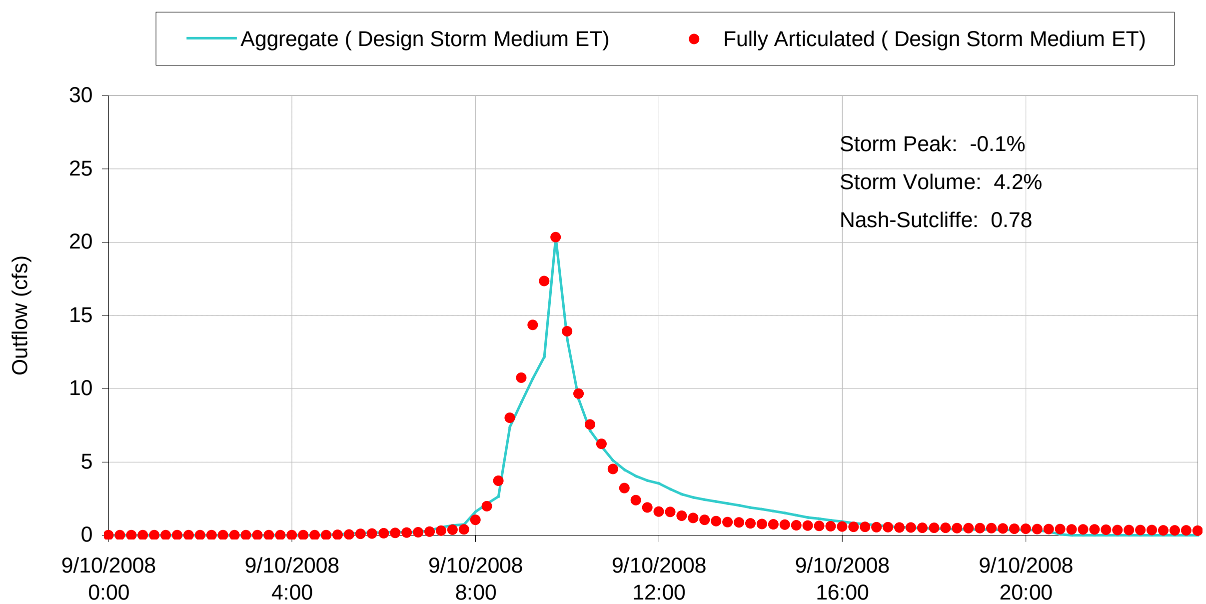

Figure 2-31. Fifteen minute time step, aggregated versus articulated (with BMPs).

There are a few notable observations from these sensitivity analyses. First, simulation time step seems to have the most influence on temporal resolution of peak flow. In both the baseline and the BMP scenarios, the peak flow occurs at 9:00 a.m. for the hourly time step and at 9:45 a.m. for the 15 minute time steps. The second notable observation is the effect of the modeled BMPs on both volume and peak flow. The BMP scenarios at both time steps predicted more storm volume for the aggregate relative to the articulated configuration. Although both networks contain the same kinds and total storages for the various BMPs in plan, the aggregate network generalizes the connectivity of the routing network. The higher outflow volume predicted by the aggregate BMP network means that the modeled BMP network provides a slightly lower volume reduction than the fully articulated network (5 percent for the hourly time step, versus 3 percent for the 15 minute time step). Detailed routing provides greater attenuation of the flows. Although the baseline run did not show any difference in the responses, the BMP scenario accentuates the effects of flow attenuation. Because the optimization objective is volume control and not peak flow, the selected simulation time step is not as much of a concern. However, because the 15 minute time step gives a better overall agreement between the aggregated and articulated networks, it is preferred over the hourly time step for this pilot study modeling. In addition, the fact that BMP performance is slightly under-predicted with the aggregate BMP configuration provides an additional margin of safety for the predicted volume control benefit.

Model Run-Times

One of the most notable advantages of the aggregate BMP is the time savings for each model run. These reductions in time have a large impact during optimization runs which typically require in excess of 10,000 iterative model runs over the simulation time period. Table 2-13 shows a comparison of model characteristics for three configurations: (1) the original XP-SWMM model configuration; (2) the fully articulated *SUSTAIN* baseline; and (3) the simplified aggregate *SUSTAIN* baseline models. The model comparisons presented were all run using the same weather boundary condition: D-storm with average antecedent recovery conditions at a 15 minute simulation time step.

Table 2-13. Comparison of model characteristics for three configurations

Characteristics	Configuration		
	XP-SWMM	*SUSTAIN* articulated	*SUSTAIN* aggregate
Number of catchments	179	85	1
Number of pipes	350	36	1
D-storm peak (cfs)	N/A	24.52	24.80
D-storm volume (cubic feet)	N/A	46.38	46.38
Single run-time (sec.)	25	1	< 1
10,000 runs (hr)	69.5	2.75	< 1

The run-time values presented above for the XP-SWMM model were derived from simulating a single storm event (9/24/2008) using the version of the model obtained from Kansas City that was exported into an SWMM5 format. Estimates of run-times for 10,000 runs were calculated by multiplying a single-event run-time by 10,000 (which represents a possible number of iterations associated with an optimization run).

2.5. Optimizing BMP Opportunity for CSO Mitigation in the 069 Watershed

The previous objectives of this effort have established a calibration baseline condition and modeled the BMP network associated with the approved design plan for the 100-acre pilot site. Model testing also demonstrated the validity of a streamlined spatial representation for model representation. Because WSD has committed to implement the design plan for the 100-acre pilot site, it was included as part of the model baseline for optimization. The previous analyses presented thus far represent the foundational elements on which optimization scenarios are based. The central question within the minds of regional policy makers is what degree of management is required to mitigate CSO throughout the larger 069 sewershed? Exploratory management alternatives include (1) extending the proposed GI design plan (GI on public rights of way) to the remainder of the 069 sewershed; (2) expanding the scope of GI to include implementation of certain practices on private land; and (3) exploring gray infrastructure options for supplemental CSO storage at the regulator outlet. The objectives for optimization are to (1) maximize runoff volume control; and (2) minimize the total capital cost of implementation, as needed, to satisfy the allowable exceedance criteria for CSO (i.e., treating 100 percent of D-storm runoff). Figure 2-32 conceptually illustrates the development sequence of exploratory optimization scenarios relative to established baseline conditions.

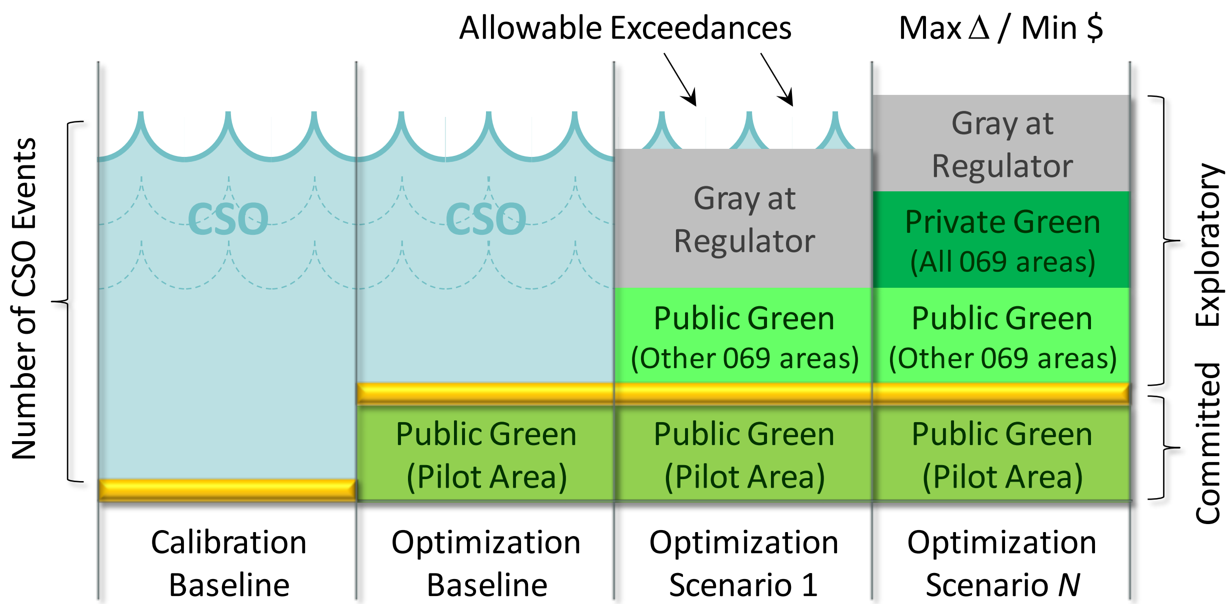

Figure 2-32. Conceptual sequence of optimization scenarios relative to baseline conditions.

SUSTAIN provides a platform for synthesizing information derived from various independent but complementary research efforts in Kansas City. The respective conclusions of the studies discussed in Section 2.1 are maintained during the synthesis because of the important assumptions associated with each component. For example, the BMP design plan for the 100-acre pilot area incorporates site feasibility surveys of public rights of way in the BMP designs; therefore, the relative BMP sizing and placement rules were maintained both within the pilot area and during extrapolation to other parts of the 069 sewershed. The WinSLAMM application quantifies benefits for management alternatives on private property parcels throughout the sewershed. Table 2-14 maps out certain key *SUSTAIN* optimization requirements with the relevant study from which they were based. The updated SWMM model refers to the reconfigured SWMM5 baseline calibration model described in Section 2.3, for which development was partially based on the XP-SWMM model.

Table 2-14. *SUSTAIN* application data needs and associated data source (research study)

SUSTAIN requirements: ● Available -- Not available	Updated monitoring data	Updated SWMM model	BMP design plan	Desktop analysis	WinSLAMM application[a]
Calibration Baseline	●	●	--	--	●
Optimization baseline	--	●	●	--	--
CSO control targets	--	●	--	●	--
Pipe routing information	--	●	--	--	--
Dry-weather sewer flow	--	●	--	--	--
BMP specifications	--	--	●	--	●
BMP capital cost	--	--	●	●	--

a. For private property

The remainder of this section (1) describes how the spatial extent of the model was expanded to the 069 sewershed and its overflow regulator; (2) defines the objective functions and constraints for the optimization problem formulation; (3) describes how BMP costs were derived from local contractor bid data; and (4) presents the *SUSTAIN* optimization results and sensitivity analysis.

2.5.1. *CSO 069 Model Configuration*

The CSO 069 watershed (480 acres) was subdivided into five subwatersheds ranging in size from 58.9 to 139.7 acres, with an average size of 96.2 acres. As previously described, the aggregate BMPs within the 100-acre pilot study area were maintained as constant for the optimization baseline condition. For the remaining areas outside the 100-acre pilot study area, the relative BMP to area ratio was prescribed, with the optimization decision variable defined as the percentage of the remaining 069 outfall drainage area receives GI practices according to the same proportions applied within the pilot study area. In addition, the volume of the gray storage basin was also defined as a decision variable for the scenarios when a supplemental storage basin was an available alternative.

Because model testing showed that the aggregate BMP configuration was valid and representative for subwatersheds around 100 acres in size, the remainder of the area within CSO 069 was delineated into subwatersheds of similar size in which aggregate BMP rules could be applied. In each subwatershed, the main sewer truck line was retained to create a composite network of primary pipe segments with aggregate BMP drainage areas. This network representation allowed for two key advantages for the model, namely, (1) the ability to use a simplified aggregate BMP approach in each of the five subwatersheds; and (2) the ability to preserve the primary flow network that ultimately deliver the water volume to the regulator. Figure 2-33**Error! Reference source not found.** is a map showing the subwatersheds, pipe connections, and the relative location of the regulator assessment point for CSO 069.

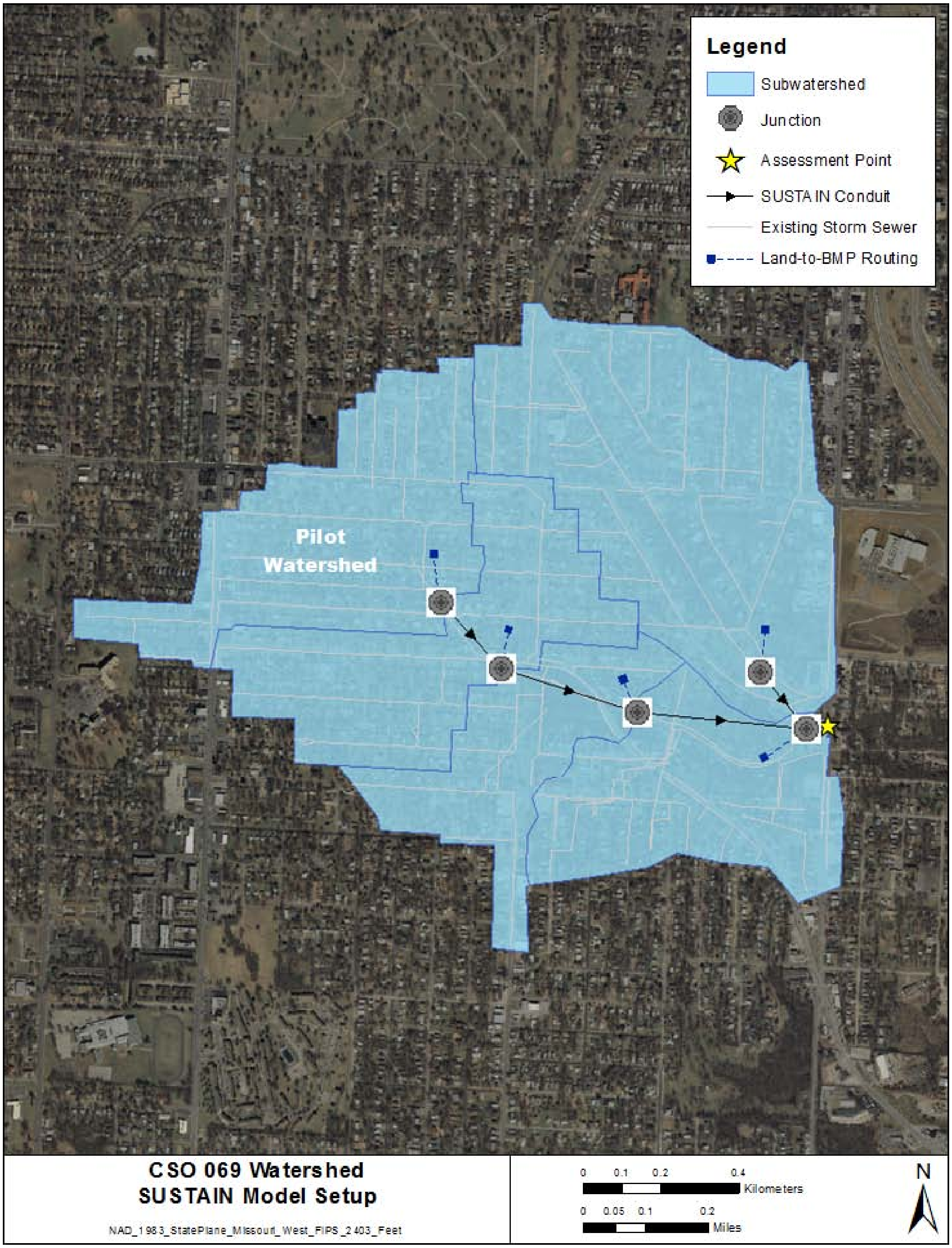

Figure 2-33. Subwatersheds, pipe connections, and regulator assessment point for CSO 069.

For the baseline 069 sewershed model, the calibrated time series from the 100-acre pilot site were extrapolated throughout the 069 sewershed on the basis of HRU distribution. Because the HRU runoff time series characterize the rainfall-runoff response, the HRU is a convenient and consistent basis for extrapolating outside of the calibrated pilot watershed. The simplified drainage network was modeled as a series of junctions and circular pipes. One key element of the 069 model is the regulator at the sewershed outlet. As shown in original the regulator design schematic (Figure 2-34), the structure behaves more like a run-through device with a depressed area in the middle of the device where water can accumulate. The top panel is the view from above while to bottom panel is the side view. Figure 2-35 is a conceptual schematic of water movement through the regulator.

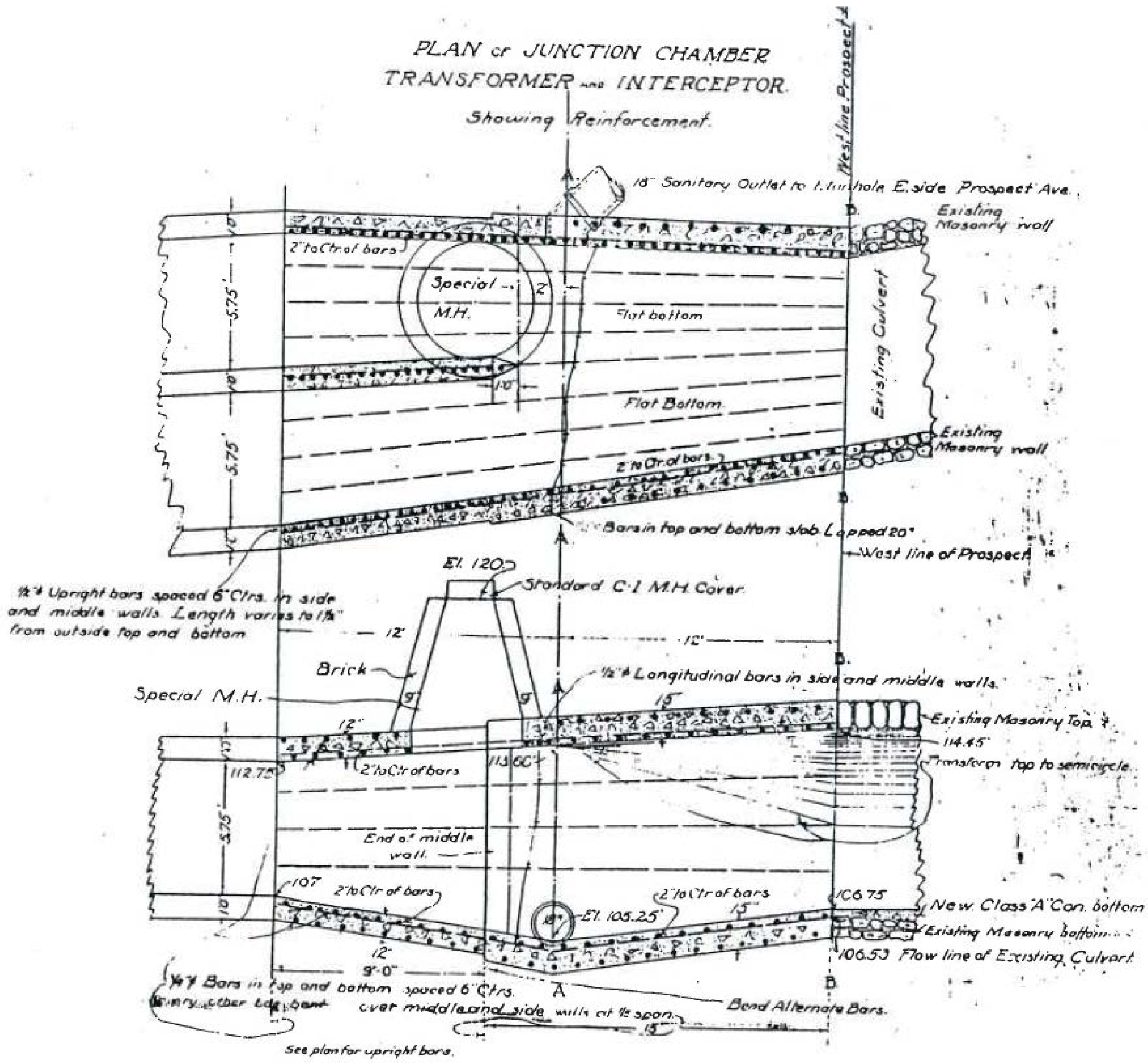

Figure 2-34. CSO 069 regulator schematic.

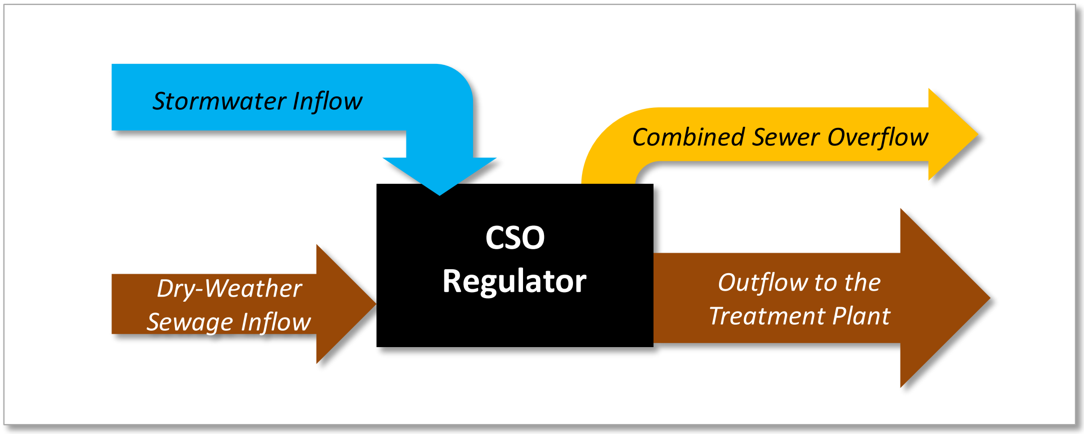

Figure 2-35. Conceptual schematic for the CSO regulator.

Water in the storage depression is diverted to the wastewater treatment plant through an 18 in. diameter pipe that runs perpendicular to the inflow direction of the water. During dry-weather flow, the sanitary flow exits the chamber through the 18 in. pipe. During wet-weather flow conditions, the increased velocity of the water will bypass the sanitary pipe outlet and continue downstream to an overflow point. In *SUSTAIN*, the total storage volume of the regulator is represented as a vertical box structure with a weir at the height of 1.5 ft, width of 7.8 ft, and an 18 in. bottom orifice. The baseline overflow frequency was confirmed by running the model with continuous time series from the 2004 typical year. Because of slight differences in regulator geometry and the head loss associated with the sanitary pipe outlet perpendicular to the line of flow, the orifice discharge coefficient was adjusted to a value of 0.24 to maintain the expected 33 overflow events for the 2004 typical year.

2.5.2. *Problem Formulation*

As previously conceptualized in Figure 2-32, the optimization baseline included the BMP designs being implemented within the 100-acre pilot area. Using the CSO 069 model configuration presented in Section 2.5.1, the optimization problems were formulated for the selected management options. The generalized multi-objective functions and constraints are presented as follows:

Minimize ∑ BMP Capital Costs
Minimize Regulator overflow volume (for the D-storm)
Subject to

- Final design plan for 100-acre pilot site
- Exploratory Management Options:
  - GI on 069 public rights of way (outside of pilot area)
  - GI on 069 private parcels
  - Supplemental gray infrastructure at the regulator

Background analysis from the OCP suggests that adequately controlling runoff volume such that no overflow occurs during the D-storm (D-storm: 1.4 in. depth, 0.6 in./hr intensity, 16.75 hr duration) would achieve the CSO allowable exceedance objective. Considering the 2004 typical year, controlling the D-storm reduces the number of overflows from 33 to 2 or 3, as further described in Section 2.5.6. Because antecedent conditions can have a significant influence on runoff generation potential and BMP performance, three sets of optimization runs were executed to provide a range of results corresponding to low, medium, and high antecedent moisture conditions. The three sets of time series are described in Section 2.3.3, under Design Storm Time Series.

2.5.3. *BMP Cost Representation*

BMP cost information is a critical element of cost-benefit optimization. Local sources were used to derive capital cost data for GI on public rights of way and gray infrastructure components while the costs of BMPs on private parcels were estimated from local and literature values as detailed below.

GI Costs

The BMP cost data used in this study were derived using March 8, 2011, contractor bid data provided by WSD for the Middle Blue River Green Solutions Pilot Project. There were both general site preparation and specific BMP-associated costs provided in the contractor bid data. The general cost components included the following items:

- Preconstruction costs (mobilization, traffic control, erosion and sediment control, surveying and construction staking);
- Tree removal and utilities relocations;
- Street and sidewalk improvements;
- Landscape restoration; and
- Mulch, plants, and other miscellaneous landscape materials.

The specific BMP-associated costs included the following items:

- Below-grade storage system structures and general backfill; and
- BMP construction for various surface BMP types (rain gardens, shallow bioretention, porous pavement, cascades, bioretention, and grass swale).

Consistent with the cost module input format used by *SUSTAIN*, the general cost components from the contractor estimate were converted to area-based BMP-associated costs. Those costs were proportionally distributed among the BMPs according to the total number of BMP units in the design plan, with the exception of mulch, plants, and other miscellaneous landscape materials items. Those costs were evenly divided among the BMP types that incorporate vegetation (i.e., rain garden, bioretention, cascade, and bioswale). The BMP-specific cost items were then averaged by BMP type to derive a unit cost. As summarized in Table 2-15, the total unit cost for each type of BMP was calculated by adding the distributed general site preparation costs with the BMP-specific costs.

Table 2-15. BMP capital costs for the 069 sewershed

BMP types		BMP cost		
		Site preparation	BMP-specific costs	Total cost per unit
Bioretention	other	$19,616	$1,938	$21,554
	shallow	$19,616	$3,247	$22,863
Bioswale		$19,616	$2,923	$22,539
Cascade		$19,616	$3,383	$22,999
Porous sidewalk		$16,163	$13.1 per square foot	Varies by surface area
Porous pavement on cube		$16,163	$10.7 per cubic foot	Varies by volume
Rain garden		$19,616	$1,249	$20,865
Storage		$19,616	$59,048	$75,210

The functional effects of GI applied to private property were modeled as (1) disconnected downspouts with rain barrels; and (2) on-site rain gardens. The WinSLAMM application did not include a phase which provided cost estimates for these BMPs; therefore, these costs were derived from local applications and literature sources. Schueler et al. (2007) published a manual through the Center for Watershed Protection (CWP), which provided construction cost estimates for both rain garden and rain barrels retrofits, and design and engineering cost estimates of 5 to 40 percent of the construction cost.

Table 2-16. Cost estimation for private parcel retrofit BMPs

BMP type	BMP cost ($ per gallon of runoff treated)			
	Construction cost		Design and engineering (40% of construction costs)	Total cost
	Literature range	Median		
Rain garden	$0.40–$0.67	$0.53	$0.21	$0.75
Rain barrel	$1.67–$5.35	$3.34	Not applicable	$2.81

Source: Schueler et al., 2007

Costs were presented in terms of runoff volume treated; however, for rain gardens, an additional step was required to translate the cost data into a convenient basis for *SUSTAIN* because the volumetric cost component in *SUSTAIN* is based on excavation volume instead of storage volume. Nevertheless, the rain gardens were parameterized with a constant uniform soil column depth, as previously shown in Table 2-10. Because the uniform soil media column has a predefined void space, there are two options for representing its cost in *SUSTAIN*: (1) calculate an equivalent excavation depth from the treatment depth; or (2) calculate a surface area equivalent cost. Using an equivalent surface area basis, the computed $5.6 per cubic feet of void space translated to an area-based cost of $10 per square foot. For the rain barrel, the unit cost of a 35-gallon unit and downspout connection was estimated to be $100 by considering a rain barrel cost of approximately $2 per gallon (Woodland Direct, 2011), which falls within the published literature range presented in Table 2-16.

Gray Infrastructure Costs

As presented in the OCP, the total capital cost of a 2 MG storage facility was estimated to be $30.6 million. The facility includes a 2 MG storage tank, 1.5 MG per day pumping station, 51MG per day screening, a 100 ft 48 in. sewer pipe, and 500 ft 12 in. force main, and an odor control facility. The estimated capital costs include an allowance of 25 percent of the total estimated construction cost for planning, engineering and design, and an additional contingency cost of 25 percent. This cost estimate is based on 2006 data and has been updated for this case study using a multiplier of 1.163 (20 city Engineering News-Record (ENR) index value of March 2011/2006 Annual Average) to reflect a 2011 cost of $35.6 million.

To represent the optimization cost function for the storage facility, the separate fixed cost elements were calculated separately from those that varied with size. The selection of a storage facility initially involved costs including upfront planning, mobilization, and design costs, regardless of the facility's size. The resulting cost function also implicitly accounts for economies of scale as the storage capacity increased beyond the initial cost investment. An initial fixed cost of $11.63 million (about one-third of the literature-based cost value, or $10 million x 1.163) was approximated to be a reasonable amount on the basis of inference from local contractor bids for certain components. The remainder of the gray infrastructure cost was approximated as a linear function of storage capacity by back-calculating the rate as follows:

$$\text{Storage Cost} = (\$35{,}600{,}000 - \$11{,}630{,}000) \div 2\ \text{MG} = \$12 \text{ per gallon} = \$89.76 \text{ per cubic foot}$$

$$\text{Total Capital Cost (\$)} = \$11{,}630{,}000 + \$89.76 \times (\text{storage volume in cubic feet})$$

2.5.4. *Optimization Sensitivity Tests*

While developing the optimization baseline model, sensitivity testing for the articulated versus the aggregated network configuration demonstrated that the simulation results were sensitive to the simulation time step (Section 2.4.2). Furthermore, because *SUSTAIN* optimization was to be run on an event basis for the D-storm instead of on a continuous simulation basis where moisture recovery is dynamically accounted for, the user-specified antecedent moisture condition represented a potentially significant unknown variable. Two sets of sensitivity tests were performed to test the influence of (1) model simulation time step; and (2) antecedent moisture conditions on the predicted cost-effectiveness curve derived through optimization.

Simulation Time Step Sensitivity Analysis

Sensitivity testing (low, medium and high recovery conditions) of overflow volume reduction at the regulator outlet revealed a surprising trend that initially seemed counterintuitive. The analysis presented in Section 2.4.2 suggests that because more runoff volume was associated with the 15 minute time step compared to hourly, using the smaller time step would result in a more conservative overflow reduction estimate during optimization. However, the opposite appeared to occur. Figure 2-36 summarizes the influence of model simulation time step on the optimization results and suggests that the 15 minute time step consistently has a higher percent volume reduction along the entire cost-effectiveness curve than the hourly time step. On further investigation it was discovered that it was actually the difference in resulting baseline volume associated with the different time steps that was responsible for the higher percent volume reduction as shown.

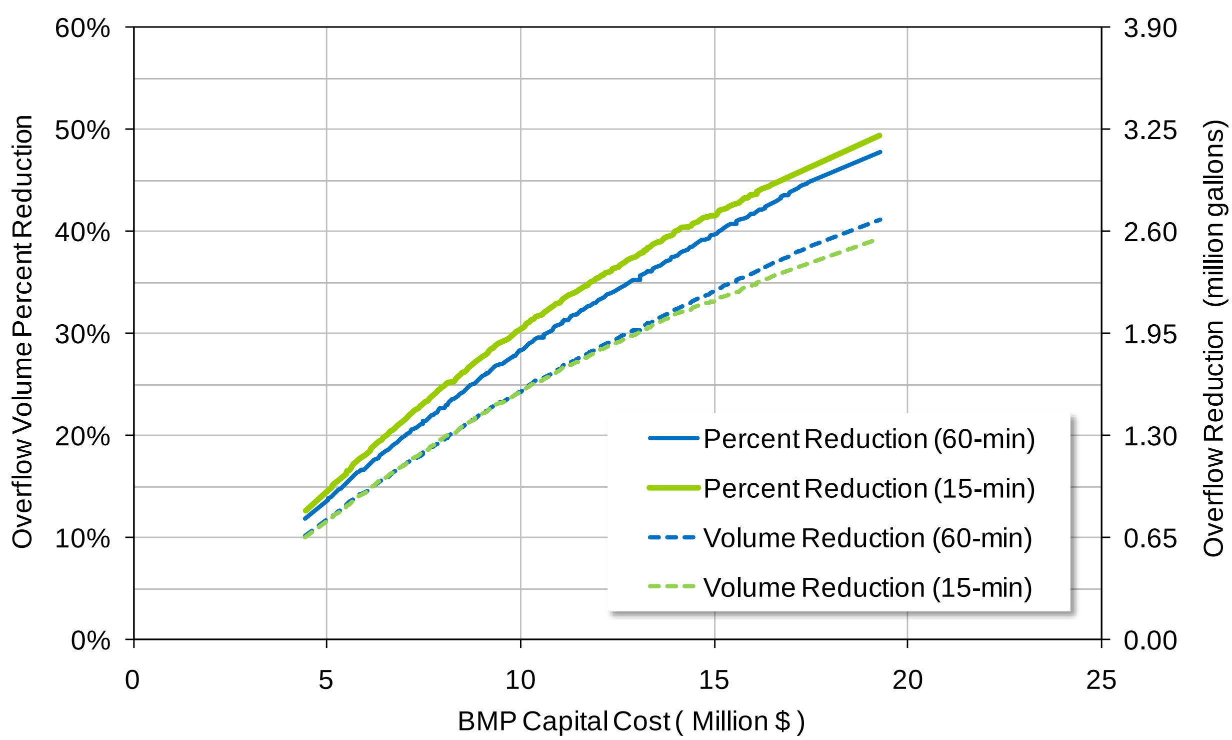

Figure 2-36. Sensitivity of model simulation time step on optimization results.

In addition to overflow volume percent reduction, the absolute overflow volume reduction for the D-storm was plotted for both time steps. The graphs for absolute volume reduction are also shown in Figure

2-36 as a function of the associated BMP capital costs. Up until around the $10 million point, the absolute volume reductions for both time steps seem to track very closely; however, after that point, the 15 minute time step curve tends to follow a lower trajectory than the hourly simulation time step. Another factor at play behind the different responses is attenuation associated with routing through the pipe network to the regulator. In general, the smaller 15 minute time step does a better job of predicting the peak attenuation than the hourly time step simulation because it has less temporal averaging; consequently, the resulting peak attenuation at a 15 minute time step can be slightly higher. That is why the overall volume reduction for the 15 minute time step trails the hourly time step even with increasing GI spatial extent.

Antecedent Moisture Condition Sensitivity Analysis

Optimization runs were generated for three antecedent moisture conditions to provide a range of response for the D-storm. Figure 2-37, which was previously presented as Table 2-7 during the discussion about how the D-storm time series were developed, compares antecedent moisture conditions for the D-storm. Note the differences in dry days and evaporation rates associated with each condition.

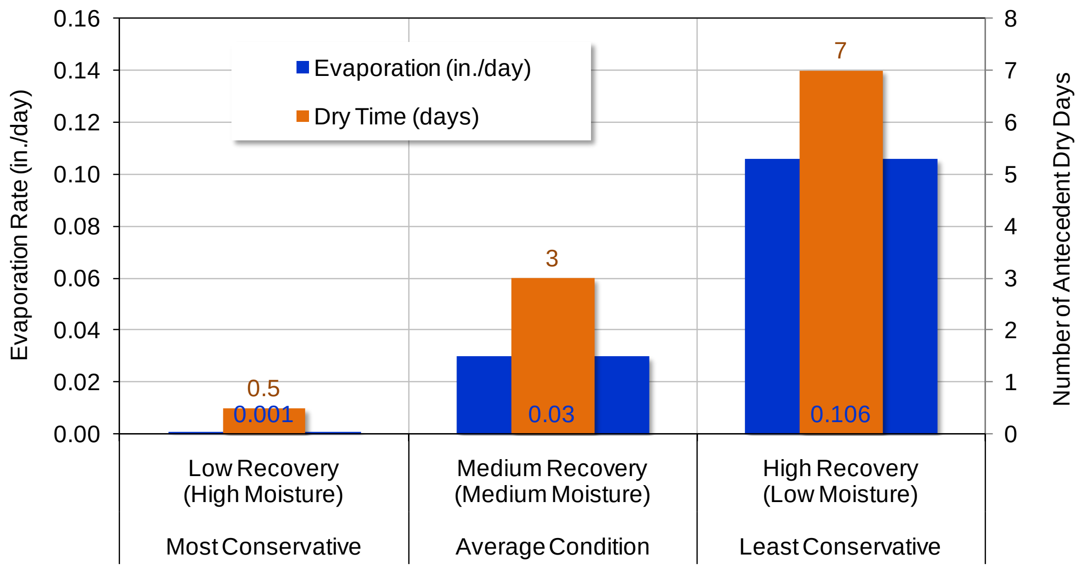

Figure 2-37. Comparison of antecedent recovery conditions for the D-storm.

For this analysis, the cost-effectiveness curves associated with optimization of GI in public areas served as the basis for comparison. Figure 2-38 illustrates the influence of antecedent moisture conditions on optimization results.

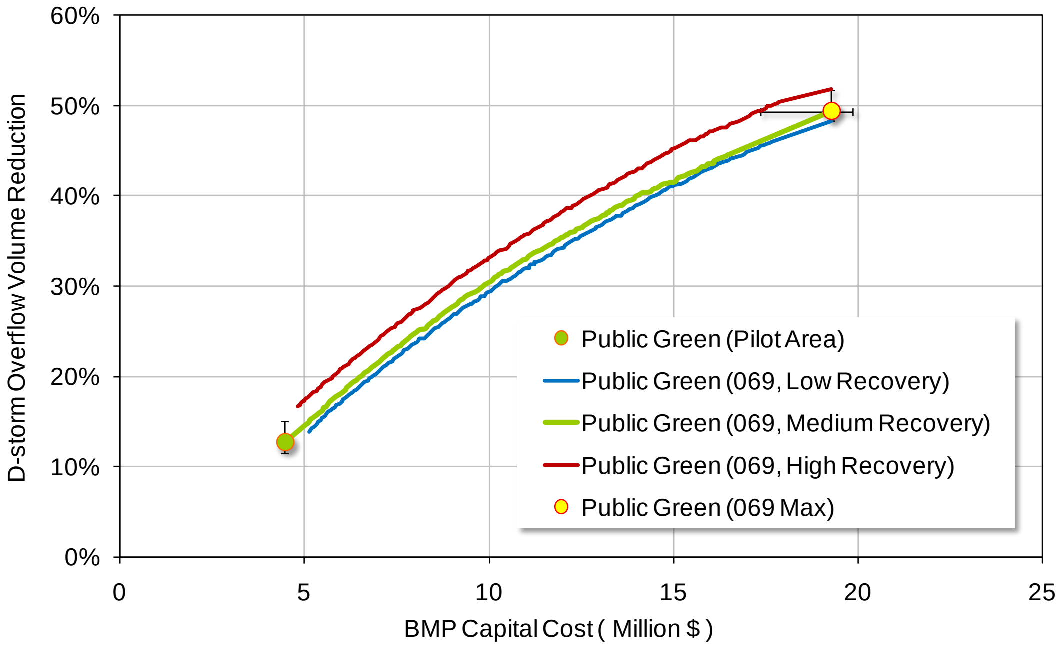

Figure 2-38. Sensitivity of antecedent moisture conditions on optimization results.

Comparing those curves reveals a number of interesting patterns. One of the first noteworthy observations is how close the medium recovery curve is to the low recovery curve. The nonlinear relationship between the product evaporation rate and the number of days is evident in the spread between the three graphs. Looking at the point on Figure 2-38 labeled Public Green (069 Max) reveals that at a fixed cost interval, the spread in volume reduction between the three scenarios is relatively small (–1.1 to +2.4 percent) compared to the range of cost variation around a fixed volume reduction (+3 to –9.9 percent). The respective ranges of variability are plotted as vertical and horizontal error bars in Figure 2-38. Table 2-17 summarizes the sensitivity of optimized treatment cost and associated overflow reduction for the three levels of antecedent moisture conditions.

Table 2-17. Sensitivity of cost-effectiveness to changes in antecedent moisture condition

Antecedent moisture condition	Reduction variation (fixed cost)			Cost variation (fixed reduction)		
	Cost ($ million)	Overflow reduction	Percent difference	Overflow reduction	Cost ($ million)	Percent difference
Low recovery	$19.26	48.3%	-1.1%	49.4%	$19.83	3.0%
Medium recovery	$19.26	49.4%	--	49.4%	$19.26	--
High recovery	$19.26	51.8%	2.4%	49.4%	$17.36	-9.9%

The range of the horizontal and vertical error bars around the point associated with maximum projection of the GI design plan for the 100-acre pilot site to all public rights of way throughout the 069 sewershed represent the range of uncertainty associated the selected initial condition associated with moisture storage, and its influence on optimization results. For subsequent analyses, cost-effectiveness curves for the medium recovery condition are plotted with the associated horizontal and/or vertical error bars to illustrate the possible range of variability associated with optimization results.

2.5.5. *Exploratory Management Scenarios*

Three optimization scenarios were developed to evaluate the cost-benefit of the exploratory management alternatives. Although the optimization objective is 100 percent containment of the Type-D storm, plotting the cost-effectiveness curves associated with each scenario provides insight into the cost-benefit trajectory toward achieving the management goal of controlling the Type-D storm. The baseline condition and a predetermined sequencing of three exploratory optimization scenarios were simulated. Table 2-18 provides a summary and description of the baseline and the three exploratory optimization scenario sequences.

Table 2-18. Summary and description of baseline and exploratory optimization scenarios

Optimization scenario		Description
Baseline	Public green (pilot area)	Full adoption of the BMP design plan within the 100-acre pilot study area
Exploratory	Gray only	Baseline + supplemental gray storage at the 069 regulator outlet
	Public green + gray	Baseline + public green expanded to other 069 areas + gray supplemental storage
	Public + private green + gray	Baseline + public green expanded to other 069 areas + private green opportunity + gray supplemental storage

The optimization scenarios were run using the D-storm time series, with the medium antecedent moisture conditions; however, the projected range of variation associated with low and high antecedent moisture conditions was also plotted using error bars around key junctions along the trajectories. Figure 2-39 shows the key junctions and cost-effectiveness curve trajectories for the three exploratory optimization scenarios. Because the optimization target is 100 percent containment of D-storm overflows, Figure 2-40 zooms into the Optimization Target box in Figure 2-39 to show a comparison of overflow compliance costs for the three exploratory scenarios, with error bars denoting the range of variation associated with high and low antecedent moisture conditions.

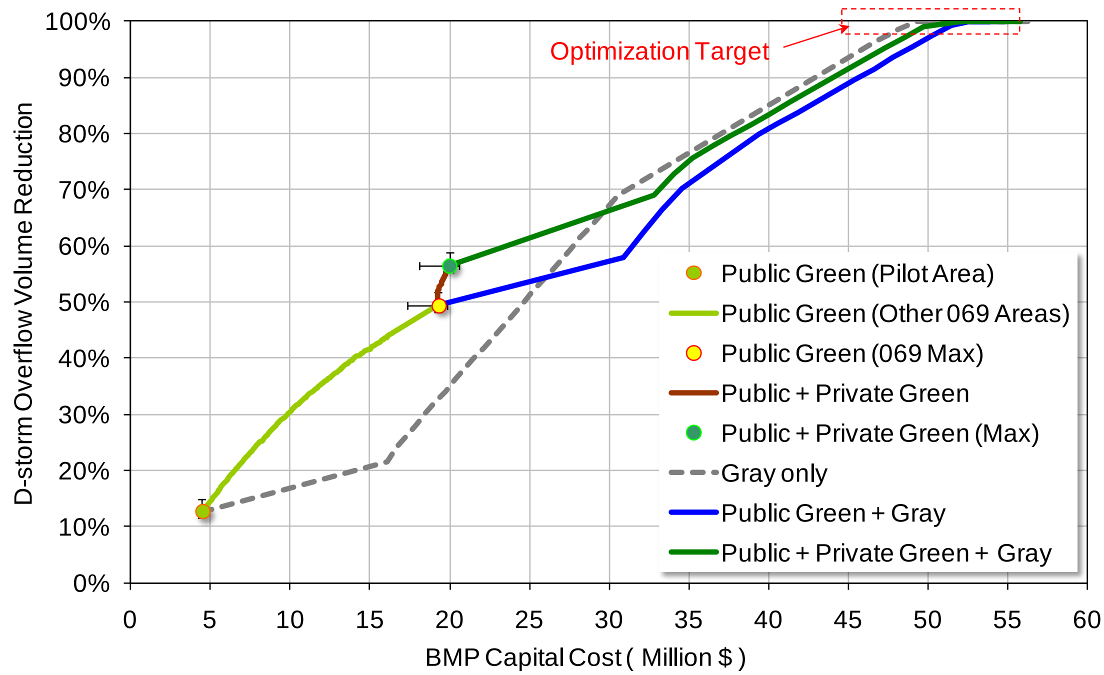

Figure 2-39. Cost-effectiveness junctions and trajectories for exploratory optimization scenarios.

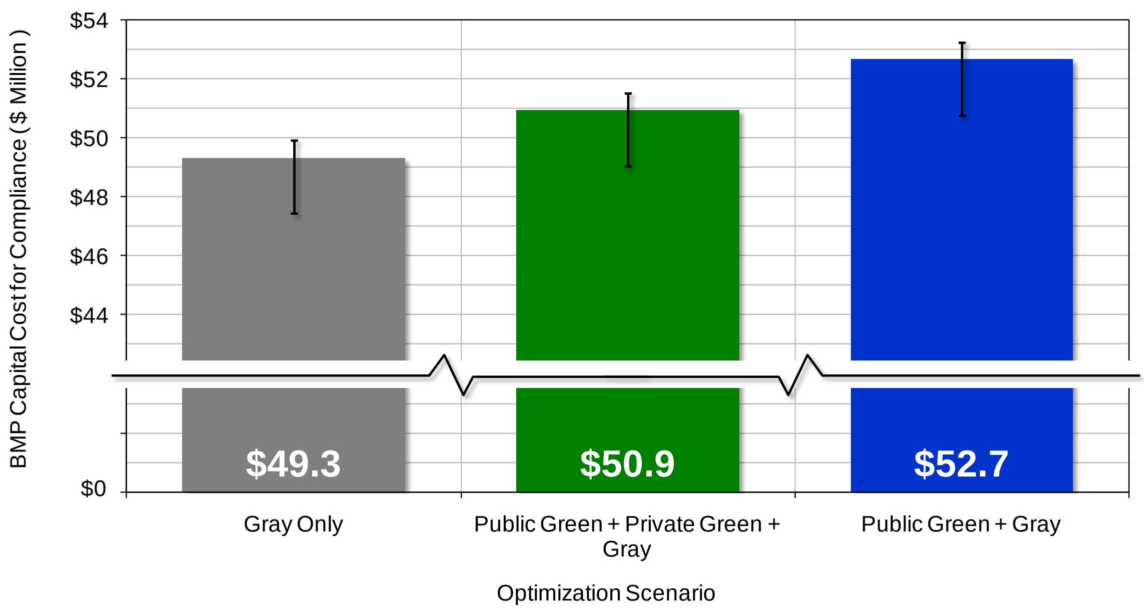

Figure 2-40. Comparison of overflow compliance costs for the three exploratory scenarios.

Among the exploratory optimization scenarios, proposed GI options for both public and private land were maximized, with the exception of the gray only scenario, where GI was not considered. The difference in cost is attributable only to the size of the gray supplemental storage associated with each of the three scenarios. Table 2-19 shows the component sizes and costs from the exploratory optimization scenarios.

Table 2-19. Management component size and costs for exploratory optimization scenario

Scenario	Management component		Total storage capacity (gallons)	Total cost ($)	Unit storage volume cost ($/gallon)
Public green	Bioretention	other	520,023	$4,310,671	$8.29
		shallow	82,109	$519,610	$6.33
	Bioswale		44,313	$102,447	$2.31
	Cascade		64,188	$522,682	$8.14
	Porous sidewalk		59,301	$381,698	$6.44
	Porous pavement on cube		11,404	$180,020	$15.79
	Rain garden		474,081	$6,069,606	$12.80
	Pipe storage		915,905	$7,178,998	$7.84
Private green	Rain barrels		14,662	$41,480	$2.83
	Rain gardens		950,443	$706,000	$0.74
Gray	Gray only		2,778,970	$44,880,833	$16.15
	Public green + gray		1,819,660	$31,681,177	$17.41
	Public + private green + gray		1,617,700	$32,651,283	$20.18

2.5.6. *Validating Overflow Control Using Continuous Simulation for a Typical Year*

Optimization was performed using the D-storm series as the driver for rainfall and runoff for a range of antecedent moisture conditions. However, the design storm approach does not necessarily tell us which storms are controlled under the context of a continuous simulation run. For continuous simulation, an overflow event can be caused by a smaller event that occurs immediately after a series of events that have saturated both the ground and the BMP storage capacity. For this validation effort, BMP selections corresponding to the three points crossing the 100 percent D-storm containment threshold (as summarized in Table 2-19) were tested on a continuous simulation basis using the 2004 typical rainfall and ET time series as the driver. Storm separation was performed on the 2004 year by dividing the time series into discrete storm events for comparison. The storm separation process assumed a minimum inter-event time of 12 hours, with a minimum storm size of 0.1 in. Of the 50 discrete storm events that resulted for 2004, 6 had an overall rainfall depth greater than 1.4 in. Those storms (as summarized in Table 2-20) theoretically represent events that would otherwise be allowed to overflow the regulator.

Table 2-20. Storms summary for the six largest storm events in 2004

Storm start time	Storm end time	Rainfall depth (in.)	Peak intensity (in./hr)	Average ET rate (in./hr)	Antecedent dry hr
D-storm[a]		1.4	0.6	0.03	72
8/27/04 17:00	8/28/04 18:00	1.570	0.65	0.092	49
3/4/04 4:00	3/5/04 12:00	1.680	0.180	0.018	12
8/23/04 8:00	8/24/04 21:00	1.750	0.790	0.092	79
5/18/04 6:00	5/19/04 17:00	1.840	0.280	0.081	94
9/5/04 17:00	9/6/04 8:00	1.980	0.870	0.066	156
6/9/04 3:00	6/10/04 22:00	2.090	0.520	0.108	221

a. Assumes average antecedent moisture conditions (3 dry days, 0.03 in./day ET)

The validation test supported confirmation that the design objectives had been met. The simulation results revealed that three of the six events overflowed under the Gray Only solution; whereas only two of the six events overflowed for both of the Green + Gray scenarios. Both solutions exceeded the design objective of six overflow events per year. The storms dates and the overflow volume and peak flow rate are summarized in Table 2-21. Note that the June 9 event barely crested the regulator storage facility with a marginal peak discharge rate of 0.0157 cfs.

Table 2-21. Overflow events summary

Scenario	Overflow events			
Baseline (No BMPs)	Overflow occurs for all storms ≥ 0.28 in., with a total of 33 overflow events in 2004.			
Near optimal solutions	**Storm start time**	**Storm end time**	**Overflow peak flow rate (cfs)**	**Overflow volume (MG)**
Gray only	6/9/04 3:00	6/10/04 22:00	0.0157	0.001
	8/23/04 8:00	8/24/04 21:00	39.0	3.185
	9/5/04 17:00	9/6/04 8:00	119.0	7.487
Public green +gray	8/23/04 8:00	8/24/04 21:00	31.0	2.638
	9/5/04 17:00	9/6/04 8:00	110.0	6.772
Public + private green + gray	8/23/04 8:00	8/24/04 21:00	26.5	2.216
	9/5/04 17:00	9/6/04 8:00	95.7	5.837

Multiple factors affect the occurrence of overflow events; with rainfall intensity and antecedent condition the dominant factors. Of the six rainfall events with the total depth greater than 1.4 in. (D-storm rainfall depth), only three have peak intensities greater than 0.6 in./hr (D-storm peak intensity). Two of the three storms produced overflow in all three scenarios.

Take for example, the 1.68 in. storm event for March 4, 2004, shown below as Figure 2-41. That storm did not cause an overflow at the regulator storage facility. The event has a total rainfall depth of 1.68 in., but it had a peak intensity of only 0.18 in. per hour. The rainfall volume was well distributed over a relatively longer time than the other storms presented in Table 2-19.

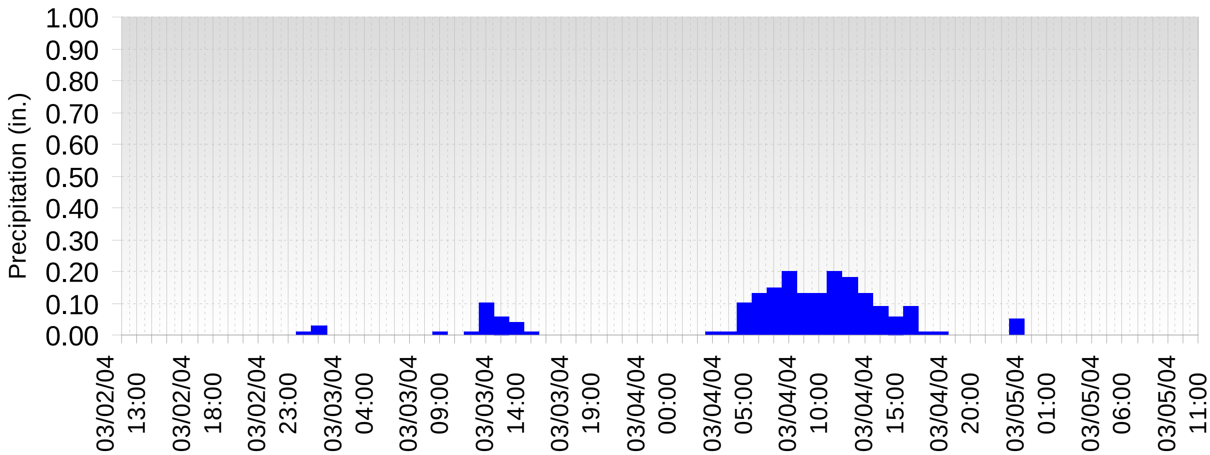

Figure 2-41. Hyetograph for the March 4, 2004, storm event.

The August 27, 2004, storm, shown below as Figure 2-42, also did not produce overflow. That event had a peak intensity of 0.65 in./hr; however, when assessed in the broader context of average ET rate (relatively high summer rate) and longer antecedent dry hours, the results suggest that GI was able to provide a little more control benefit for the event than the Gray Only solution could provide. The combined effect of higher ET and longer antecedent dry period resulted in (1) less overall runoff from the watershed; and (2) better GI BMP performance eliminated the overflow.

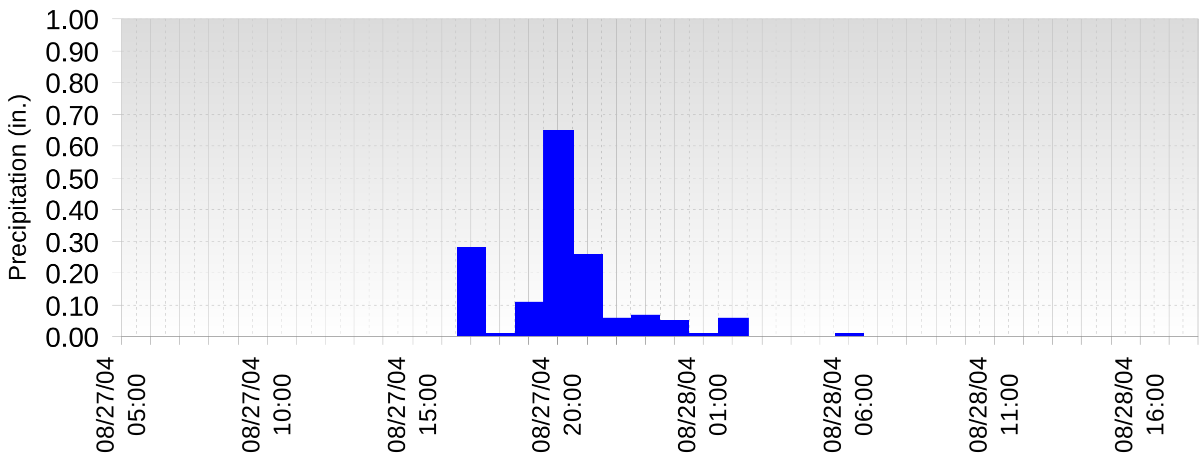

Figure 2-42. Hyetograph for the August 27, 2004, storm event.

Another interesting event is the June 9 event shown below as Figure 2-43. That storm has the highest total rainfall depth (2.09 in.); however, the peak intensity was only 0.52 in./hr (lower than the 0.6 in. peak of the D-storm). The graph shows that storm had a pattern of smaller intensity rainfall for several hours before the most intense peak. Although its peak intensity was less than the D-storm intensity, this storm still produced a marginal overflow under the Gray Only scenario. A closer look at the storm reveals that that 53 percent of the total volume (1.11 in.) fell gradually over the course of a full day before the arrival of the 0.52 in./hr peak. The conditions on the ground were primed for an overflow, even with a peak that was lower than the one associated with the design storm.

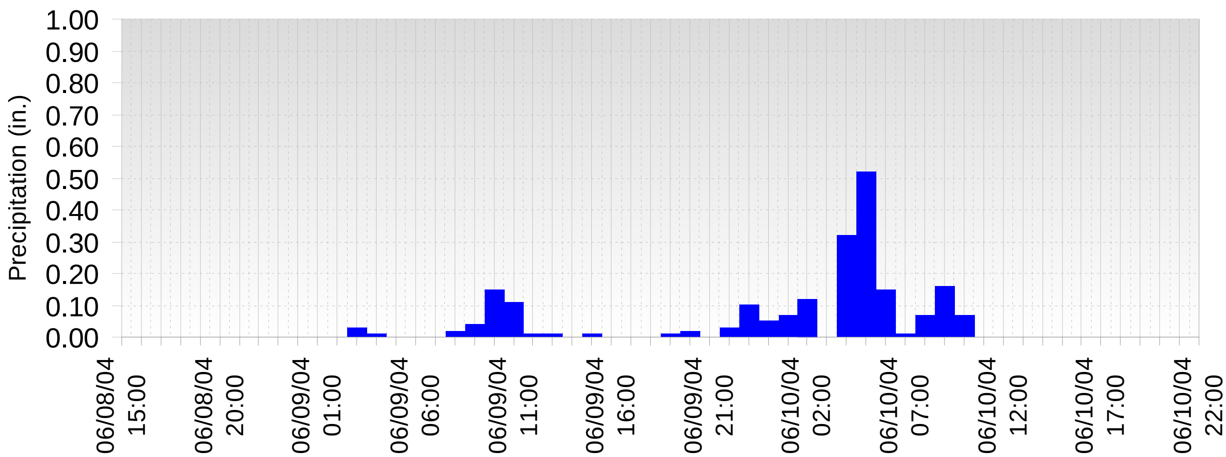

Figure 2-43. Hyetograph of the June 9, 2004, storm event.

Figure 2-41 through Figure 2-43 demonstrate the important role of continuous simulation at capturing the dynamic nature of storm-related phenomena. Observations like those gained from continuous simulation investigation can paint a better overall picture of natural system and provide some meaningful information to inform the decision-making process.

2.5.7. *Comparison of Gray versus Green Overflow Reduction Effectiveness*

Although gray storage has a much higher unit storage volume cost (as previously shown Table 2-19), the total cost of gray solution for meeting the control target is lower than the cost of green alternatives because more GI is needed to achieve the same level of gray performance. In other words, not all storage is created equal. GI tends to reduce volume reduction from the bottom of the hydrograph, whereas the supplemental gray storage directly treats the top of the hydrograph because of its physical location immediately downstream of the regulator overflow. There are two other phenomena at play in GI worth noting. First, small storms may saturate GI storage, depleting the available storage capacity during consecutive storms. Second, large intense storms may fall at a rate that is higher than the infiltration rate into GI, which also may tend to diminish their effectiveness. For these reasons centralized gray storage facilities, if measured on the basis of number of overflows is more cost-effective in this case for controlling overflow. Exploratory scenarios were simulated to further compare the green and gray alternatives in reducing overflows. Figure 2-44 presents the number of overflows in a weather typical year (2004) with various storage capacity provided by green versus gray facilities. The graph shows that given the same storage capacity, the number of overflows associated with gray solutions was lower than that of the green alternatives.

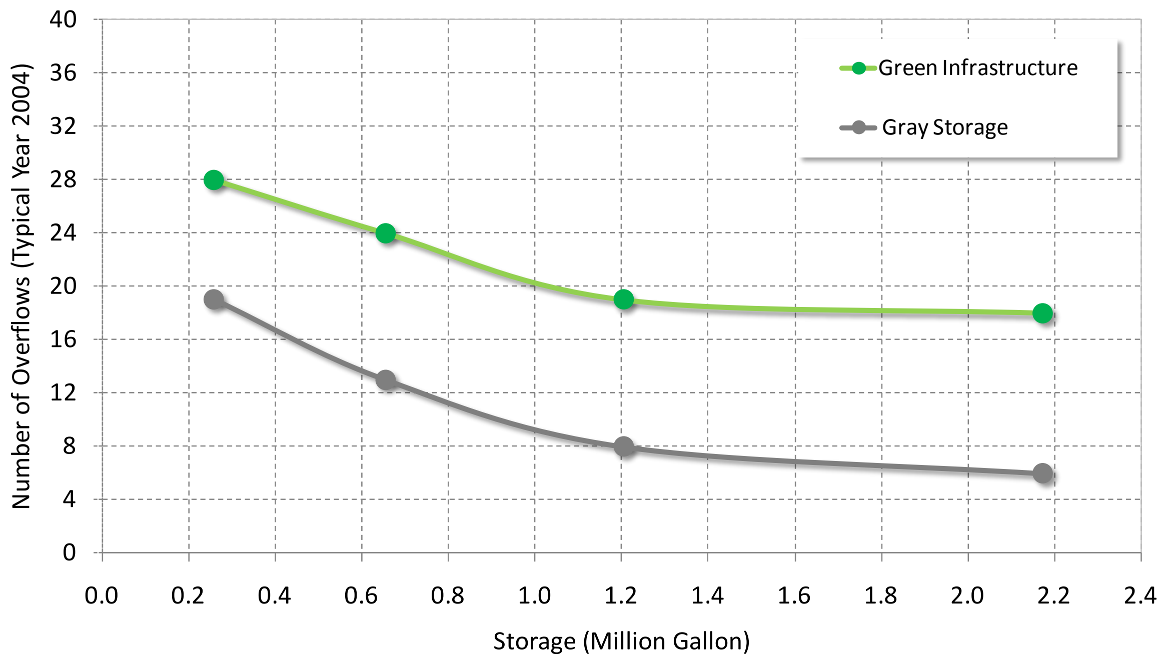

Figure 2-44. Comparison of CSO 069 number of overflows with green versus gray storage capacities.

Using the four storage volume points on the plot above, overflow volumes for both green and gray storage were normalized to present an expected annual overflow volume reduction per unit volume storage provided. These results are presented below as Figure 2-45. The plot suggests that on the basis of unit storage volume provided, in this case the gray solution consistently outperforms the green storage scenario. This trend also appears to increase with increasing storage volume.

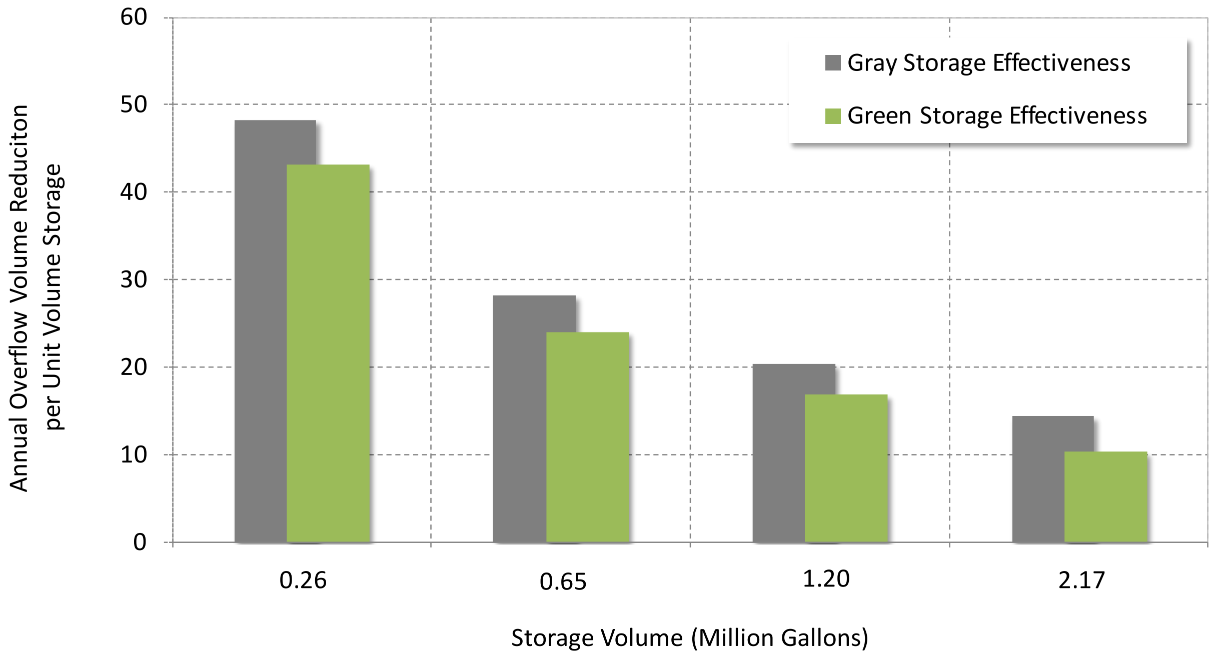

Figure 2-45. Comparison on annual overflow volume reduction per unit storage volume provided.

It is important to note that this analysis only considers physical volume of each treatment type, and not the treatment volume. For GI, storage capacity is recovered by means of gravity outflow through underdrains, infiltration, and ET, depending on the practice. For gray infrastructure, flow in the storage basin is pumped out of the system to create more capacity. The rate of recovery associated with infiltration and ET is lower than the pumping rate of gray infrastructure. Therefore, the potential treatment volume of gray infrastructure per unit of actual volume is greater than that of GI.

2.5.8. *Optimization Summary and Conclusions*

The optimization analysis of BMP opportunity for CSO mitigation in the 069 watershed yielded some interesting findings. The findings can be summarized in terms of (1) implications for planning and management decisions; and (2) implications on modeling approach development and assumptions.

Optimization results had certain management and planning implications for the study area. First, extrapolating the proposed design plan from the 100-acre pilot study site to the remainder of the 069 sewershed suggested that CSO mitigation objectives could not be achieved by only implementing GI on public rights of way, as defined by the design plan—more is needed. Second, adding GI on private parcels provided an additional 6 to 8 percent volume reduction. The most notable observation about GI on private parcels was demonstrated by the slope of the associated cost-effectiveness curve. This curve had a steep slope indicating that the additional benefit realized by including private property opportunities came at lower cost relative to when GI was limited to public rights of way or if only gray infrastructure was applied. It is important to note that the GI alternatives proposed for this study are urban retrofit projects. For this reason, they are likely more expensive than new GI construction costs because of significant overhead costs associated with site preparation, reconstruction of curbs and sidewalk system, and the traffic control measures needed during construction. In addition, this project is a pilot based on an approach not typically used in this area. The uncertainty and risk with constructing the GI in this area therefore likely includes a higher bid cost than if this were a regular practice within Kansas City. As a result, GI on private parcels (or for that matter, GI in new development areas) would likely become less costly as the technology and understanding matures. New construction GI costs would probably be integrated into the overall construction and planning cost, making GI under those circumstances much more cost-effective. Third, the results suggest that the combination of GI (as defined by the proposed design plan) plus supplemental gray storage at the regulator costs more than implementing only a slightly larger gray supplemental storage at the regulator. It is important to note that the management conclusions should be interpreted in the context of the associated modeling assumptions, as further described below.

This study also evaluated the sensitivity of certain modeling assumptions and configurations on the results. The three modeling elements evaluated and tested for sensitivity included (1) model simulation time step; (2) antecedent moisture conditions; and (3) the use of a design storm for optimization versus a continuous simulation. The first element evaluated was the influence of the model simulation time step on the optimization cost-effectiveness curve. Two parallel runs were performed using 15 minute and 60 minute time steps. There were only slight differences in the resulting cost-effectiveness curves associated with the two different simulation time steps. Because both runs generated differing baseline runoff conditions, the resulting BMP performance and regulator response gave mixed results. Nevertheless, because time of concentration estimates for the sewershed suggested that the travel time of peak flow was less than one hour, the 15 minute time step was used as the basis for the remainder of the analysis. The second element evaluated was the influence of antecedent moisture conditions on model predictions. The D-storm was tested under dry, average, and wet soil moisture conditions. The model showed varied responses under the three antecedent moisture conditions (i.e. drier conditions produced better performance at a lower cost than wetter conditions); however, the relatively large size of the D-storm tended to contain variability within a narrow range. The third element evaluated was the use of a design storm to drive the optimization instead of an observed weather time series. The D-storm was used for optimization because it was previously identified as the critical condition for CSO. In other words, controlling the D-storm was expected to result in attainment of CSO mitigation objectives. To validate if the BMP sizes derived from optimization would perform as designed, the resulting BMP configurations were also run using continuous simulation for a weather typical year (2004). The test showed that the recommended cost-effective solutions were able to reduce CSO from 33 overflows per year (under baseline conditions) to fewer than the 6-overflow allowance (2 to 3 overflows). The typical year validation run also revealed some interesting observations about the nature of overflows. One of the overflow events was caused by a 2.09 in. storm, where 53 percent (1.11 in.) fell gradually over the course of a 24 hour period, followed by a second burst of the remaining 0.98 in. over only 7 hours. Although the rainfall sequence causing the overflow had a smaller volume and peak than the D-storm, its relatively short duration, along with the fact that it occurred under saturated watershed conditions, resulted in an overflow at the regulator storage facility. Conversely, another storm larger than the D-storm did not cause an overflow because it occurred in July after a long dry antecedent period; therefore, the storm did not yield as much runoff. The model sensitivity analyses provided some good insights and understanding about factors that most influence CSOs.

This study has demonstrated that *SUSTAIN* can provide a versatile platform for (1) integrating multidisciplinary data and methods, and (2) evaluating multiple competing factors toward achieving stormwater and CSO management goals. The results demonstrate how the model can integrate modeling and management assumptions to evaluate the implications on the complex behavior of GI and gray infrastructure solutions. In the future additional analysis and expansion of model capabilities could be used to explore other aspects of the management of CSOs in Kansas City. For example, the modeling performed in this study limits GI in public rights of way as defined by the design plan. A broader application of GI technologies could be evaluated to see how much additional benefit would be derived. In addition the cost-benefit analyses could be performed with O&M costs in addition to the capital cost of construction, contingencies, and design fees considered in this study. Evaluation of the long-term life-cycle costs could result in a different optimization result. Finally the *SUSTAIN* formulation could be expanded to consider the other benefits of GI beyond the driving factors of overflow frequency and cost, such as aesthetic improvement benefit, community educational opportunity, increased property value, volume reduction of treatment plant inflow, carbon sequestration, possible reduction in heat island effects, or other potential benefits. When GI benefits are being evaluated and quantified in a triple-bottom-line context (environmental, social, economic), certain factors may be prioritized over others even though they are not the lowest cost options available. For example, GI implementation and maintenance could possibly be a way of creating employment opportunity for a municipality (e.g., green jobs), which can ultimately contribute to sustaining a local economy. Furthermore, GI may also provide aesthetic appeal to a community, which increases property values, which in turn, may increase tax revenue. If a portion of the new tax revenue is directed towards O&M of GI facilities, the management cycle becomes self-sustaining.

Chapter 3. Case Study: Louisville, Kentucky

EPA's ORD conducted a pilot project demonstrating the use of GI for CSO control in Louisville, Kentucky. The primary purpose of this case study was to demonstrate the tradeoffs between green and gray infrastructure alternatives. This case study effort was designed to address three goals: (1) test the sensitivity of key BMP hydrologic input parameters in *SUSTAIN* using local monitoring data to provide guidance for model calibration; (2) demonstrate replication of an existing hydraulics model of storm drain network and CSO regulator; and (3) characterize the cost-benefit relationship between a number of green and gray infrastructure options for mitigating CSO. This case study also provides the *SUSTAIN* user community with a demonstration of the application of the model.

The focus area for this case study is the Lousiville-Jefferson County Metropolitan Sewer District (MSD) CSO 019 sewershed west of downtown Louisville, Kentucky, which is bounded by the Ohio River and Interstate I-64 to the north and I-264 to the west (Figure 3-1). The sewershed drains 1,094 acres of mixed land use dominated by single-family residential neighborhoods. A large rail yard operated by Norfolk Southern Corporation is also adjacent to North 30th Street. The existing CSO 019 outfall is on the north edge of the sewershed along North 34th Street between Rudd Avenue and I-64. Overflows discharge directly to the Ohio River. An InfoWorks hydraulic model estimated the sewershed produced 297.91 MG of overflow volume as a result of 60 discrete overflow events based on the 2001 typical year precipitation record (MSD, 2008). Later refinements to that model using recent monitoring data were provided by Thomas Waters, from O'BRIEN & GERE, for this case study effort. The refined model resulted in the output that estimated a fewer number of overflows for the base scenario.

One of the project goals at the onset of the effort was to test the sensitivity of BMP parameters during calibration to monitored inflows and outflows from various BMP types that are built and monitored by MSD at local demonstration projects. However, such data were not available for use in this effort. In lieu of observed BMP monitoring, the sensitivity analysis tested and quantified the sensitivity of key input against their impact on predicted BMP outflow volumes.

This chapter presents (1) a summary of background supporting information; (2) the case study goals; (3) the methodology and findings of a BMP model sensitivity analysis for key input parameters; (4) a discussion about the replication of the existing condition InfoWorks watershed model baseline in an SWMM5 modeling environment and the subsequent derivation of an optimization baseline condition; and finally (5) the BMP selection and placement optimization analysis of green and gray infrastructure opportunities for CSO mitigation in the MSD service area.

3.1. Background

The MSD serves the Louisville metro area, which includes all of Jefferson County, with a 2009 population of roughly 722,000 (MSD, 2010). MSD serves a tributary area of approximately 385 square miles of which the CSS area encompasses 37 square miles (approximately 10 percent of the total area). The agency was established in 1946 and charged with the responsibility to manage the city's sanitary sewer and drainage system. In 2004, the EPA filed legal enforcement actions against MSD. In August 2005, MSD entered into a consent decree with EPA and the Kentucky Environmental and Public Protection Cabinet. The consent decree required compliance with the clean water act by the end of 2020 for CSOs, and 2024 for SSOs. The consent decree required the development of a Final CSO LTCP and the Final Sanitary Sewer Discharge Plan by December 31, 2008. These documents were incorporated into an Integrated Overflow Abatement Plan (IOAP). The IOAP was finalized and incorporated into an amended consent decree in April 2009. The approved plan includes control of CSO discharges to levels prescribed in the CSO Control Policy by December 31, 2020 (MSD, 2011).

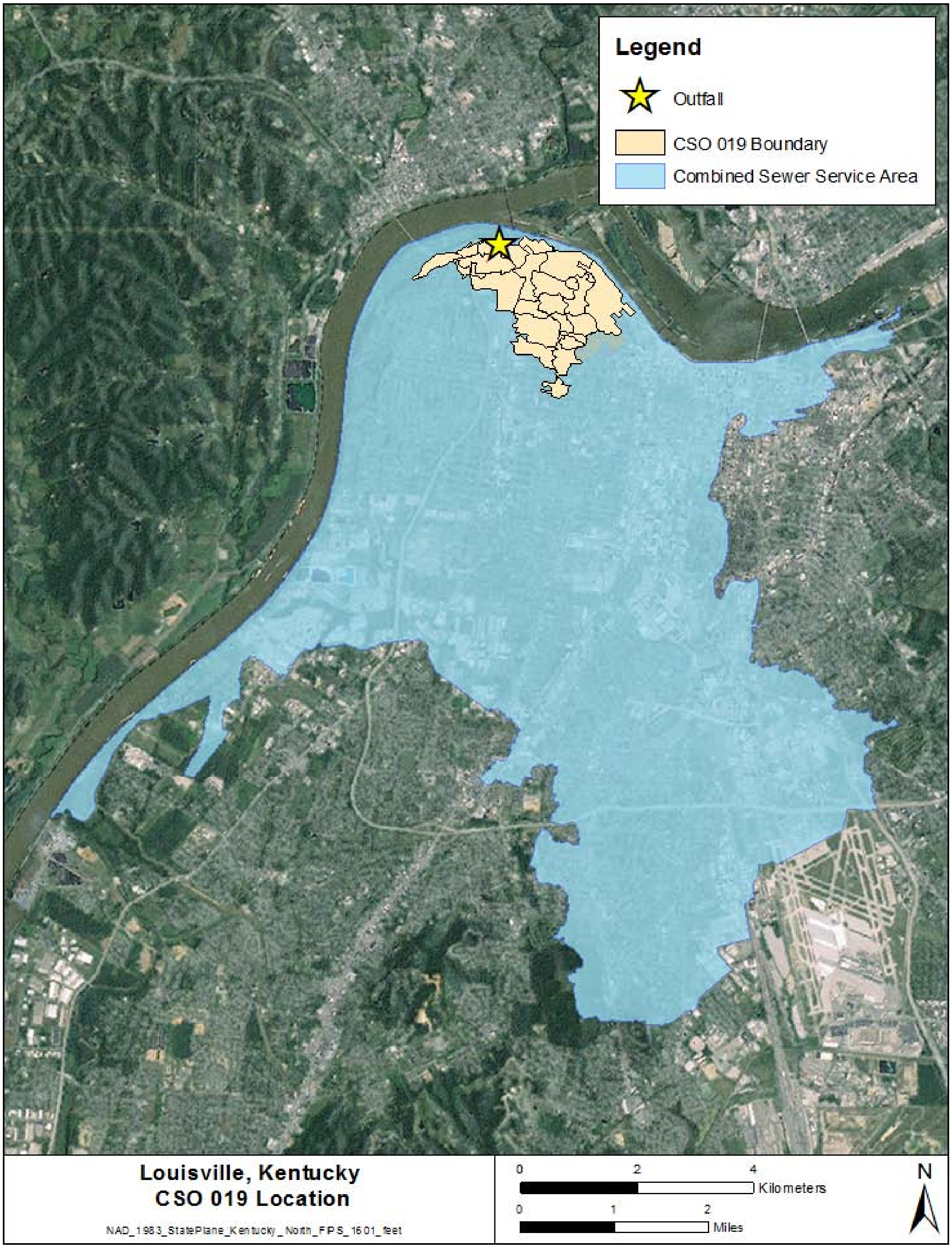

Figure 3-1. Location of CSO 019 sewershed.

The Final CSO LTCP uses conventional infrastructure (gray) projects such as storage facilities, system optimization projects including real-time controls to maximize in-line storage and ability to shift flow within the system, and GI. Gray infrastructure projects were defined without considering the potential beneficial performance of GI to achieve CSO control. At the time (2006 – 2007) GI facilities were viewed by many regulators as unproven and the overflow reduction benefits not quantifiable over the long-term. As a result, GI is incorporated into the I OAP such that MSD assumes the risk for the effective performance of GI, and must demonstrate its effectiveness. If shown effective, Louisville will have an opportunity to resize gray infrastructure on the basis of the documented benefits of the GI. To promote the use of GI to achieve necessary reductions, MSD committed to spending approximately $6 million per year for the first six years of LTCP implementation, followed by an allocation of $1 million per year for the nine subsequent years, for a total GI budget of $47 million (MSD, 2009). GI implementation would increase if additional implementation of GI was demonstrated to be sufficient to replace or downsize gray infrastructure cost-effectively.

3.1.1. *InfoWorks Model*

MSD's initiatives to develop and refine both separate sanitary and CSS models date back to the early 1990s. Most recently, MSD developed a baseline runoff and hydraulic model of its combined sewer area using the InfoWorks modeling platform, a proprietary watershed and hydraulics modeling system. Output from the originally developed version of the CSO 019 InfoWorks watershed model was initially provided as the baseline model for this case study. However, when a revised version became available, the model baseline was revised to reflect those changes. The latter model ultimately became the version that was integrated with *SUSTAIN* for this case study effort.

The IOAP model, developed in 2008, is a one-year continuous simulation performed using the 2001 selected typical precipitation year. The model predicted 60 annual overflow events at the outfall to the Ohio River and was the basis for initial conceptual designs of the Portland Wharf Storage Basin (Section 3.1.2). No overflow monitoring data were available at the time when this model was calibrated.

An update to the 2008 IOAP model calibration was being developed concurrent with this case study in 2011. However, the advantage of the latter model revision over the former was that it was based on recently collected monitoring data that captured overflow events between January and June of 2010. Modifications were made to the outfall configuration and some subcatchment properties. The updated model calibration was rerun using the same typical year 2001 precipitation time series, and predicted a decrease in the number of overflow events relative to the original version.

3.1.2. *Portland Wharf Storage Basin*

MSD commissioned conceptual designs and capital funding for constructing the Portland Wharf Storage Basin to reduce the number and accumulative volume of CSOs from the CSO 019 sewershed. That basin was envisioned as a 6.37 MG concrete storage basin and pump station. The storage basin was expected to reduce the annual average overflow volume to 52 MG resulting with a CSO target of eight overflow events per year using the 2001 rainfall time series. The proposed location of the storage basin was just north of the CSO 019 regulator between I-64 and the Ohio River, as shown in Figure 3-2. In 2008 dollars, the expected capital cost of the project was estimated to about $20 million.

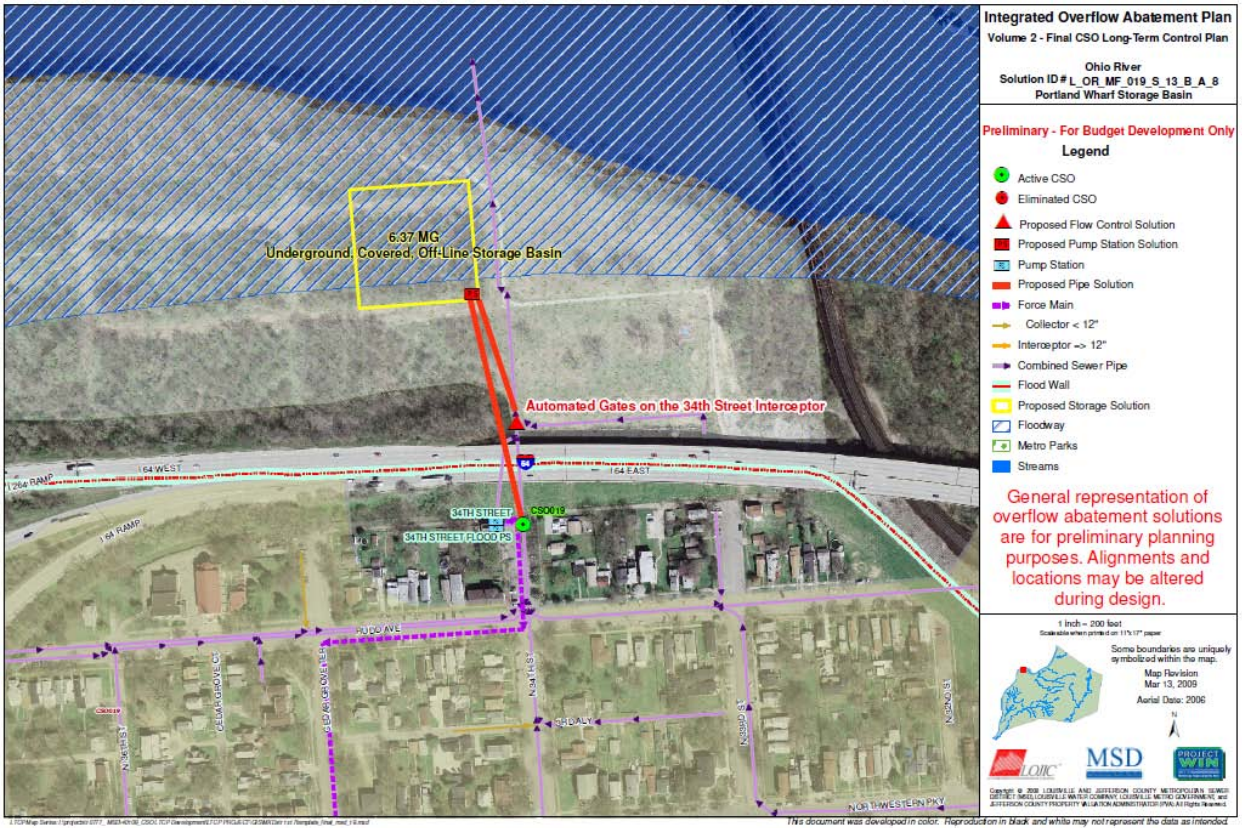

Figure 3-2. Proposed location of the Portland Wharf Storage Basin and Pump Station.

3.2. Overview of Case Study Goals

The three goals for this case study are to (1) demonstrate applying *SUSTAIN* to replicate an existing InfoWorks hydraulics model of a storm drain network and CSO regulator; (2) perform a BMP modeling analysis to test and quantify the sensitivity of key input parameters versus their impact on predicted BMP outflow volumes; and (3) characterize the cost-benefit relationship between a number of green and gray infrastructure options for mitigating CSO. These goals were first defined at the onset of the effort; but they were further refined during the model setup, application, optimization, and results interpretation process. Throughout this chapter, a strong emphasis was placed on describing specific aspects of the *SUSTAIN* application process, and relating it back to the case study objectives. The following sections further elaborate on each of the three case study goals.

3.2.1. *Replication of an Existing Hydraulics Model*

The MSD has invested in an InfoWorks runoff and hydraulic model to characterize the dynamics of its combined sewer area. The purpose of the InfoWorks model is to characterize the detailed connectivity of the drainage network and represent existing conditions as closely as practical, whereas for *SUSTAIN*, the primary modeling objective is to characterize the critical condition associated with the baseline model as closely as possible, while making every effort to gain computational efficiency wherever possible. To provide consistency between *SUSTAIN* solutions and the InfoWorks baseline model, it was important to ensure that the *SUSTAIN* replica of the network and regulator was indeed representative of the existing InfoWorks model, especially for CSO critical conditions.

The watershed model baseline represents the existing condition rainfall-runoff response. It characterizes the nature of the current physical system before any additional management activities are implemented. It also represents the baseline from which any stormwater improvement will be measured, and the starting point for BMP selection and placement optimization. Because it forms the basis for comparative assessment of alternatives, establishing a representative baseline condition with confidence is a critical first step in any modeling effort. It becomes especially important where cost-benefit optimization of future management objectives is a primary focus of the modeling effort.

This application also provides *SUSTAIN* users with an example of how scale and resolution affect the model results, efficiency, and accuracy. This case study application also examines the use of a simplified routing network that preserves the essential features of the system response, while improving computational efficiency. *SUSTAIN* provides the user with a range of options for handling spatial scale and resolution. For smaller watershed or study areas, it is both feasible and practical to use a more detailed or *articulated* routing network, meaning that smaller pipe networks, specific BMPs and associated drainage areas, are explicitly defined. For larger-scale applications, using a fully articulated approach can becomes cumbersome, impractical, and resource intensive because of the size and complexity of the associated network. To provide an alternative, simplified approach, *SUSTAIN* provides an aggregated BMP option that reduces the complexity of drainage network while preserving the dominant physical basis of the BMP performance. Although the aggregate BMP approach significantly reduces the network complexity, it also sacrifices some details of the model network and routing. This case study tests the performance of a simplified aggregated approach versus a higher resolution routing network. Three natural questions arise:

- How much network simplification can be introduced without significantly compromising model accuracy or precision?
- What components of a fully articulated drainage network are appropriate candidates for aggregation, and to what degree can they be aggregated?
- How much computational advantage does aggregation provide?

Because MSD has accepted the InfoWorks model calibration as representative of existing conditions, this case study evaluates the ability of *SUSTAIN* to replicate the calibrated InfoWorks model. In testing model performance and accuracy, *SUSTAIN*'s ability to mirror the InfoWorks model response was evaluated. The InfoWorks application used a higher resolution network, while the *SUSTAIN* replica used an aggregated, computationally streamlined drainage network. Successful model replication was measured by (1) evaluating the percent difference between the *SUSTAIN* and InfoWorks model results; and (2) computing the efficiency of the streamlined *SUSTAIN* network at replicating results generated by the higher resolution InfoWorks network, especially for critical conditions associated with CSO.

3.2.2. *BMP Parameter Sensitivity Analysis*

An initial objective of this case study was to validate the BMP performance in *SUSTAIN* using monitoring data collected at local demonstration projects. However, monitoring data were not available at the time of this case study; therefore, that objective was later refined to test the relative sensitivity and response of key BMP calibration parameters in *SUSTAIN*.

Of the various BMPs considered for use in the study area, bioretention cells are the practice that provides the most flexibility in how it is represented. The sensitivity analysis used a factorial experimental design approach to test various hydrologic parameters in a single bioretention cell. Three input parameters were varied. They included (1) the vegetation-dependent multiplier for estimating ET; (2) the Horton saturated infiltration rate of the bioretention cell media; and (3) the Horton maximum infiltration rate of the bioretention cell media. High and low values for each of these three parameters were applied to show the range of influence on predicted BMP outflow volume, for eight different scenario combinations. The factorial experiment design approach applied in this context, together with the analysis results, provide examples of how to manage predictive uncertainty associated with BMP model parameterization in *SUSTAIN*.

3.2.3. *Cost-benefit Relationship between Gray and Green Infrastructure for Mitigating CSOs*

The third case study objective is to investigate cost-benefit relationships between green and gray infrastructure for mitigation of overflows in the CSO 019 sewershed in light of the planned Portland Wharf Storage Basin. The objective builds on outcomes from the previous objectives by using the calibrated watershed optimization baseline model as the basis. The analysis considers a series of individual green and gray infrastructure implementation scenarios to mitigate CSOs in the watershed, as well as different combinations of integrated green and gray solutions. The analysis will hinge on integrating five different implementation scenarios:

1. Use of gray infrastructure only, specifically the Portland Wharf Storage Basin. The tank volume is set as the optimization decision variable, and cost data are derived from Louisville's cost versus size relationships provided by MSD in a spreadsheet format;
2. Use of downspout disconnections only. Downspout disconnection has been identified as a relatively low cost way of reducing stormwater runoff. This option evaluates the cost-benefit impact of fully implementing a downspout disconnection incentive program throughout the sewershed. It is assumed that full adoption of downspout disconnection occurs before additional structural GI measures are adopted;
3. Use of GI only. This scenario reflects management by GI only. It explores the cost-benefit impact of GI beyond full implementation of the downspout disconnection program;
4. Use of gray infrastructure in combination with downspout disconnections; and
5. Use of gray infrastructure, downspout disconnections, and GI in combination. This scenario reflects a full build-out condition of GI with supplemental gray infrastructure required to meet increasing reduction intervals.

The results from the first three scenarios are evaluated independently to determine the cost-effectiveness of each practice in achieving CSO mitigation objectives. The last two scenarios evaluate a combination of green and gray solutions. The optimization objective is to identify the point at which CSO mitigation objectives will be achieved at the lowest cost. Sensitivity testing of both cost and sizing assumptions will be conducted to provide ranges of predicted management outcomes. The cost effectiveness curve will also be evaluated to show percent utilization of each practice at each solution. GI utilization results will also be mapped by subwatershed to gain insight into the optimal spatial placement of these practices derived under the defined objective and constraints.

3.3. Replication of an Existing Hydraulics Model

In *SUSTAIN*, modeled stormwater runoff is the forcing function that drives BMP simulation. Watershed models use site-specific spatial and temporal elements to characterize the rainfall runoff response. The watershed model runoff time series represent the existing condition (or baseline), which serves as the reference point from which stormwater management effectiveness will be measured. A critical first step of a *SUSTAIN* application establishes or confirm a representative baseline condition with a high degree of confidence in its applicability. The baseline becomes especially important in the context of cost-benefit optimization of future management objectives, because the model baseline is foundational to results interpretation and resulting conclusions. The watershed model baseline condition must represent variability throughout the watershed, including the influence of physical features associated with both surface and subsurface behavior.

MSD developed a baseline runoff and hydraulic model of its combined sewer area using the proprietary modeling platform InfoWorks. Although it is based on same underlying equations as SWMM, InfoWorks uses a different approach to solve the equations. InfoWorks has the ability to export the input configuration file to an SWMM5 compatible file format. The portion of the InfoWorks model representing the CSO 019 sewershed was exported to SWMM5 format and reviewed for key hydrologic parameters. This section summarizes the findings of the model reviews. Two model calibrations were available for review: (1) the original 2008 IOAP model; and (2) the refined 2011 model which was recalibrated using observed monitoring data collected from January through June of 2010. The model review revealed an inter-basin transfer occasionally occurs between CSO 019 and adjacent CSO 190 for interceptor relief. Because this effort focuses on management objectives within CSO 019, it was necessary to isolate only runoff contributed from CSO 019 as the baseline for subsequent optimization.

The InfoWorks model represents a combined sewer area with 203 subcatchments and 647 pipes or connections as shown in Figure 3-3. The model uses a kinematic wave routing method and does not account for backwater flow. Each subcatchment can vary slope, depression storage, overland flow coefficients, widths, and impervious cover. The InfoWorks model was used to inform selected parameters for *SUSTAIN*, including roughness coefficient, pervious depression storage, and infiltration. The subcatchment and routing network were also simplified for *SUSTAIN* from the original InfoWorks configuration to reduce run-time while preserving model responsiveness, which is demonstrated in section 3.3.5.

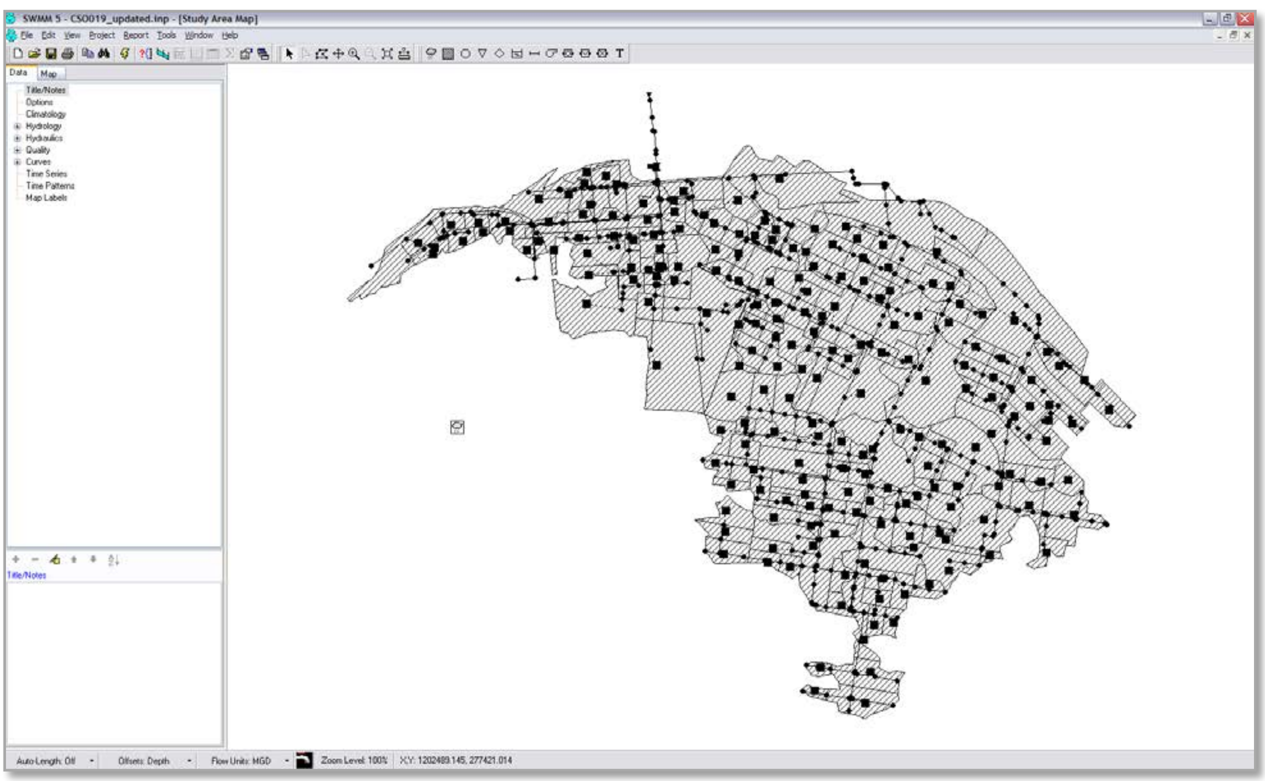

Figure 3-3. InfoWorks model configuration exported to EPA-SWMM5.

SUSTAIN provides the user an option to link to an existing sewershed model using unit-area (one acre) runoff time series for each land unit or hydrologic response unit (HRU) for representing land rainfall-runoff responses as boundary conditions. When linking to an existing watershed model, *SUSTAIN* uses unit-area runoff time series files as input and associates those with the land cover distribution present within the delineated drainage area boundaries to drive the routing and BMP simulations. A GIS representation of the unique land use types serves as the physical link that *SUSTAIN* uses to tabulate area distributions within each catchment.

Other spatial characteristics of the baseline model representation were considered. For this application, there was a desire to simplify the size and complexity of the network, within reason, in a way that minimized distortion of system behavior and response. The level of model detail was selected to match the required response and purpose of the application and management questions under consideration. For the purposes of watershed optimization modeling, reduction of computational time results in a more efficient optimization process and the ability to explore a wider range of management alternatives.

This section describes the steps taken to develop a baseline watershed model condition. Those steps include (1) land cover development; (2) subcatchment delineation; and (3) model calibration. The following sections describe each of those steps in greater detail.

3.3.1. *Land Cover Development*

In a watershed model, land unit representation must be sensitive to the features of the landscape that most affect hydrology, including surface cover, soil type, and slope. Experiences have shown these three watershed features have the most impact on hydrology. In urban areas, it is important to estimate the division of land use into pervious and impervious components. Because the focus of this study is volume control, it is not necessary to further subdivide land use beyond pervious and impervious cover; however, rooftop areas were distinguished from other impervious areas to facilitate rerouting flow from downspouts as a management alternative. Slope might also be an important factor in some areas. In a commonly used watershed model land unit characterization approach, the unique combination of land cover, soil type, and slope form HRU. This section looks at each of these three components in an effort to characterize an appropriate basis for representing runoff boundary conditions.

Soil Type

The available soil survey GIS information (NRCS, USDA, 2006) suggested that soil type was fairly homogenous throughout the study area. There was no extensive soil infiltration testing data available to either refine or refute the validity of the GIS soil surveys. When soil hydrologic groups are not homogenous in a watershed, further subdividing pervious land cover according to soil hydrologic group can provide improved resolution. However, for this application, soil type was not used as a distinguishing land element.

Slope Analysis

Slope can play an important role in watershed modeling because it controls the magnitude and, to a lesser degree, the timing of peak flows. GIS coverage of slope in the CSO 019 sewershed was derived from a data set of 2 ft elevation contours (LOJIC, 2003) and is presented as Figure 3-4. Slopes in the watershed are generally less than 1 percent. Areas of high slope tend to closely trace and highlight building features and highway embankments. While those slopes appear prominent, they are more associated with structural features within the watershed rather than the actual topographic configuration of the watershed.

Further review of the existing InfoWorks model configuration also suggested that slope does not vary greatly within the CSO 019 sewershed. The 203 subcatchments defined in the InfoWorks model were delineated in GIS and joined with a table of their physical properties, including slope, width, and depression storage. A spatial distribution of subcatchment slope as defined in the InfoWorks model is presented as Figure 3-5. The map confirms that slope does not vary widely in the watershed. The slope of most subcatchments is less than 0.15 percent.

Surface Cover Analysis

This analysis used data sets in GIS format for roads, impervious surfaces, and building rooftops (LOJIC, 2003). The roads layer contained the footprint of the road rights of way. The impervious surfaces layer included sidewalks, driveways, parking lots, alleyways, and other distributed impervious surfaces. The building footprint layer was used to represent rooftop area in the watershed. Those three layers were merged into a single raster representation, with rooftops distinguished from other types of impervious cover. The void space between impervious features was defined as pervious area. A map showing the distribution of surface cover types for the CSO 019 sewershed is presented below as Figure 3-6. That overlay resulted in a distribution of three unique combinations of HRUs that capture both the physical texture of the watershed.

In summary, on the basis of these analyses, it was determined that not enough variability exists to warrant additional spatial resolution by explicitly incorporating either soil type or slope into the delineation of the subcatchements. Instead, only the three land cover types presented in Figure 3-6 were used to represent the physical texture of the watershed surface.

3.3.2. *Subcatchment Delineation*

The original InfoWorks model configuration for the CSO 019 divided the sewershed into 203 subcatchments with areas ranging from 0.61 acre to 53.86 acres. For lumped parameter models such as SWMM, having more subcatchments provides more latitude for creating a spatially variable response. In other words, a higher resolution better approximates a distributed parameter response. However, increasing the number of subcatchments and routing connections also increases the complexity and run-time for a single model run. By making land cover the smallest modeling unit, some of the heterogeneity of the system is transferred from the catchment into the land cover distribution. As a result, the catchment resolution, and the number of network connections, can be judiciously aggregated with acceptable losses of the spatial variability of the runoff response.

The 203 subcatchments defined in InfoWorks were aggregated into 20 subwatersheds for model calibration on the basis of the larger delineation provided by MSD. The number of modeled pipe segments was also reduced from 647 in the InfoWorks model to 24 in the *SUSTAIN* model. Figure 3-7 compares the original InfoWorks subcatchment boundaries with the subwatershed boundaries used in *SUSTAIN*. After aggregating some of the subcatchments, it was appropriate to only explicitly model pipes greater or equal to 3 ft in diameter, because 3 ft is the smallest pipe size connecting aggregated subcatchments to the pipe network. In two instances, pipes smaller than 3 ft (2 ft and 2.5 ft) diameter were modeled to complete necessary routing connections. Although this section describes how the model was spatially reconfigured for model calibration purposes, Section 3.3.5 evaluates the larger implications associated with model spatial resolution, simulation time, and predictive precision.

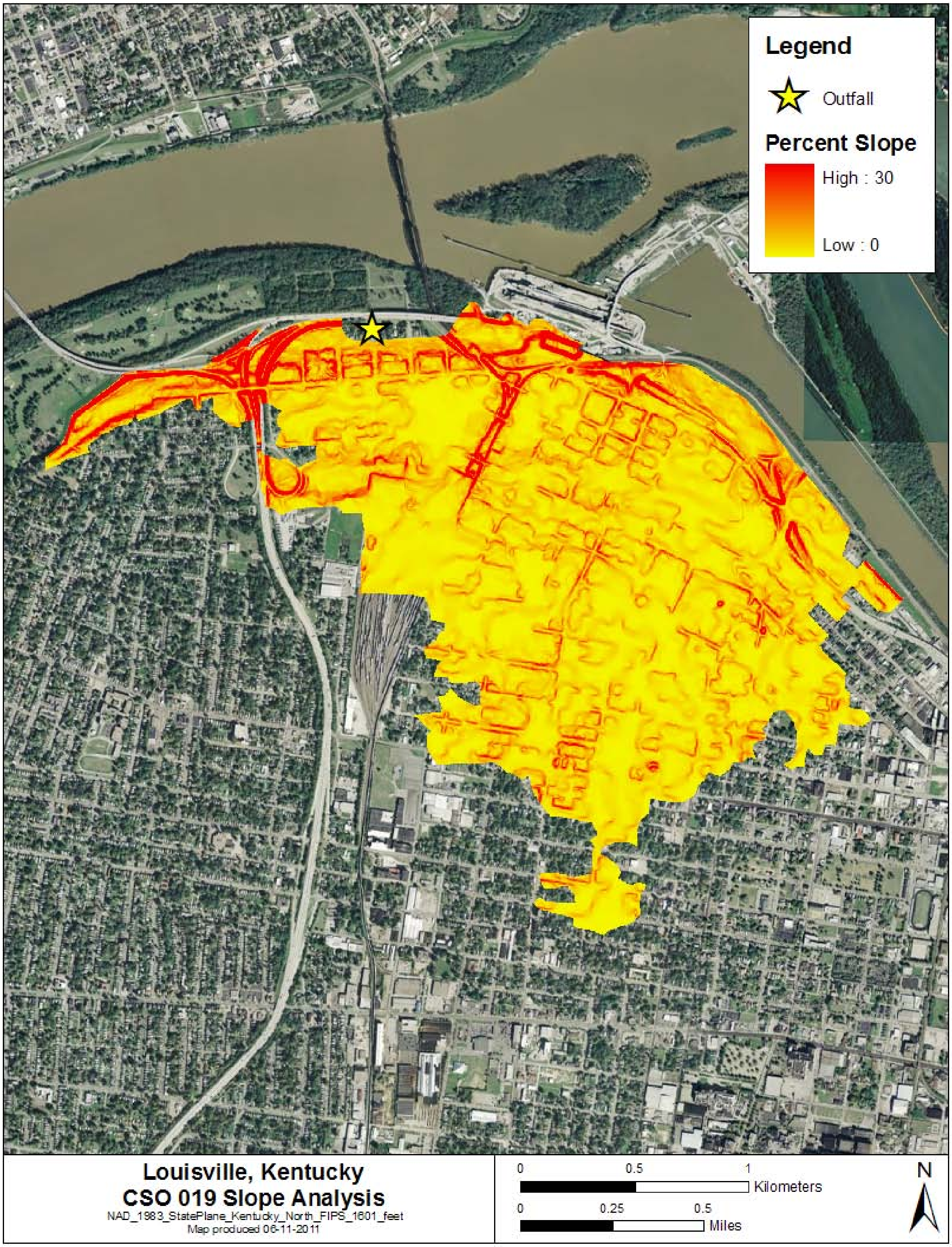

Figure 3-4. CSO 019 sewershed slope derived from topographic contours.

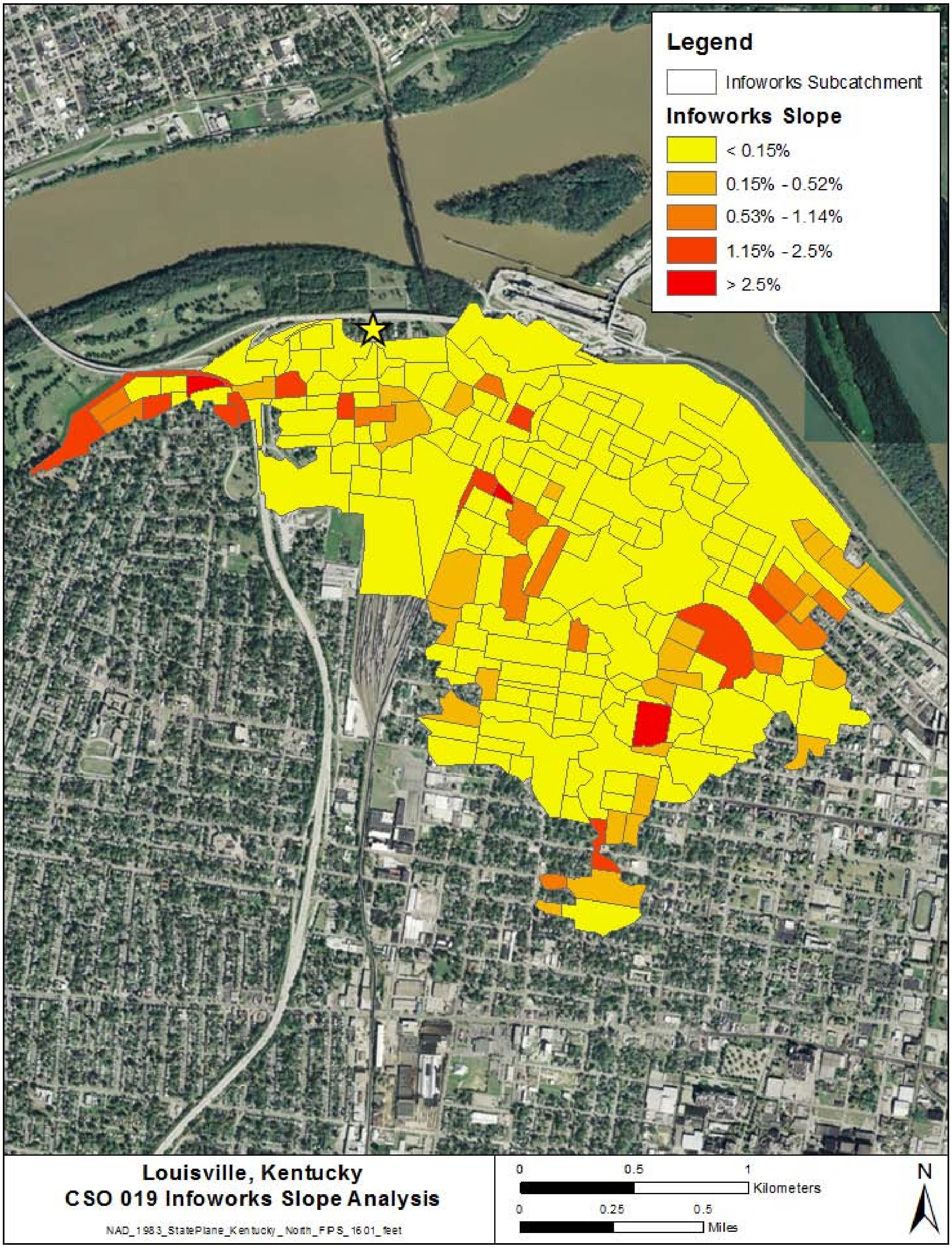

Figure 3-5. CSO 019 sewershed InfoWorks model slope analysis.

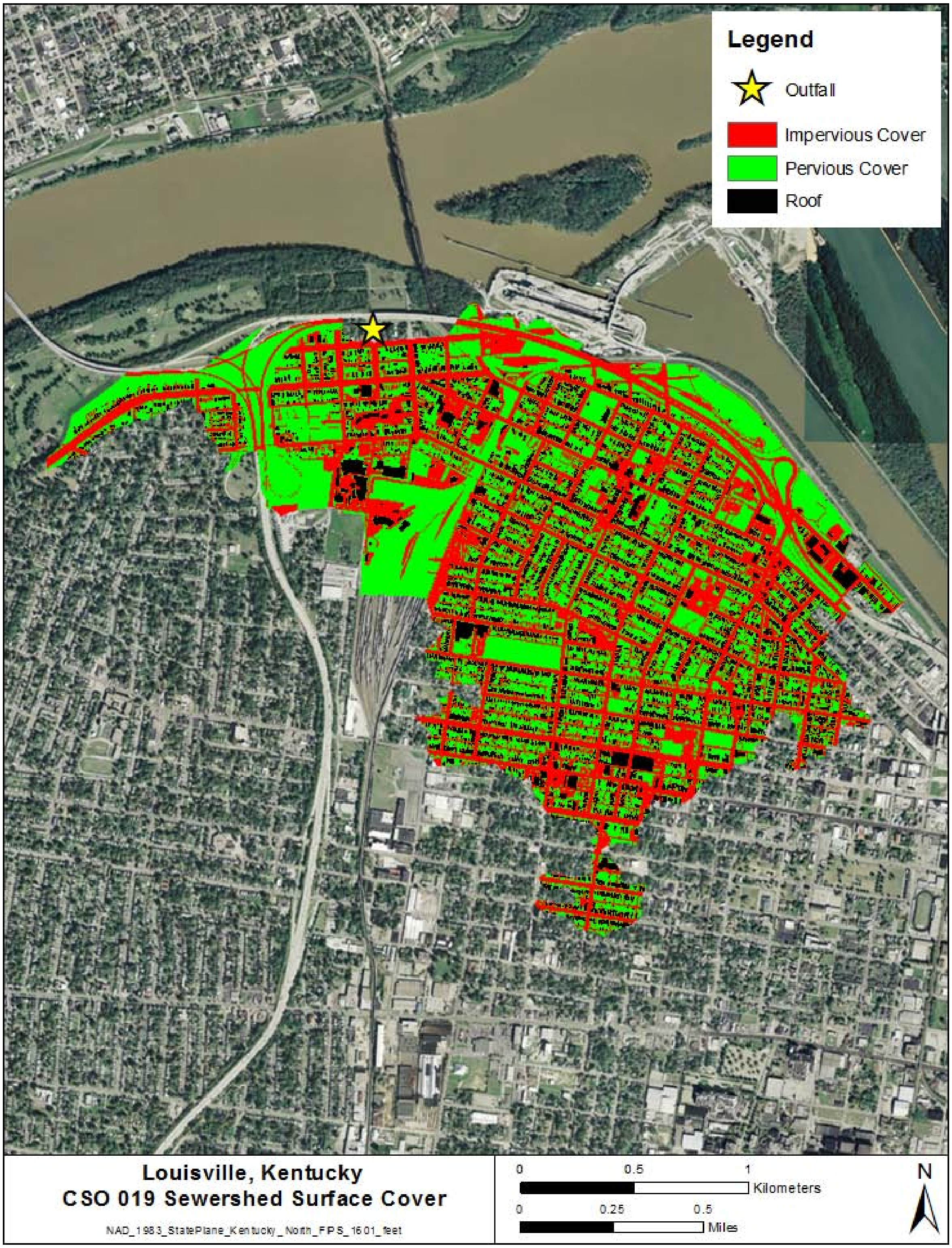

Figure 3-6. CSO 019 sewershed surface cover distribution.

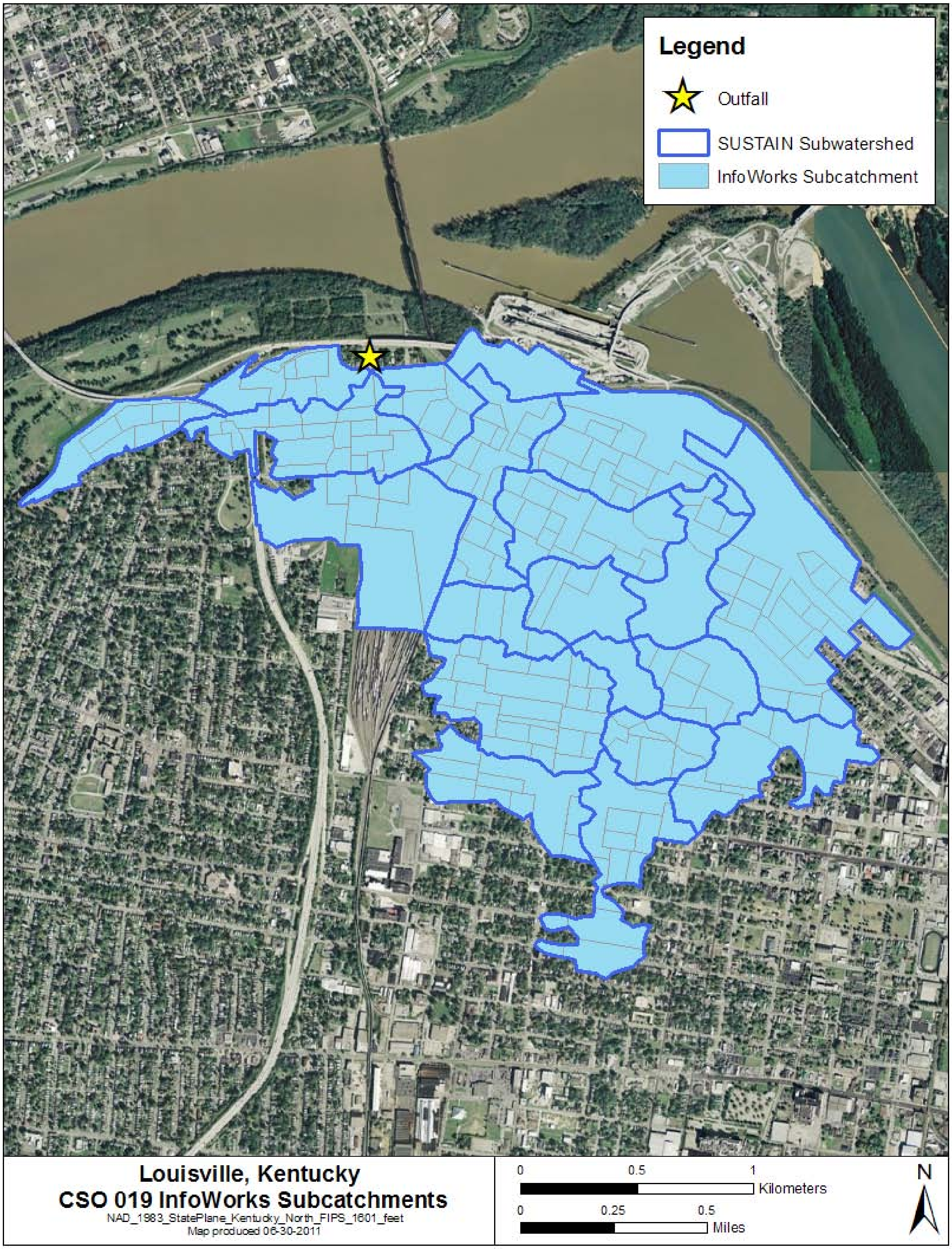

Figure 3-7. Comparison of InfoWorks and *SUSTAIN* subwatershed delineations.

3.3.3. *Review of Baseline Model Calibrations*

During the model calibration process, parameters are expressed uniquely for each land cover type. The objective of the calibration process is to identify a unique set of parameters that remain constant for all instances of that land cover in the study area, such that the spatial variation of the sewershed response becomes a function of only the land cover distribution in each subarea. Parameters from the MSD 2011 InfoWorks modeling effort were used as source for *SUSTAIN* model parameter values.

For this effort, the calibration objective was to characterize model performance for the typical Louisville precipitation year 2001. Figure 3-8 shows the monthly precipitation distribution for the typical year 2001, also shows the monthly number of overflow events out of the eight largest storm events. MSD established the typical precipitation year through a statistical analysis of the historical rainfall record from 1949 through 2002 (MSD, 2007). The 2001 precipitation year rainfall record consists of 62 storm events ranging in depth from 0.1 in. to 3.15 in. assuming 12 hr inter-event time and a minimum storm size of 0.1 in.

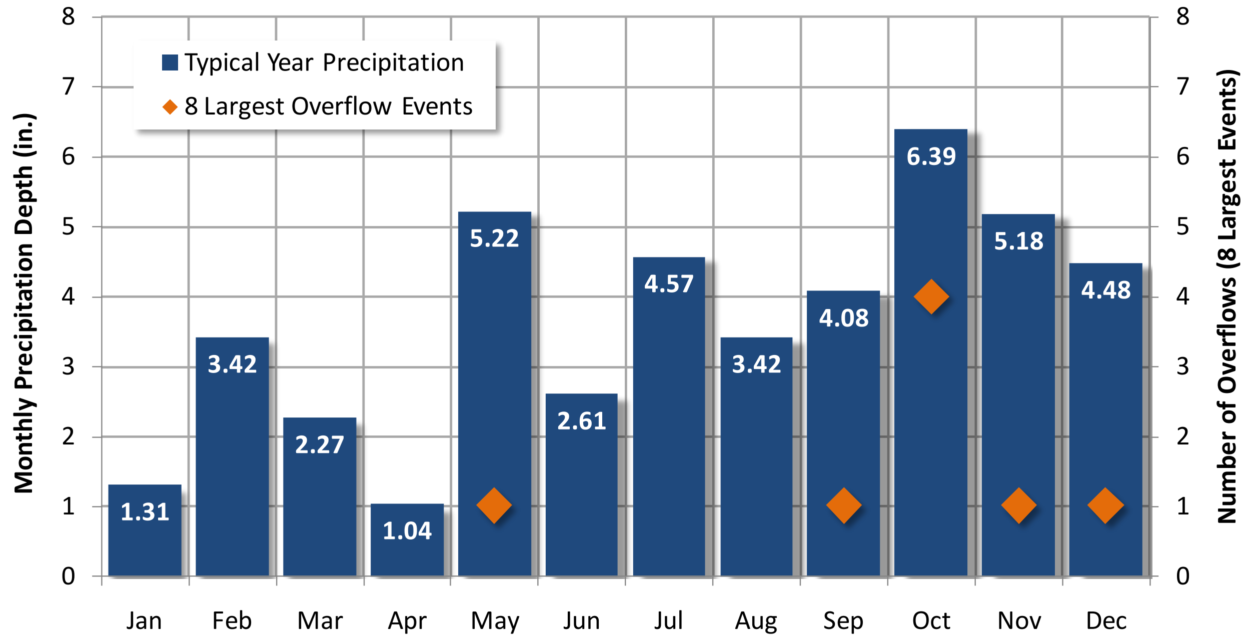

Figure 3-8. Distribution of typical year 2001 precipitation data by month.

Calibration parameters were adjusted during the process until an acceptable match of benchmark calibration metrics was achieved. The calibration process is elaborated later in this section. Some of the key parameters were those associated with (1) depression storage and overland flow; (2) infiltration; and (3) DCIA. The earlier parts of this section describes those three general aspects of model parameterization and time series generation, while the later summarizes model testing, output summarization, time series comparisons, and calculating calibration indicator metrics.

Depression Storage and Overland Flow

Depression storage describes the depth of storage available for surface ponding. The subcatchment roughness coefficient describes Manning's N for overland flow. Both the roughness coefficient and depression storage parameters are set independently for pervious and impervious areas. The values of the parameters were held constant between the 2008 and 2011 model calibrations across all subcatchments. The values are presented blow in Table 3-1.

Table 3-1. Roughness and depression storage parameters for pervious land cover

Land cover type	Parameter	2008 InfoWorks	2011 InfoWorks
Pervious areas	Roughness coefficient (unitless)	0.2	0.2
	Depression storage (in.)	0.2	0.2

Depression storage and roughness coefficient for impervious land cover varied by subcatchment for both the 2008 and 2011 InfoWorks model calibrations. Table 3-2 presents a comparison of the area-weighted average InfoWorks model parameters for the 2008 and 2011 CSO 019 model calibration.

Table 3-2. Area-weighted average InfoWorks model parameters for CSO 019

Land cover type	Parameter	2008 InfoWorks	2011 InfoWorks
Impervious areas	Roughness coefficient (unitless)	0.013	0.013
	Depression storage (in.)	0.059	0.058
Other	Slope (%)	0.230%	0.200%
	Width (ft)	55.050	62.910
	Percent zero (%)	40.960%	42.070%

Values for the impervious cover type in *SUSTAIN* were estimated by calculating the area-weighted average of the values in the InfoWorks model using impervious area as the weighting factor. The same approach was also applied to estimate values for slope, width, and percent of impervious cover with zero depression storage. To capture spatial resolution in the sewershed, a set of impervious time series was developed for each subwatershed rather than applying a single impervious time series uniformly across the basin using area-weighted parameter values. Catchments from the InfoWorks model were grouped by *SUSTAIN* subwatershed (Figure 3-7). A set of impervious cover parameters was then calculated by subwatershed using an impervious area-weighted average of the parameters for catchments grouped in that sewershed. The ranges of the area-weighted parameters by subwatershed are presented below as Table 3-3.

Table 3-3. Area-weighted subwatershed parameter ranges applied in *SUSTAIN*

Parameter	Minimum value	Median value	Maximum value
Depression storage (in.)	0.04	0.05	0.10
Slope (%)	0.00%	0.08%	1.20%
Width (ft)	37.82	60.15	99.64
Percent zero (%)	1.94%	45.30%	55.19%

Infiltration

The Horton infiltration method is an empirically based model parameterized by specifying an initial (maximum) infiltration rate and a final, saturated infiltration rate. The model assumes that infiltration begins at a constant, maximum rate that decreases exponentially over time. The shape of the curve as the infiltration rate changes from initial to final is controlled by a decay rate specific to the type of soil (USEPA, 1998). The relationship is commonly presented as

$$f_t = f_c + (f_o - f_c)e^{-kt}$$

where f_t is the infiltration rate at time t, f_o is the initial maximum infiltration rate, f_c is the saturated infiltration rate, and k is the decay constant.

The MSD modeling guidelines document for hydraulic and hydrologic modeling provides suggested Horton infiltration values on the basis of hydrologic soil type (MSD, 2007). Parameter value consistent with Type D soils were set for all subcatchments in InfoWorks and were left unchanged in the *SUSTAIN* model configuration. The Horton infiltration values used are presented in Table 3-4.

Table 3-4. Horton infiltration parameters from Louisville Infoworks models

Parameter	2008 IOAP model	2011 calibration
Maximum infiltration rate (in./hr)	3.00	3.00
Saturated infiltration rate (in./hr)	0.30	0.30
Infiltration decay rate (hr^{-1})	2.00	4.14

Evaporation

While evaporation is often considered negligible for single storm or design storm events, it is an important part of the annual water balance when performing long-term, continuous simulation modeling. MSD developed a distribution of constant daily evaporation rates by month for use in hydraulic and hydrologic modeling applications in the county (MSD, 2007). The distribution of evaporation rates by month is presented below in Figure 3-9.

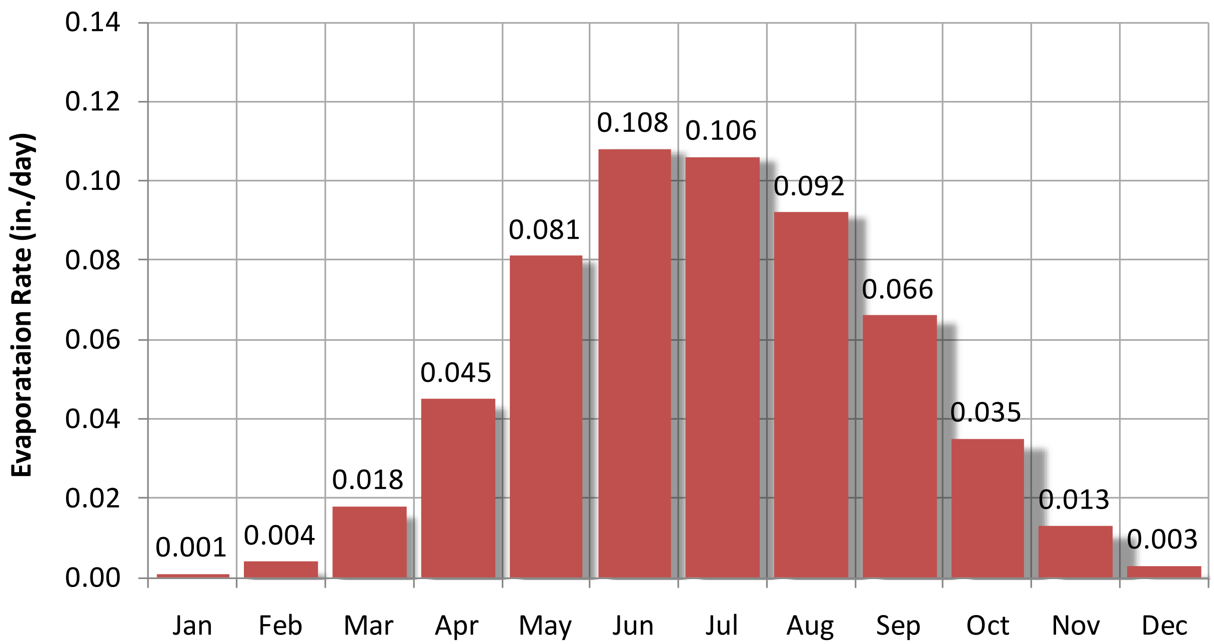

Figure 3-9. Monthly distribution of typical daily evaporation rates.

Dry-Weather Flow

Dry-weather flow is defined as flow through the sewer network when there is no precipitation. While dry-weather flows often show little or no effect on storm peaks, they can account for a sizable percentage of flow volume and use a large portion of the system capacity. Dry-weather flows are also described using monthly, daily, or hourly diurnals that represent patterns of system water use. InfoWorks distributes dry-weather flow from each catchment using population data and a per capita flow rate.

The representation of dry-weather flow in *SUSTAIN* was developed using the population data and per capita flow rates used in the InfoWorks model to calculate daily dry-weather flow from each subcatchment. The daily dry-weather flows were added to calculate a total daily dry-weather flow volume for the CSO 019 sewershed. Because *SUSTAIN* requires time series in a unit-area format, the total daily dry-weather flow volume was divided by the total acres in the CSO 019 sewershed.

Stormwater Runoff Calibration

A set of unit area (one acre) time series was generated using the EPA SWMM5 modeling platform to represent the 20 unique impervious series and 1 representative pervious land use for each subwatershed in the CSO 019 sewershed. The runoff time series were then used to drive the routing and BMP simulation in *SUSTAIN*. The pervious land cover parameters were previously shown in Table 3-1. Impervious land cover parameters, summarized in Table 3-3, varied by subwatershed. They were computed as area-weighted composites from the individual InfoWorks subwatersheds contained within the 20 aggregated *SUSTAIN* subwatershed boundaries. The SWMM model calculated runoff time series using hourly precipitation and evaporation time series for representative year 2001. Figure 3-10 conceptually illustrates the data flow sequence for both InfoWorks baseline model (1st Pass) and *SUSTAIN* model configuration (2nd Pass). The key difference between the two passes is how the diffuse runoff losses are represented in the model. The 1st pass, i.e., InfoWorks baseline model, represents the diffuse runoff losses by reducing the impervious area, and the 2nd pass, i.e., the calibrated *SUSTAIN* model, represent the losses using the regression relationship described later in this section.

Although the InfoWorks and SWMM5 have differences in terms of their specific computational methods, hydrographs generated by the models should be comparable for the same conditions and model configurations. As previously noted, an SWMM5 export of the InfoWorks model configuration has served as the only available documentation of model parameters for the recently updated calibration. Review of the model files indicated that runoff volumes were calibrated in part by adjusting the impervious area footprint in the model. While the impervious surfaces identified in Figure 3-6 are the actual impervious footprint, it commonly recognized that not all of the impervious runoff reaches the regulator (or even the collection system inlets). As illustrated in Figure 3-10, there are diffuse runoff losses throughout the system from the time precipitation hits an impervious surface to the time resulting runoff reaches the regulator. Examples of these losses include things like disconnected imperviousness, surface ponding or flooding, or even pipe exfiltration.

Although modeling effective impervious area is sufficient for calibrating a model baseline for InfoWorks, the *SUSTAIN* baseline configuration needs to explicitly account for all of the water in the system. This is because BMP selection and placement involves physical changes to the landscape of the model. For example, BMPs are often designed on the basis of the contributing impervious drainage area footprint. Two SWMM models were run to reconcile the difference. Each model used identical parameters, but varied the impervious area distribution. The first model used the calibration-adjusted *effective* impervious area from InfoWorks, while the second used the physical impervious footprints as characterized in the land cover GIS layer (LOJIC, 2003). The difference in runoff between the two runs represents diffuse runoff losses upstream of the regulator overflow. To quantify the flow difference between the two models, a regression relationship between the two runs was developed, as presented in Figure 3-11.

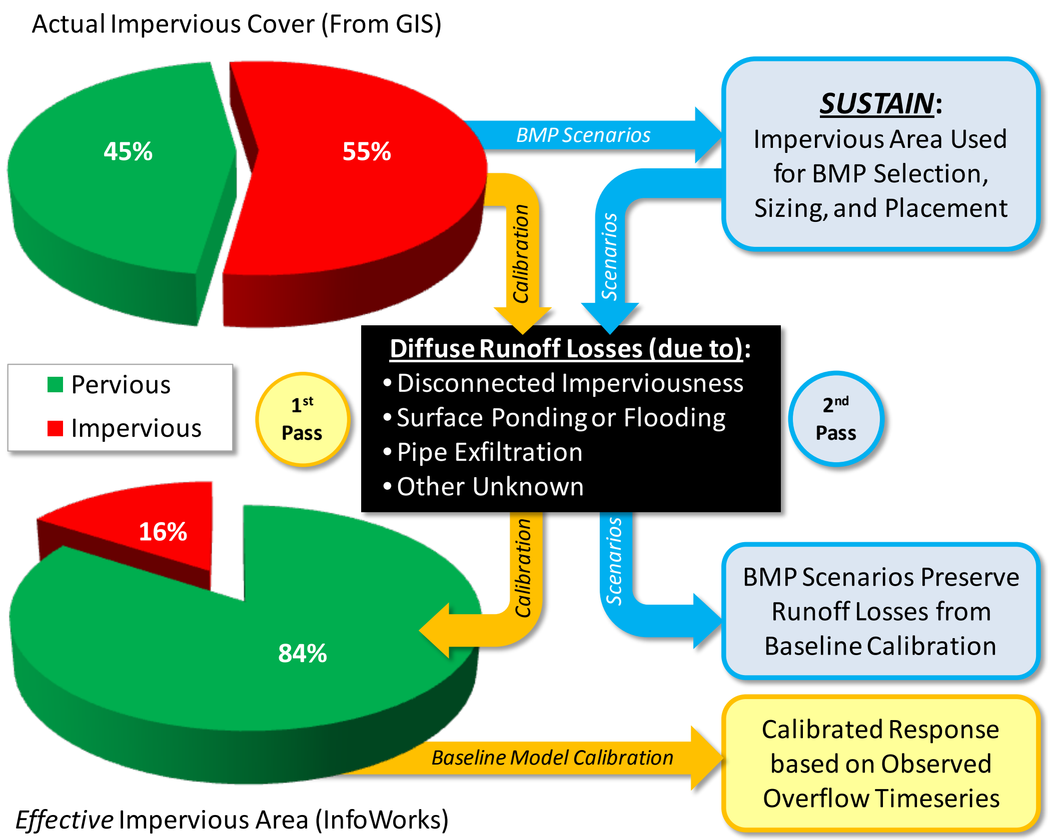

Figure 3-10. Conceptual data flow sequence for baseline calibration and BMP scenario model runs.

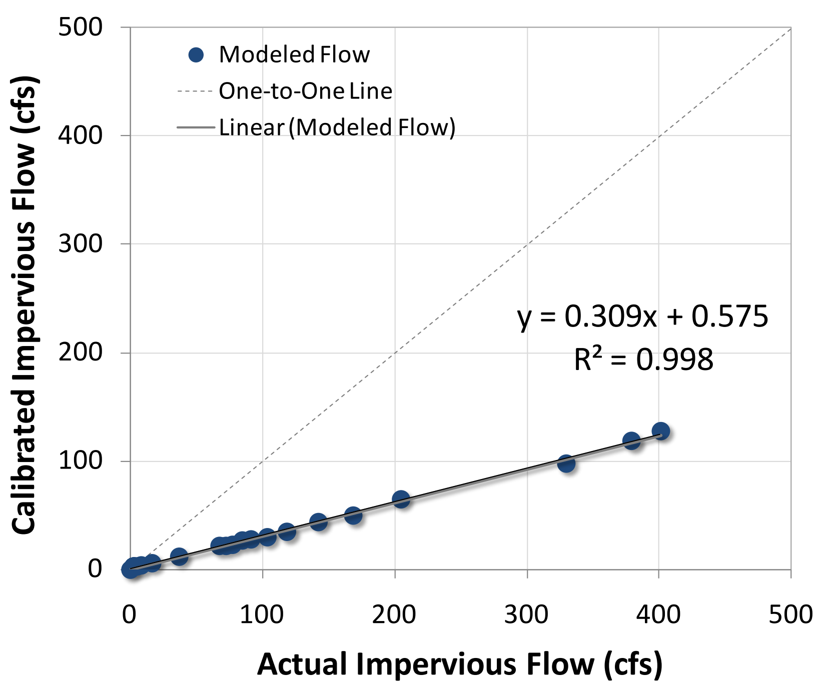

Figure 3-11. Calibrated versus actual impervious flow.

The plot shows a strong linear trend between inflows from the two model representations. It also shows that only about 31 percent of the actual impervious area runoff reaches the regulator. This suggests that it is reasonable to simply remove a fixed percentage of the water from the system before it reaches the regulator. This approach provided a consistent way to quantify the observed relationship associated diffuse losses during baseline calibration and preserve the response to the BMP scenarios.

The runoff-loss-adjustment described above was applied to the actual impervious area model configuration, as shown in Figure 3-11, to represent the *SUSTAIN* baseline calibration. This configuration was compared against exported time series from the InfoWorks model calibration. A one-to-one plot of *SUSTAIN* versus InfoWorks regulator inflow volume and peak flow (for discrete storm events) was used to test the quality of the baseline model replication. These plots are shown as Figure 3-12. A perfect replication of the InfoWorks baseline would plot along the dotted one-to-one line. Figure 3-12 show a strong fit between the *SUSTAIN* and InfoWorks calibrations for both total inflow volume and peak flow. The regression lines report R^2 values of 0.999 for total inflow and 0.990 for peak flow. The value of R^2 varies between 0 and 1, where higher values indicate a stronger correlation.

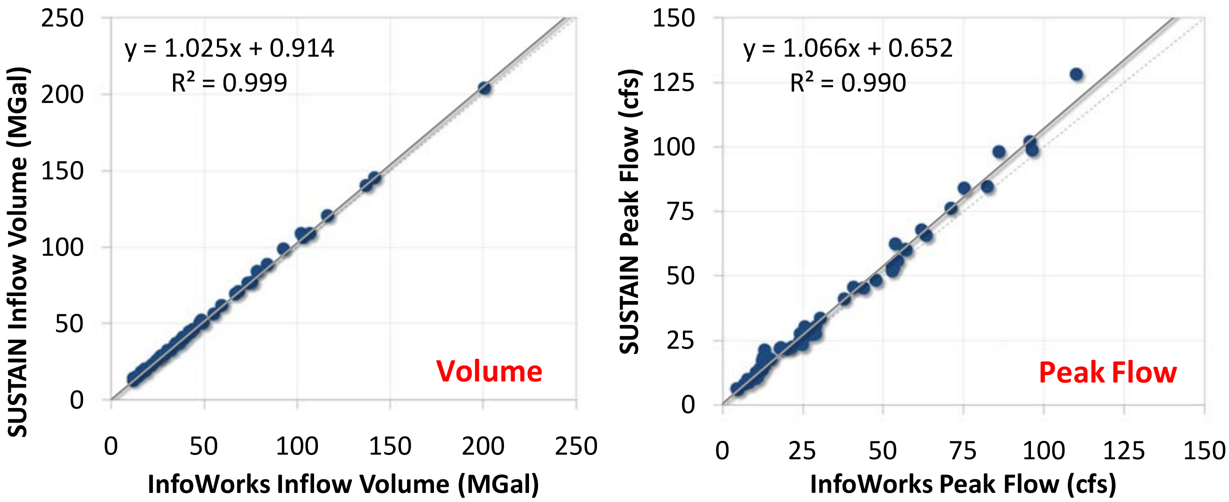

Figure 3-12. InfoWorks versus *SUSTAIN* modeled inflow volume and overflow peak.

Because CSO are mostly associated with larger storm events, it was important to further investigate the goodness of fit, i.e., percent difference in flow volume, peak, and timing—as measured by Nash and Sutcliffe (1970), for larger storms using additional validation metrics. First, the 62 discrete storm events were also categorized into ten percentile-bin intervals (two bins have seven storms, and eight bins have six storms) to discern the goodness of fit metrics variability by storm size. Second, the percent error was calculated between the *SUSTAIN* and InfoWorks baseline models. Percent difference between the two model configurations was calculated for both volume and peak as follows:

$$Percent\ Difference = \frac{(SUSTAIN - InfoWorks)}{InfoWorks}$$

where the InfoWorks result served as the replication target. Positive values of a given metric indicated that the *SUSTAIN* baseline over predicted the InfoWorks result, whereas negative values indicated that it under predicted the InfoWorks result. The range of computed metrics within each percentile bin were summarized and presented as the box-and-whiskers graph shown in Figure 3-13. As shown in Figure 3-12, the correlations between InfoWorks and *SUSTAIN* modeled inflow and overflow peak have positive intercepts. The positive intercept indicates there is a constant difference, which explains the trend that as storm size increases, the percent difference between the *SUSTAIN* and InfoWorks configurations decreases for both flow peak and volume. This trend is more visible with the percent difference comparison as shown in Figure 3-13. The effects of model aggregation become evident in the *SUSTAIN* configuration because of the tendency to over predict volumes and intensities. For example, model aggregation reduces time of concentration and lowers routing precision, resulting higher peak flow and less opportunity for water losses. Nevertheless, percent differences decreases with increasing storm size, and is the lowest for the largest storms, which are more critical for accurately replicating because they are the ones associated with overflows.

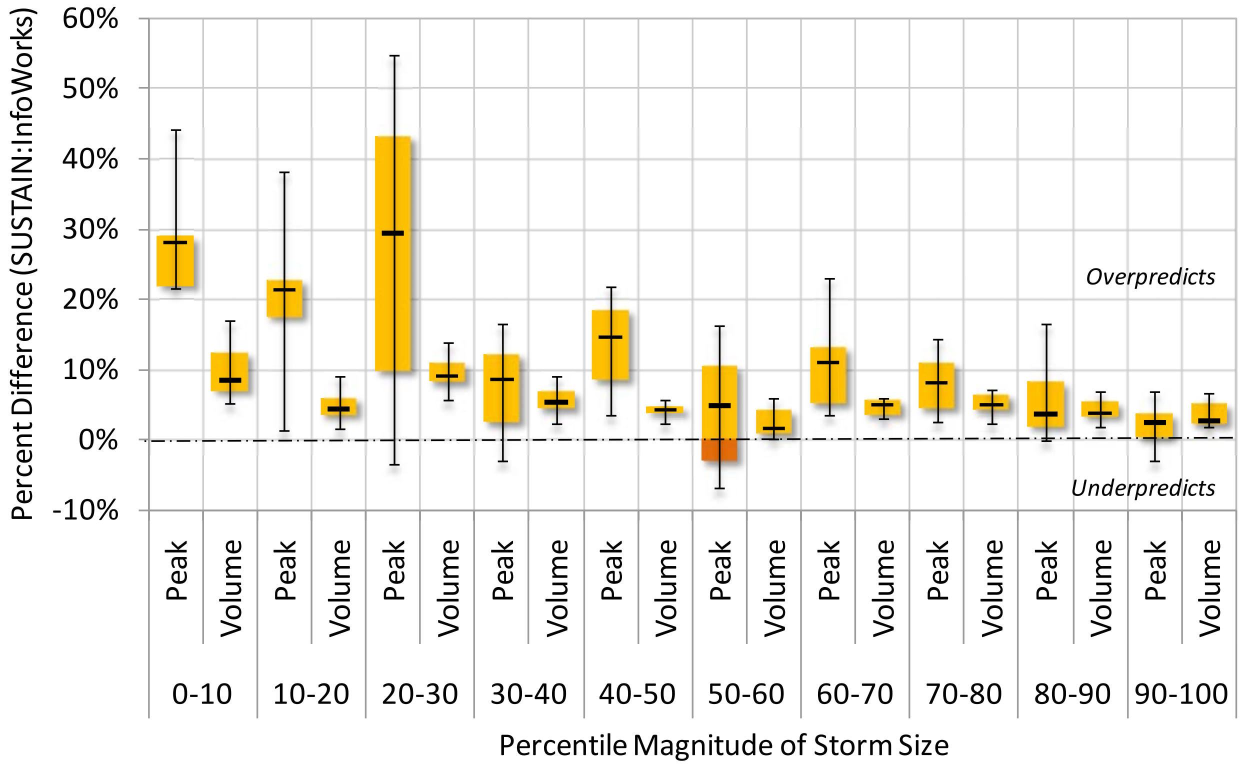

Figure 3-13. Percent difference between *SUSTAIN* and InfoWorks model calibration metrics.

Another metric that is commonly used for assessing the performance of continuous simulation hydrology models is a model efficiency metric, *E*, developed by Nash and Sutcliffe (1970). Nash and Sutcliffe interpret the model efficiency metric *E* as follows:

- Values below zero suggest that the mean of observed data is a better predictor than the model;
- A value of 0 indicates that the observed data mean is equally as good a predictor as the model; and
- The closer the model efficiency is to 1, the better it predicts observed data.

For example, a Nash-Sutcliffe value of 0.70 indicates that the mean square error of the difference between observed data and model prediction is 1.00–0.70 or 30 percent of the variance in the observed data. Based on typical hydrology modeling practice, obtaining a value of 0.70 or larger generally indicates adequate model fit.

A plot of Nash-Sutcliffe coefficients by storm percentile comparing regulator inflows from the *SUSTAIN* versus 2008 InfoWorks models is presented in Figure 3-14. The plot also shows a log-space Nash-Sutcliffe, which is calculated by taking the natural log of flow values before performing other calculations. The log-space Nash-Sutcliffe is another way to measure model performance for high flow events because it emphasizes model prediction of the peak flows.

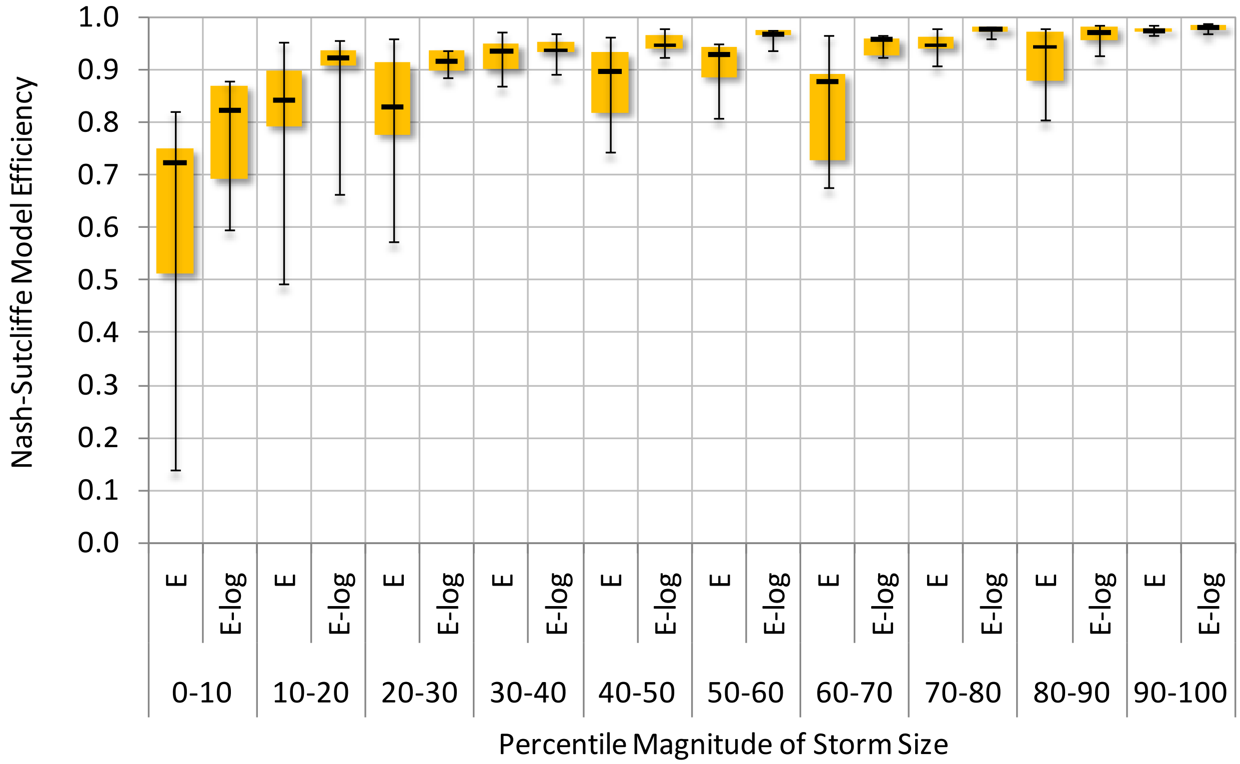

Figure 3-14. Plot of Nash-Sutcliffe by storm size for *SUSTAIN* versus InfoWorks regulator inflows.

Once again, Figure 3-14 confirms the goodness of fit across a range of hydrologic conditions. It suggests that the efficiency of the *SUSTAIN* model representation for matching InfoWorks model time series is generally at or above 0.9 for storm events above the 30th and 100th percentile. Model replication efficiency begins to degrade rapidly for storm events below the 30th percentile as evident from the lower average values and higher variability. Nevertheless, these smaller events are well below the target containment values for optimization. Finally, Table 3-5 presents a summary of model performance as defined by the selected calibration metrics for the 8 largest calibrated storm events on record.

Table 3-5. Model calibration performace metrics for eight largest storms events causing overflow

Start date	End date	Precipitation (in.)	Volume (percent difference)	Peak (percent difference)	Nash-Sutcliffe *E*
5/7/01 14:00	5/8/01 14:00	2.03	4%	5%	0.97
9/9/01 10:00	9/10/01 9:00	1.57	7%	2%	0.97
10/5/01 13:00	10/6/01 10:00	1.43	10%	6%	0.97
10/11/01 5:00	10/12/01 18:00	1.58	3%	7%	0.98
10/13/01 6:00	10/14/01 21:00	1.60	-1%	2%	0.97
10/23/01 14:00	10/25/01 8:00	1.56	3%	0%	0.95
11/28/01 4:00	11/30/01 13:00	3.13	2%	2%	0.97
12/16/01 8:00	12/18/01 8:00	2.11	2%	7%	0.99

3.3.4. *CSO 019 Regulator Calibration*

After characterizing the stormwater inflow boundary condition, the next objective of the baseline calibration was replicating the InfoWorks regulator response in a *SUSTAIN* environment. As previously noted, 62 storms were evaluated during watershed calibration for the 2001 precipitation year. Properly characterizing what happens at the regulator junction is as important as characterizing the stormwater inflow boundary condition because combined stormwater and dry-weather sewage sometimes result in a regulator overflow. Figure 3-15 is a conceptual schematic of the CSO regulator activity. As was done for the stormwater inflow validation, similar metrics were used to validate the quality of the regulator replication.

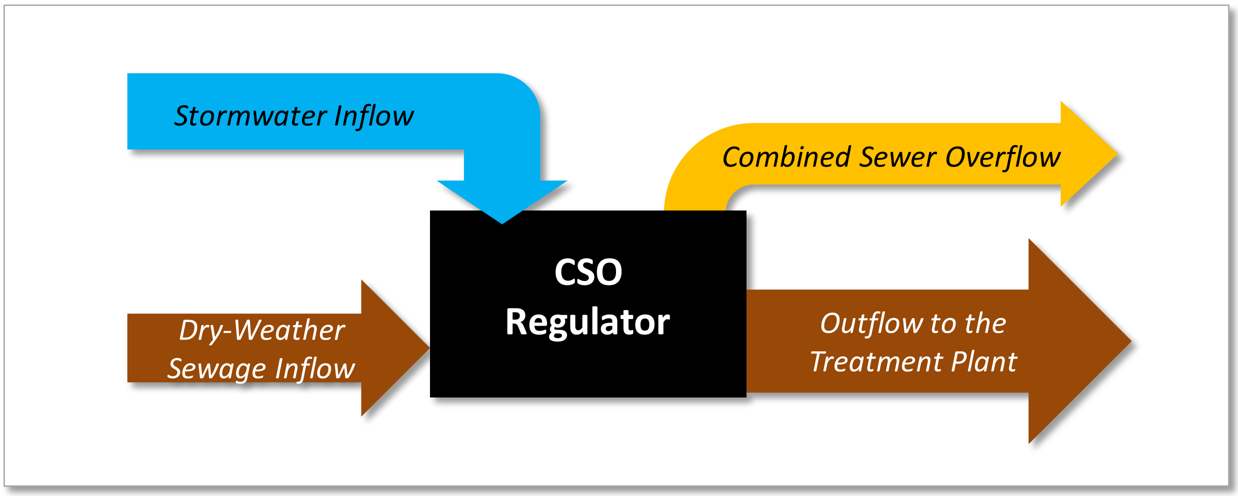

Figure 3-15. Conceptual schematic for the CSO Regulator.

The physical outfall configuration for the CSO 019 sewershed consists of a weir located at the end of an 11.5 ft diameter pipe. Flow from the pipe terminates at the weir and is diverted through a 24 in. orifice leading to the 38th Street pump station. At the pump station, it is transferred to an interceptor and ultimately to the wastewater treatment plant. During events that exceed the capacity of the weir, excess volume crests the 2.75 ft weir and continues down the outfall pipe to where it discharges into the Ohio River. Figure 3-16 shows a schematic cross-section of the 11.5 ft circular pipe where it meets the outfall weir.

The actual model representation of the outfall structure in *SUSTAIN* differs slightly from the schematic shown in Figure 3-16. The *SUSTAIN* regulator object is modeled as a box with two outlet structures: an orifice and a weir. The orifice is located at the bottom of the box whereas in reality the orifice is physically located in the side of the pipe. To account of this difference in representation the orifice discharge coefficient was varied as a calibration parameter at ultimately set at 0.155. In the 2011 InfoWorks model the height of the weir was also increased from 2.75 ft to 4.25 ft. The physical size of the regulator box used in *SUSTAIN* (25 ft × 25 ft × 4.25 ft) was also subtracted from the 160 ft pipe. Discussion with model developers from MSD revealed that this change was imposed to account for uncertainty in model elevations caused by several different surveying datums referenced over a number of decades. For consistency, the *SUSTAIN* model incorporated this change in weir height.

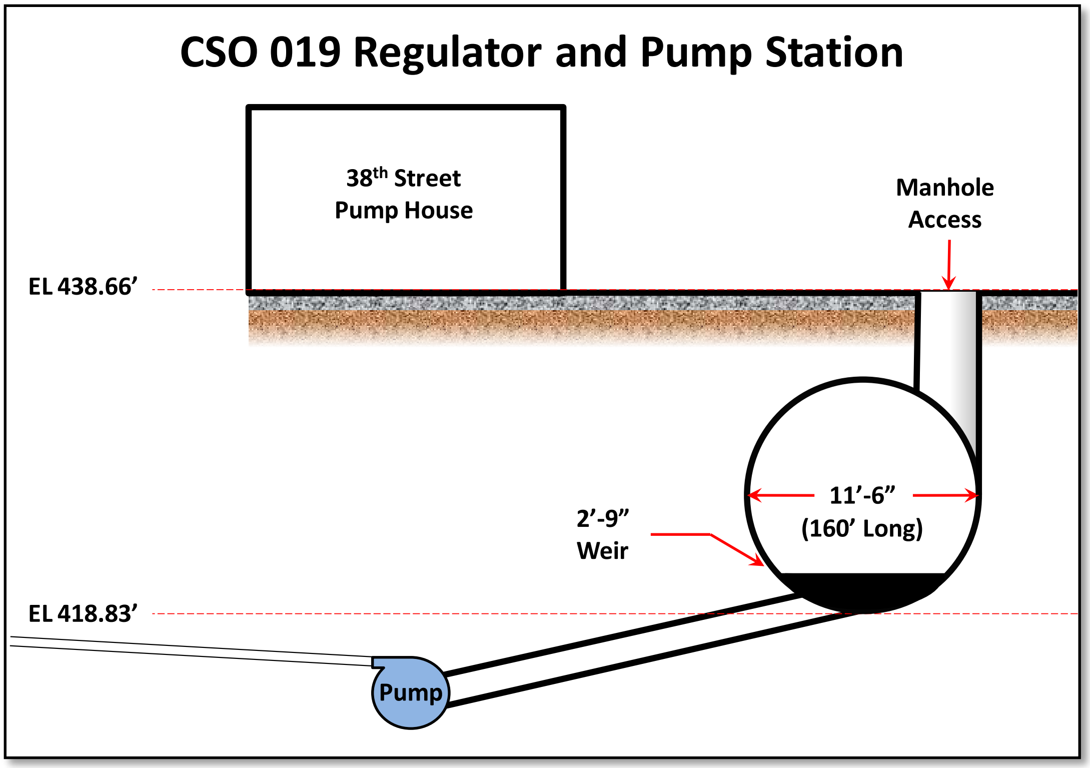

Figure 3-16. Conceptual cross-section of the CSO 019 outfall structure.

Figure 3-17 plots *SUSTAIN* versus InfoWorks total overflow volume and peak flow rate for water overflowing the regulator. The eight largest overflow events identified by the 2008 IOAP model are highlighted as diamonds on both panels of the graph. Also, eight new overflow events occurred in *SUSTAIN* that did not occur in InfoWorks—this will be discussed later. Notice that neither volume nor peak flow was distinctly predictive of overflow. In other words, the eight largest volumes are not the eight largest peaks. Instead, overflow occurs under a critical condition caused by a combination of factors.

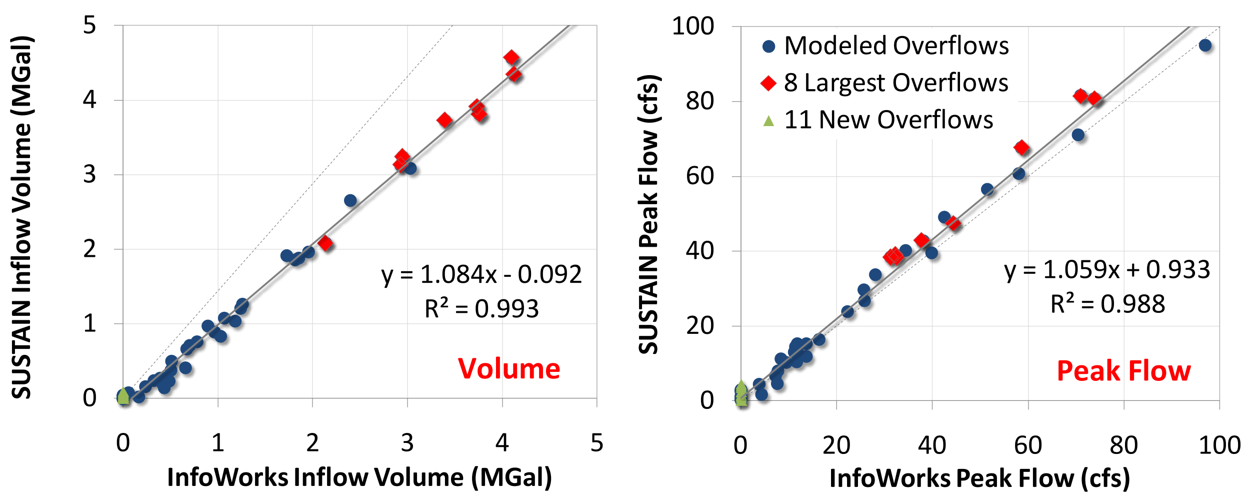

Figure 3-17. InfoWorks vs. *SUSTAIN* modeled overflow volume and overflow peak.

During the *SUSTAIN* calibration, there were 11 additional overflow events observed that did not occur in InfoWorks. A closer look at these events reveals that all had short durations and relatively small in overflow volume and flow rate. Aggregation of the 203 InfoWorks subcatchments into 20 subwatersheds in the *SUSTAIN* model and the simplification of the routing network from 647 conduit segments to 26 offers an explanation for predication of these additional events. The detailed InfoWorks model included conduits ranging in size from 1.5 ft to11.5 ft while the *SUSTAIN* representation mostly excluded pipes smaller than 3 ft in diameter. Consequently, the *SUSTAIN* model representation provides less attenuation capacity in its conduit network than the original InfoWorks, which also tends to make it slightly more conservative in its prediction.

All 11 new events listed in Table 3-6 are in the lowest fifth percentile for both overflow volume and peak flow rate. Because these events will be easily captured under any BMP scenarios, it is expected that they will have no consequential impact for achieving the overflow target during optimization.

Table 3-6. Summary of additional predicted overflows

Start time	End time	Overflow volume (MG)	Peak flow (cfs)
1/19/2001 0:15	1/19/2001 14:00	0.027	1.02
4/1/2001 5:00	4/1/2001 17:45	0.022	1.61
4/3/2001 4:00	4/3/2001 16:15	0.002	0.32
5/24/2001 6:15	5/24/2001 18:30	0.003	0.44
7/3/2001 17:45	7/4/2001 6:45	0.057	3.66
7/24/2001 14:45	7/25/2001 4:15	0.084	4.01
8/19/2001 1:15	8/19/2001 14:00	0.022	1.45
8/23/2001 15:45	8/24/2001 4:45	0.075	4.53
8/31/2001 23:00	9/1/2001 11:30	0.013	1.09
10/16/2001 2:45	10/16/2001 15:45	0.036	2.52
12/8/2001 5:00	12/8/2001 19:15	0.095	2.37

3.3.5. *Model Run-Time Considerations*

The *SUSTAIN* replica of the CSO 019 sewershed incorporates considerable simplification from the InfoWorks version that used as a basis for model setup and testing. The resulting model can be used to examine the trade-off between model performance and computational efficiency. Savings in model computation time become significant when performing optimization analysis. Table 3-7 summarizes the model simplification and the computational savings in model run-time for a single continuous simulation of the typical precipitation year 2001.

Table 3-7. Comparison of model representations and run-time

Model characteristics	InfoWorks calibration	*SUSTAIN* configuration	Percent reduction
Number of subcatchments	203	20	90%
Number of pipe segments	647	26	96%
Estimated run-time (minute)	60 [a]	0.5	99%

a. InfoWorks run-time based on conversations with modeler running only the CSO 019 sewershed.

Both single run-times presented in Table 3-7 may seem acceptable considering the complexity of a hydraulics model, the scale of the watershed, and the goals of the model application; however, the benefits come to light when thousands of iterative simulations are needed during optimization runs. Figure 3-18 shows the estimated run-times required to perform a 10,000 run optimization using the model configurations described in the table above compared to a single run.

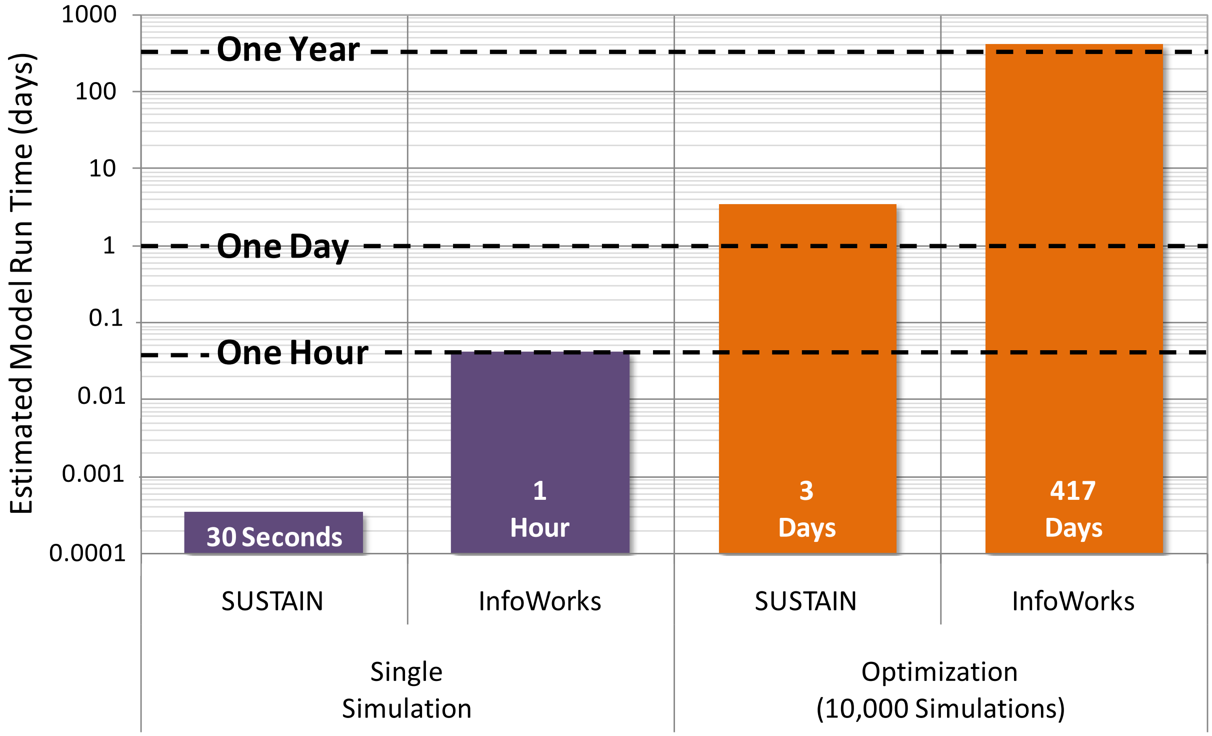

Figure 3-18. Comparisons of single simulation and optimization modeling run-times.

When performing a single simulation the difference between waiting one hour or half a minute may be beneficial for gaining the additional accuracy. However, it is important to keep in mind the optimization objectives, which in this case, are to minimize the number of CSO regulator overflows. The model has been shown to perform very well for the largest events associated with overflows, despite the relatively coarse spatial resolution. When a large number of runs are needed for the optimization process, shorter run-times can support the practical application of the system within realistic time frames of hours or days. Since optimization scenarios are typically run with various objectives, assumptions, and management scenarios, a shorter run-time also facilities the use of the system for exploratory analysis. With careful examination of the tradeoff between accuracy and simplification an appropriate level of resolution can be identified consistent with the management questions under consideration.

3.4. BMP Parameter Sensitivity Analysis

Both the geometric representation and the parametric representation of BMP properties have an influence on the way a BMP responds in *SUSTAIN*. Sometimes an irregularly shaped BMP must be simplified as a rectangular or square box in the model. At the same time, some BMP calibration parameters are more influential on how the BMP responds than others. The first part of this section demonstrates how an actual BMP plan was translated from construction drawings into a BMP configuration in *SUSTAIN*. The second part shows how a traditional laboratory analytical approach (full factorial experimental design) was adapted and applied to study the sensitivity of key BMP configuration parameters in *SUSTAIN*. Finally, this section concludes with quantifying the range of the response variations for the sensitivity analysis. As previously noted, this analysis was conducted using a single bioretention cell.

3.4.1. *BMP Representation*

MSD participated in the design, construction, and current monitoring of a GI demonstration project at the Office of Employment and Training at 600 Cedar Street in downtown Louisville, Kentucky. The project is adjacent to a 3-acre parking and that drained to inlets directly connected to the storm sewer. Three bioretention cells and 2,000 square feet of porous asphalt were installed along with several bioinfiltration areas and porous paver features to decrease the volume of stormwater runoff to the city's CSS from the parking lot. A single bioretention cell in the southwest corner of the parking lot was selected to evaluate the sensitivity of BMP simulation parameters.

A map of the project location and bioretention cell site are shown in Figure 3-19. The map shows an overlay of the construction drawings on an aerial photo of the site. An image of the site schematic was extracted from the construction drawings and geo-referenced to a current aerial photo in ArcGIS. The drainage area and BMP location were then delineated using the geo-referenced construction plans.

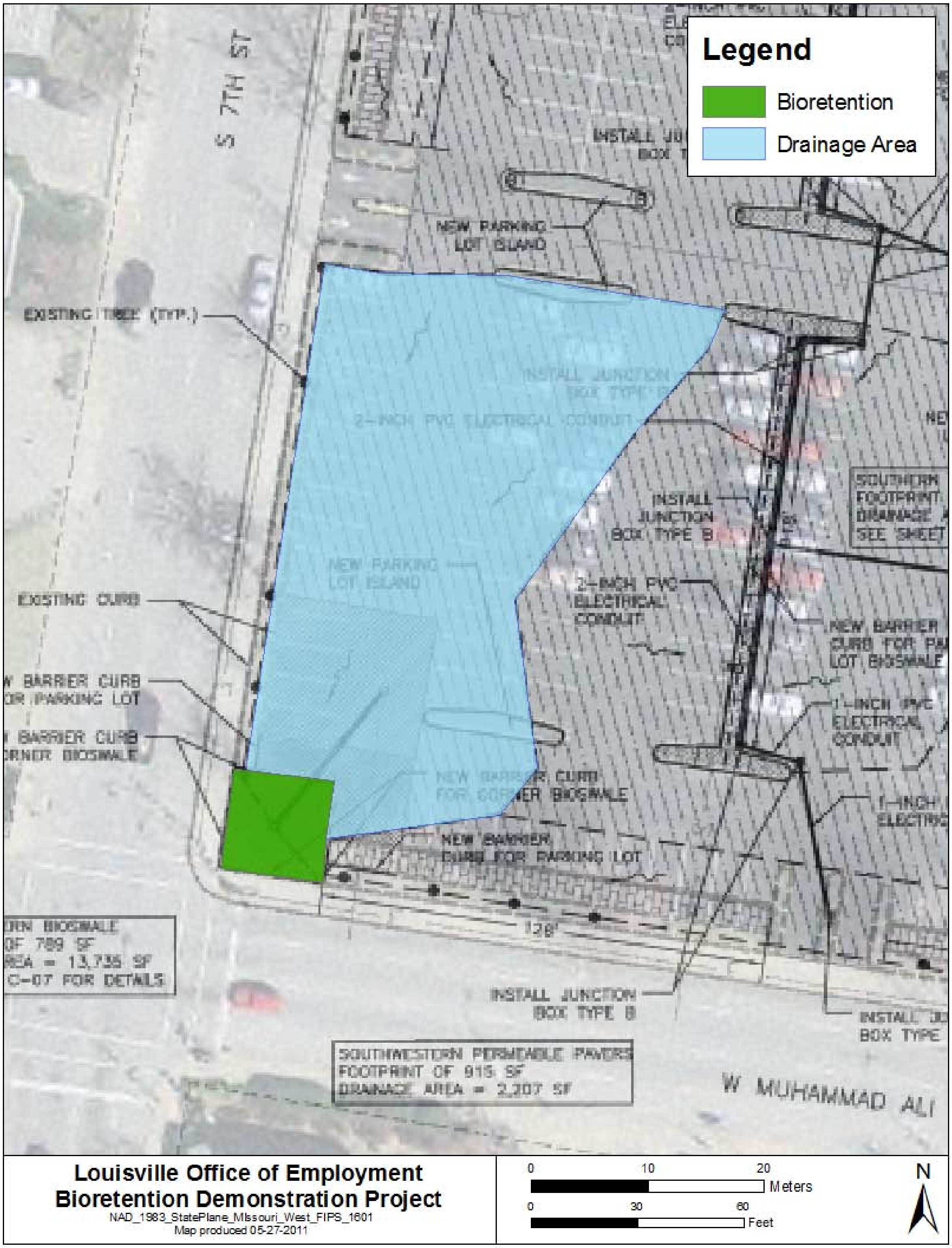

Figure 3-19. Office of Employment bioretention cell site location and drainage area.

A *SUSTAIN* model representation of the bioretention cell was constructed using drainage area and dimensional information from the design plans in Figure 3-20. The bioretention cell is designed to receive runoff from a 0.3-acre section of the parking lot. In *SUSTAIN*, the bioretention cell was configured using a length and width of 30 ft for a total surface area of 900 square feet. The typical bioretention cell cross section presented shown in Figure 3-20 was used to construct the BMP vertical profile (Strand Associates, 2010).

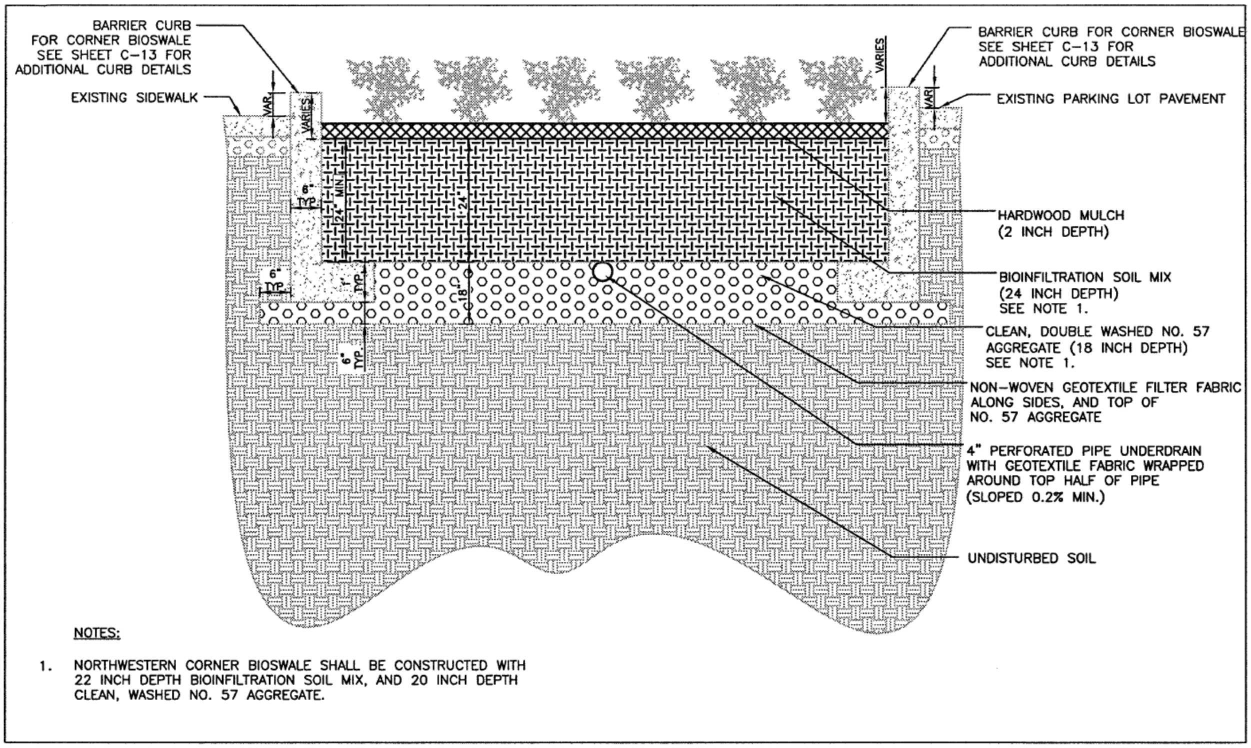

Figure 3-20. Bioretention cell subsurface cross-section from design plans (Strand Associates, 2010).

The figure shows a soil media depth of 24 in. and an underdrain depth of 18 in. A 6 in. ponding depth was used in the *SUSTAIN* model configuration. A complete list of the physical BMP parameters used for model setup is presented in Table 3-8. Each parameter in the respective *SUSTAIN* BMP interfaces, shown in Figure 3-21 (surface), Figure 3-22 (substrate), and Figure 3-23 (infiltration), is also highlighted in the figures (as A-F), corresponding to how they are labeled in Table 3-8.

Table 3-8.Summary of BMP parameters used for bioretention cell configuration.

Figure group	Parameter	Value
A	Length (ft)	30
	Width (ft)	30
B	Orifice diameter (in.)	0
C	Ponding depth (ft)	0.5
D	Soil media depth (ft)	2
	Soil media porosity	0.3
E	Underdrain depth (ft)	1.5
	Underdrain porosity	0.4

Figure group	Parameter	Value
F	Maximum infiltration rate (in./hr)	5
	Decay constant (1/hr)	0.2
	Drying time (days)	3
	Maximum volume (in.)	48

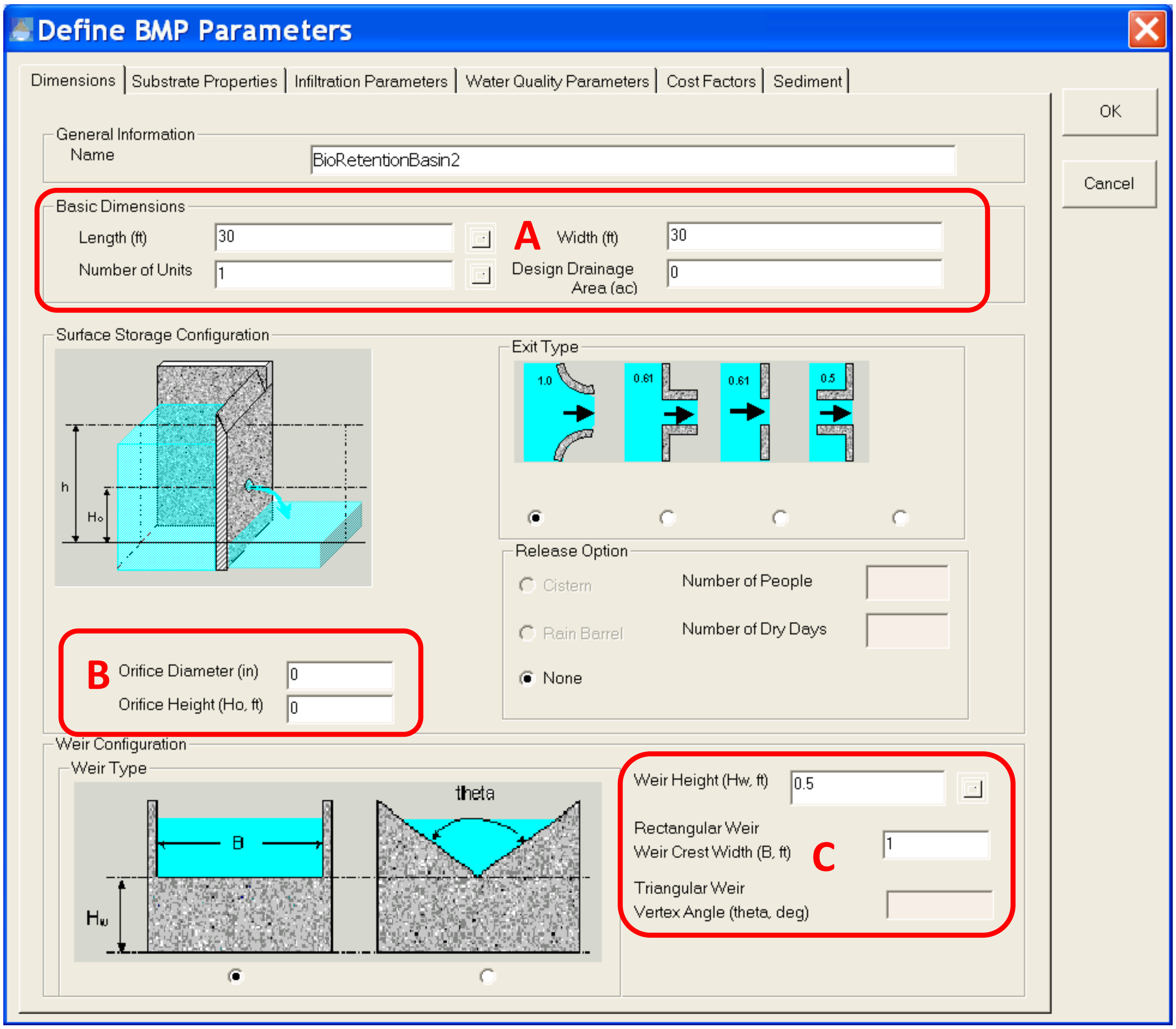

Figure 3-21. *SUSTAIN* surface parameter input screens for bioretention cell.

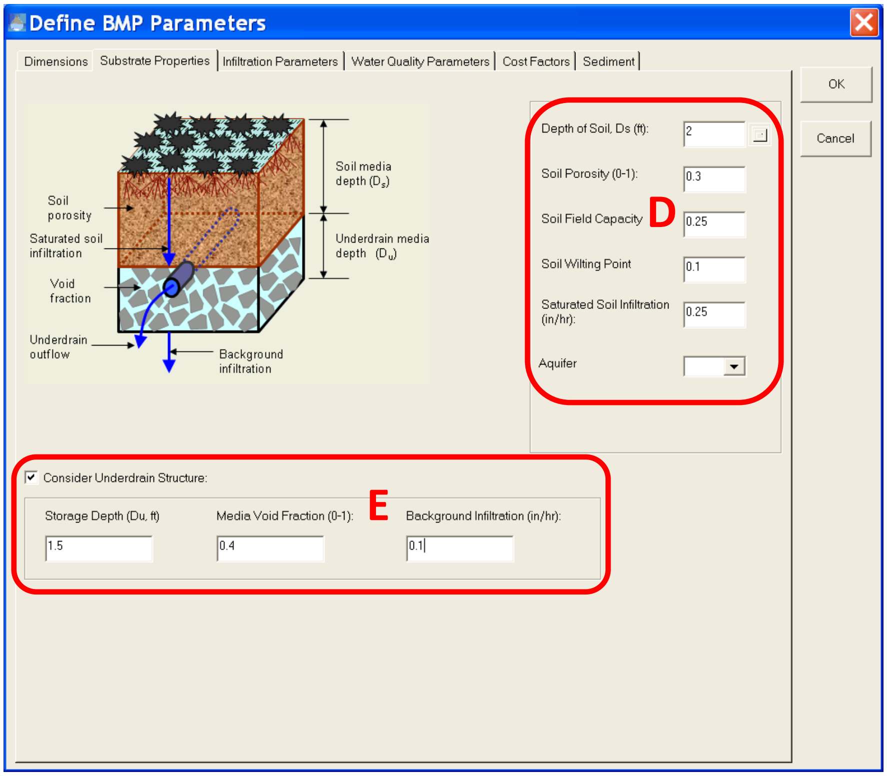

Figure 3-22. ***SUSTAIN*** **substrate parameter input screens for bioretention cell.**

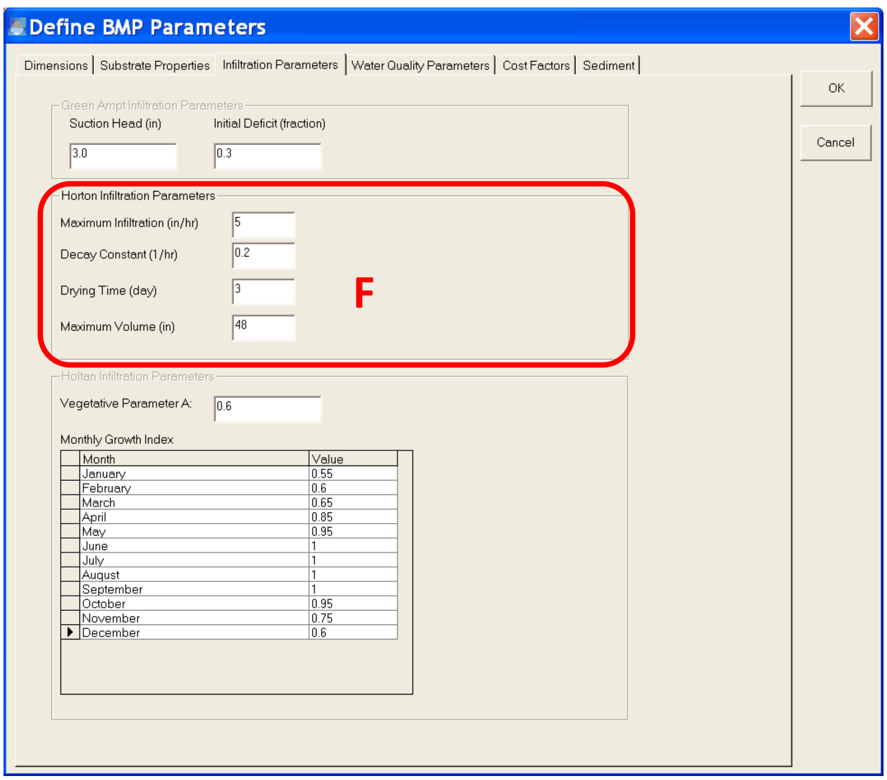

Figure 3-23. ***SUSTAIN*** **infiltration parameter input screens for bioretention cell.**

Some additional observations about BMP configuration and setup are as follows:

- The bioretention cell configuration from the design plans did not show an orifice for outflow of water that ponds on the surface; therefore, the orifice diameter was set to zero. In this case, the orifice height was also set to zero. Other orifice related parameters such as the exit type were not used in this case;
- The background infiltration rate should be set as the infiltration rate for the native soils into which the bioretention cell is installed. The parameter was treated as a variable in Section 3.4.2 and was left blank accordingly in Figure 3-21 (near figure group E); and
- Typically, not all BMP parameters are used in every simulation. In this case, the Horton infiltration method was used to simulate the BMP media infiltration process. Therefore, only the Horton infiltration parameters were used. .

Not all BMP configuration parameters are found on the design or construction plans. If site specific data was not collected in the design study, values for soil field capacity, wilting point, and the infiltration parameters are best evaluated through other local data sources, such as geotechnical reports, or academic literature reviews. In this application, porosity and underdrain void fraction were assumed. A list of BMP parameters and suggested information sources is presented in Table 3-9.

Table 3-9. Suggested information sources for obtaining BMP parameters

Key information sources: ● = **Primary source** ⦿ = **Secondary source** -- = **Not applicable**	**Design plans**	**Geotechnical report**	**Academic literature**
BMP dimensions	●	--	--
Infiltration rates	--	●	⦿
ET multiplier	--	--	●

3.4.2. *Factorial Experiential Design*

A factorial experiment was designed to test the sensitivity of three independent BMP parameters. Factorial experiments are designed to evaluate multiple responses from three or more independent variables and quantify the magnitude of each response (Berthouex and Brown, 2002). This type of experiential design limits the number of experiments needed to evaluate multiple independent variables. The factorial framework is often implemented in laboratory settings to minimize the use of material resources, lab time, and person-hours expended while maximizing the utility of data collected.

Three BMP parameters were evaluated, that included the ET multiplier and two Horton infiltration parameters, the saturated infiltration rate (f_c) and maximum infiltration rate (f_o). The ET multiplier can vary for each BMP and is applied to the ET rate at each time step. Low and high ET multiplier values were selected to represent turf grass at low and high ET conditions (Bedient and Huber, 1992). A monthly distribution of constant daily ET rates was used for the simulation as referenced in Section 3.3.3.

The saturated infiltration rate (f_c) is the rate at which water can infiltrate under saturated soil conditions. The initial infiltration rate (f_o) is the infiltration rate for unsaturated soil. Low and high infiltration parameters were selected on the basis of MSD suggested values for hydrologic soil group Type C and D soils (MSD, 2007). Those are suggested parameter starting values by MSD's hydraulic modeling guidelines document. The rate of change between the maximum and saturated infiltration rate is controlled by an infiltration decay coefficient (*k*) that was held constant at 0.2 hr^{-1}. Selected values for each of three parameters are listed in Table 3-10.

Table 3-10. Low and high values selected for three evaluated BMP parameters

Parameter	Low	High
ET multiplier	0.35	0.85
Saturated infiltration rate (in./hr)	0.10	0.25
Maximum infiltration rate (in./hr)	3.00	5.00

The number of experimental runs incorporated into a full factorial analysis is a function of the number of variables being tested and can be calculated as 2^x, where 2 is the number of conditions (low and high) and *x* is the number of variables. For this analysis, eight simulations were constructed to test three key variables, although the sensitivity of more than three variables could be explored. A matrix outlining the variables for each of the eight simulation runs is presented below in Table 3-11.

Table 3-11. Matrix of the eight designed experimental runs showing values for the three parameters

Simulation number	ET multiplier	Saturated infiltration, f_c (in./hr)	Maximum infiltration, f_o (in./hr)
1	0.35	0.10	3
2	0.85	0.10	3
3	0.35	0.25	3
4	0.85	0.25	3
5	0.35	0.10	5
6	0.85	0.10	5
7	0.35	0.25	5
8	0.85	0.25	5

The 2001 precipitation time series was used as the boundary condition for each of the eight simulations. The *SUSTAIN* bioretention cell configuration described previously was used for draining 0.3 acre of impervious parking lot. Other than the variables outlined in Table 3-11, all simulation parameters were held constant. Each simulation was evaluated for total outflow volume from the bioretention cell.

3.4.3. *Results*

Figure 3-24 shows the average annual reduction in BMP total outflow for all eight scenarios as a percentage of the baseline condition where no BMP is present. The sensitivity of each parameter is evaluated as the difference in average response (outflow volume) between the high condition and low condition. Average BMP outflow percent reduction versus low and high conditions for the three tested variables is shown in Figure 3-24.

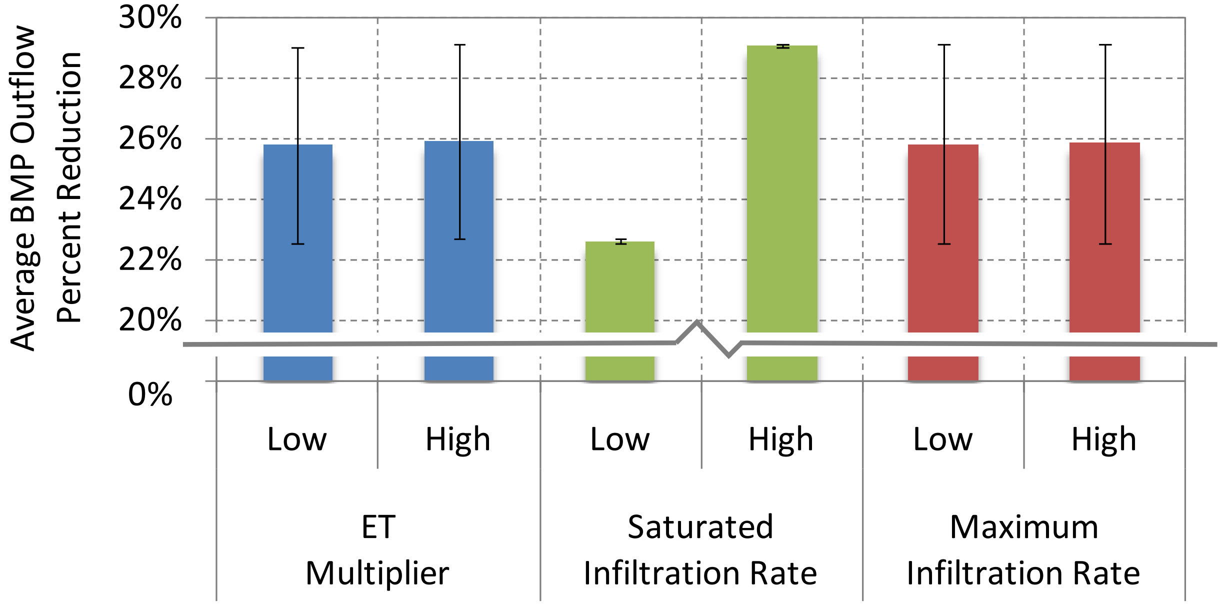

Figure 3-24. Average annual reduction in total BMP outflow for all eight scenarios.

The error bars, represented as lines at the top of each bar in Figure 3-24, show the range of variability (minimum and maximum) for the averaged outflow values. Wide bands for a given parameter suggest that variability is controlled not by that parameter but by one of the other two. For the saturated infiltration rate, the very narrow bands on the error bar suggest that variability in BMP outflow is controlled foremost by controlling the value of that parameter.

The variation in average response between low and high conditions can also be calculated by subtracting the average annual BMP outflow for the low condition from the high condition for each of the three parameters. Table 3-12 presents the average variation in total BMP outflow expected on the basis of the range of BMP parameters presented in Figure 3-24.

Table 3-12. Summary of average annual BMP variation in response between low and high conditions

Parameter	Average variation (gal. per year)	Percent of baseline
ET multiplier (unitless)	267.68	0.13%
Saturated infiltration rate (in./hr)	13,211.92	6.46%
Maximum infiltration rate (in./hr)	14.34	0.01%

The saturated infiltration rate is the most sensitive of the three parameters evaluated, followed by the ET multiplier, and the maximum infiltration rate. The range of BMP responses in the table above varies by three orders of magnitude. When setting individual BMP parameters, the range of expected responses can be interpreted from the table above as follows:

- Increasing the ET multiplier from 0.35 to 0.85 will decrease the average annual flow volume by 56 cubic feet, or 0.13 percent of the baseline annual flow volume;
- Increasing the saturated infiltration rate from 0.10 to 0.25 in. per hr will decrease the average

annual flow volume by 2,674 cubic feet, or 6.46 percent of the baseline annual flow volume; and

- Increasing the maximum infiltration rate from 3 to 5 in. per hr will decrease the average annual flow volume by 3 cubic feet, or 0.01 percent of the baseline annual flow volume.

Results of the sensitivity analysis suggest prioritizing research and interpretation of model values for the saturated infiltration rate, which shows a 6.5 percent variation in annual average outflow when selecting an f_c value suggested for Type C versus Type D soils. While it is important for the purpose of accurate model representation, the ET multiplier and maximum infiltration rate each show a less than 1 percent variation in annual average outflow when selecting representative low and high parameter values.

3.5. Cost-benefit Relationship between Gray and Green Infrastructure for Mitigating CSO

The central question in the minds of regional policy makers is how might the cost of planed gray infrastructure be offset through the use of GI alternatives? Exploratory management alternatives relevant to the case study area include (1) a downspout disconnection program that redirects rooftop runoff to rain barrels and existing pervious land; (2) implementing green street and green parking practices in conjunction with a downspout disconnection program; and (3) exploring the supplemental gray infrastructure necessary to satisfy the optimization objectives when GI is completely built-out. The objectives for optimization are to (1) minimize annual number of overflows and volume; and (2) minimize the total capital cost of implementation, as needed, to satisfy the allowable CSO exceedance criteria (eight events per year). Figure 3-25 illustrates the development sequence of exploratory optimization scenarios relative to the established baseline condition.

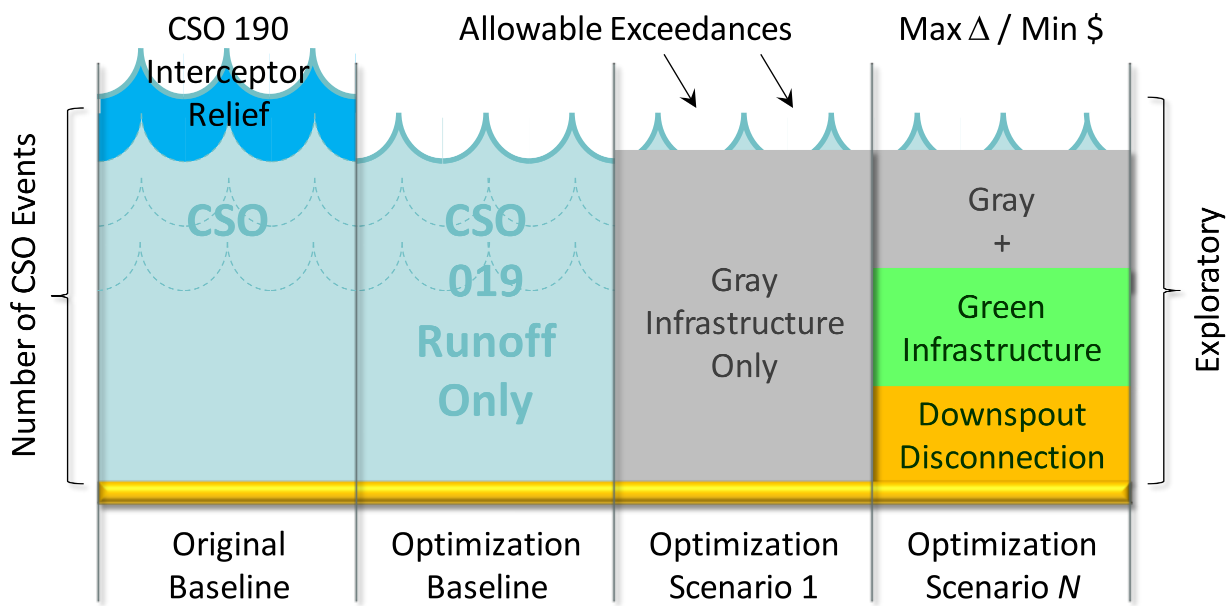

Figure 3-25. Conceptual sequence of optimization scenarios relative to baseline condition.

3.5.1. *Green Infrastructure Opportunities*

MSD performed an analysis of potential BMP opportunities in the CSO 019 sewershed. Those data sets were available as GIS shapefiles and represent a screening level analysis of possible BMP opportunities in the watershed. This study was not a comprehensive cost feasibility or on-site assessment of limiting factors such as conflicting utility infrastructure, hardscaping, or other landscape features. The types of BMPs evaluated in this analysis include (1) bioinfiltration; (2) downspouts disconnection; (3) green alley; (4) green parking lot; (5) reforestation; (6) tree lawn retrofit; and (7) intersection bump out. A map highlighting the possible BMP opportunities and drainage areas is presented in Figure 3-26.

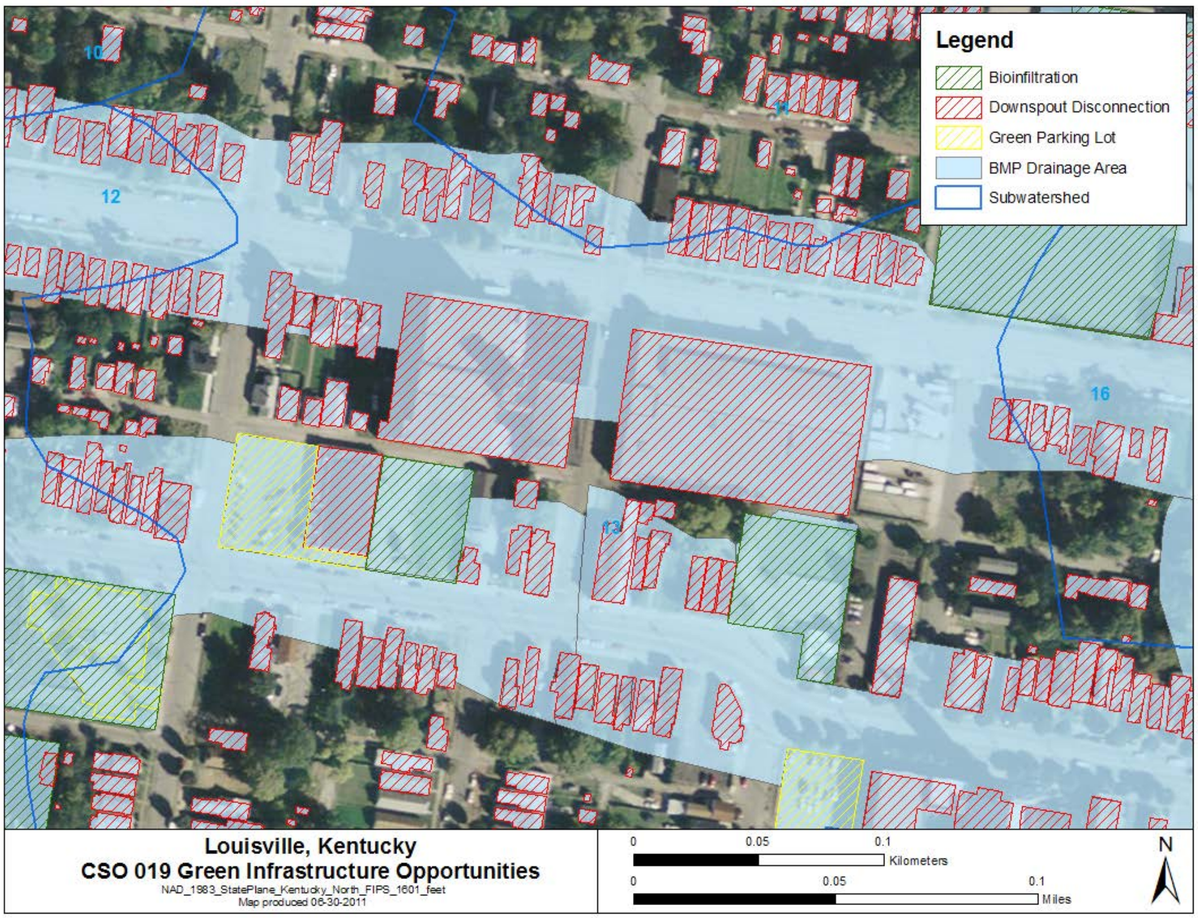

Figure 3-26. CSO 019 GI opportunities and treated drainage areas.

The BMP opportunities presented in Figure 3-27 are indicative of common BMPs that are considered acceptable practices in MSD's service area. When represented in the *SUSTAIN* model, each BMP has an associated treatment capacity (ponding volume + substrate volume + underdrain volume). In a subwatershed, the collective volume of individual BMPs represents the total treatment capacity for the subwatershed. It is likely that during implementation, other suitable types of BMPs could be identified that were not included in this study. Treatment capacity provides a standard basis of comparison when implementing other types of BMPs. This case study focused on the following BMP types that directly control impervious runoff, including:

- Rain barrel and downspout disconnection;

- Green street and green alley related opportunities, mainly bioinfiltration facilities, including bioretention, curb extension bioretention, and bioswale; and
- Green parking lot using combination of pervious pavement and bioinfiltration.

Figure 3-27 illustrates examples of downspout disconnection to a rain barrel, typical green street bioinfiltration, and typical green parking with bioinfiltration and pervious pavement. Rain barrels collect rooftop runoff and drain the water to pervious land during dry days. Green street bioinfiltration practices are along the streets to collect and treat runoff from impervious road, sidewalk, and driveways. Green parking lots adopt pervious pavement in the parking areas and use bioinfiltration practices in medians and islands to reduce the runoff.

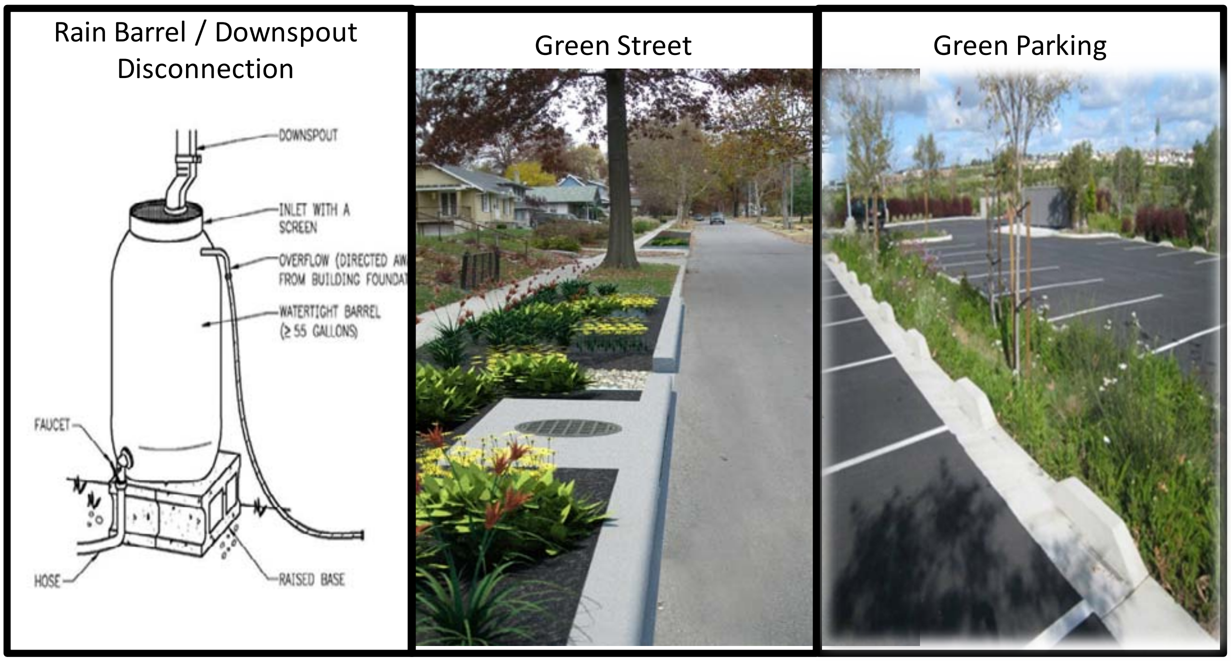

Figure 3-27. Examples of GI practices for Louisville, Kentucky.

3.5.2. *SUSTAIN BMP Representation*

An aggregate BMP approach was implemented to represent the BMP opportunities in the CSO 019 sewershed model. The aggregate BMP consists of five components including (1) rain barrels; (2) downspout disconnections; (3) green street bioinfiltration; (4) green parking pervious pavement; and (5) green parking bioinfiltraiton. The modeled GI BMP drainage pathways are illustrated in Figure 3-28. The figure is a conceptual diagram of the treatment pathways showing the relationship between different tributary land cover types for the potential BMPs. Disconnected rooftops represent downspouts that are no longer connected directly to the sewer main via a lateral. Instead, runoff from downspouts is directed to a rain barrel for use as a non-potable water supply. Both outflow and overflow from the rain barrel is directed to adjacent pervious area before being routed to the outlet.

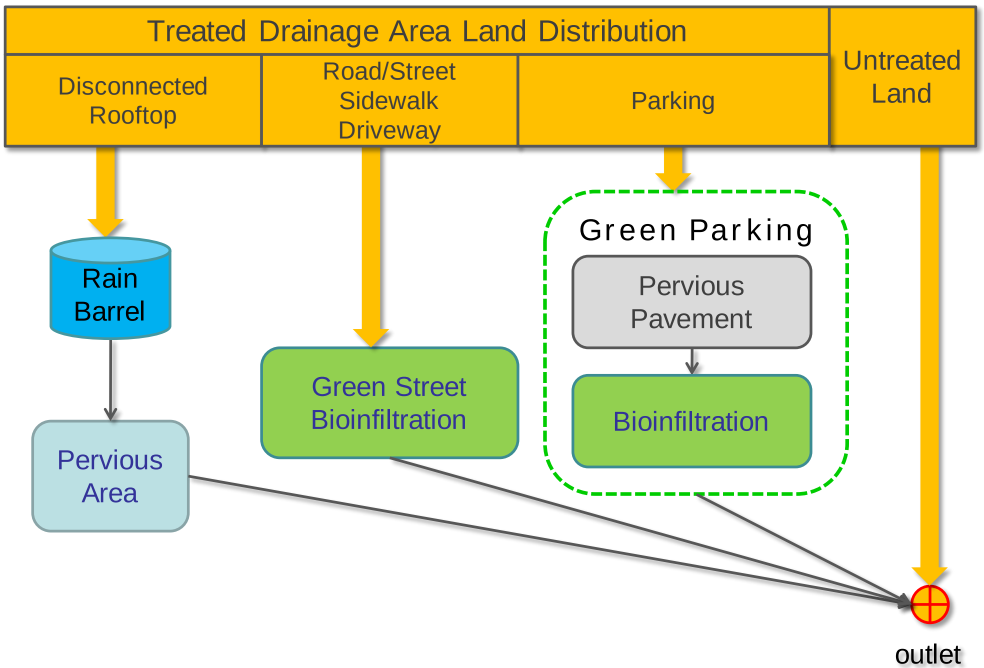

Figure 3-28. CSO 019 GI BMP drainage networks.

Table 3-13 lists the BMP design dimensions and specifications of the BMP types represented. Two sets of BMP design capacity scenarios were explored in this study to capture (1) 0.75 in. of runoff; and (2) 1.0 in. of runoff. The 0.75 in. capacity is considered as a level acceptable to MSD (MSD, 2011). The 1.0 in. capacity scenario explored the implication on cost-effectiveness by applying a more rigorous design capacity. The vertical designs of the BMPs are held constant for the two design capacities, and the various design capacities are obtained by varying the BMP surface areas. The BMP units are sized assuming a 0.25 acre drainage area.

Table 3-13. BMP design dimensions and specifications

Parameter	Rain barrel	Bioinfiltration	Pervious pavement
Surface parameters			
Unit size (0.75 in. runoff) (gal)	60	350	450
Unit size (1.00 in. runoff)	60	470	600
Design drainage area (acre)	0.005	0.25	0.25
Ponding depth (ft)	N/A	1	0
ET multiplier	0	1.5	0.5
Substrate parameters			
Substrate depth (ft)	N/A	2	2
Substrate porosity	N/A	0.35	0.35
Substrate field capacity	N/A	0.3	0.2
Substrate wilting point	N/A	0.1	0.05

Parameter	Rain barrel	Bioinfiltration	Pervious pavement
Substrate infiltration parameters			
Maximum rate (in./hr)	N/A	10	10
Minimum rate (in./hr)	N/A	1	2
Decay constant (1/hr)	N/A	1	2
Dry time (day)	N/A	3	3
Maximum volume (in.)	N/A	48	48
Underdrain parameters			
Underdrain depth (ft)	N/A	1	2
Underdrain porosity	N/A	0.4	0.4
Infiltration rate (in./hr)	N/A	0.3	0.3

The substrate layer infiltration parameters were selected on the basis of MSD guidance for well-draining, hydrologic soil group Type A soils. Those parameters control the rate at which water passes through the substrate layer into the underdrain. The background infiltration parameter controls the rate at which water passes from the underdrain into native soils. Section 3.4 discussed the sensitivity of this background infiltration rate on the total annual outflow from BMPs and suggests that this is the limiting parameter in the BMP simulation related to infiltration. To address this key parameter, the decision was made to use a background, or final, infiltration rate in the BMPs consistent with the value used in the InfoWorks watershed model and the calibrated *SUSTAIN* model, which was 0.3 in. per hr.

The amount of upstream impervious area drainage to each BMP was also essential to evaluating the overall effectiveness. The baseline model integration presented in Section 2.3 was used as the basis for configuring BMP tributary area. In each of the subwatersheds, one aggregated BMP was configured to represent the GI practices described in Section 3.5.1. The number of units of each BMP type was calculated by dividing the corresponding drainage area by the unit's design drainage area. The distribution of treatable impervious areas among subwatersheds and land use types was estimated on the basis of analysis of the GIS coverage of BMP opportunities provided by MSD and presented in Figure 3-26. The distribution of treatable impervious area by subwatershed is shown in Table 3-14.

Table 3-14. Distribution of impervious areas that can be treated by GI

Subwatershed	Untreated impervious (acre)	Treated impervious area				
		Rooftop disconnection (acre)	Green street (acre)	Green parking (acre)	Total treated impervious (acre)	Total treated impervious (%)
1	7.6	7.4	20.2	2.0	29.6	79.6%
2	27.6	9.1	5.1	1.1	15.3	35.7%
3	14.5	1.2	6.0	13.2	20.5	58.6%
4	11.9	6.9	6.2	0.7	13.8	53.7%
5	7.0	5.9	3.8	0.8	10.5	59.9%
6	10.8	0.0	0.0	0.0	0.0	0.0%

Subwatershed	Untreated impervious (acre)	Treated impervious area				
		Rooftop disconnection (acre)	Green street (acre)	Green parking (acre)	Total treated impervious (acre)	Total treated impervious (%)
7	9.5	2.9	4.4	0.0	7.4	43.7%
8	7.8	1.7	15.4	0.5	17.6	69.4%
9	5.8	2.6	0.8	0.0	3.4	37.1%
10	19.9	13.5	5.3	0.3	19.0	48.9%
11	8.5	6.1	1.1	0.2	7.4	46.6%
12	12.5	8.5	6.3	2.6	17.4	58.2%
13	18.8	11.7	6.3	1.5	19.6	51.0%
14	9.7	12.2	7.6	2.2	22.0	69.3%
15	8.0	5.5	1.6	0.1	7.3	47.7%
16	10.8	8.9	10.8	1.0	20.6	65.6%
17	12.0	6.8	3.7	1.2	11.7	49.3%
18	0.6	5.2	9.7	1.9	16.9	96.6%
19	45.1	12.5	19.3	4.4	36.3	44.6%
20	6.8	7.0	3.1	0.0	10.1	59.7%
Total	255.1	135.8	136.9	33.7	306.3	54.6%

3.5.3. *SUSTAIN Portland Wharf Storage Basin Representation*

For the purposes of this study, the gray infrastructure considered was the Portland Wharf Storage Basin (Section 3.1.2). The basin was represented in the *SUSTAIN* model as an impervious storage unit, simulated in the model with a zero infiltration rate and ET multiplier. It was placed in the network downstream of the CSO 019 regulator and receives overflow from the regulator weir. A constant pumping rate was applied to the storage unit designed to empty the 6.37-MG tank within 24 hours when water level is greater than zero. Volume exceeding the sum of the storage and pumping capacity discharges from the storage basin and was considered a system overflow.

3.5.4. *BMP Cost Representation*

GI Costs

The cost for the GI BMPs is listed in Table 3-15. The GI cost calculation spreadsheet provided by MSD was used to estimate the unit cost of bioinfiltration and pervious pavement. The cost calculation spreadsheet was developed on the basis of actual construction bid data submitted for the GI demonstration project at the Office of Employment and Training (Section 3.4.1). The cost per downspout disconnection is obtained through verbal and email communication with MSD (MSD, 2011). The cost of a 60 gallon rain barrel is approximately $120 when considering a rain barrel unit cost of $2 per gallon (Woodland Direct, 2011).

Table 3-15. GI BMP construction cost (in 2011 dollars)

BMP types	Sized to control 0.75 in. runoff		Sized to control 1 in. runoff	
	Unit surface area (sq ft)	Unit cost	Unit surface area (sq ft)	Unit cost
Bioinfiltration	350	$14,842	470	$17,398
Pervious pavement	450	$17,082	600	$19,506
Rain barrel (60 gallon)	$120			
Downspout disconnection (per 200 sq ft of rooftop)	$100			

Gray Infrastructure Costs

MSD provided estimates of construction cost of the Portland Warf Storage Basin at five intervals as percent of the tank's total capacity. A mobilization cost of $3 million was assumed. A plot of the cost estimates is shown in Figure 3-29.

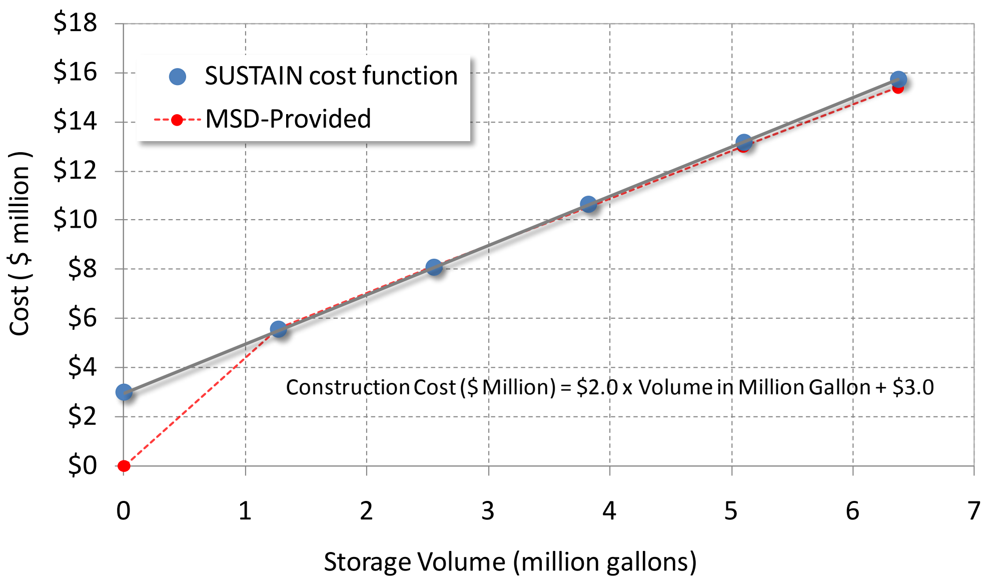

Figure 3-29. Portland Warf Storage Basin cost function (in 2008 dollars).

The cost values were converted from gallons to cubic feet, which is consistent with the standard units in *SUSTAIN*. On the basis of the cost estimates presented in Figure 3-29, a cost function for the Portland Wharf Storage Basin was expressed in 2008 dollars using the following equation:

Total Construction Cost ($) = $3,000,000 + $14.96 × (storage volume in cubic foot)

For the *SUSTAIN* model configuration, the cost function was converted to 2011 values by applying ENR construction cost index values, i.e., 8,310 for 2008 and current value of 9,104 for June 2011. The cost function in 2011 used the following equation:

Total Construction Cost ($) = $3,288,000 + $16.40 × (storage volume in cubic foot)

3.5.5. *Exploratory Management Scenarios*

Five exploratory management scenarios were developed to evaluate the cost-effectiveness of (1) gray infrastructure only; (2) downspout disconnection only; (3) gray infrastructure with downspout disconnection; (4) GI only; and (5) maximum build-out of GI with supplemental gray storage. Table 3-16 is a summary and description of the optimization scenarios.

Table 3-16. Summary and description of baseline exploratory management scenarios

Optimization scenario	Description
Gray only	Exploratory runs that includes only the Portland Wharf Storage Basin and varies the tank volume to control the number of annual overflows.
Downspout disconnection only	Exploratory runs using only the extent of downspout disconnection identified
Downspout disconnection + gray	Exploratory run that optimizes using a mix of downspout disconnections and gray storage in parallel.
Downspout disconnection + green	Exploratory runs with only green option, including downspout disconnections
Maximum green + gray	Fixed maximum green options, and exploratory gray options

Those five management scenarios are designed to answer the following key questions:

- What is the cost-effectiveness of using gray infrastructure only to reduce annual overflow?
- What is the cost-effectiveness of using GI only to reduce annual overflow?
- How much annual overflow volume can be reduced by implementing GI?
- What is the optimal combination of green and gray infrastructure for reducing the annual overflow volume?

3.5.6. *Optimization Problem Formulation*

Using the CSO 019 baseline model configuration presented in Section 2.3 with the BMP representations presented in Sections 3.5.2 and 3.5.3, optimization problems were formulated for the exploratory management options.

The generalized multi-objective functions and constraints are presented as follows:

Minimize $\sum$ BMP construction costs
Minimize Regulator overflow count (eight allowable overflows for 2001 simulation)
Subject to

- Maximum extent of identified GI opportunities
- Maximum size of Portland Wharf Storage Basin
- Combinations of exploratory management options:
  - Gray Infrastructure Only
  - Downspout Disconnection Only
  - Downspout Disconnection + Gray infrastructure
  - Downspout Disconnection + GI
  - Green build-out + Gray Infrastructure

MSD set an overflow target of eight events per year for the CSO 019 sewershed. The Portland Wharf Storage Basin was sized to meet that target on the basis of the 2008 IOAP model (MSD, 2008). GI practices could reduce the size of the tank if they prove a more cost-effective measure. During the optimization process, the decision variables were (1) the percentage of area treated by the various GI practices, as listed in Table 3-14, and (2) the size of the Portland Wharf Storage Basin for supplemental gray storage. Because BMP construction costs for GI practices heavily influence the resulting solutions, a sensitivity analysis was performed using additional BMP cost literature values to demonstrate a range of expected construction costs and discuss the uncertainty associated with costing GI practices. The cost for both storage basin and GI practices in this analysis were based on construction cost; O&M cost is not considered due to lack of local data. It is recognized that O&M cost is an important factor in the assessment of the total long-term cost and the comparison of gray storage and GI options.

3.5.7. *Optimization Results*

Optimization was performed for the five management scenarios discussed in Section 3.5.5. Figure 3-30 shows optimization results as cost-effectiveness curves for the five exploratory management scenarios. Effectiveness is plotted in terms of overflow counts (points – read on the left axis), and overflow volume reduction (lines – read on the right axis).

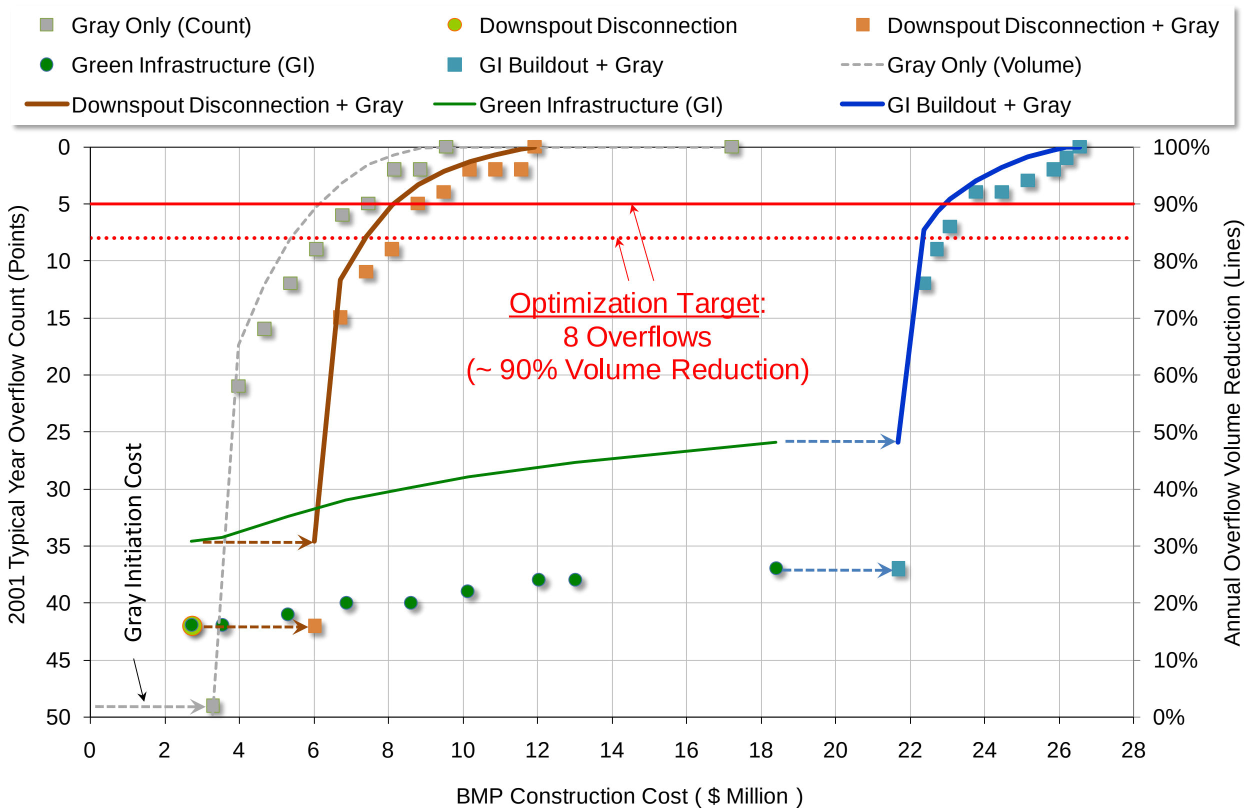

Figure 3-30. Cost-effectiveness curves for exploratory management scenarios.

The following observations are made in the interpretation of the results. First, any selection of gray infrastructure solution results in an immediate cost of $3.29 million for mobilization and other activities associated with building the storage basin. In the figure, the *Gray Initiation Cost* is always represented as a dashed arrow in each scenario that includes a gray component. Those costs are incurred regardless of the size of the storage basin and do not directly correspond to any reduction in overflow volume. As the tank increases in size, the trajectory of the cost-effectiveness curve maintains a steep slope that flattens only when approaching an overflow volume reduction of 100 percent.

For each optimization scenario the curve of overflow volume reduction tracks consistently above the discrete points representing the number of overflows at varying levels of implementation. Using the number of annual overflows as an objective presents a slightly diminished view of overall performance when compared to a true overflow volume reduction. Because overflow events are discrete points, it is possible for BMPs to provide additional volume reduction without affecting the overflow count. Flow attenuation associated with GI provides reduction in volume that does not translate directly into reductions in the number of overflows. That is clearly shown at the highest extent of GI, where a 50 percent overflow volume reduction still causes 37 overflows. On the other hand, the smallest gray storage provides about 65 percent volume reduction and only allows 21 overflows. Because the optimization goal was to reduce the number of overflows, together with the fact that the gray alternatives directly address overflow containment, the gray alternative seems to be more cost-effective. However, it is important to remember that the optimization objective drives the optimization result.

Third, GI costs seem disproportionally large compared to gray costs. Two aspects associated with how GI representation is worth noting: (1) the cost assumptions; and (2) the sizing criteria. Just as the optimization results are driven by the specified optimization objective, cost-effectiveness is driven by the associated cost assumptions and modeled BMP performance. The next section further explores the sensitivity of those BMP characteristics on model results.

Four solutions from the GI-only cost-effectiveness curve were selected for further detailed evaluation. Each point along the cost-effectiveness curve presented in Figure 3-31 corresponds to a unique combination of BMP selections from a single simulation run. For a given solution, the selection of BMPs can be (1) quantified in terms of the magnitude of build-out; and (2) analyzed spatially in terms of BMP selections throughout each subwatershed.

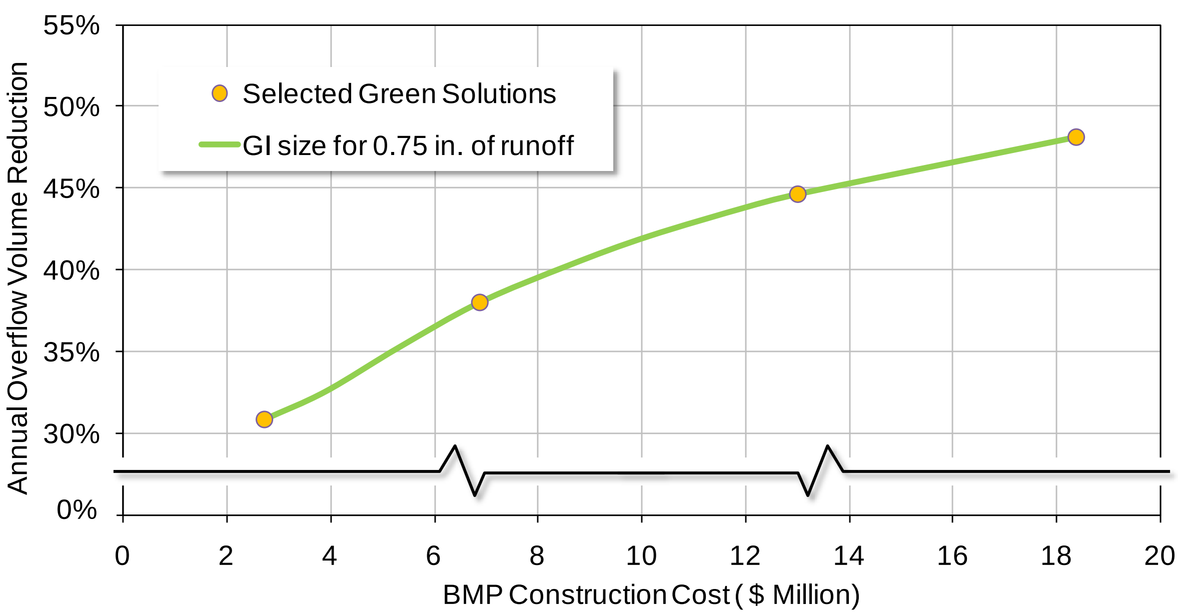

Figure 3-31. Four selected GI solutions along the cost-effectiveness curve.

The utilization percentage of each practice for the four solutions is plotted in Figure 3-32. Percent utilization for each solution is defined as the ratio of how much of the available opportunity was used divided by the total available opportunity. Percent utilization is computed as follows:

$$Percent\ Utilization = \frac{(Maximum\ Available\ GI\ Storage\ Volume - GI\ Solution\ Storge\ Volume)}{Maximum\ Available\ GI\ Storage\ Volume}$$

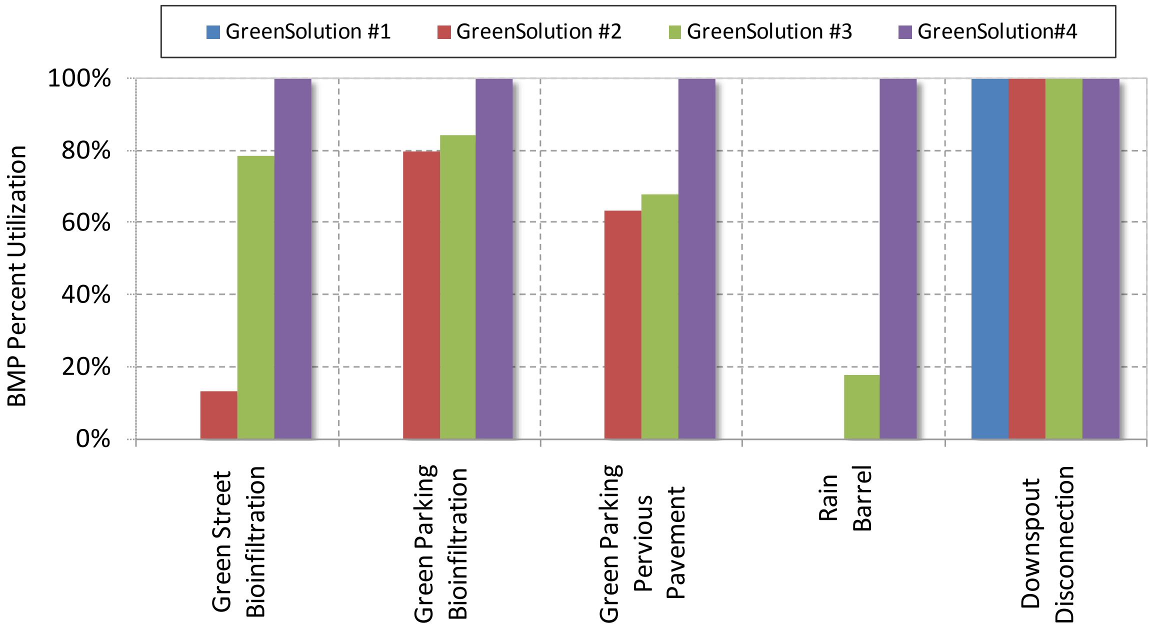

Figure 3-32. GI BMP percent utilization at four selected solutions.

Figure 3-32 shows that using downspout disconnections is selected for maximum implementation in all four solutions. That is because of the user-imposed assumption that structural GI practices are implemented only after full adoption of the downspout disconnection program, which was also shown to be the most cost-effective practice modeled. Of the structural BMPs, rain barrels are first selected only in Solution #3 and maximized only in Solutions #4, suggesting that those practices were considered least cost-effective for reducing volume. Rain barrels were configured in the model as an intermediate storage that receives flow from disconnected downspouts and then conveys outflow to pervious land. A low utilization percentage suggests that allowing water to route from disconnected downspouts directly to pervious land is more cost-effective in terms of achieving overflow volume reduction than adding rain barrels as an intermediate storage (with its additional associated cost). It is only fully implemented after all other options have been exhausted. Notice that the utilization of all five GI practices is 100 percent for Solution #4 where maximum build-out is achieved.

3.5.8. Optimization Sensitivity Analyses

Section 3.5.7 presents the optimization results and cost-effectiveness curve for the five exploratory management scenarios discussed in this case study. In the discussion it notes that the cost of GI is disproportionately high compared to the modeled gray components. Two key aspects of the GI parameterization are identified as heavily influencing the cost and modeled performance of the practices: (1) the BMP cost assumptions; and (2) the BMP performance sizing criteria.

This section explores sensitivity testing associated with those key aspects of the model configuration and discusses the implications of parameter assumptions on the model results. In addition to the GI cost provided by MSD, two alternative cost scenarios are presented, which use literature cost value and remove retrofit costs from the original MSD cost estimates. The results show how cost assumptions at the BMP unit level can affect the total cost of achieving the optimization target. The influence of BMP size on BMP performance and total construction cost is evaluated by considering two alternative criteria sizing BMPs to capture and treat (1) 0.75 in. of runoff; and (2) a more stringent target of 1.00 in. of runoff.

BMP Cost Sensitivity Testing

The cost-effectiveness curves for GI-only and the integrated green and gray infrastructure options cost are much higher than the gray-only scenario. Further review of those costs suggests that the Louisville GI costs might be higher than BMP construction costs cited in literature. The unit costs presented in Section 3.5.4 fall at the upper end or beyond the range of values typically expected from literature. Table 3-17 presents a comparison of local GI cost estimates against available bid costs from a GI project in Kansas City, Missouri, and literature values published by the CWP.

Table 3-17. Comparison of BMP costs per gallon of treatment capacity from various sources

BMP type	Louisville MSD ($/gallon)[a]		CWP[a] report ($/gallon)	Kansas City bid cost ($/gallon)	Kansas City[b] modified bid cost ($/gallon)
	GI retrofit	New construction			
Bioinfiltration	2.91	1.94	1.16	9.73	4.18
Pervious pavement	3.36	2.24	1.34	6.44	2.77
Rain barrel	2	2	2	2.83	2.83

a. Construction cost only.

b. On the basis of construction bid cost, excluding 5 percent contingency cost, 3 percent tree removal and utility relocation cost, and 43 percent sidewalk and street improvement cost.

Two main factors identified that account for the high cost estimates are (1) the cost estimates were derived on the basis of demonstration project bids without a local precedent on which to base the costing; and (2) retrofit components for demolition, curb and sidewalk replacement, and repaving were included in the cost estimates, which are only indirectly related to BMP construction. To test the sensitivity of BMP cost and examine the uncertainty in the cost estimate data, two additional GI scenarios were run that use alternative cost data. Those alternative cost scenarios are plotted in Figure 3-33 for comparison with the original GI cost-effectiveness curve. Figure 3-33 shows only the volume reduction curves. Note that the optimization target of eight overflow events per year corresponds to about a 90 percent annual overflow volume reduction.

Cost Alternative 1 is based on the BMP costs provided by MSD but removes the retrofit aspects of those cost estimates to represent the cost for implementation as part of new construction. CWP suggested that retrofit base construction costs generally exceeded the cost of new construction BMPs by a factor of 1.5 to 6 (CWP, 2007). In this alternative, the factor of 1.5 was applied to the MSD cost values to estimate new construction cost for bioinfiltration and pervious pavement. The cost of rain barrels and downspout disconnection remained the same.

Cost Alternative 2 is a low-end estimate based solely on published literature values. Because BMP retrofit costs are extremely variable depending on site conditions and retrofit design complexity (CWP, 2007), the low-end literature BMP retrofit cost values were examined. CWP listed a low-end larger bioretention retrofit BMP of $7.5 per cubic foot of runoff treated in 2006 dollars, which is equivalent to $8.72 in current dollar value. The MSD costing spreadsheet indicates a value of $21.75 per cubic foot of runoff treated in current dollars, which is 2.5 times higher than the low-end literature values. As a result, the MSD costs were divided by 2.5 to derive the low-end retrofit BMP cost values.

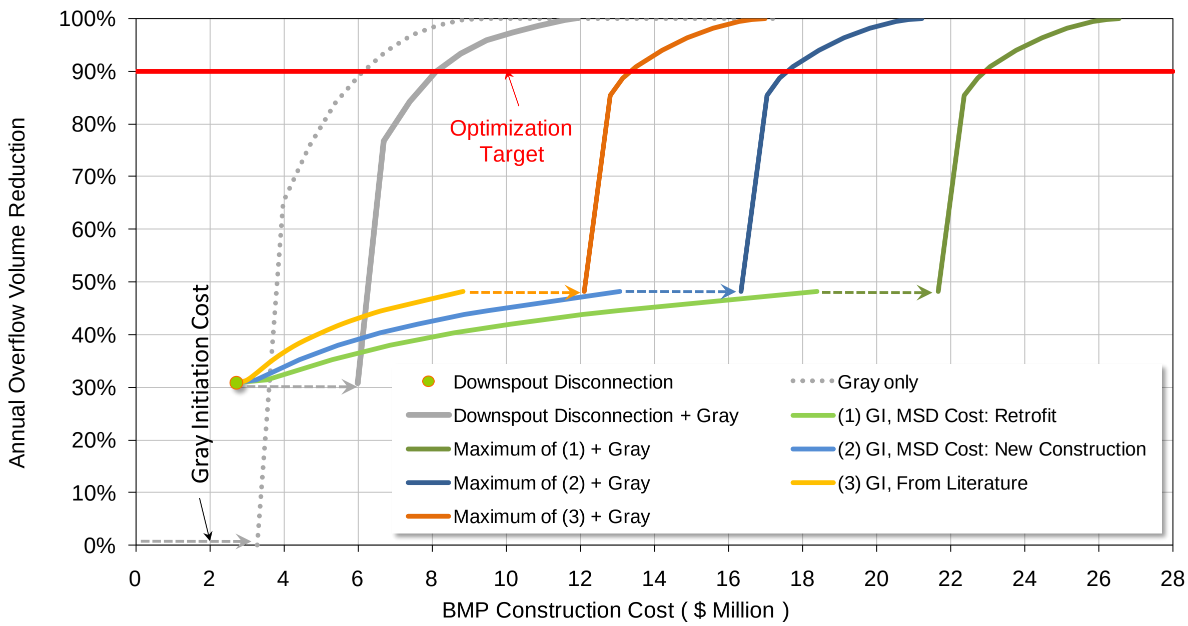

Figure 3-33. Sensitivity analysis for GI cost assumptions.

Figure 3-34 shows three versions of full implementation of GI practices from the cost-effectiveness curve using the original cost data provided by MSD along with Cost Alternatives 1 and 2 discussed above. The range of total implementation cost that results from the three curves demonstrates the sensitivity of BMP cost parameters and suggests that the range of probable assumptions could more than double the calculated implementation cost in the CSO 019 sewershed.

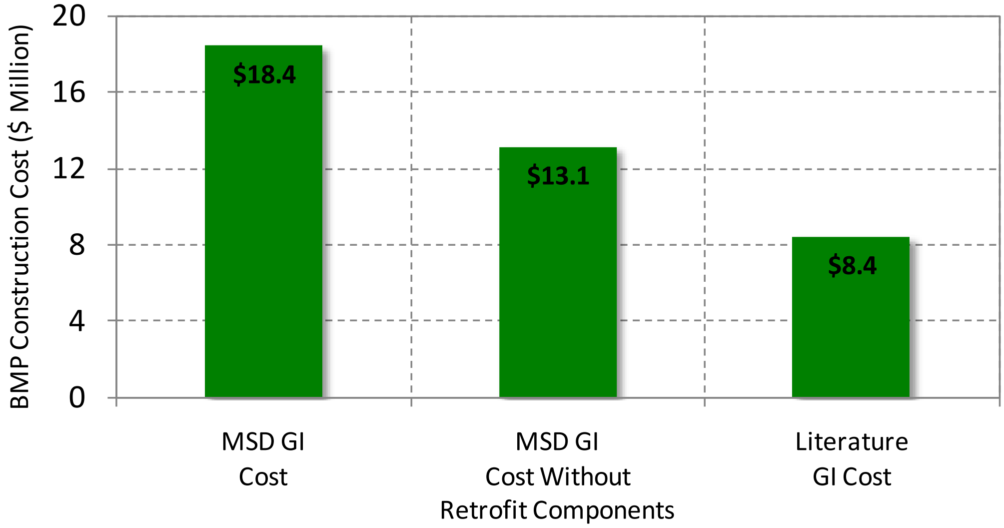

Figure 3-34. Comparison of full build-out of GI for the three cost scenarios.

During optimization, the construction cost of each GI practice is a key parameter that strongly influences the modeled cost-effectiveness of annual overflow reduction. Assumptions regarding BMP construction costs could vary the total cost of full implementation, without O&M, by up to $10 million.

GI Sizing Criteria

The amount of treatable area, or area routed to BMPs, is another key BMP sizing assumption that influences the modeled performance of GI practices. BMPs were sized according to two different performance criteria (Section 3.5.2) intended to treat 0.75 in. and 1.00 in. of runoff were compared. The cost-effectiveness curves for the two scenarios are presented below as Figure 3-35.

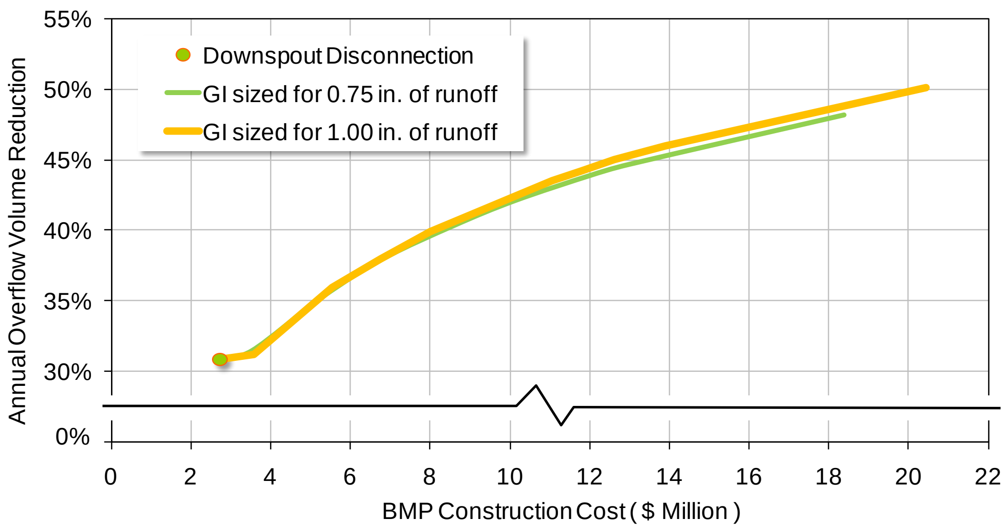

Figure 3-35. Comparison of GI cost-effectiveness curves size to treat 0.75 in. and 1.00 in. of runoff.

Both GI cost-effectiveness curves tracked almost identically until about 35 percent overflow reduction when the 1.00 in. treatment scenario begins to show marginally better performance. The curve for the

1.00 in. treatment scenario maintains the same final trajectory tracking slightly above the 0.75 in. treatment scenario and to a higher final cost with marginal benefit in terms of overflow volume reduction. In the two scenarios, only the physical BMP footprint was changed. The amount of treatable impervious area in the watershed was fixed at 54.6 percent (Table 3-14). While increasing the size of the BMPs increases the opportunity to provide overflow volume reduction, the achievable overflow volume reduction remains limited by the amount of impervious area routed to the BMP.

3.5.9. *Optimization Summary and Conclusions*

The optimization analysis of gray and green BMP opportunities for CSO mitigation in the 019 sewershed yielded some unique insights in terms of the implication of the optimization problem formulation and objective function on model results, and the influence of BMP cost and sizing assumptions on simulation results. This case study specifically (1) demonstrates techniques for replicating a baseline hydraulic model used in CSO sewersheds; (2) highlights the sensitivity of key BMP hydrologic parameters in a factorial experimental design framework; and (3) evaluates the cost-effectiveness of gray infrastructure versus GI for CSO management while testing modeling assumptions related to cost functions and BMP sizing.

In Section 3.5.7 the importance of the optimization objective on the optimization result is observed. For this case study, the optimization objective was to reduce the number of annual overflow events. The results were also summarized in terms of percent overflow volume reduction for reference purposes. The cost-effectiveness curves presented highlighted that there was not necessarily a one-to-one relationship between overflow volume and the number of discrete overflow events. Downspout disconnections and the introduction of GI practices initially appear to provide a more cost-effective means of achieving a 30 to 35 percent reduction in overflow volume. However, the practices provide marginal benefit in terms of meeting the objective target of eight overflow events per year.

Nevertheless, there are some indirect benefits associated with total volume reductions that were not specifically addressed in this case study because they were not considered during the optimization. Two immediate examples are apparent. First, water quality improvement was not an optimization objective. GI might provide significant water quality benefits that might not directly affect CSO reduction. The volume reduction associated with GI use in conjunction with gray could actually have beneficial impact downstream in the receiving water even though it might not reduce the number of overflows. Given the same downstream assimilative capacity, reduction in overflow volume can translate into lower pollutant concentrations in the receiving waterbody for the overflow discharge. Second, recall that flow volume that does not crest the weir at the regulator is directed through the 24 in. orifice (Section 3.3.4) to the 38th Street pump station where it is conveyed to a wastewater treatment plant. This study did not attempt to quantify the cost-benefit relationship between decreased flow volumes and decreased operating costs at the treatment plant. It is expected that additional savings could be realized in terms of reduced pumping costs and reduced treatment costs at the wastewater treatment plant.

This case study also demonstrated the flexibility that the *SUSTAIN* modeling framework provides for both formulating and investigating management questions in the context of CSO mitigation planning. Similarities between commonly accepted modeling approaches allow for easy replication of existing sewershed models. Network simplification can substantially improve model run-time for optimization while maintaining accuracy over critical conditions. As highlighted in Section 3.3.4, the network simplification resulted in additional overflow events for the *SUSTAIN* baseline mode as compared to the InfoWorks baseline model. However, review of those events revealed that each fell below the fifth percentile overflow volume and would likely not affect optimization results, which are driven mainly by the largest overflow events. Understanding the critical modeling condition, which in this case study is complete capture of the ninth largest overflow event, was an important consideration during problem formulation. This understanding helped to balance setup considerations associated with preserving model accuracy while significantly reducing model run-time. Section 3.3.5 presented estimated model run-times for the simplified *SUSTAIN* model and the InfoWorks model used as a baseline for replication.

Sensitivity analyses were performed to bracket the range of uncertainty associated with certain important modeling assumptions and their effect of optimization results. As described in Section 3.5.8, sensitivity analyses were performed on assumptions related to both BMP cost and sizing criteria (represented by amount of treatable impervious area). Sensitivity testing of both BMP costs and treatable drainage area suggest that assumptions made regarding those parameters were highly influential on the optimization modeling results, with cost assumptions having the greatest observable impact. Varying the cost between literature values and local bid data showed that GI construction cost could vary by a factor of two or more.

Thinking about treatable impervious area in the context of the Portland Wharf Storage Basin provides additional insight regarding the favorable cost-effectiveness of this practice. The storage basin is at the most downstream point in the network beyond the CSO 019 regulator and receives only overflow volume from the regulator weir. Essentially, the Portland Wharf Storage Basin can receive flow from 100 percent of impervious areas in the watershed as compared with only 54.6 percent for GI practices. Its position beyond the regulator means that while runoff from 100 percent of impervious areas have the opportunity to reach the storage basin, only *overflows* will ever reach that point in the network, making the storage basin a highly specialized practice. In contrast, GI practices are subjected to all runoff volume from treatable impervious area with no distinction between flows to the treatment plant or overflows.

Finally, it is crucial to interpret the optimization results in light of the findings about problem formulation, model assumptions and sensitivity of BMP parameters. The results suggest that gray infrastructure is more cost-effective than GI at achieving the objective of eight overflow events per year and that it is infeasible to achieve the objective without the use of gray infrastructure. If another objective was formulated, for instance total annual volume reduction, the expected results and BMP selection could be substantially different. GI cost functions based on direct BMP construction costs only or derived from bid data not related to a retrofit demonstration project but rather from new construction with local precedent for GI might yield more cost-effective GI solutions.

Chapter 4. Lessons Learned

The case studies presented in this document highlight the power and utility of *SUSTAIN* as a decision making tool. By applying the system to the conditions in Kansas City and Louisville, the application explored hydrologic response, management options, and their effects on a highly urbanized system. The resulting study provides useful and practical information that can help managers to understand, measure, and evaluate the benefits of GI in urban watersheds. The lessons learned from these case studies benefit two audiences –managers/decision makers and practitioners:

- *Management Lessons:* These case studies were used to address locally derived questions regarding the selection, placement, and strategy for the use of BMPs to mitigate CSOs. The results provide a template for the development of similar decision making frameworks in other regions outside of the case study application area.
- *Modeling Lessons:* The development of the application framework and execution for the case studies in Kansas City and Louisville provides a template for similar applications in other regions. Although there were similar goals, each case study demonstrates how the model can be adapted and configured to represent the system and formulate the optimization problems based on local constraints including (1) the available supporting information; and (2) the specified control targets. The modeling examples presented provide meaningful guidance for the *SUSTAIN* user community.

The *SUSTAIN* model developed for these CSO case studies was based on the existing municipal collection system models. Efforts included developing a *SUSTAIN* model which replicated the response of the municipal model hydrologic response, calibration of a baseline runoff model to match either an existing model or available flow monitoring data, and the development of a lumped or aggregated model to better manage the computational run-times required for optimization. In order to address the case study questions, the *SUSTAIN* model then incorporated the collection system hydraulic elements at the regulator and any existing or proposed controls were incorporated into the model. The model was used to evaluate the case study questions, which focused on optimizing GI and gray infrastructure to achieve a CSO control target, and comparing the performance and cost of GI to conventional storage facilities at the downstream end of the systems.

The existing system model was designed to represent a series of scenarios that provide the context for decision making. Figure 4-1 is a schematic of the general sequence of scenarios used for CSO management optimization using GI and gray infrastructure.

First, there needs to be a baseline model that represents the existing condition. This model provides the basis for calibration. Second, it is important to recognize that the baseline for optimization may differ from the existing condition baseline if there are existing or planned management activities for which commitments have already been made. In such a case, these activities must be appropriately reflected in the model and considered as part of optimization baseline. Third, exploratory management scenarios for optimization should include a mix of different alternatives, each with its respective cost assumptions. Fourth, the control target must be clearly defined. Finally, optimization is then formulated with the objectives of achieving the stated control target while minimizing the cost of implementation. The iterative interpretation of the results of each step will help to guide and refine the optimization objectives.

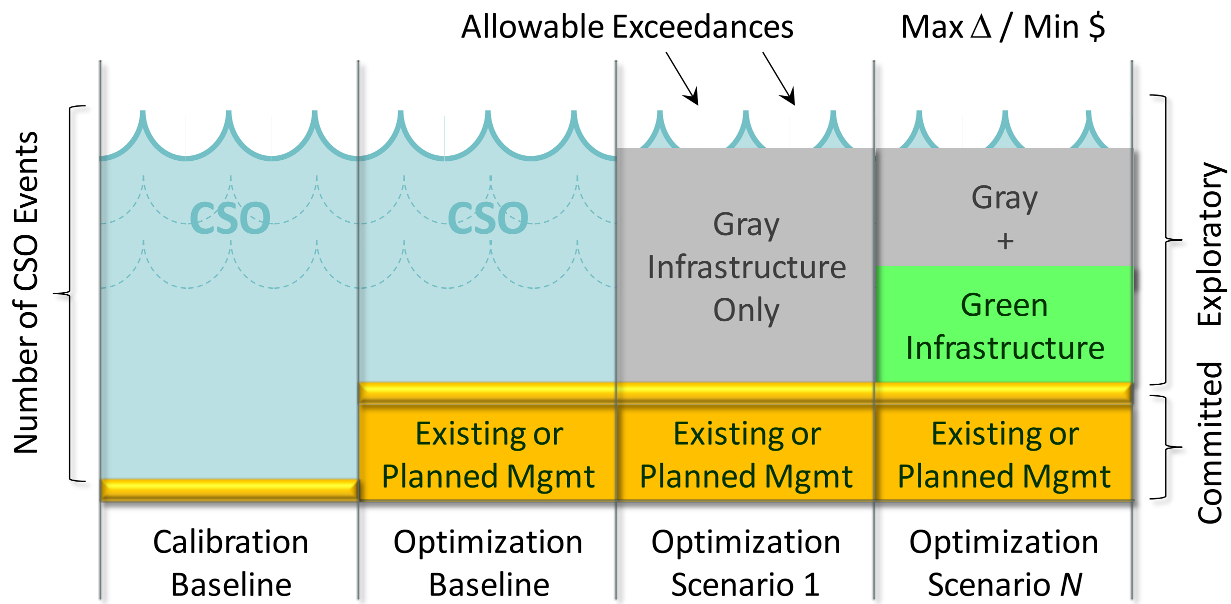

Figure 4-1. Theoretical construct for CSO management optimization problems.

The Louisville case study tested the ability of GI to cost effectively complements or replaces a CSO storage basin for CSO area 019, a 1,094 acre project area. The criterion for overflow control was specified as a control level of 8 overflows per year. In Louisville, the alternate gray infrastructure control was identified as a 6.37 MG storage basin. Opportunities for GI placement were defined by Louisville MSD and were situated to manage approximately 55% of the tributary area. The case study evaluated the level of control that could be achieved with GI, its associated cost, and how green and gray infrastructure could be collectively optimized to accomplish a cost effective solution.

In Kansas City, a 480 acre tributary to CSO 069 was identified by the City as an opportunity for control using GI. The control target was the elimination of overflows during a specific design storm. In the development of the City's LTCP, this design storm condition was anticipated to correlate to 6 overflows per year. Kansas City is currently implementing GI controls in 100 acres of the tributary area. This condition was reflected in the baseline for the optimization scenario.

For both the Kansas City and Louisville studies, the exploratory scenarios included both green and gray infrastructure and the associated cost considerations. Constraints and cost of both green and gray infrastructure were applied consistent with constraints as identified by the municipalities.

4.1. Management Lessons

In both Kansas City and Louisville, the primary management objective was to reduce the frequency of overflows. There were differences in the problem formulation dependent on site conditions, the current adoption of BMPs, and the alternate structural (gray infrastructure) solutions identified. Table 4-1 summarizes and compares the key management considerations that influenced the results from the Kansas City and Louisville case studies. A number of these components are worth noting. First, GI in Kansas City was constrained in the analysis on the basis of the committed design plan that was under construction. In other words, GI approaches were already established for the 100 acre pilot area. For this reason, the implementation of the plan was assumed as part of the baseline for optimization. Future GI placement in the balance of the tributary area was then extrapolated consistent with the approach applied in the initial 100-acre area. The number of new opportunities for BMPs was constrained by the design plan template, which resulted in only 57 percent of the impervious area runoff reaching any BMP. In contrast, Louisville had identified potential new GI sites which could be applied throughout the study area. Second, the control targets for the two case studies differed. The control target for optimization in the Kansas City case study was 100 percent capture of a critical condition design storm, which was intended to correlate to 6 overflows per year. Attainment of the allowable exceedance criteria of 6 overflows was also tested using continuous simulation for the typical year represented by 2004. For this precipitation record there were only 2 or 3 overflows, because the D-storm itself was a conservative design storm. For the Louisville case study, the target was an allowable exceedance frequency for a statistically-derived typical year.

Table 4-1. Comparison of case study components that influenced management alternatives

Key management components	Case study application	
	Chapter 2: Kansas City, MO	**Chapter 3: Louisville, KY**
Control target	Design Storm: 100% capture of the critical condition D-storm Validation: Continuous simulation for statistically identified 2004 typical year Allowable Exceedance: 6-overflows/year	Typical Year: 2001 statistically identified as a typical year for management Allowable Exceedance: 8-overflows/year
Optimization baseline (committed activity)	The pilot area (which is about 25% of the 069 sewershed area) has a committed GI design plan. Actual BMP construction was already underway at the time of study.	Isolate runoff to regulator from immediate study area for baseline runoff. Remove diverted interceptor inflow to regulator.
Exploratory management alternatives	1. Extrapolate GI design plan template to the remainder of the watershed 2. GI opportunity on private parcels 3. Determine supplemental gray storage capacity downstream of regulator	1. Downspout disconnection 2. GI opportunity in sewershed 3. Consider proposed gray storage design downstream of regulator
Spatial constraints for GI	City GI design plan constrained to public rights-of-way as specified by engineering plan. Based on the configuration of the GI practices as designed, about 57% of the total impervious area is tributary to GI opportunity.	GIS map of all potential GI opportunity in the sewershed. About 55% of the total impervious area is tributary to GI opportunity.
Physical constraints for gray infrastructure	Proposed storage tank and pump station downstream of regulator outfall. Reduce the size	Proposed storage tank and pump station downstream of regulator outfall. Verify required size to meet management objectives.

4.1.1. What are some of the factors that most influence cost-effectiveness of both GI and Gray Infrastructure?

One of the most influential factors affecting the ability of GI to reduce CSO frequency toward an overflow frequency target is the fraction of the CSO catchment area that can be routed for treatment to the various BMPs. In Kansas City, the proposed design plan for the pilot area limited GI facilities to public rights-of-way. Because GI was constrained to public rights-of-way in Kansas City, the potential tributary area managed is likewise constrained to area that readily drains to those facilities. Figure 4-2 summarizes the impervious land cover distribution upstream of private and public GI facilities in the Kansas City 069 sewershed. The graph shows that full build-out of proposed GI opportunities would be able to treat 57 percent of the total impervious area.

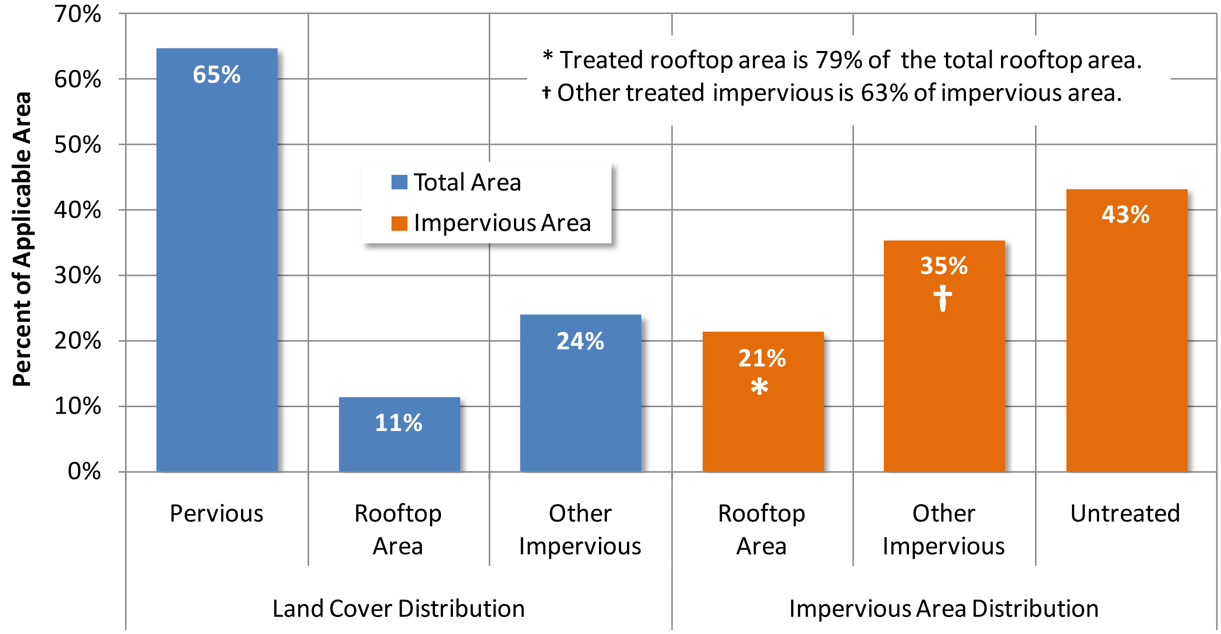

Figure 4-2. Kansas City 069 land cover distribution and impervious area distribution tributary to GI.

Similarly, Figure 4-3 summarizes the impervious land cover distribution upstream of different GI facilities in the Louisville 019 sewershed. The GI opportunities that were identified by Louisville MSD were suitable to manage 55% of the area in the sewershed.

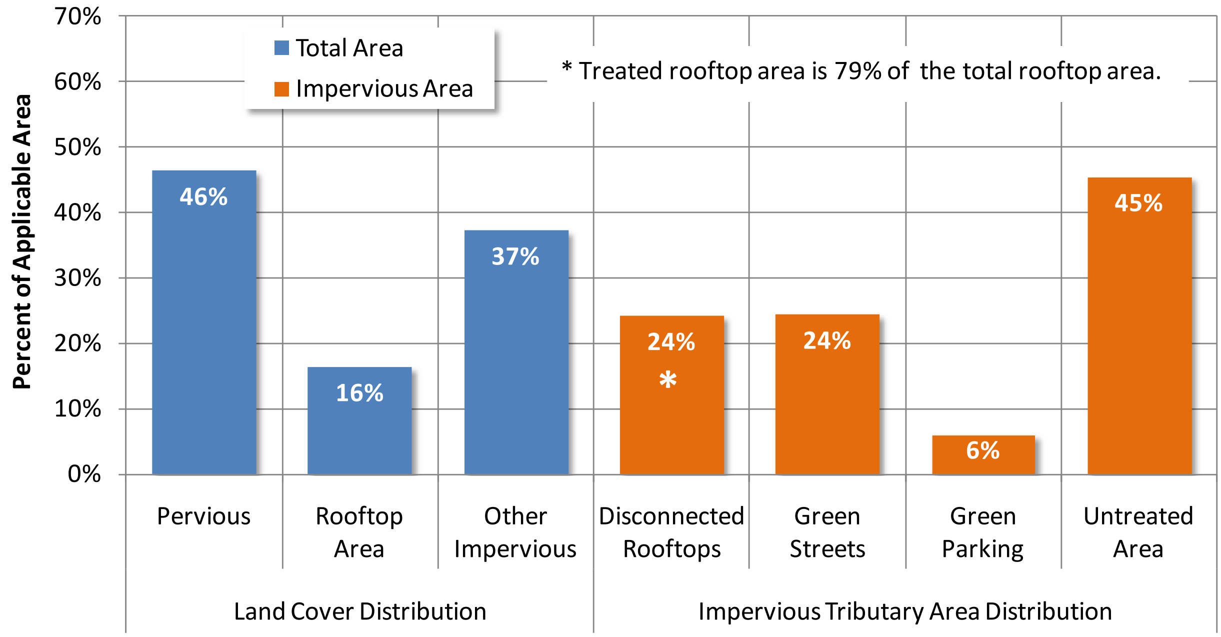

Figure 4-3. Louisville 019 land cover distribution and impervious area distribution tributary to GI.

Because CSO control targets are typically defined based on overflow frequency, it is important to maximize the total area controlled. Even a small amount of uncontrolled area can result in CSO discharges. If CSO control targets also consider annual volume, the total area controlled may not be as significant. However with the current case studies, which focus on a frequency target, this hypothesis was not specifically tested.

As the focus of the case study application is the definition of cost effective solutions for CSO control, the analysis is highly sensitive to costs of construction as well as life cycle costs. Costs used in these case studies were based on local municipal data associated with material and construction costs. (Broader costs, such as O&M, were not available from the municipalities for either GI or alternate gray infrastructure facilities.) The material and construction costs were found to be highly influenced by the means of implementation. The Kansas City project was implemented as a retrofit project which resulted in a number of other project elements being included in the construction contract. This had the impact of increasing the cost associated with GI implementation. In contrast, projects on private property may have limited cost to the municipality. For example, roof disconnection was by far the most cost-effective practice in both the Louisville and Kansas City case studies. In Louisville, the only cost included for this practice was the labor for a trained technician to certify proper disconnection of a downspout. In fact, Louisville includes downspout disconnection as part of an incentives program that provides a $100 credit to individual homeowners for each disconnected downspout. The reason why this practice was shown to be so cost effective is that for the price of the incentive and/or certification costs, the entire associated roof area now has an opportunity to infiltrate into the lawn or garden instead of directly draining into the collection system along with driveway and road runoff.

Table 4-2 is a list that summarizes some of the most influential factors for predicting cost-effectiveness.

Table 4-2. Summary of factors that most influence cost-effectiveness

	Case study application	
List of factors	**Chapter 2: Kansas City, MO**	**Chapter 3: Louisville, KY**
Treated tributary area (GI vs. gray)	GI constrained to public rights of way (57% treatment potential for impervious area). Gray infrastructure is physically located after the CSO regulator; therefore, volume provided is applied to 100% of the tributary area.	Full-GI build-out opportunity results in 55% of impervious area being treated. Gray infrastructure is physically located downstream of the regulator and sized based on overflow volume for intended control target.
Disconnected rooftops	Private parcel rooftop area is subject to capture by rain barrels as specified by the WinSLAMM study. A very cost-effective practice; however, it is opportunity limited (only 15% of private parcel rooftop area remains that has not been disconnected).	Incentive program includes payment to private parcel owners for each disconnected downspout. Only cost includes incentive payments or performance certification expenses. Also limited by opportunity.
Site preparation costs (retrofit vs. capital improvement plan (CIP)-integrated)	Much of the high GI cost was attributable to *Site Preparation* costs including curb installation, traffic control and other costs included in the construction project but which may not be directly associated with BMP construction. As retrofit project, these costs become associated with GI implementation.	Sensitivity analyses on GI cost assumptions show a swing of about 50% in cost-effectiveness between full-retrofit, CIP-integrated, and other literature-based cost figures for GI.
Time-dependent cost efficiencies	This case study assumed constant cost components with time. It did not account for cost efficiencies over time because of contractor experience, reduced project uncertainty, and economies of scale.	Sensitivity analyses provided a range of cost-effectiveness as a function of different cost assumptions. This analysis can provide some indirect insights about the possible range of efficiency associated with time-dependent design refinements.

List of factors	Case study application	
	Chapter 2: Kansas City, MO	Chapter 3: Louisville, KY
O&M costs	This case study focused on capital costs for optimization purposes. It did not consider O&M costs. Other studies have shown that wide-spread adoption of GI has a job creation benefit.	This case study also focused on capital costs for optimization; however, it is recognized that long-term O&M can also have an impact on cost-effectiveness comparisons between BMPs.

4.1.2. *How does the control target affect cost-effectiveness of management alternatives?*

Flows discharged by green and gray infrastructure affect different portions of the hydrograph. As a result of this difference, the amount of control accomplished by the same volume removal differs. First, management capacity placed near the origin of runoff will tend to capture the rising limb of the hydrograph, whereas capacity placed downstream of a CSO regulator is primarily focused on the flow which cannot be captured by the wastewater collection system. Second, the mode by which the volumes are dewatered affects the amount of water that can be potentially managed by the facility. GI practices that rely on infiltration may require more time to regain capacity than gray practices, although this is dependent on the characteristics of each system. Figure 4-4 shows typical capture and dewatering modes of GI and gray infrastructure capacity in the context of a CSO collection system.

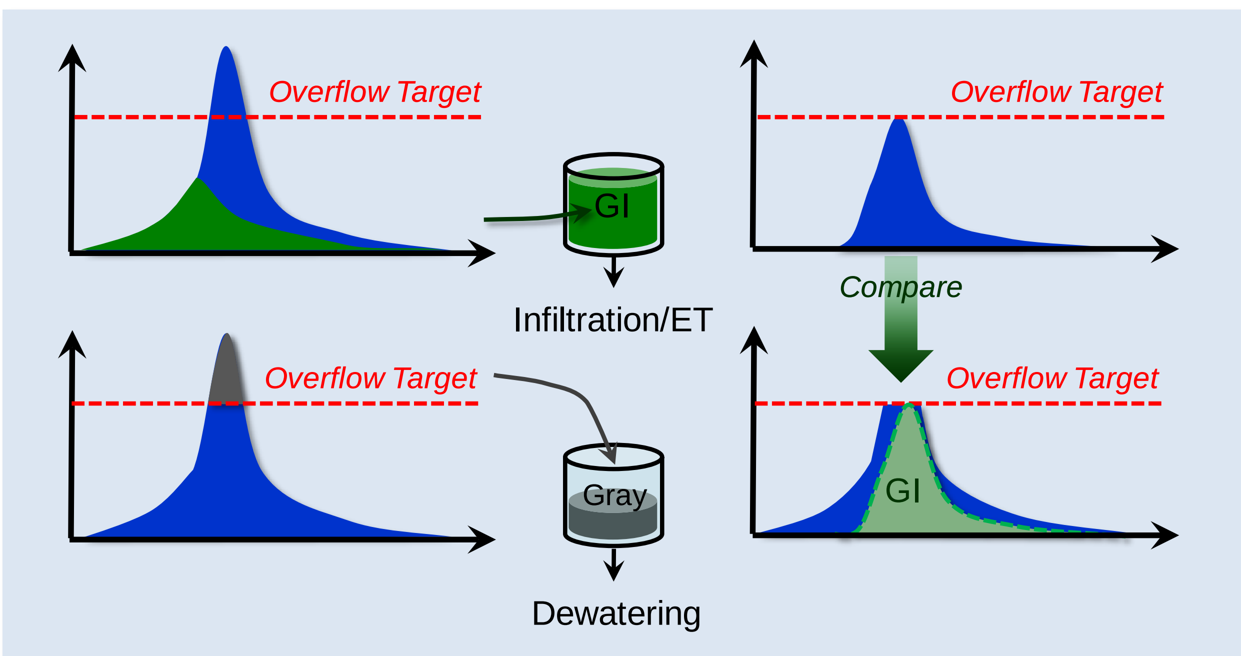

Figure 4-4. Typical capture and dewatering modes of GI and gray BMPs in a CSO collection system.

The selected control target for optimization has the greatest impact on the mode of treatment that is considered cost-effective within the context of GI versus gray infrastructure in a CSO collection system. If the control target is to minimize overflow frequency, gray infrastructure may be able to be applied more strategically to address the top of the hydrograph, which is typically the critical condition associated with overflows. In a frequency context, an overflow event still counts as *one* overflow regardless of amount of water that actually discharges. On the other hand, when the control target is overflow volume, the volume controlled and associated with the GI practice will more directly correlate to overflow volume. The GI practices may have additional benefits when considered in the context of the broader interceptor system and wastewater treatment plant, although this was beyond the scope of these case studies.

In the Louisville case study, flow attenuation associated with GI provides a reduction in volume that does not translate directly into a reduction in the number of overflows. With full build-out of GI (within the placement limitations previously discussed), a 50 percent reduction in the overflow volume was projected, although this scenario only reduced 12 out of 49 overflows (about 24 percent reduction in the number of overflows). For GI, volume reduction still outpaced frequency reduction; however, the difference in the percentage reduction between volume and frequency were not as disparate for gray infrastructure as they were for green.

Current trends in the industry, as reflected in recent consent decrees and proposed plans, are to focus to a greater degree on volume control as opposed to frequency targets. This is the control approach in both Philadelphia and Cincinnati, which have approved LTCPs (PADEP, 2011). Similarly; the Northeastern Ohio Regional Sewer District is looking to couple green with gray to get additional, cost-effective volume reduction in their collection system (USEPA, 2011). Their management questions are more related to whether adding green or adding more gray is a better investment for achieving this goal. The industry trends and rationale for adopting volume-based standards is understandable given what is known about collection system responses to different modes of treatment.

4.1.3. *Can GI be used effectively to complement existing or planned Gray?*

GI may be used to complement the benefits of gray infrastructure for CSO control. Because GI captures the rising limb of the hydrograph, it tends to reduce the overall volume of runoff that reaches the regulator. In these case studies, coupling gray controls with GI also tended to reduce the overflow volumes more effectively than the addition of gray storage capacity. In Kansas City various scenarios reflecting gray infrastructure or a mix of gray with green were defined that had comparable anticipated cost. The performance was tested in the continuous simulation validation in the Kansas City study. For the two largest allowable overflow events, an interesting trend was observed when comparing management scenarios using only gray infrastructure versus supplementing with different amounts of GI. For the two largest allowable exceedance events, Figure 4-5 presents a comparison of overflow volume for (1) gray only; (2) GI on public rights-of-way + gray; and (3) GI on public rights-of-way and on private parcels + gray. Recall that the number of overflow events for typical year 2004 was fewer than the six allowable overflow events. However, applying more GI resulted in (1) a smaller required gray capacity; and (2) a progressively smaller amount of water overflowing the storage facility. The lesson learned is that in places where gray infrastructure controls already exist, adding GI to supplement controls upstream in the collection system can potentially be an effective way of reducing overflow volumes from the system. The effectiveness of such an approach in other areas will depend on the local setting, including the physical constraints, management opportunities, cost information, and other site-specific considerations.

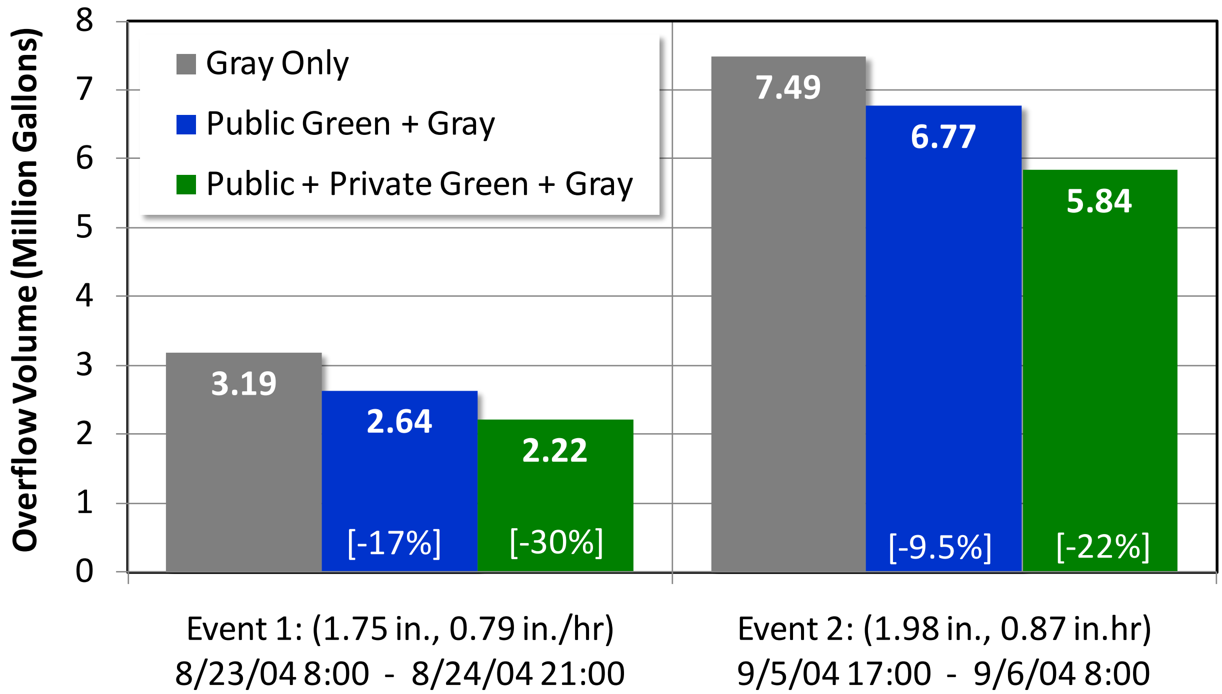

Figure 4-5. Comparison of overflow volumes for Kansas City exploratory management scenarios.

4.2. Modeling Lessons

SUSTAIN uses large numbers of model runs in order to evaluate the optimization scenario. Therefore, model run-times are a critical concern in the application of *SUSTAIN*. The best practice in the application of *SUSTAIN* modeling is to rely on the simplest approach that is able to adequately represent the system at hand, in light of the application objectives. Because hydrology and hydraulics models like those used in *SUSTAIN* are a theoretical construct of natural/man-made hybrid systems, they need to be tested to verify that they provide a reasonable representation of the proposed system. The model should be sensitive to and reflective of the key processes that most influence the management decisions that will be explored using the model. The model should also strategically simplify the problem, taking into consideration the relevant information that is needed, while recognizing and quantifying any error propagation in as much as it affects management decisions that are to be made using the model.

This subsection summarizes some of the modeling lessons learned through the setup and execution of the Kansas City and Louisville CSO optimization models.

4.2.1. *What are some of the critical data that are required for performing these evaluations?*

This case study effort highlighted the importance of a representative baseline model. The model baseline is the foundational element upon which all subsequent analyses depend. It also tends to be the place where the largest body of supporting data exists for characterization. For both case studies, there were good precipitation time series, flow monitoring data for a number of storms, and good spatial data to characterize land use and impervious cover. A significant amount of effort was invested to ensure that the baseline watershed model could (1) adequately and consistently predict the temporal patterns (volume, peak flow, and timing) of coincident observed historical records; and (2) be shown to be representative of a wide range of storm conditions, including critical condition CSO events. The model was tested and confirmed using a weight-of-evidence approach that compared both modeled versus observed time series plots and computed statistical metrics.

One of the more significant hydrologic factors in determining the impact of various BMPs is the fate of precipitation that is generated from impervious areas. In all drainage systems there is a reduction in runoff losses throughout the system that occurs from the time precipitation hits an impervious surface to the time it reaches the regulator. These diffuse losses may include things like disconnected imperviousness, surface ponding or flooding, or possibly even pipe exfiltration. It is important to recognize how these are reflected in the baseline model because improvements to the collection system to mitigate this behavior may tend to influence the amount of water delivered to the sewer system, and the CSO regulator. As BMP projects are implemented, some of these drainage inefficiencies may be corrected—this must be considered in sizing the BMP network. In other words, fixing the baseline drainage problems could increase the rate and volume of runoff, resulting in more flow to be managed than currently predicted.

The original Kansas City and Louisville model configurations dealt with impervious areas differently, which in turn impacted the ability to consider potential drainage changes as BMPs were implemented. In the Kansas City baseline model, DCIA in rights of way and for adjacent driveways, etc. treated all imperviousness as connected. For parcels (particularly rooftop areas), DCIA was estimated and applied based on surveys of disconnected downspouts. Therefore, the effective impervious area was physically represented at the source, and this representation could be maintained in the *SUSTAIN* model. In the Louisville case study, the baseline model originally defined an *effective* imperviousness approach, whereby the total physical footprint distribution of pervious and impervious area was adjusted to account for a reduction in the impervious area that was effectively connected to the system. However, there was no specific identification of which areas were directly connected. Therefore, the optimization baseline was modified to explicitly account for runoff origination by adding a reduction term to account for diffuse losses throughout the network. Careful attention was paid to how the baseline models were configured and applied because these assumptions will often play a significant role in how results are interpreted.

The placement opportunities for BMPs define the extent to which GI can beneficially impact flow volume and overflow frequency. In each of the case study communities, limitations were placed on the locations available for GI placement, which in turn led to a definition of the maximum potential effectiveness of the GI in controlling CSO discharges. Some of these limitations were physical constraints of the landscape that were derived during the engineering and design process. Other limitations were defined based on land use or ownership criteria resulting from the local decision making process. The restrictions placed on GI must be understood in order to evaluate the management scenarios.

Because optimization measures cost-effectiveness, there is a strong dependence on the available BMP cost information. These case studies included costs associated with both GI and gray infrastructure. Uncertainties in the local cost data used can strongly influence the management conclusions. Cost data may reflect different levels of precision (i.e. planning, engineering estimate based on design, bid prices), the implementation year (affecting the cost index), or the types of costs included in the data presented (construction, engineering, contingencies, etc.). The experience with BMP retrofit projects is often that other infrastructure improvements are incorporated into these projects, which influence the cost basis for comparison. Similarly, gray infrastructure costs need to be defined over the full potential range of application in order to fully assess the tradeoff between green and gray approaches. Decisions on how costs will be applied for GI on private property likewise need to be addressed.

The Louisville case study was used to compare the potential impact of various cost methodologies for GI. Three different cost scenarios for GI were evaluated based on (1) data from retrofit projects; (2) CIP projects that included GI; and (3) literature values. Total costs varied widely based on the costing methodology used.

Each of these issues needs to be identified and an approach selected. The best way to constrain propagation of uncertainty in this type of modeling is to constrain uncertainty associated with the key building blocks of the optimization model. Certain steps were taken during model development to establish a consistent basis for model extrapolation to other areas that were not monitored.

4.2.2. *How detailed does the model needs to be in order to properly represent the system?*

Another key aspect of the study involved managing model complexity. It is important to keep in mind at all times the purpose of the modeling study, as well as the questions that need to be answered. The model should only be as complex as necessary to address modeling objectives and answer the management questions. Especially in the context of optimization model development, there is a fine balance to be struck between model complexity and run-time efficiency. *SUSTAIN* provides the aggregate BMP approach as a way to simplify the complexity of the network while preserving the robust responsiveness of the system being modeled; however, as with any model, the burden of proof falls on the modeler to prove its validity. The Kansas City study tested the sensitivity and behavior of an aggregated routing representation alongside a fully-articulated network. The Louisville case study model included a simplified drainage network that replicated the InfoWorks baseline model in *SUSTAIN*. Both case studies demonstrated examples of model simplification that were robust enough to adequately address the volume reduction optimization objective, while significantly reducing simulation time.

4.2.3. *How can one demonstrate that a model is adequately representative of the system?*

Sensitivity tests provide an informative way of showing a range of responsiveness associated with key assumptions and processes. After going through the process of baseline model testing and confirmation with observed data, sensitivity analyses were performed to bracket the range of uncertainty associated with certain important modeling assumptions, and their effect of optimization results. For the Louisville case study, sensitivity tests were performed on common BMP model parameters to identify which assumptions had the most influence on model results. A range of GI cost assumptions were also applied to show the resulting impact on predicted GI cost-effectiveness. For the Kansas City case study, sensitivity analyses were performed on both model simulation time and antecedent moisture conditions associated with the critical condition design storm. Cost-effectiveness curves for optimization solutions, and associated capital cost-benefit estimates, were presented as a range of variability attributable to the bands of uncertainty associated with the underlying modeling assumptions. As a final test, the optimization solutions were also validated using continuous simulation for an average precipitation year (2004). Model validation showed that the use of a critical condition storm also inherently provided some margin of safety for optimization, because the D-storm is a conservative representation of a frequency target. The validation test confirmed that CSO mitigation objectives had been achieved by optimizing to the design storm. All of these independent tests and validations were performed as part of a weight-of-evidence approach to establish model defensibility.

4.2.4. *How is the model applied in an iterative, adaptive process?*

The iterative, cyclical nature of the model application process was highlighted through these case studies. Two formative drivers frame the typical *SUSTAIN* application process. The first driver is the set of management questions to be addressed. Thoughtfully outlining the management questions is essential to the development of the appropriate model application, and the selection of the appropriate model complexity, processes to be simulated, and required testing and analysis. Essential the understanding of management questions is the financial implications of the decision process. Second, the management questions must be translated into numeric objectives that are used for optimization. These two formative drivers inform all subsequent decisions regarding the model setup including data, complexity, and interpretation of results. As part of the application process is the identification of data collection and monitoring needs to support both the application and future testing of the model results.

Figure 4-6 is a conceptual flowchart of the *SUSTAIN* application process. This flowchart shows two *feedback* loops. If and when new information becomes available that better characterizes the baseline or critical conditions, the model can be updated to incorporate new information. If new management questions arise, or if the results provide new insights into the management options and new formulation can be tested.

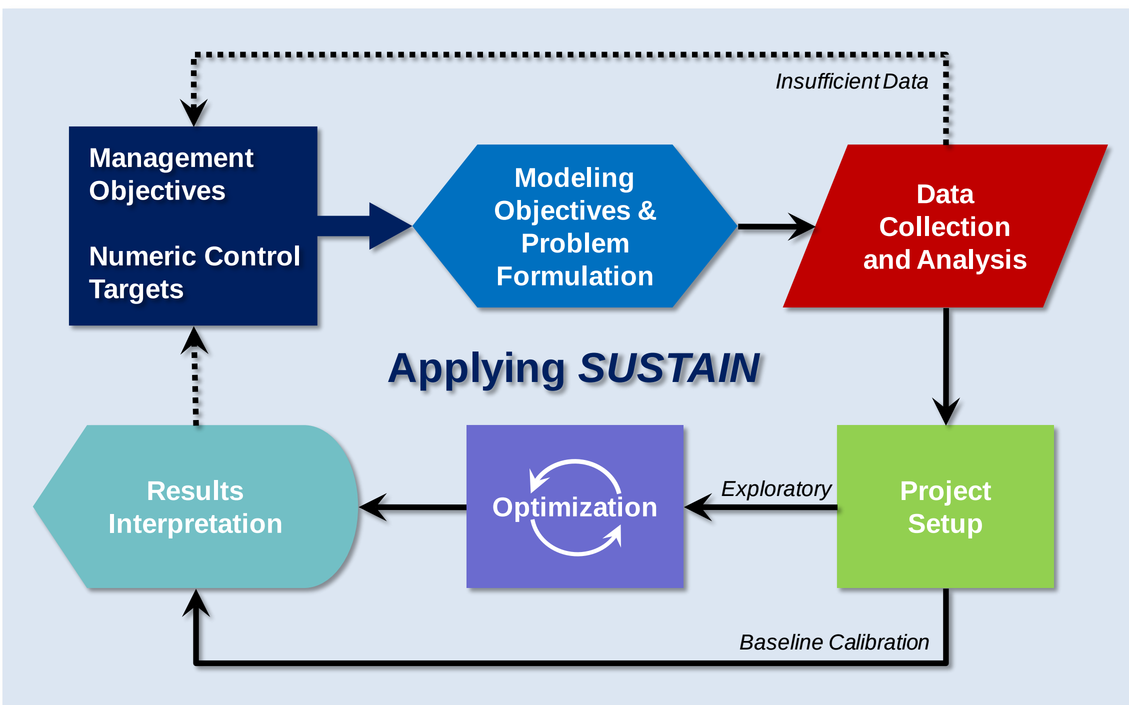

Figure 4-6. *SUSTAIN* application sequence

During the case study applications, this feedback process was illustrated. For example, for the Kansas City Case Study, an XP-SMMM model was provided as the baseline model for optimization; however, a revised calibration was necessary because new and improved monitoring data became available that better reflected the critical conditions associated with management objectives.

Chapter 5. Conclusions and Recommendations

SUSTAIN is a comprehensive modeling system that provides users with the ability to evaluate the cost effectiveness of urban stormwater management techniques across a wide range of conditions – various urban densities, climate, and geologic settings. As the *SUSTAIN* modeling system begins to be applied to address management questions, the range of applicability and functionality can be demonstrated. As illustrated by the case study applications included in this report, optimization tools can be very powerful when combined with hydrologic modeling and cost analysis in the *SUSTAIN* modeling framework.

The recent enhancements to *SUSTAIN* documented in this report and applied during the case study development process, provided selective improvements to the functionality and flexibility of the modeling system. In particular, the addition of a sub-hourly time step improved the ability of *SUSTAIN* to predict hydrologic response and peak flow from design storms used as a basis for planning many CSO and stormwater programs. Verification of the aggregate BMP approach supported the use of the model in Kansas City and Louisville. It also provided guidance for other regions where users want to evaluate the benefits of many, in some cases hundreds or thousands, of smaller BMPs across a large catchment.

Even with the new enhancements and tools provided in *SUSTAIN*, applying the system to a catchment should not be considered an *automated* or simple task, instead it requires careful formulation of the management questions and the optimization objectives. Set up of the model, as demonstrated in the case study applications, also requires deciding on the appropriate level of detail, such as the number of sub-catchments and resolution used to represent BMPs, as well as the associated data collection, model testing/calibration, and development of the baseline condition. Application of the model optimization tools is iterative, and users may want to consider testing multiple cost and management assumptions before developing their recommendations.

These case studies have provided users with an overview of two urban settings in Kansas City and Louisville, and demonstrated how *SUSTAIN* was used to support a cost-benefit evaluation of CSO management alternatives. The two case studies have also shown how *SUSTAIN* was used to analyze, streamline, and extrapolate BMP representation throughout the respective study areas; and demonstrated how to evaluate various combinations of green and gray management alternatives. The case study applications led to the follow general observations and conclusions:

- *SUSTAIN* is a comprehensive decision support tool with many useful features and functions. Successful and meaningful application largely depends on accurate representation of the baseline, BMP alternatives, and the associated BMP costs.
- *SUSTAIN* application process is iterative and adaptive, meaning that once the *SUSTAIN* modeling framework is established, it can be adapted to answer various management questions and test underlying assumptions.
- Model simplification becomes critical when optimization is applied to a larger area or when multiple smaller BMPs are distributed widely across a catchment. The aggregate BMP concept and utility provided in *SUSTAIN* is proven to be a viable and useful technique in the evaluation of the benefit of stormwater management practices, especially smaller GI practices, across a large area. When the aggregate BMP tools are used, the appropriate aggregation spatial scale should be carefully selected to maintain reasonable predictive capability and accuracy.
- The optimization process is highly sensitive to BMP cost data used in selecting solutions for each application. As a result, performance of sensitivity analysis and evaluation of cost control measures or economies of scale are recommended wherever *SUSTAIN* is applied.

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