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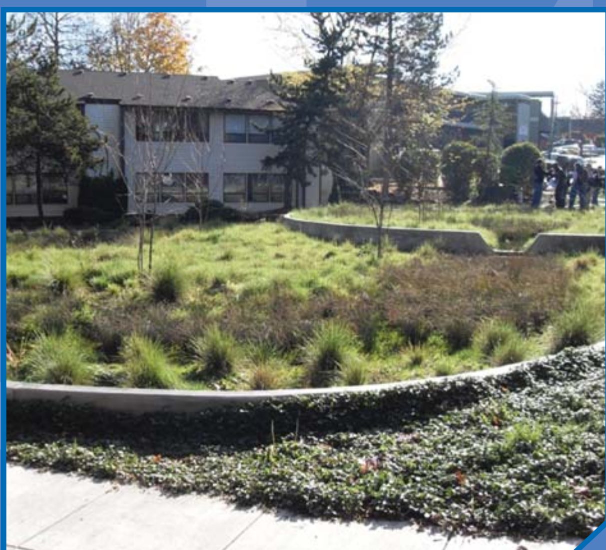
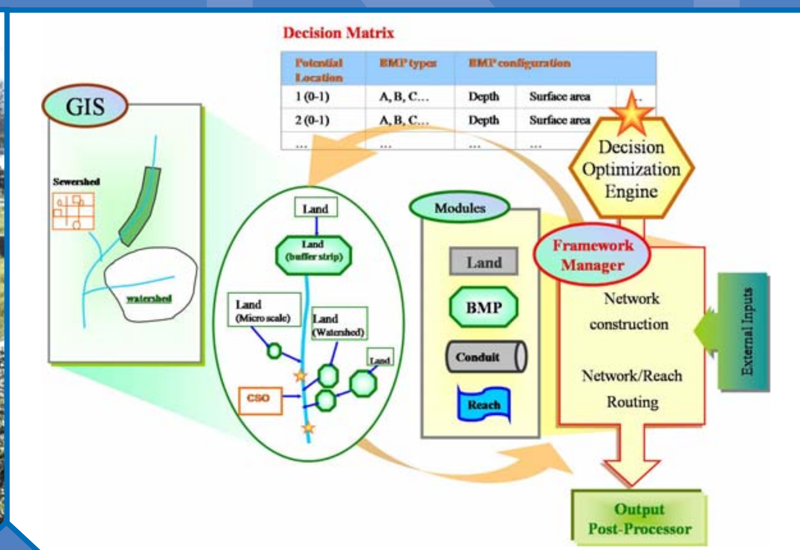
SUSTAIN - A Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality

REPORT





Office of Research and Development
National Risk Management Research Laboratory - Water Supply and Water Resources Division

SUSTAIN—
A Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality

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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 that mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a 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 subsurface 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 ecosystems. 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 document has been produced as part of the laboratory's strategic long-term research plan. EPA's Office of Research and Development has made it available to help the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

Abstract

Watershed and stormwater managers need modeling tools to evaluate alternative plans for water quality management and flow abatement techniques in urban and developing areas. A watershed-scale, decision-support framework that is based on cost optimization is needed to support government and local watershed planning agencies as they coordinate watershed-scale investments to achieve needed improvements in water quality.

The U.S. Environmental Protection Agency (EPA) has been working since 2003 to develop such a decision-support system. The resulting modeling framework is called the System for Urban Stormwater Treatment and Analysis INtegration (*SUSTAIN*). The development of *SUSTAIN* represents an intensive effort by EPA to create a tool for evaluating, selecting, and placing BMPs in an urban watershed on the basis of user-defined cost and effectiveness criteria. *SUSTAIN* provides a public domain tool capable of evaluating the optimal location, type, and cost of stormwater BMPs needed to meet water quality goals. It is a tool designed to provide critically needed support to watershed practitioners at all levels in developing stormwater management evaluations and cost optimizations to meet their existing program needs. Due to the complexity of the integrated framework for watershed analysis and planning, users are expected to have a practical understanding of watershed and BMP modeling processes, and calibration and validation techniques.

SUSTAIN incorporates the best available research that could be practically applied to decision making, including the tested algorithms from SWMM, HSPF, and other BMP modeling techniques. Linking those methods into a seamless system provides a balance between computational complexity and practical problem solving. The modular approach used in *SUSTAIN* facilitates updates as new solutions become available.

One major technical requirement for *SUSTAIN* is the ability to evaluate management practices at multiple scales, ranging from local to watershed applications. The local-scale evaluation involves simulations of individual BMPs and analyses of the impact of various combinations of practices and treatment trains on local water quantity and quality. The larger-scale evaluation could involve implementing hundreds or thousands of individual management practices to achieve a desired cumulative benefit. The required simulations and cost comparisons of such large-scale, distributed BMP options place significant challenges on the computational accuracy and simulation time for system modeling. *SUSTAIN* incorporates an innovative, tiered approach that allows for cost-effectiveness evaluation of both individual and multiple nested watersheds to address the needs of both local- and regional-scale applications.

Previously available modeling tools are significantly limited with respect to simulation of sediment generation and its fate through natural runoff and treatment at a BMP. *SUSTAIN* partially resolves these sediment routing issues by considering three sediment fractions (i.e., sand, silt, and clay), but this

approach remains a compromise because the state-of-the-art knowledge and the needed monitoring data are still limited.

The *SUSTAIN* framework provides a comprehensive system with a modular structure that facilitates the incorporation of improved technologies in optimization, BMP simulation, and computational efficiency. A flexible integration and implementation of these improved methods and algorithms will be the focus of further enhancements to *SUSTAIN*. Expanding the *SUSTAIN* capabilities will allow users to choose the level of complexity and simulation detail that best suits project needs. EPA intends to support expansion of the capabilities and functionalities of the system to meet continuing water quality goals and the needs of the user community.

This document describes the rationale for developing the framework and the uses of the framework; explains the system's design, structure, and performance; details the underlying methods and algorithms that provide the framework's predictive capabilities; and demonstrates the framework's capabilities through two case studies.

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Acronyms and Abbreviations

BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BOD	Biochemical Oxygen Demand
BMP	Best Management Practice
CALTRANS	California Department of Transportation
COD	Chemical Oxygen Demand
CSO	Combined Sewer Overflow
CSTR	Continuously Stirred Tank Reactor
DEM	Digital Elevation Model
DEQ	Department of Environmental Quality
EMC	Event Mean Concentration
EPA	U.S. Environmental Protection Agency
ET	Evapotranspiration
GA	Genetic Algorithm
GB	Gigabyte
GI	Green Infrastructure
GIS	Geographic Information System
HSPF	Hydrologic Simulation Program—FORTRAN
LID	Low Impact Development
LSPC	Loading Simulation Program in C++
MS4	Municipal Separate Storm Sewer System
NCDC	National Climatic Data Center
NHD	National Hydrography Dataset
NLCD	National Land Cover Dataset
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
NSGA-II	Non-dominated Sorting Genetic Algorithm II
NWS	National Weather Service
O&M	Operation and Maintenance
PET	Potential Evapotranspiration
SUSTAIN	System for Urban Stormwater Treatment and Analysis INtegration
SWMM	Stormwater Management Model
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
USGS	U.S. Geological Survey
USLE	Universal Soil Loss Equation
VFSMOD	Vegetative Filter Strip Model
WINSLAMM	Source Loading and Management Model for Windows

Chapter 1 Introduction

Surface water degradation resulting from the effects of urbanization on hydrology, water quality, and habitat is an issue of primary focus for multiple agencies at the federal, state, and local levels. A few examples of critical management issues facing planners and policy makers are ensuring the protection of source waters and the management of stormwater through peak flow mitigation, installation of sediment and erosion control devices, or implementation of best management practices (BMPs). Many management actions are needed throughout watersheds to achieve the desired effects on flow mitigation and pollutant reduction; however, no single standardized solution can be effective in all locations. Factors such as watershed size, scale, existing human activities, and natural characteristics can vary dramatically from one place to another. The major challenge faced by decision makers is how to select the best combination of practices to implement among the many options available that result in the most cost-effective, achievable, and practical management strategy possible for the location of interest.

Realizing the need for improved tools to support that challenge and the opportunities presented by emerging science and technology, the U.S. Environmental Protection Agency (EPA) initiated a research project in 2003 to develop a fully integrated decision support framework for the selection and placement of stormwater BMPs at strategic locations in urban or developing watersheds. Development of a software system to meet that challenge has been conducted in a phased process. The resulting system, described in detail in this document, is called the *System for Urban Stormwater Treatment and Analysis INtegration* (*SUSTAIN*). This document and the *SUSTAIN* Version 1.0 system represent the culmination of work under Phase II of development. The software, companion user manual, and periodic updates will be available on the *SUSTAIN* Web site hosted by EPA, (http://www.epa.gov/ednnrmrl/models/sustain/).

This document describes the rationale for developing the framework and the uses of the framework; explains the system's design, structure, and performance; details the underlying methods and algorithms that provide the framework's predictive capabilities; and demonstrates the framework's capabilities through two case studies. The initial needs analysis and model review documentation developed under Phase I are also included in the appendices. This document, where appropriate, also examines the limitations of the current framework and recommendations for enhancing the framework to be addressed in future development phases.

1.1. Project Rationale

A wide range of programs exist in the United States to support the protection and restoration of waterbodies (i.e., rivers, lakes, estuaries). Most programs involve linking land-based actions to water quantity or quality goals with the ultimate goal of reducing the impacts on receiving waters. Models of varying scales and complexity have long been a part of developing mitigation plans, identifying management needs, and evaluating alternatives. Examples of situations where modeling can support decision making include source water protection plans, municipal separate storm sewer system (MS4) permits under the National Pollutant Discharge Elimination System (NPDES) Stormwater Program (Phase I and II), total maximum daily load (TMDL) implementation plans, and watershed-based master plans and restoration studies.

In each case, water quality professionals need a framework to help address key stormwater management issues, e.g., to do the following:

- Evaluate and select management options to achieve a loading target set by a TMDL
- Develop cost-effective management options to implement a municipal stormwater program
- Evaluate pollutant loadings and identify appropriately protective management practices for a source water protection study
- Determine a cost-effective mix of green infrastructure (GI) measures to meet optimal flow reduction goals in a combined sewer overflow (CSO) control study

Over the past decade, significant progress has been made in expanding our understanding, through detailed laboratory and field studies, of the wide array of available management techniques and their function and impact on urban hydrology and water quality processes. Today, managers increasingly incorporate a combination of on-site, GI technologies with more traditional structural practices as part of comprehensive watershed restoration plans. As a result, many municipalities implement various site-scale techniques (i.e., bioretention, rain barrels, swales, infiltration trenches) at different points throughout a drainage area to mitigate both the flow and associated pollutant impacts of urban drainage. Practitioners now need to evaluate both the localized site-scale benefits and the cumulative effects of implementing hundreds or even thousands of those practices across a broad watershed landscape.

Concurrent with the evolution in management techniques, significant advances have been made in information technology over the past decade. Previous modeling of management alternatives was limited to highly simplified approaches for larger-scale regional studies. Next generation modeling systems now enable more detailed simulation techniques in combination with optimization tools, resulting in the ability to rapidly evaluate and compare multiple alternatives. Significantly faster computational speeds allow for interactive consideration of process-based simulations of flow and water quality with optimization searches. Software that facilitates spatial analysis, database management, and model execution is now readily available for practical application. Integration of simulation techniques with geographic information systems (GIS) has improved our ability to evaluate watershed management through multiple scales and at varying levels of complexity. Improved scientific understanding and advances in computational resources have now provided the opportunity to build more sophisticated and robust water resources modeling tools to support decision making.

On the basis of an understanding of the needs of the user community, *SUSTAIN* was developed to address the following major design objectives:

- It is intended for knowledgeable model users, including those at the local level, who are familiar with the technical aspects of watershed modeling
- It provides users with the ability to evaluate the effects of multiple management practices and placement strategies to support decision making
- It is specifically designed for and applicable to mixed land uses present in predominantly urban watersheds

SUSTAIN includes hydrologic/hydraulic and water-quality modeling in watersheds and urban streams. It has the capability to search for optimal management solutions at multiple scales to achieve desired water-quality objectives based on cost-effectiveness.

SUSTAIN was developed by combining publicly available modeling techniques, costs of management practices, and optimization tools in a geographically based framework to achieve the design objectives. *SUSTAIN* facilitates the objective analysis of multiple water quality management alternatives while enabling consideration of interacting and competing factors such as location, scale, and cost. In developing *SUSTAIN*, the most applicable algorithms for simulating urban hydrology, pollutant loading, and treatment processes were packaged together from those in multiple, distinct models. The simulation processes incorporated into *SUSTAIN* have not been known to be previously bundled in a publicly accessible modeling framework.

1.2. Overview of *SUSTAIN*

SUSTAIN is a framework that facilitates a comprehensive stormwater management analysis of watersheds at multiple scales. *SUSTAIN* was carefully constructed to ensure a seamless package that provides a consistent level of technical rigor, employs the latest technology, and performs cost-effectiveness analysis to derive practical solutions to real-world problems. *SUSTAIN* includes algorithms for simulating urban hydrology, pollutant loading, and treatment processes packaged from multiple models that individually address such processes. To provide flexibility for future updates, the system uses linked modules that perform simulations on watershed land surfaces, in management practices, and through routing networks. *SUSTAIN* uses a graphical interface to allow users to visualize the study area, select locations for placement of management practices, and define the linkages among the various landscape features. The analytical framework lets users apply optimization tools to explore the wide range of possible cost-effective solutions.

Because many models are used to address watershed problems, and some regions have a long history of model development and testing, *SUSTAIN* was designed to interface with external models. Through the use of file exchanges (i.e., time series files), *SUSTAIN* can import externally generated watershed modeling information and can export time series results to receiving water models for additional detailed analysis.

1.2.1. Structure of SUSTAIN

SUSTAIN is built on a base platform interface using ArcGIS, which provides the user access to the framework components: a BMP siting tool; a watershed runoff and routing module; a BMP simulation module; a BMP cost database; a post-processor; and an optimization module.

Figure 1-1 shows a generalized schematic of the overall framework. The ArcGIS-based Framework Manager (FM) is the overarching component that manages the data exchanges between the framework components. It provides linkages between external inputs, the land simulation, the BMP simulation, the conveyance simulation, the optimization module, and the post-processor. The FM checks for necessary data requirements before calling for simulation and optimization components.

Each module in the framework serves a specific function and is typically applied in series. The application usually begins with the use of the BMP siting tool, which uses the ArcGIS platform and user-guided rules to determine site suitability for various BMP options (Table 1-1). The land simulation module is used to generate runoff time series data to drive the BMP simulation. The conveyance module provides routing capabilities between land segments or BMPs or both. Users also have the option to import time series data from external watershed models (e.g., Hydrologic Simulation Program Fortran (HSPF) or Stormwater Management Model (SWMM)) instead of performing new land simulations in *SUSTAIN*.

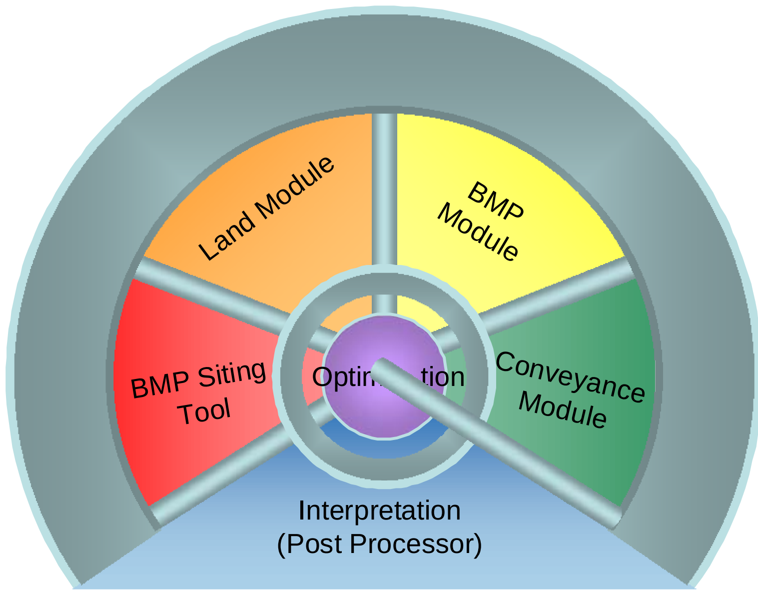

Figure 1-1. Overview of *SUSTAIN* components.

The process-based BMP module provides simulation of management practices by using a combination of processes for storage retention, open-channel controls, filtration, biological purification, and mechanical structure facilitated separation. The cost database is organized according to BMP construction components (e.g., grading, backfilling, filter fabric) and populated with unit costs for each component. The optimization module uses results from other modules in the framework for evaluating and selecting a combination of BMP options that achieve a given pollutant-reduction goal at minimum cost. The optimization module is designed to efficiently search for this combination of BMPs. Finally, a post-processor presents the optimization results in a cost-effectiveness curve.

Table 1-1. Management Practices Supported by *SUSTAIN*

Management Practice
Bioretention
Cistern
Constructed Wetland
Dry Pond
Grassed Swale
Green Roof
Infiltration Basin
Infiltration Trench
Porous Pavement
Rain Barrel
Sand Filter (non-surface)
Sand Filter (surface)
Vegetated Filterstrip
Wet Pond

From the GIS framework, the user first sets up a project representing a network of drainage areas, BMPs, and routing components. *SUSTAIN* then uses externally generated land use-associated flow and water quality time series data or internally generated data from BMP contributing areas and routes them through BMPs to predict flow and water quality time-series data at selected downstream locations. The user defines the assessment locations in the watershed where results are to be analyzed or compared (Figure 1-2).

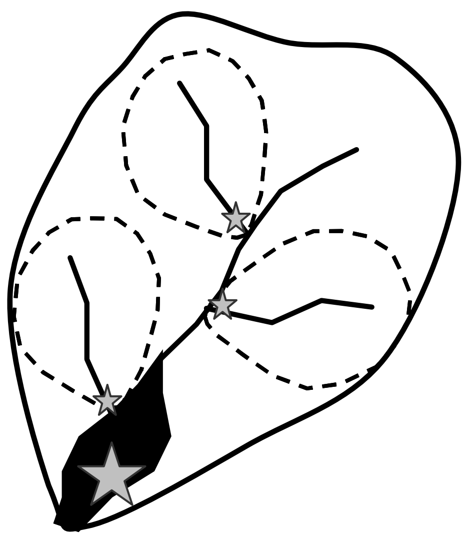

Figure 1-2. Watershed assessment points.

SUSTAIN's optimization capability helps users identify desired economical BMP solutions that achieve user-defined management target(s). Another benefit of the framework is its ability to reveal the BMP cost- and pollutant-reduction effectiveness relationship, referred to as the cost-effectiveness curve. A sample cost-effectiveness curve is shown in Figure 1-3. Each point on the curve represents an optimal combination of BMPs that will collectively remove the targeted amount of pollutant load at the least cost. The BMP cost-effectiveness curve provides valuable information on the minimum costs at various reduction goals, the maximum achievable pollutant reductions, as well as the marginal costs.

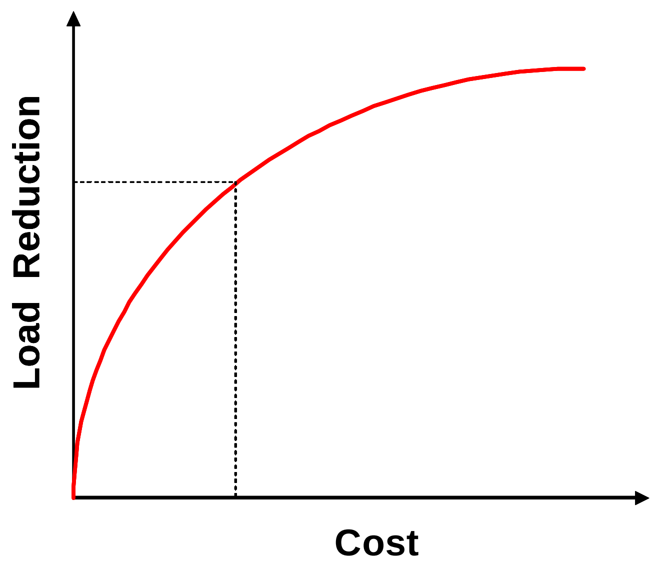

Figure 1-3. Sample cost-effectiveness curve.

1.2.2. Multiple Scale Application Features

Practitioners are confronted daily with the need to evaluate management practices at multiple scales, from an individual site to regional watershed studies. The site-scale evaluation might require a detailed assessment of individual BMPs or combinations of BMPs (i.e., treatment trains). Larger-scale watershed studies, typically over 100 square miles, could involve hundreds or thousands of individual management practices to achieve a desired cumulative benefit. Simulating and performing cost comparisons for each of these individual *distributed* BMP options would place a significant challenge on the accuracy and simulation time for modeling. Two approaches were developed in *SUSTAIN* to address the watershed scaling issue: *aggregation* and *tiered* or *nested* analysis methods. These methods facilitate the use of *SUSTAIN* at multiple scales as shown in Figure 1-4.

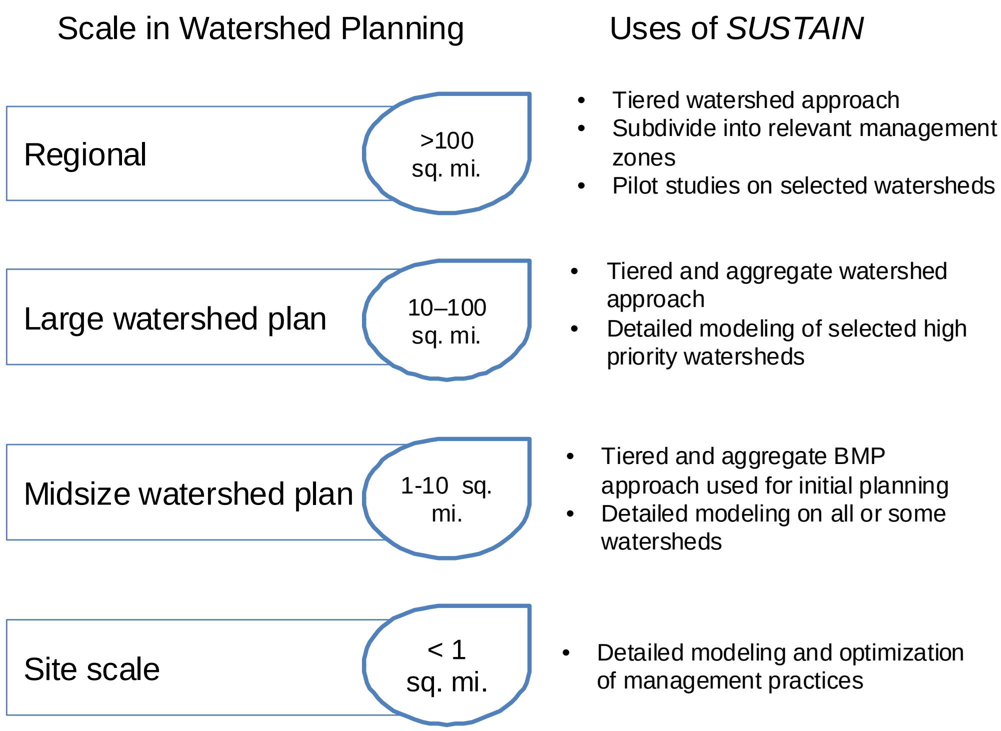

Figure 1-4. *SUSTAIN*'s multiple scales of application.

As an alternative to the explicit representation and routing of multiple distributed BMPs, the *aggregate* BMP approach creates a virtual BMP that represents all similarly functioning treatment devices in a watershed. This option can significantly reduce computational effort, especially when distributed BMPs are involved in the optimization process as decision variables. The aggregated approach uses four generic BMPs in sequence, each representing the function of many similar BMPs: on-site interception, on-site treatment, routing/attenuation, and regional storage/treatment.

For large watersheds that require detailed analyses, *SUSTAIN* provides a methodology for tiered or sequenced analysis. As illustrated in Figure 1-5, a relatively large watershed can be subdivided into several smaller subwatersheds on which detailed analysis is performed to derive a tier-1 cost-effectiveness curve. The tier-2 cost-effectiveness curve is derived from the three tier-1 curves by considering all feasible optimal combinations of BMPs that produce the target load reduction at the minimum cost.

The tiered approach can be applied to large watersheds that contain several subareas and to small watersheds that require the development of a detailed management plan, e.g., at a parcel or a street block level.

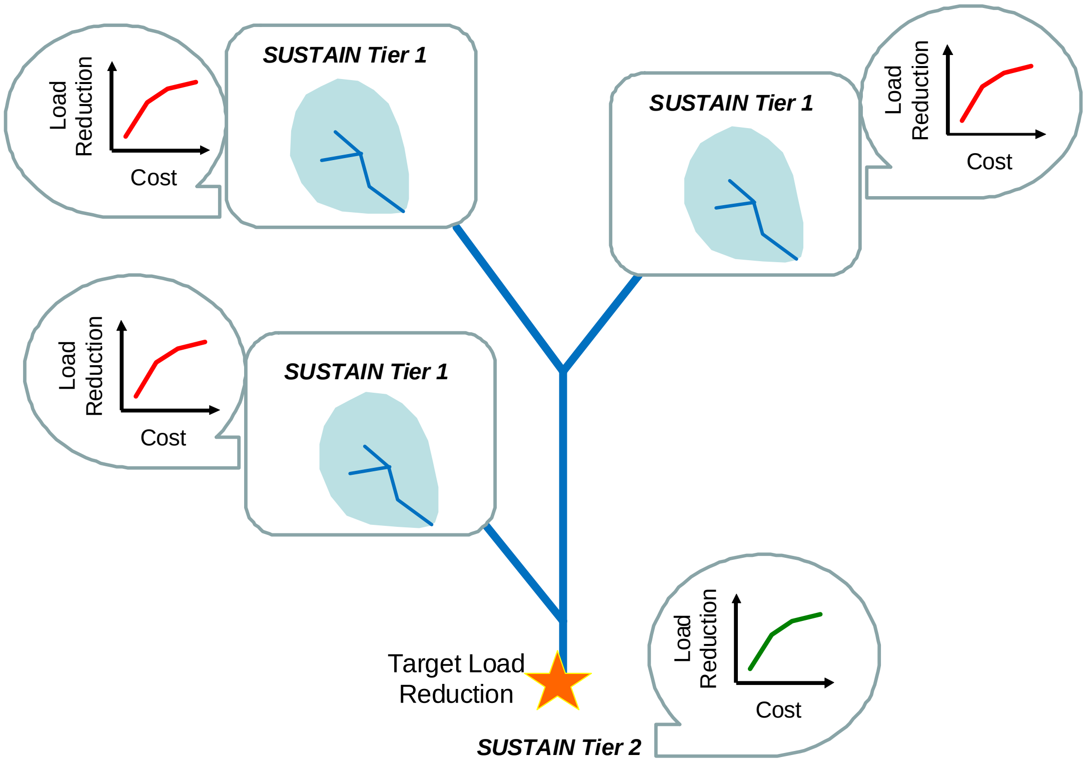

Figure 1-5. Tiered application of *SUSTAIN* for developing cost-effectiveness curves.

The tiered optimization in *SUSTAIN* not only provides an efficient and manageable means of analysis for large-scale applications, but also allows users flexibility in the placement of assessment points and in evaluating explicit expectations of load reductions at upstream locations.

1.3. The Role of *SUSTAIN* in Watershed Applications

Various practitioners, municipalities, and watershed groups at the regional and local levels can use the *SUSTAIN* framework to address a variety of management practice planning questions. Users might turn to *SUSTAIN* for the following:

- Developing TMDL implementation plans
- Identifying management practices to achieve pollutant reductions in an area under an MS4 stormwater permit
- Determining optimal GI strategies for reducing volume and peak flows to CSO systems
- Evaluating the benefits of distributed GI implementation on water quantity and quality in urban streams

The *SUSTAIN* modeling framework can be employed at multiple phases in the watershed management process and at varying levels of detail (Figure 1-6). When applied early in the study phase, the analysis is typically at a low level of detail to explore the potential benefits of BMPs. After the initial assessment, *SUSTAIN* can be applied in greater detail as part of implementation planning to help identify the preferred management practices and develop the associated capital costs. Once a plan is implemented, *SUSTAIN* can be used to track and assess the performance of the installation using the monitoring data collected before and after installing BMPs. The monitored data can also be used to recalibrate and reverify *SUSTAIN* for extrapolating future benefits from additional BMPs.

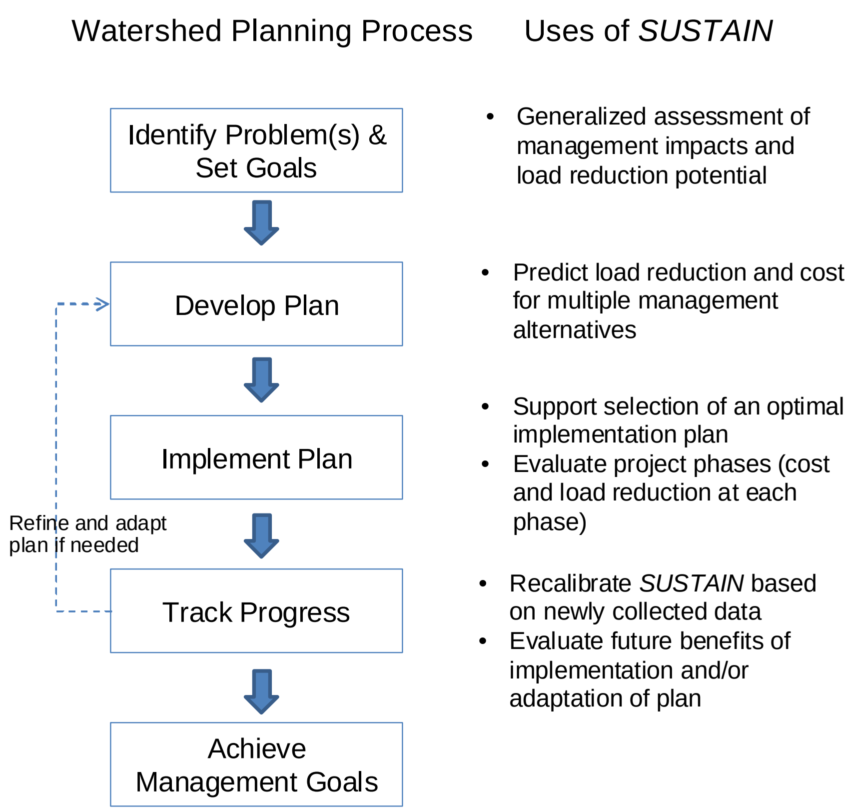

Figure 1-6. Using *SUSTAIN* in the watershed planning process.

Within the context of each application, *SUSTAIN* provides the flexibility to support the application goals and address the localized issues of concern. Two examples of applications as described below include TMDL development and implementation, and the use of GI to help control CSOs.

1.3.1. TMDL Development and Implementation

TMDL projects are plans to reduce loadings to meet a defined water quality standards objective in impaired water (USEPA 1991). Each state defines impaired waters on its Clean Water Act (CWA) section 303(d) list. For lake TMDLs, the 303(d) listing might identify a nutrient impairment that results in periodic algal blooms and is limiting the ability of the lake to be used for recreation and as aquatic habitat. The TMDL development requires estimating nutrient loadings and evaluating the loading *threshold* that would keep the lake within acceptable water quality conditions and meeting applicable water quality standards. *SUSTAIN* uses the embedded SWMM rainfall-runoff routines to develop the loading characteristics from the land areas. The framework is ideally suited to evaluate the load reduction potential as part of examining the *reasonable assurance* that the TMDL can be achieved at the prescribed load reductions. After the TMDL is developed, *SUSTAIN* can be used to develop the implementation plan that identifies the best combination of management practice type(s) and location(s), and the associated cost load reductions.

In some areas, TMDL implementation is addressed by a municipal stormwater permit. For communities working to comply with wasteload allocations assigned in a TMDL, *SUSTAIN* provides a method to integrate stormwater permit activities with the requirements of the TMDL. Capitalizing on mapping and data collection activities typically undertaken as part of the MS4 implementation, *SUSTAIN* can be used to enumerate specific measures necessary for meeting TMDL reductions throughout the affected area. The framework can be used to pinpoint the best locations for optimizing pollutant reductions and to determine the mix of management practices that will achieve necessary load reductions for the least cost.

Examples of the TMDL-related investigations that *SUSTAIN* supports include the following:

- Optimizing the geographic focus of management activities (near the waterbody of concern or away from it)
- Evaluating the benefits of installing rain barrels or rain gardens in a near-lake region
- Enumerating specific management practices that must be implemented to satisfy the TMDL
- Developing a funding request
- Developing a projection of reduction potential for phased installation over time

1.3.2. Evaluation of GI Practices as Part of a CSO Control Program

Even with advances in sewer technology (e.g., sewer separation and deep storage), problems still remain with the operation of existing urban wastewater systems (NRDC 2006). Examples include impaired performance of wastewater treatment plants resulting from the influx of stormwater (infiltration and inflow), constraints on urban growth caused by an inadequate infrastructure, and aging combined sewer systems, which can require costly rehabilitation (USEPA 2004). CSO control programs typically focus on infiltrating or storing runoff to minimize peak flows to collection systems and reduce the frequency and size of overflow events. Programs are developed and implemented to comply with mandated CSO long-term control plans. Such challenges have led to the development of sustainable strategies for urban stormwater and wastewater management and new alternatives to the traditional centralized sewer systems, which comprise laterals, submains, and trunk lines all leading to a central treatment facility (Chocat et al. 2007). Although large storage structures, tunnels, and sewer separation have been used successfully to significantly reduce CSOs in major cities, increased effectiveness and multiple benefits can be derived by adopting new GI approaches in combination with traditional approaches.

As a means to reduce volume entering a wastewater system and reduce its peak flows, GI can be applied through source controls and engineered BMP systems to infiltrate, evapotranspirate, or store stormwater runoff for beneficial uses (USEPA 2007). Those approaches are to keep stormwater runoff from entering a combined sewer system and reduce overflows (USEPA 2004). In addition, many GI approaches can be included in adaptive management strategies designed to be resilient to such system changing factors as population growth and climate change (USEPA 2008).

SUSTAIN is designed to support linkage to other related models such as detailed sewer system models or receiving water models of affected rivers, lakes, and estuaries. Where existing sewer and watershed models are available, *SUSTAIN* can be used to predict the most inexpensive GI practices that will result in reduced overflow volumes and frequency.

1.4. *SUSTAIN* Application Process

A typical *SUSTAIN* application scenario begins with the definition of study objectives, followed by data collection, project/model setup, formulation of the optimization problem, and analysis of results. Figure 1-7 is a flow diagram illustrating the typical step-by-step process in *SUSTAIN* applications.

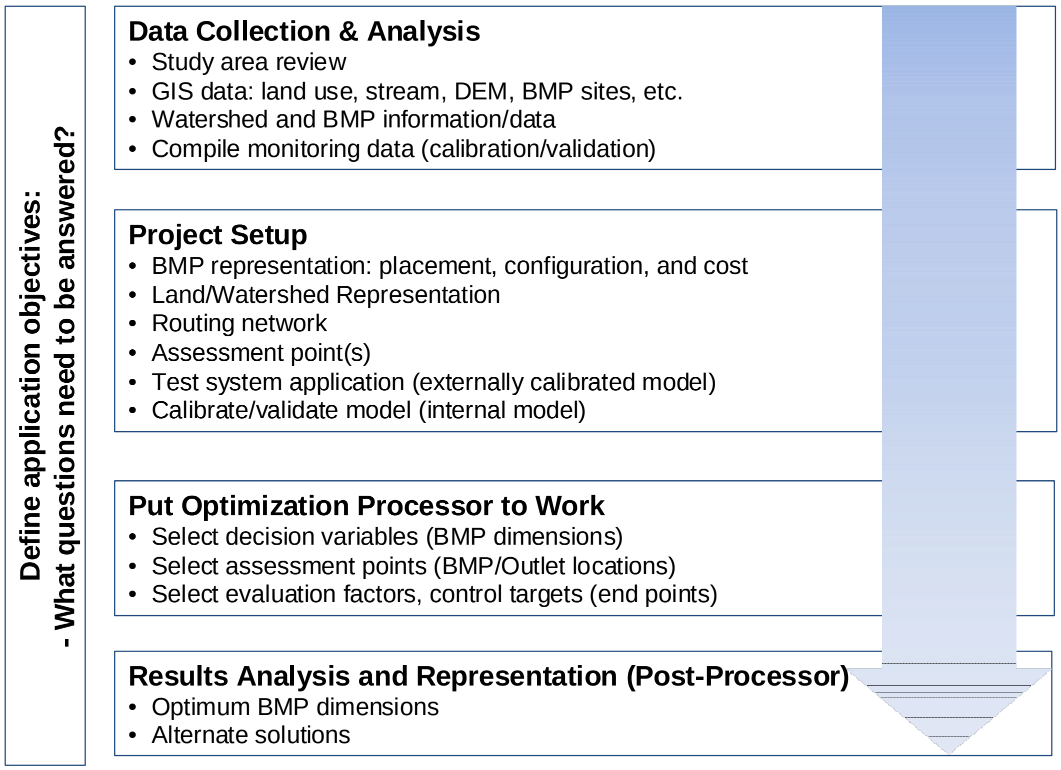

Figure 1-7. ***SUSTAIN* application process.**

Fundamental to the setup and application of *SUSTAIN* is a clear definition of the study objective(s)—*What is the question that is to be answered by the analysis?* For example, the objective of the study might be to identify the set of management options (including both site- and regional-scale techniques) that achieve a required level of pollutant load reduction (i.e., annual load in lbs/yr). For a CSO study, the objective might be stated as, "to reduce frequency of overflow through extensive retrofit of the drainage area." The reduction in overflow can be measured by the magnitude of peak flows in a collection system. The study objectives will define the scope and extent of the *SUSTAIN* application, which could include the areas to be modeled, runoff and pollutant factors to be simulated, additional data collection needs, the locations where the output will be evaluated (i.e., assessment points), and the determination of the optimization evaluation factors and control targets (i.e., endpoints). At each control target, *SUSTAIN* is capable of producing outputs in various time averaging periods and frequencies of occurrences that will facilitate the evaluation and comparison of management alternatives. The following lists the examples of output variations.

- Average annual flow volume percent reduction based on an existing condition
- Average annual flow volume
- High-flow rate and allowed maximum duration (user specified)

- Peak-flow value and maximum exceedance frequency
- Average annual sediment/pollutant load percent reduction with respect to an existing condition
- Average annual sediment/pollutant load (load target)
- Average sediment/pollutant concentration (the maximum average concentration allowed)
- High sediment/pollutant concentration and duration (concentration threshold value and allowed maximum duration when concentration exceeds the threshold)
- Long-term average sediment/pollutant load (daily, monthly, annual, or any user specified time frame)
- Exceedance frequency (the threshold value and maximum exceedance frequency allowed)

SUSTAIN has been designed with inherent flexibility in the formulation and setup of the application. The careful definition of the project objective, associated evaluation factors, and control targets will ensure the most appropriate and useful application.

The data collection process for a *SUSTAIN* application is similar to most modeling projects and involves a thorough compilation and review of information available for the study area. It generally includes gathering applicable regional and site-scale GIS data layers, digital elevation model (DEM) data, stream networks, locations of BMPs, land use data, critical source information, and monitoring data for calibration and validation. A summary of typical data needs is shown in Table 1-2.

Setting up the *SUSTAIN* project involves using the data collected to establish a representation of the land and pollutant sources in the watershed as well as the routing network, assessment points, and management practices to be evaluated. For site-scale analysis of management practices, locally derived higher-resolution site scale data will likely be required.

If the continuous time series data of flow and associated sediment/pollutants from a locally calibrated model study is available, the data can be imported into *SUSTAIN* without recreating them. Most models that operate on an hourly or shorter time step, such as HSPF, SWMM, Source Loading and Management Model for Windows (WINSLAMM), are compatible with *SUSTAIN*. When importing information from an externally generated model, the *SUSTAIN* application builds on the documentation, testing, calibration, and validation of the external model.

After project setup, the optimization module synthesizes information from the BMP, land, and conveyance modules and generates solutions that are looped back for evaluation using the same modules again. Via this evolutionary search process, the optimizer identifies the best or most cost-effective BMP solutions according to the user's specific conditions and objectives. Finally, the post-processor analyzes optimization results using specific graphical and tabular reports that facilitate the classification of storm events for analysis, viewing the time series of specific storm events, evaluating BMP performance by storm event, and developing the cost-effectiveness curves for treatment alternatives.

Table 1-2. Typical Data Needs for *SUSTAIN* Application

Data	Data Type	Need	Data Source
Land use	ESRI Grid	Required for defining land use distribution	National Land Cover Dataset (NLCD) (http://seamless.usgs.gov/website/seamless/viewer.php) or locally derived
Land use lookup	Dbf Table	Required for assigning land use categories and groupings	Standard National Land Cover Dataset (NLCD) land cover code for NLCD land use (http://landcover.usgs.gov/classes.asp). or land cover mapping code for locally derived data
External Model	ASCII Text Files	Required for external model linkage	Time series generated by calibrated model; by land use
Digital Elevation Data (DEM)	ESRI Grid	Required for automatic delineation of drainage areas	(http://seamless.usgs.gov/website/seamless/viewer.php) or locally derived source
Stream Network	ESRI Shape File	Required for automatic delineation of drainage areas and for placing on-stream management practices	National Hydrography Dataset (NHD) from http://nhd.usgs.gov/data.html
Precipitation	ASCII Text File	Required for internal land simulation and for estimating storm sizes for the post-processor	National Climatic Data Center (NCDC). NCDC Summary of the Day (daily data) can also be obtained from (EarthInfo Inc., http://www.earthinfo.com).
Other weather data	ASCII Text File	Required if snow melt is simulated for internal land simulation	NCDC (temperature, evaporation, and wind speed)
Pipes	Data Entry	Required if pipe/conduit is simulated	Shape and dimensions (e.g., length, width, diameter)
Stream Geometry	Data Entry	Required if stream routing is simulated	Cross-sectional geometry (shape and related dimensions)
Management Practices	Data Entry	Required	Characteristics of installed and proposed management practices (e.g., size, shape, media, design specification); dependent on type of practice
Flow	ASCII Text File	Required for calibration of internal modeling of runoff; recommended for system testing	USGS real time data (http://waterdata.usgs.gov/nwis/rt) or local sampling
Water Quality	ASCII Text File	Required for calibration of internal modeling of water quality; recommended for testing of water quality predictions	USGS surface water data (http://waterdata.usgs.gov/nwis/sw) or EPA STORET data (http://www.epa.gov/storet/dw_home html) or local sampling

1.5. About this Report

This report provides the description and documentation to support the release of of *SUSTAIN* Version 1.0. As it is developed, EPA will release additional model information on the *SUSTAIN* Web site. The Web site also provides user guidance and responses to frequently asked questions regarding the operation and use of the model.

This *SUSTAIN* documentation report is organized as follows:

Chapter 1 provides a general overview of the framework, its development, typical applications, and application process.

Chapter 2 describes the structure of the framework, the roles and interactions of its major components, and its operational characteristics.

Chapter 3 provides the detailed documentation of the analytical procedures and simulation processes, including equations and variables, which are adopted and incorporated into various parts of *SUSTAIN*.

Chapter 4 presents two case studies to demonstrate how the framework is applied for selection and placement of BMPs.

The appendices include a needs analysis for developing a comprehensive placement framework, a review of land and BMP simulation models, and a summary of expert opinions on the current state-of-the-art in optimization concepts and methods to support development of the optimization component in *SUSTAIN*. It includes the rationale and supporting information used in formulating the framework design and selecting land and BMP simulation techniques that appear in *SUSTAIN*.

Chapter 2 *SUSTAIN* Design and Structure

SUSTAIN is a comprehensive, multiscale watershed and water quality modeling application built on an ArcGIS platform linked to multiple simulation modules, an optimization module, and a post-processor, which analyzes and helps interpret the results. The modular design of *SUSTAIN* has multiple advantages compared to previous modeling applications including the ability to incorporate simulation of new management practices as they are evolved, to operate independently for specific small watershed applications, and to provide flexibility to address multiple watershed scales.

This chapter describes the system's infrastructure, its major modules, and software platforms. It also explains how they are linked and interact.

The *SUSTAIN* installation requires ESRI's ArcGIS 9.3 and the Spatial Analyst extension. The application is compatible with Microsoft Windows 98, 2000, NT, XP, and Vista operating systems and requires at least 1GB of computer memory and 5GB of free space on the hard disk. The system also requires Microsoft Excel 2003, which is used as a post-processor for analyzing and interpreting results.

SUSTAIN comprises the following modules:

Framework Manager—to serve as the command module of *SUSTAIN*, manage data for system functions, provide linkages between the system modules, and create a simulation network to guide the modeling and optimization activities

Land module—to generate runoff and pollutant loads from the land through internal land simulation or importing precalibrated land simulation time series

BMP module—to perform process simulation of flow and water quality through BMPs

Conveyance module—to perform routing of flow and water quality in a pipe or a channel

Optimization module—to evaluate and identify cost-effective BMP placement and selection strategies for a preselected list of potential sites, applicable BMP types, and ranges of BMP size

Post-Processor—to perform analysis and summarization of the simulation results for decision making

2.1. Framework Manager

The FM performs data management, spatial analysis, and network visualization. It integrates components from the GIS network, such as streams, conduits, and land uses, with relevant simulation modules, draws external time series data (e.g., rainfall, runoff) as required, and checks for necessary data requirements before calling for simulation and optimization components.

SUSTAIN is designed to interactively identify and manage the required databases, including geographic and tabular data sets. The primary function of data management is to define the paths where data are stored and to identify required data elements. *SUSTAIN* provides the option to store required geographic data on the hard disk or in a file-based geodatabase, which is a native data structure used by ArcGIS. The geodatabase is composed of tables and queries that allow data sharing and interchange among *SUSTAIN's* modules.

The FM builds on the ESRI ArcGIS (version 9.3) platform to support the placement of BMPs, delineation of BMP tributary drainage areas and flow paths, and development of a schematized watershed simulation network that might include land parcels, management practices, and stream reaches. The GIS component also serves as the user interface and includes the main application window with menus, buttons, and dialog boxes. The GIS interface allows a user to read and edit spatial and temporal data sets.

All commonly used Microsoft Office applications can be easily linked to the platform. Microsoft Excel, a popular and powerful application for displaying and manipulating simulation time series data and scientific graphics, was chosen as the post-processor for *SUSTAIN*.

Figure 2-1 shows the framework design, including system components, relationships between components, and general flow of information.

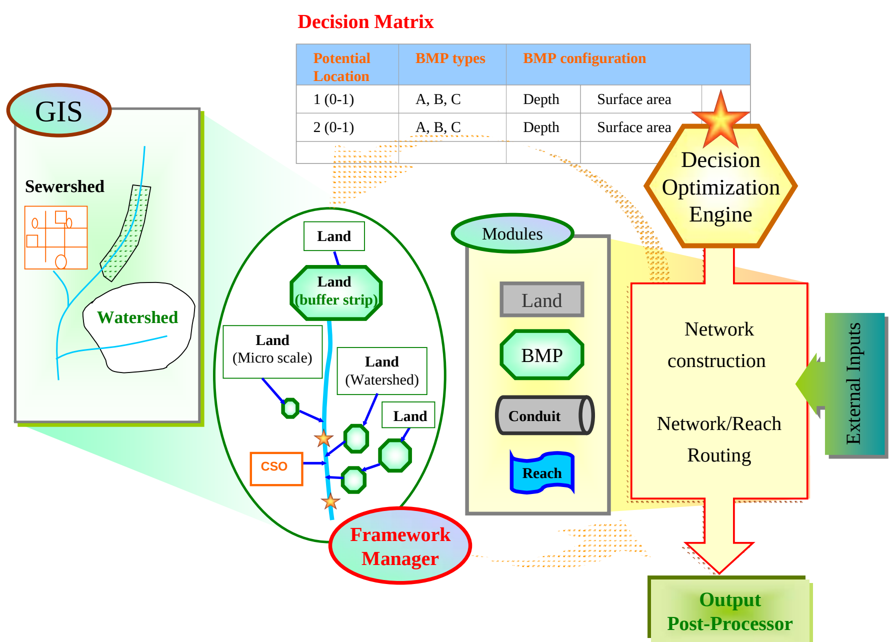

Figure 2-1. ***SUSTAIN* components and flow chart.**

The *SUSTAIN* framework is designed to perform the following sequence of operations.

- From the GIS view and database, the framework first develops a simulation network that defines the relationship between land-area units, BMPs, and stream systems on a watershed
- The FM then identifies the modules (Land, BMP, Conduit, and Reach) to be used and prepares model input files
- The FM routes the external inputs to appropriate modules and their outputs to the Output Post-Processor or other models
- The FM sends outputs from Output Post-Processor to the Decision Optimization Engine

- The Optimization Engine evaluates the current option and selects the next preferred option from that contained in the Feasible Option Matrix on the basis of cost and defined flow and water quality criteria. The preferred option can be a different combination of BMP locations and types. The Feasible Option Matrix contains types, configurations, locations, and costs of feasible BMP options
- *SUSTAIN* performs numerous iterations of the sequence until the user-defined convergence criteria are met
- The tool does not automatically select the best solution but is expected to be used as a tool to explore and test various approaches and eventually select optimal solutions on the basis of user-defined criteria and constraints

2.2. Simulation Modules

SUSTAIN's modular simulation core consists of three standalone simulation modules: the landscape simulation module (Land), the standalone BMP module (BMP), and a conveyance simulation module (Conduit and Reach) as shown in the central box of Figure 2-1.

To provide a seamless and efficient operation, *SUSTAIN* selects and incorporates simulation routines from commonly used watershed and receiving water models (e.g., SWMM (Huber and Dickinson 1988), HSPF (Bicknell 2001), and Loading Simulation Program—C++ (LSPC) (Tetra Tech and USEPA 2002). The following is a summary list of simulation routines and the model where the routines were adopted:

- Watershed/landscape models: SWMM's atmospheric, land surface, and groundwater compartments
- Conveyance and pollutant routing: in HSPF/LSPC RCHRES and SWMM Transport compartment
- BMP simulation models: Prince George's County BMP module (Tetra Tech 2001) and selected buffer zone simulation techniques from the VFSMOD (Munoz-Carpena and Parsons 2003)

The VFSMOD is programmed in FORTRAN computer language and compiled as a standalone dynamic link library, whereas other simulation modules are coded in the visual C++ programming language.

The standalone simulation modules are packaged within *SUSTAIN* to perform the generation and transport of sediment and other pollutants at the source (land use type), in the BMP, and in the conveyance system. Table 2-1 shows the interaction between the Land, BMP, and Conveyance modules to handle transport of sediment in *SUSTAIN*. It shows the inputs, the methods used to simulate the sediment transport, and the resulting outputs from these simulation modules. Table 2-2 shows the interaction between the Land, BMP, and Conveyance modules to handle transport of other pollutants in *SUSTAIN*. It also shows the inputs, the methods used to simulate the water quality processes, and the resulting outputs from the simulation modules.

Table 2-1. Simulation of Sediment Transport in *SUSTAIN*

Land

Inputs

- Climate time series data
- Coefficients and exponents for soil detachment, washoff, and scour equations for the pervious land
- Buildup and washoff rates of solids on impervious surfaces

Simulation Methods

- Production and removal of sediment on/from pervious land segment is computed using the HSPF sediment algorithms
- Accumulation and removal of sediment on/from the impervious land segment is computed using the SWMM buildup and washoff algorithms

Outputs

- Outflow time series
- Concentrations time series of total sediment

↓

Split total sediment concentration into sand (0.05–2.0 mm diameter), silt (0.002–0.05 mm diameter), and clay (< 0.002 mm diameter) concentrations.

↓ ↓

BMP ⟷ **Conveyance**

BMP

Inputs

Inflow time series.

- Concentration time series for sand, silt, and clay particles
- Settling velocity, critical shear stress, and density for sand, silt, and clay particles

Simulation Methods

- Simulation of transport, deposition, and scouring of the sediment in BMP is computed using the HSPF sediment transport algorithms for a lake
- Exchange of cohesive sediments with the bed is calculated on the basis of the bed shear stress and user-defined critical shear stress for deposition and for scour
- Bed shear stress is calculated as a function of an average flow velocity, average water depth, and mean particle size of the bed sediment in a BMP

Outputs

- Outflow time series
- Concentration time series for sand, silt, and clay particles

Conveyance

Inputs

- Inflow time series
- Concentration time series for sand, silt, and clay particles
- Settling velocity, critical shear stress, and density for sand, silt, and clay particles

Simulation Methods

- Simulation of transport, deposition, and scouring of the sediment in stream is computed using the HSPF sediment transport algorithms
- Exchange of cohesive sediments with the bed is calculated on the basis of the bed shear stress and user-defined critical shear stress for deposition and for scour
- Bed shear stress is calculated as a function of the slope and hydraulic radius of the reach

Outputs

- Outflow time series
- Concentration time series for sand, silt, and clay particles

Table 2-2. Transport Simulation of Other Pollutants in *SUSTAIN*

Land

Inputs

- Climate time series data
- Buildup and washoff rates of the selected pollutant on the pervious and the impervious land surface

Simulation Methods

- Accumulation of the selected pollutant on pervious and impervious land segments is computed using the SWMM buildup functions. Power, Exponential, and Saturation functions are provided for computing the pollutant buildup loading on the land
- Removal of the selected pollutant on pervious and impervious land segments is computed using the SWMM washoff algorithms. Exponential, Rating Curve, and Even Mean Concentration methods are provided for computing the pollutant washoff loading from the land

Outputs

- Outflow time series
- Concentrations time series for the selected pollutant

↓ ↓

BMP ⟷ **Conveyance**

BMP

Inputs

- Inflow time series
- Concentration time series for the selected pollutant
- 1st order decay rates for the selected pollutants
- Background concentration (C*) for the selected pollutants
- Percent removal rate from the underdrain media for the selected pollutants

Simulation Methods

- Pollutant mixing is simulated with completely mixed tanks (CSTRs) in series in a BMP
- Pollutant removal is calculated by first order decay with background concentration, i.e., k-C* method (Kadlec and Knight 1996)
- Pollutant removal through the underdrain media is calculated on the basis of the user-defined percent reduction for the selected pollutants

Outputs

- Outflow time series
- Concentration time series for the selected pollutant

Conveyance

Inputs

- Inflow time series
- Concentration time series for the selected pollutant
- 1st order decay rates for the selected pollutants

Simulation Methods

- Pollutant routing is computed by assuming a single, continuously stirred tank reactor method in a reach
- Pollutant removal is calculated by 1st order decay rate in a reach (no C*)

Outputs

- Outflow time series
- Concentration time series for the selected pollutant

When operated in simulation mode, computation time can be a concern for a large watershed-scale application because many BMP/conduits might be involved. To get realistic information about their run time, the following test runs of *SUSTAIN* were performed:

- Different numbers of the same BMP unit and multiple simulation periods
- Different numbers of the same conduit unit and multiple simulation periods
- Different combinations of BMPs and conduits and multiple simulation periods

The test examples were prepared for 1, 10, and 50 units (BMPs, conduits, or BMP/conduit combinations) for simulation durations of 1, 5, and 10 years. The simulation time step of 5 minutes was used for all simulation runs. The computer configuration used for the tests was a 1.6 GHz CPU, 768 MB RAM, and Windows XP operating system.

The results (Figure 2-2) show that the runtime increases almost linearly with the increase of the number of simulation units (i.e., BMP, conduit, or BMP/conduit combination). The runtime also increases linearly with the increase in simulation period.

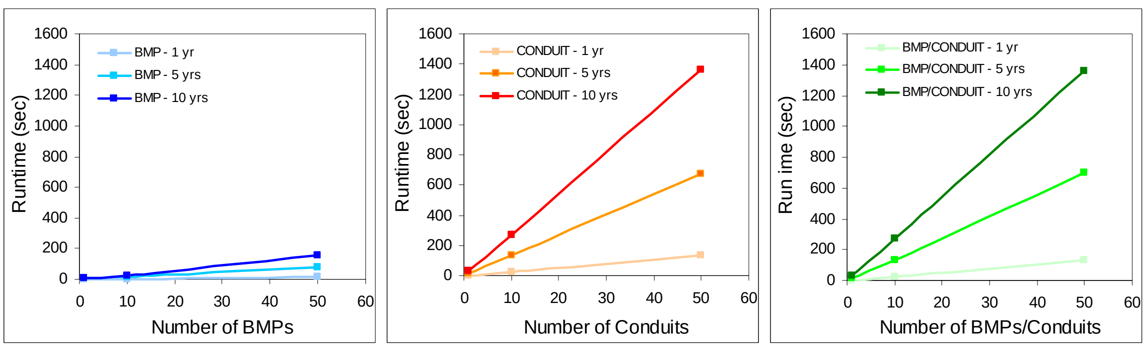

Figure 2-2. Comparison of runtime for various simulation units and periods.

The results (Figure 2-3) also reveal that conduit simulation consumes much longer run times (approximately nine times longer) than BMP simulation, mainly because it requires solving the coupled continuity equation and Manning's equation for conduit flow routing.

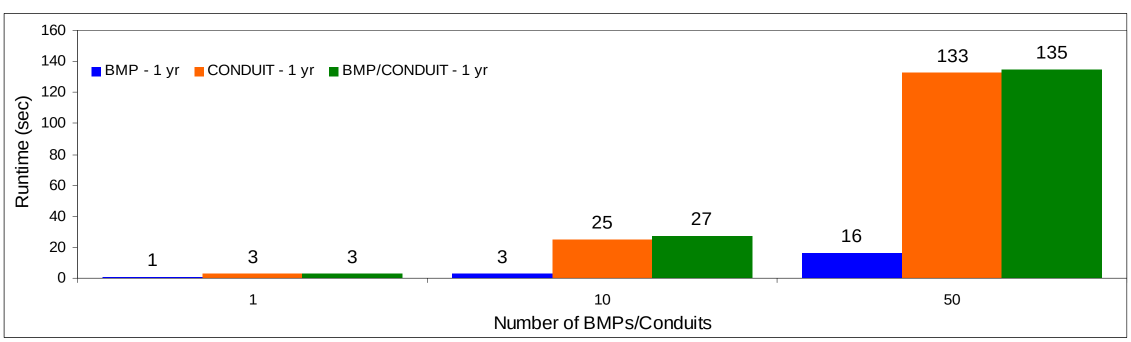

Figure 2-3. Comparison of runtime for 1-yr simulation of various units.

To reduce the computational burden, it is desirable to simplify the routing simulation, particularly through conduits, during optimization runs. Additional research is needed to develop credible methods that balance the computational efficiency and accuracy of hydraulic routing in conduits.

2.3. Optimization Module

SUSTAIN's optimization module uses evolutionary optimization techniques to identify the most cost-effective BMP selection and placement alternatives that satisfy the user-defined decision criteria. The optimization module is interfaced with the BMP and land modules during the search process in an iterative and evolutionary fashion to pass the performance data from simulation modules and cost information of a viable set of BMPs to the optimization module. The optimization module then systematically compares the cost and performance data and modifies the search path to generate a new set of viable BMP options and repeats the process until the set criteria to end the iteration are reached.

Two optimization techniques are supported by *SUSTAIN*: the Scatter Search method and the Non-dominated Sorting Genetic Algorithm II (NSGA-II) method. The Scatter Search method is a meta-heuristic search technique that has been explored and used in optimizing complex systems (Glover et al. 2000; Laguna and Marti 2002; Zhen et al. 2004). NSGA-II is an advanced genetic algorithm based on Pareto dominance, and uses non-domination and distribution instead of fitness value to score individuals (Deb et al. 2000). Section 3.5.2 has more expanded discussion of the Scatter Search and NSGA-II methods.

To validate the performance of both search techniques, they were tested against a known solution. The objectives were twofold: (1) to evaluate the ability of Scatter Search to pick a known best solution for a single BMP given multiple pollutant performance functions and multiple pollutant load reduction objective criteria, and (2) to evaluate the ability of NSGA-II to generate a cost-effectiveness curve for a known, linear solution for a single BMP.

For the known best solution, a hypothetical BMP was constructed that reduced both sediment and total nitrogen loads. The properties of this BMP were specified to yield a sediment removal effectiveness that was exactly double its nitrogen removal effectiveness. The cost-effectiveness curves were divided into 10 equally spaced intervals. The objective functions for the optimization tests were to minimize the cost of achieving 20 percent, 40 percent, and 90 percent pollutant removal for both sediment and nitrogen (for a total of six hypothetical scenarios, labeled A through F). The scenario objective functions and results are as follows:

A. Minimize the cost to achieve a 20 per cent sediment and 10 per cent nitrogen removal. There is a minimum cost solution that achieves both of these criteria.

B. Minimize the cost to achieve a 20 per cent sediment and 20 per cent nitrogen removal. Nitrogen is the limiting pollutant that increases optimal cost from Scenario A.

C. Minimize the cost to achieve a 40 per cent sediment and 20 per cent nitrogen removal. There is a minimum cost solution that achieves both of these criteria.

D. Minimize the cost to achieve a 40 per cent sediment and 40 per cent nitrogen removal. Nitrogen is the limiting pollutant that increases optimal cost from Scenario C.

E. Minimize the cost to achieve a 90 per cent sediment and 40 per cent nitrogen removal. There is a minimum cost solution that achieves both of these criteria.

F. Minimize the cost to achieve a 90 per cent sediment and 90 per cent nitrogen removal. There is no possible solution that can achieve both of these criteria.

The scenario results are presented in Figure 2-4, where the green circles represent both the known solution and the solution selected by the optimizer.

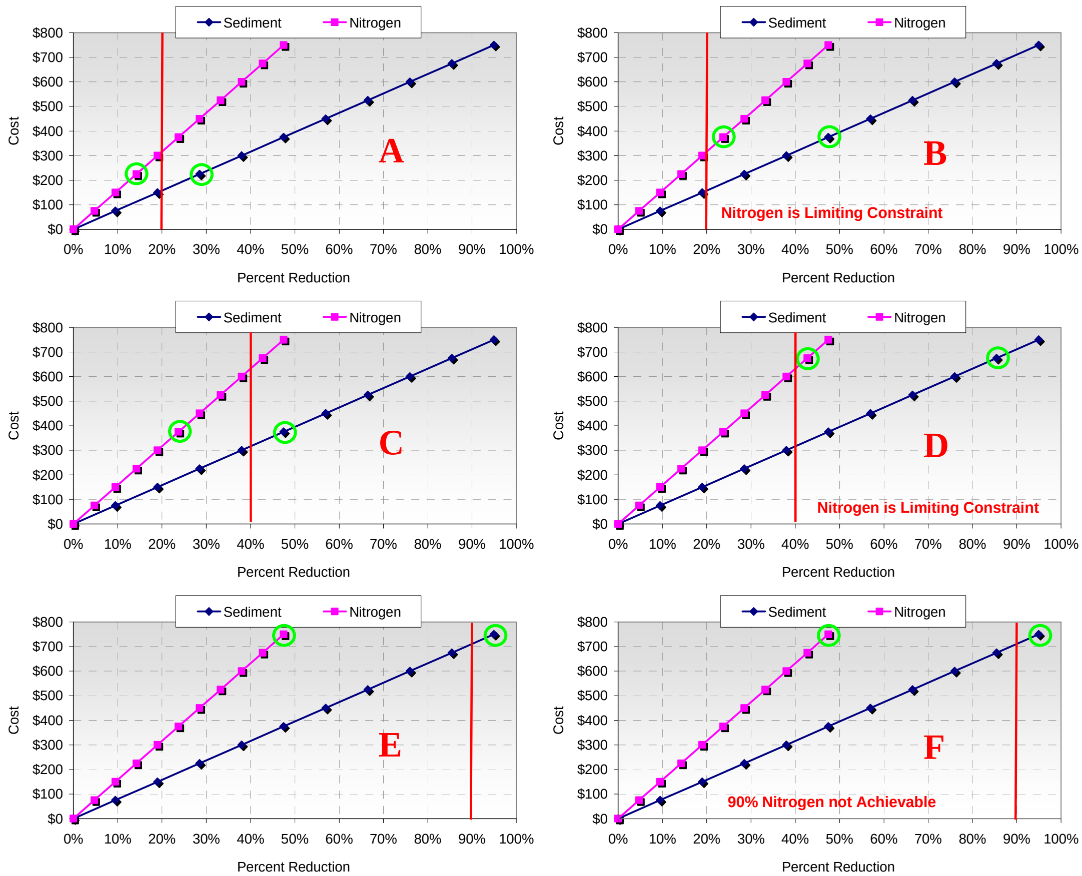

Figure 2-4. **Scatter Search evaluation scenario results.**

The ability of NSGA-II to find and create the linear nitrogen and sediment removal cost-effectiveness curves was also evaluated. Figure 2-5 shows the NSGA-II solution plotted against the known linear solutions. Both the Scatter Search and NSGA-II optimization techniques were able to find a known linear solution with 100 percent efficiency (in terms of accuracy). In addition, both optimization techniques were able to select an optimum solution, given multiple objectives for controlling sediment and nitrogen simultaneously. Finally, the NSGA-II technique was able to predict a known linear cost-effectiveness curve.

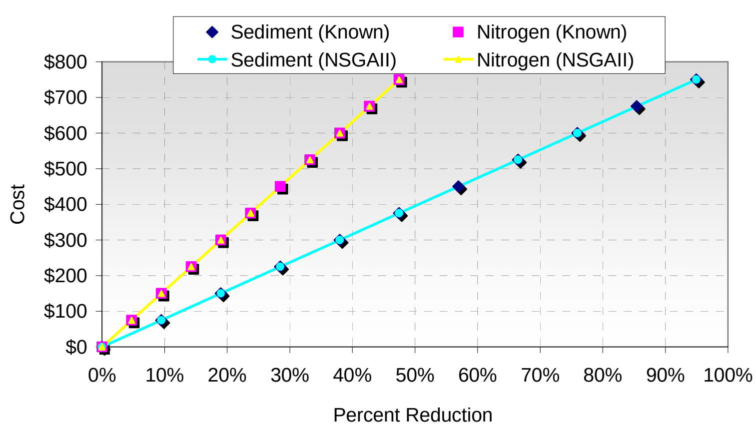

Figure 2-5. **NSGA-II evaluation scenario results.**

Operationally, *SUSTAIN*'s optimization module incorporates a tiered approach that allows for cost-effectiveness evaluation of both individual and multiple, nested watersheds to address the needs of both regional- and local-scale applications.

2.4. Post-Processor

The interpretation of time series results can be a daunting task, especially when multiple output locations, scenarios (e.g., without BMPs, with BMPs, and pre-developed conditions), and parameters of interest (e.g., inflows, outflows, pollutant loads and concentrations) must be considered. Natural precipitation-driven process simulation also produces a highly variable set of responses, ranging in magnitude, duration, intensity, treatment containment volume, attenuation, and pollutant removal effectiveness. This information is stored at hourly or sub-hourly intervals, and can span several years, depending on the length of simulation.

The primary objective of *SUSTAIN*'s post-processor is to mine the modeling results to derive the most meaningful data to characterize the effectiveness of management strategies. The post-processor achieves this objective through the use of graphical and tabular reports of the model output. The post-processor uses Microsoft Excel 2003 to develop the following four analysis components of the model outputs.

Storm Event Classification—This component evaluates the precipitation data that drive the simulation and categorizes them into a series of storm events on the basis of predefined criteria for duration and antecedent moisture conditions. It produces a set of precipitation events over which BMP performance will be evaluated (Figure 2-6, for details regarding interpretation of the graph see Section 3.6).

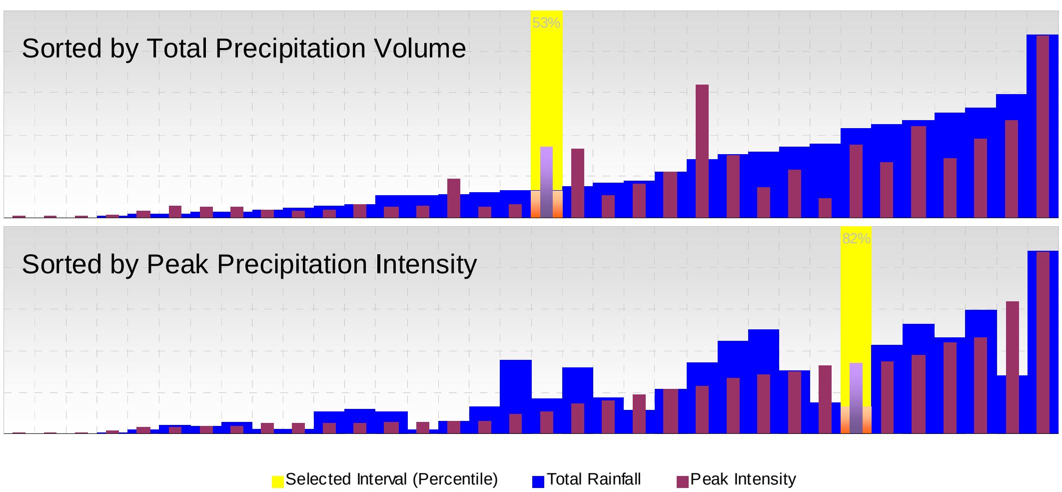

Figure 2-6. Example storm event classification graph.

Storm Event Viewer—This component is used to visualize BMP performance hydrographs and pollutographs for specific storm events. It provides performance measurements at an assessment point for the specified storm events (Figure 2-7, for details regarding interpretation of the graph, see Section 3.6).

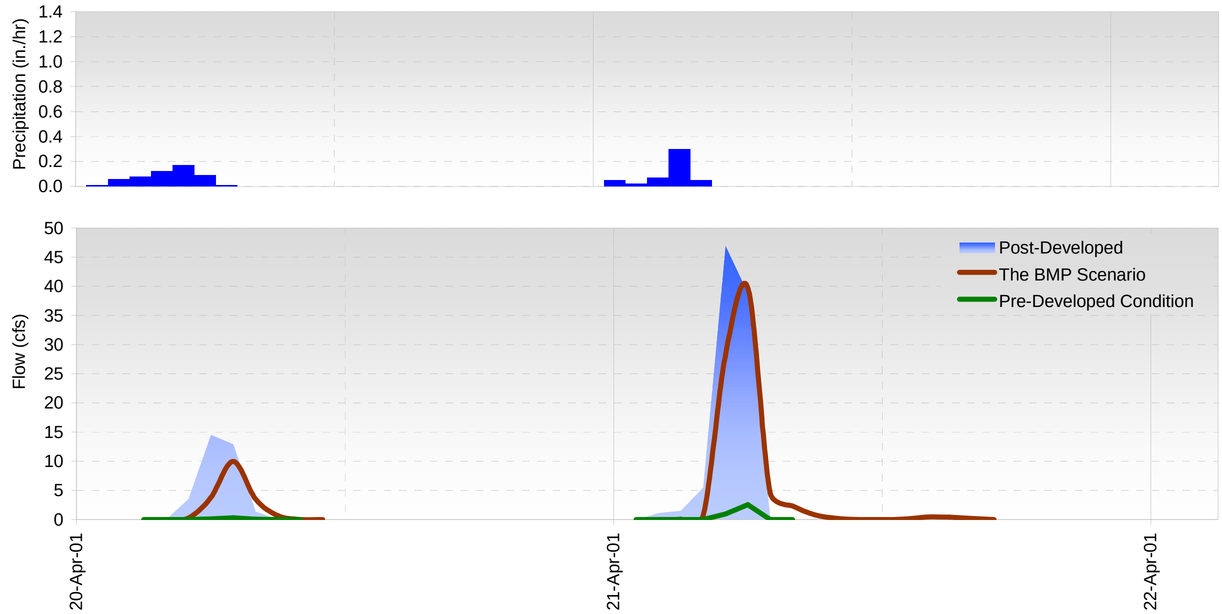

Figure 2-7. Example storm event viewer graph.

Performance Summary Report—This component summarizes the performance of the modeled management strategy for all defined storm events. It paints a picture of the types of storms that are contained at the selected assessment point, as well as those that are bypassed and untreated. The report can be used to identify appropriate design storms that meet a specified treatment objective for modeling evaluation (Figure 2-8, for details regarding interpretation of the graph see Section 3.6).

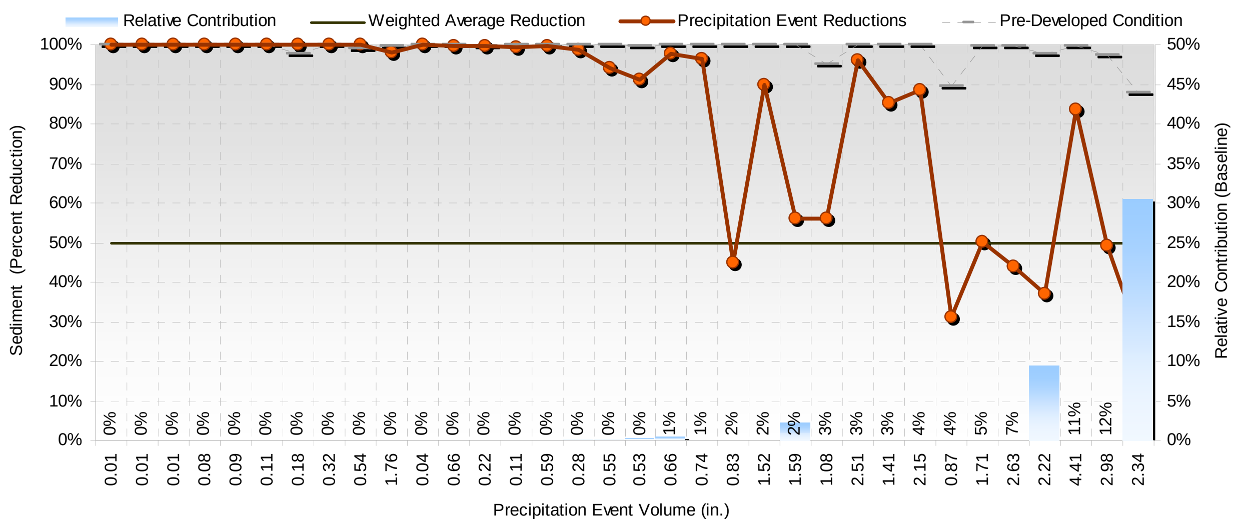

Figure 2-8. Example performance summary report graph.

Cost-Effectiveness Report—This component generates the cost-effectiveness curve at a specified assessment point and plots other inferior solutions that were attempted during the simulation. It also characterizes several key indicators associated with the cost-effectiveness curve, such as BMP surface storage volume, surface area, and soil storage volume. The knowledge of how these indicators change at various points along the cost-effectiveness curve would help develop cost-effective strategies (Figure 2-9, for details regarding interpretation of the graph, see Section 3.6).

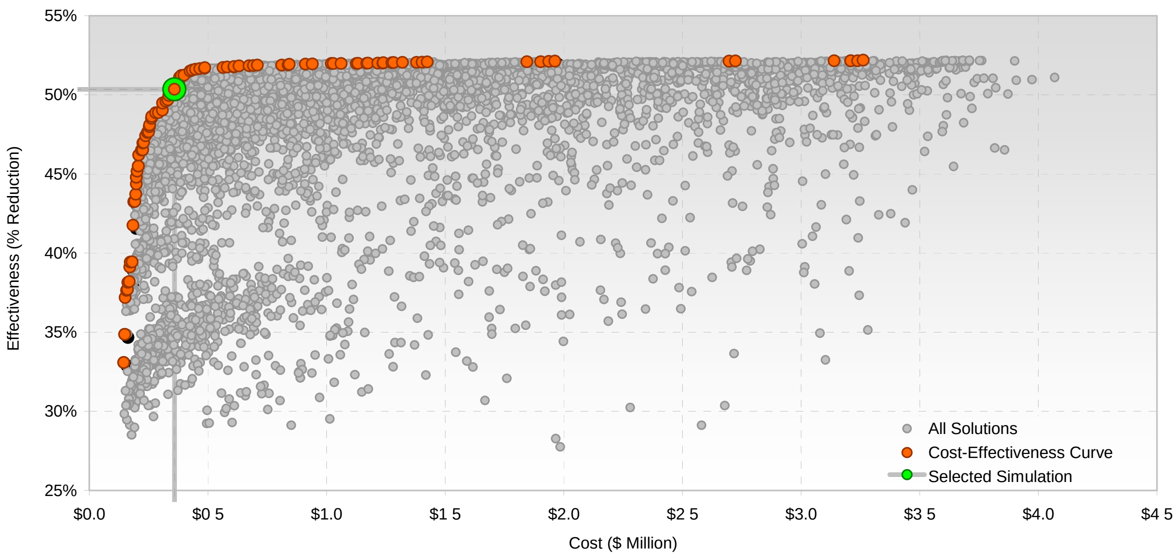

Figure 2-9. Example cost-effectiveness curve.

2.5. Summary

This chapter provided an overview of the structure of *SUSTAIN*, system requirements, major simulation and optimization modules, input data processing and output results interpretation, and interoperational linkages among the modules. The framework has been designed to maximize computational efficiency while preserving the flexibility to represent a wide range of watershed conditions and management practice configurations.

Chapter 3 provides a detailed description of each module and relevant algorithms, and the technical underpinnings and assumptions associated with the framework.

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Chapter 3 Simulation Methods and Algorithms

This chapter describes the methods and algorithms that were built into *SUSTAIN*. *SUSTAIN's* simulation capabilities are embedded in three modules—land simulation, BMP simulation, and conveyance simulation—that are used in combination to support a range of watershed simulation needs and are tied together by an overarching framework manager that performs data management, BMP site selection, the routing network creation, and other functions. In addition to the simulation modules, *SUSTAIN* includes an optimization module to evaluate and identify cost-effective BMP placement strategies and a post-processor to facilitate analysis and interpretation of model results. Table 3-1 summarizes an overview of the modules, components, and methods included in *SUSTAIN*.

The FM serves as the command module of *SUSTAIN* to manage data for system functions, provide linkages between the system modules, and create the necessary routing network required for simulation and optimization activities.

In the land simulation module, 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 2001); the particle size distribution for the eroded sediments is represented as fractional distribution of sand, silt, and clay.

The BMP module uses a combination of process-based algorithms, including weir and orifice control structures, flow routing and pollutant transport, infiltration, evapotranspiration, and pollutant loss/decay simulation. A functional BMP module was incorporated by adopting the Prince George's County BMP Module (Tetra Tech 2001). The module was further enhanced by adding continuous stir tank reactors (CSTRs) in series and associated pollutant removal based on Kadlec and Knight's (1996) k'–C* model, a Green-Ampt infiltration option, and dynamic simulation of evapotranspiration. For stream buffer strip simulation, the process-based algorithm applied in the VFSMOD was adopted.

The conveyance simulation module is used to simulate movement of water and pollutants among the physical parts of the watershed (land, BMP, conduit, reach). The module simulates flow and pollutant routing and employs the kinematic wave and CSTR approach used in the SWMM Transport compartment. A sediment transport component that employs the well-known algorithms from the HSPF and LSPC models is included.

This chapter documents the function, design, inputs, and outputs of each *SUSTAIN* module and all associated components.

Table 3-1. Modules and Components in *SUSTAIN*

Module	Component	Methodology
Framework Manager	Data management component	Path identification GIS Interfaces
	BMP site selection component	ArcGIS Site suitability criteria Highlighted suitability areas
	Routing network component	ArcGIS interfaces
Land module	Weather component	Precipitation Snowmelt Evaporation
	Hydrology component	Internal simulation Infiltration: Green-Ampt equation Overland flow Groundwater flow External simulation Unit area flows and loads File linkages
	Water quality component	Erosion Pollutant buildup Pollutant washoff Particle size distribution
BMP module	Simulation component	Storage routing method Infiltration/filtration methods Evapotranspiration method Underdrain method Pollutant routing and removal methods
	Buffer strip component	Overland flow routing Pollutant interception
	Aggregate BMP component	Interception Treatment Storage
	Cost database component	Unit area cost estimates Construction components
Conveyance module	Routing component	Flow routing Sediment Transport pollutant routing
Optimization module		Problem formulation NSGA-II Scatter Search Tiered analysis
Post-processor	Storm evaluation Storm viewer Performance summary report Cost-effectiveness report	

3.1. Framework Manager

Table 3-2 provides an overview of the required inputs, the methods used to manage and process the inputs and the resulting outputs from the FM module of *SUSTAIN*. Three major components of the FM are described in Sections 3.1.1, 3.1.2, and 3.1.3.

Table 3-2. Summary of Inputs, Methods, and Outputs in FM

Framework Manager
Inputs
– Geodatabase file with spatial and tabular data – Cost database file – Define GIS layers and lookup tables – Define suitability criteria for BMP locations (optional) – Place BMPs at the suitable locations on the map – Define assessment point(s)
Methods
– BMP suitable locations map is created using the BMP siting tool (optional) – BMPs are placed on the map using the BMP placement tool – BMP drainage areas are delineated using the auto/manual delineation tools. The system allows importing the existing drainage areas – A routing network is created by connecting a drainage area to a BMP and a downstream BMP through a reach or a conduit conveyance system – LAND, BMP, REACH, and CONDUIT simulations are carried out by calling the dynamic link libraries compiled in visual C++
Outputs
– BMP suitable locations map – Input text file for LAND simulation module – Input text file for BMP, REACH, and CONDUIT simulation modules – Model simulation results – Display simulation results at the assessment point

3.1.1. Data Management Component

The data management component compiles and organizes the data required to run *SUSTAIN*, including geographic data in vector, raster, and/or tabular format. It also includes a cost database (BMPCosts.mdb) in Microsoft Access format. *SUSTAIN* supports the use of either a personal geodatabase or a file-based geodatabase as the primary repository for all geographic data sets. A file-based geodatabase is a collection of spatial and/or temporal data sets organized into a series of indexed folders and files. Each file-based geodatabase can store up to one terabyte of information. This option is recommended over the use of a personal geodatabase, which is limited in size to two gigabytes and does not support the storage of raster information. During various data processing steps, *SUSTAIN* creates a large number of intermediate data sets and stores them on the hard disk specified.

The data management component is navigated through two levels using GIS interfaces. The first level of data management identifies the path to the cost database, the file geodatabase, and the temporary directory where all the intermediate geographic data are stored. The second level of data management identifies the required data layers. The required data set includes land use data in raster format, a land use lookup table, stream network, DEM (mandatory for the automatic watershed delineation option), and time series data (mandatory for the external land simulation option).

3.1.2. BMP Site Selection

The BMP siting tool was developed to assist users in selecting suitable locations for different types of low impact development (LID) techniques or conventional BMPs. The tool is implemented using ESRI's ArcView 9.3 and the Spatial Analyst extension. Site suitability is used as the dominant factor in identifying potential site locations (USEPA 1999a). Using GIS analysis and up to eight base data layers, the siting tool helps users identify suitable sites for placement of structural BMPs on the basis of suitability criteria including elevation, slope, soil type, urban land use, roads, water table depth, stream location, and drainage area. Table 3-3 describes these eight GIS data layers that are used as the base input data for the tool.

Table 3-3. GIS Data Requirement for BMP Suitability Analysis

GIS Layer	Format	Description
DEM	Raster file	The DEM is used to calculate the drainage slope and drainage area that are used to identify the suitable locations for BMPs.
NLCD Land Use	Raster file	The USGS Multi-Resolution Land Characteristics Consortium NLCD land use grid is used to eliminate the unsuitable areas for BMPs.
Percent Imperviousness	Raster file	The impervious grid is used to identify the suitable locations for BMPs for the given suitability criteria.
Soil	Shape file	The soil data contain the soil properties such as hydrological soil group, which are used to identify suitable locations for BMPs.
Urban Land Use	Shape file	The urban land use data contain the boundaries for the buildings and the impervious areas needed to identify suitable locations for LIDs.
Road	Shape file	The road layer is used to identify suitable locations for some BMPs that must be placed within a specific road buffer area.
Stream	Shape file	The stream layer is used to define a buffer so that certain BMP types can be placed outside the buffer to minimize the impact on streams.
Groundwater Table Depth	Shape file	The groundwater table depth layer is used to identify suitable locations for the infiltration BMPs; derived from monitoring data.

Source: Lai et al. 2007

The siting tool uses a site suitability criteria matrix and is populated with default criteria that the user can change to his or her preference or local knowledge. The default criteria in the tool as shown in Table 3-4 are derived from two EPA reports (USEPA 2004a, 2004b). Users can modify these criteria through the interface.

The output of the BMP siting tool analysis is a spatial map that highlights the areas that meet the selected default or user-specified site criteria for placement of the available BMPs. The system stores the data in the BMP suitability map that can be used as a backdrop during the placement of BMPs for simulation runs. Multiple spatial maps can be created for project areas on the basis of the various criteria selected by the user. Users can also import additional data sets or geographic coverages to further refine the utility of the spatial maps. For example, if BMPs can be placed only on publicly owned land, an ownership layer can be superimposed on the siting tool results to highlight potential BMP placement locations on such land.

Table 3-4. **Default Criteria for BMP Suitable Locations Used in *SUSTAIN***

BMP	Site Suitability Criteria							
	Drainage Area (acre)	**Drainage Slope (%)**	**Imperviousness (%)**	**Hydrological Soil Group**	**Water Table Depth (ft)**	**Road Buffer (ft)**	**Stream Buffer (ft)**	**Building Buffer (ft)**
Bioretention	< 2	< 5	> 0	A–D	> 2	< 100	> 100	-
Cistern	--	--	--	--	--	--	--	< 30
Constructed Wetland	> 25	< 15	> 0	A–D	> 4	--	> 100	--
Dry Pond	> 10	< 15	> 0	A–D	> 4	--	> 100	--
Grassed Swale	< 5	< 4	> 0	A–D	> 2	< 100	--	--
Green Roof	--	--	--	--	--	--	--	--
Infiltration Basin	< 10	< 15	> 0	A–B	> 4	--	> 100	--
Infiltration Trench	< 5	< 15	> 0	A–B	> 4	--	> 100	--
Porous Pavement	< 3	< 1	> 0	A–B	> 2	--	--	--
Rain Barrel	--	--	--	--	--	--	--	< 30
Sand Filter (non-surface)	< 2	< 10	> 0	A–D	> 2	--	> 100	--
Sand Filter (surface)	< 10	< 10	> 0	A–D	> 2	--	> 100	--
Vegetated Filterstrip	--	< 10	> 0	A–D	> 2	< 100	--	--
Wet Pond	> 25	< 15	> 0	A–D	> 4	--	> 100	--

To conceptualize the physical function of BMPs with regard to their associated landscape, four categories (or types) of BMPs are presented in the siting tool: (1) point LID, (2) point BMP, (3) linear BMP, and (4) area BMP. Point BMPs and LID include practices that capture upstream drainage at a specific location and can use a combination of detention, infiltration, evaporation, settling, and transformation to manage flow and remove pollutants. Linear BMPs are narrow linear shapes adjacent to stream channels that provide filtration of runoff; nutrient uptake; and ancillary benefits of stream shading, wildlife habitat, and aesthetic value. Area BMPs are land-based management practices that affect impervious area, land cover, and pollutant inputs (e.g., fertilizer, pet waste). Table 3-5 shows the structural BMP options included in BMP siting tool.

Table 3-5. Structural BMP Options Available in the BMP Siting Tool

BMP Option	BMP Type
Bioretention	Point LID
Cistern	Point LID
Constructed Wetland	Point BMP
Dry Pond	Point BMP
Grassed Swale	Linear BMP
Green Roof	Area BMP
Infiltration Basin	Point BMP
Infiltration Trench	Linear BMP
Porous Pavement	Area BMP
Rain Barrel	Point LID
Sand Filter (non-surface)	Linear BMP
Sand Filter (surface)	Point BMP
Vegetated Filterstrip	Linear BMP
Wet Pond	Point BMP

3.1.3. Routing Network

The system routing network as conceptualized in Figure 3-1 provides the connectivity among the various simulation components (land, BMP, conduit, reach) at the watershed level. After placing BMPs on the map and creating the drainage area for each BMP, the framework manager creates the routing network by connecting the land segments that drain to each BMP and connecting each BMP to the downstream BMP through a reach or conduit segment. The connections are made automatically if the DEM is used to delineate the drainage areas. Alternatively, those connections can be made manually using the network tools in the framework manager interface.

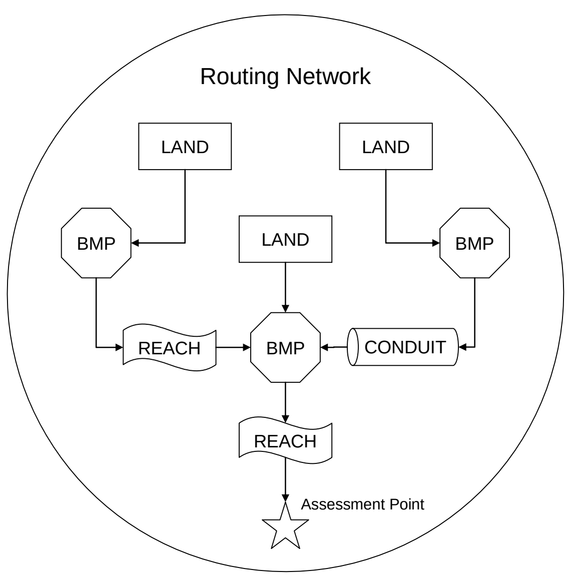


Figure 3-1. The routing network showing the connections among the simulation components.

3.2. Land Module

The land simulation module is used to derive runoff and pollutant loads from the land in one of two ways. By default, the land module computes the hydrograph and pollutograph using algorithms adapted from the SWMM (version 5) land surface compartment and sediment algorithms adapted from the HSPF model. That is called the internal simulation option, which has been tested and verified to ensure accurate transformation of the code from the original models. The second option is to use externally generated time series to represent hydrology and water quality at the landscape level. The external option allows importation of the hydrograph and pollutograph for each land use category from a pre-calibrated external watershed model such as HSPF or LSPC.

Figure 3-2 is a schematic of the land simulation processes that produce runoff from land including time-varying rain or snow accumulation and melting, evaporation from ponded surface, infiltration of rain or snowmelt into unsaturated soil, percolation of infiltrated water into groundwater, and nonlinear reservoir routing of overland flow.

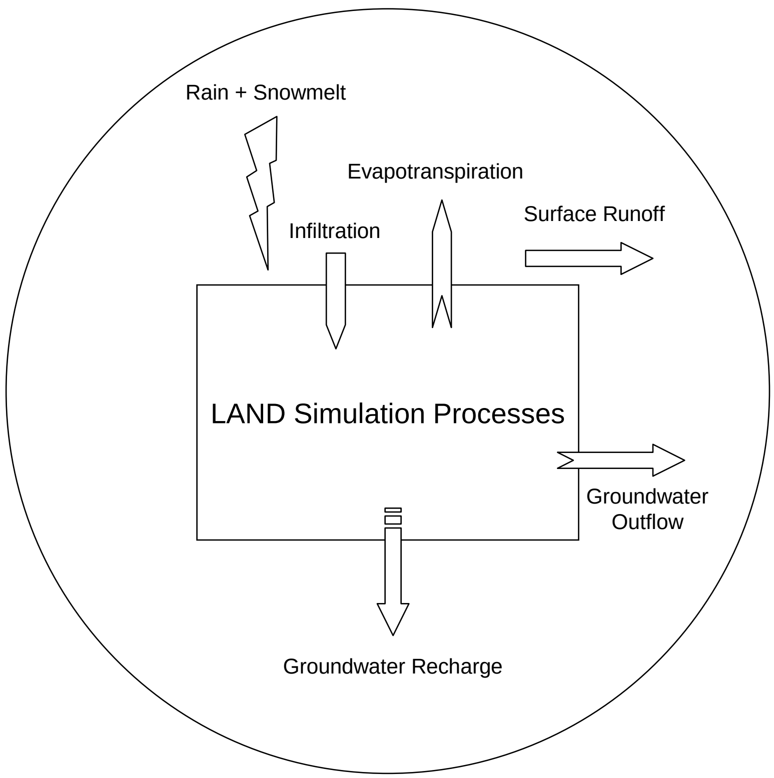


Figure 3-2. Schematic showing the land simulation processes.

Table 3-6 provides an overview of the required inputs, the methods used to process the inputs and simulate the hydrologic and water quality processes occurring on the landscape, and the resulting outputs of the land simulation module.

Table 3-6. Inputs, Methods, and Outputs of the Land Module

Land Module
Inputs Internal Option – Define pollutants – Define fraction of total sediments as sand, silt, and clay from each land use category – Reclassify/group land use categories (optional) – Define meteorological data (user-defined time step) – Define pollutant properties – Define land use properties – Define rain gauge properties – Define aquifer properties (optional) – Define snowpack properties (optional) – Define watershed properties External Option – Hourly time step – Define pollutants – Define fraction of total sediments as sand, silt, and clay from each land use category – Reclassify/group land use categories (optional) – Assign pre-calibrated land output time series for each land use group
Methods Internal Option – Weather data is processed to convert precipitation values to snow or rain according to the temperature – Snowmelt is computed using the degree-day and National Weather Service equations – Evapotranspiration is calculated using a constant ET rate or time series values supplied by the user – Infiltration is computed using the Green-Ampt equation – Overland flow is computed using the Manning's equation – Groundwater outflow is computed as a function of groundwater and surface water heads – Production and removal of sediments on pervious land is computed using the processed-based algorithms adopted from the HSPF model – Buildup and washoff of sediments on impervious land is computed using the algorithms adopted from the SWMM – Total sediment is divided into three sediment classes (sand, silt, and clay) according to a user-specified fraction for each class from each land use category – Pollutants buildup and washoff rates are computed using the functions adopted from the SWMM – Outflow, sediment, and pollutants are aggregated for all land use categories External Option – Total sediment is divided into three sediment classes (sand, silt, and clay) according to a user-specified fraction for each class from each land use category – Within each catchment area, unit-area outflow, sediment, and pollutant loads for each land unit are multiplied by actual land area to derive aggregate land contribution
Outputs – Hourly outflow time series – Hourly sediment (sand, silt, and clay) concentration time series – Hourly pollutant concentration time series

Three major components compose the land simulation module: weather, hydrology, and water quality. Multiple options are provided for representing various processes as are outlined in Table 3-7.

Table 3-7. Land Simulation Methods Used in *SUSTAIN*

Process	Option 1	Option 2	Option 3	Reference
Rainfall	Weather data file	--	--	Rossman 2005
Snowmelt	Degree-Day equation; NWS equation	--	--	Rossman 2005
Evaporation	Constant value	Monthly average value	User-supplied time series	Rossman 2005
Infiltration	Green-Ampt	--	--	Rossman 2005
Groundwater flow	Modified two-zone groundwater model	--	--	Rossman 2005 Bicknell et al. 2001
Overland flow	Non-linear reservoir	--	--	Rossman 2005
Pollutant buildup	Power function	Exponential function	Saturation function	Rossman 2005
Pollutant washoff	Exponential function	Rating curve	Event mean concentration	Rossman 2005
Street cleaning	User-specified pollutant removal efficiency	--	--	Rossman 2005
Sediment erosion and transport	Production and removal from the pervious land; Buildup and washoff from the impervious land	--	--	Bicknell et al. 2001 Rossman 2005
Particle size distribution	User defined (sand, silt, clay)	--	--	Bicknell et al. 2001

The following paragraphs explain in greater detail the methods and algorithms implemented in the weather, hydrology, and water quality components of the land simulation module.

3.2.1. Weather Component

The weather component of the land module is adapted from the SWMM atmospheric compartment (Rossman 2005) that uses the daily air temperature, evaporation, and wind speed data from the user-specified climate file. The format for climate file is consistent with that used in the SWMM, where each line in the file contains a recording station name, year, month, day, maximum temperature, minimum temperature, and optionally, the evaporation rate and wind speed. The data must be in U.S. units: temperature in degrees F, evaporation in in./day, and wind speed in mi/hr, all separated by one or more spaces.

An excerpt from the climate file format might look as follows:

ST93738 2007 1 1 43 32 0.12 13.9
ST93738 2007 1 2 45 23 0.04 5.84
ST93738 2007 1 3 54 24 0.07 4.21

The precipitation data is input in a separate file where each line of the file contains the station ID, year, month, day, hour, minute, and non-zero precipitation reading, all separated by one or more spaces.

An excerpt from the precipitation file format might look as follows:
ST448903 2007 1 1 00 00 0.12
ST448903 2007 1 1 01 00 0.04
ST448903 2007 1 2 16 00 0.07

Precipitation

SUSTAIN's land simulation module uses the precipitation data type in any one of these three formats: (1) intensity, where the value is an average rate (in./hr) over the recording interval; (2) interval volume, where the value is the volume of rain that fell in the recording interval (in.); or (3) cumulative volume, where the value represents the cumulative rainfall that has occurred since the start of the last series of non-zero values (in.). The precipitation values are converted to snow amount according to the user-specified temperature below which precipitation falls as snow instead of rain (Rossman 2005).

Snowmelt

Snowmelt is computed at each step using a degree-day equation when it is dry and the National Weather Service (NWS) River Forecast System – Snow Accumulation and Ablation Model (Anderson 1973) during rainfall periods (Huber and Dickinson 1988). The two equations are presented below.

Degree-Day Equation

During periods of no rainfall, snowmelt is computed by the Degree-Day equation:

$$Smelt = DHM \times \left(T_a - T_{base}\right) \tag{3-1}$$

where

$Smelt$ = snowmelt rate (water equivalent in./hr),
DHM = melt coefficient (water equivalent in./hr-^{o}F),
T_a = air temperature (^{o}F), and
T_{base} = snowmelt base temperature (^{o}F).

NWS Equation

During periods of rain, snowmelt is computed using Anderson's (1973) NWS equation. Anderson combines the appropriate terms for each heat budget component into one equation for the melt rate:

$$Smelt = \left(T_a - 32\right) \times \left(0.00167 + S_\gamma \times U_{adj} + 0.007 \times Prec\right) + 8.5 \times U_{adj} \times \left(EA - 0.18\right) \tag{3-2}$$

where

$Smelt$ = snowmelt rate (water equivalent in./hr),
T_a = air temperature (^{o}F),
$S_\gamma = 7.5\ \gamma$ (in.-Hg/^{o}F),
γ = psychometric constant (in.-Hg/^{o}F),
U_{adj} = wind speed function (in./in.-Hg-hr),
$Prec$ = rainfall intensity (in./hr), and
EA = saturation vapor pressure at air temperature (in.-Hg).

The psychometric constant γ is calculated as

$$\gamma = 0.000359 \times PA \tag{3-3}$$

where

γ = psychometric constant (in.-Hg/$^{\circ}$F) and

PA = atmospheric pressure (in.-Hg).

Average atmospheric pressure is calculated as a function of elevation, z:

$$PA = 29.9 - 1.02 \left[\frac{z}{1000}\right] + 0.0032 \left[\frac{z}{1000}\right]^{2.4} \tag{3-4}$$

where

z = average elevation (ft).

The wind speed function, U_{adj}, accounts for turbulent transport of sensible heat and water vapor. Anderson (1973) gives the following equation:

$$U_{adj} = 0.006\ u \tag{3-5}$$

where

U_{adj} = wind speed function (in./in.-Hg-hr) and
u = average wind speed (mi/hr).

The saturation vapor pressure, EA, is given by the following exponential approximation:

$$EA = 8.1175 \times 10^{6} \times exp\left[\frac{-7701.544}{\left(T_a + 405.0265\right)}\right] \tag{3-6}$$

where

EA = saturation vapor pressure at air temperature (in.-Hg) and
T_a = air temperature (°F).

Evaporation

Evaporation is calculated for standing water on land surfaces, subsurface water in groundwater aquifers, and water held in storage units. On the basis of the approach used in SWMM, evaporation is subtracted from the rainfall or water storage area prior to calculating infiltration. Evaporation rates can be stated as one of these three forms: a single constant value, a set of monthly average values, or a user-supplied time series input in the climate data file. If a climate file is used, the user-specified monthly pan coefficients are used to convert the pan evaporation data to free water-surface values (Rossman 2005).

3.2.2. Hydrology Component

The hydrology component simulates the rainfall runoff processes and provides the linkage between the meteorological information and movement of water into and across the land surface. The methods selected provide time variable response to meteorological inputs while using well-established methods for simulation. By building on methods that are established in the literature, users can rely on literature values and industry practice to develop input parameters for initial application and to use as a starting point for calibration.

The hydrology component of the land simulation module is adapted from the SWMM land surface and groundwater compartments (Rossman 2005). *SUSTAIN* uses the Green-Ampt method to compute the amount of infiltration of rainfall on the pervious land area into the unsaturated upper soil zone. The surface runoff is computed using Manning's equation.

Infiltration Using Green-Ampt Equation

The Green-Ampt infiltration method assumes that a sharp wetting front exists in the soil column which separates the unwetted 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).

If $I \leq K_s$, then $f = I$;

If $I > K_s$, then $f = I$, until $F = F_s = \dfrac{(\theta_s - \theta_i) \times \psi_f}{1 - I/K_s}$

Following surface saturation,

$$f = \frac{dF}{dt} = K_s \left[1 + \frac{(\theta_s - \theta_i) \times \psi_f}{F} \right] \qquad (3\text{-}7)$$

For $I > K_s$, and $f = I$ for $I \leq K_s$

where

I = inflow rate (in./hr),
F = amount of infiltration (in.),
F_s = amount of infiltration up to surface saturation (in.),
F = infiltration rate (in./hr),
K_s = saturated hydraulic conductivity (in./hr),
θ_s = saturated moisture content,
θ_i = initial moisture content, and
ψ_f = average wetting front suction head (in. of water).

This differential equation is solved iteratively to determine f at each time step by using Newton-Raphson method. The infiltration volume during the time interval is equal to the inflow volume if the surface does not saturate. If saturation occurs during the time interval, the infiltration volumes over each stage of the process within the time steps are calculated and summed. When there is no inflow, any water ponded on the surface is allowed to infiltrate and added to the cumulative infiltration volume. In using the Green-Ampt method, a complication occurs when the inflow rate starts at a value above, drops below, and then rises above K_s again during the infiltration computation. In such a case, the moisture content needs to be redistributed as the assumption of saturation from the surface down to the wetting front does not hold. A major advantage of the Green-Ampt method is that the input parameters (i.e., K_s, ψ_f, θ_s, θ_i) can be determined from physical measurements. As shown in Table 3-8, Rawls et al. (1983) provide typical values for the parameters.

Overland Flow

The conceptual view of the surface runoff calculation in *SUSTAIN* is illustrated in Figure 3-3, which is adapted from the SWMM5 user's manual (Rossman 2005). The surface of each subwatershed is treated as a nonlinear reservoir. Inflow comes from precipitation and upstream subwatersheds. The outflows are infiltration, evaporation, and surface runoff to downstream areas. The maximum surface storage capacity is composed of ponding volume, surface wetting volume, and interception volume, normalized by surface area and is represented as depth. Surface runoff per unit area, Q, occurs only when the surface water depth exceeds the maximum surface storage depth, d_p, in which case the outflow is given by Manning's equation:

$$Q = W \frac{1.49}{n} (d - d_p)^{5/3} S^{1/2} \tag{3-8}$$

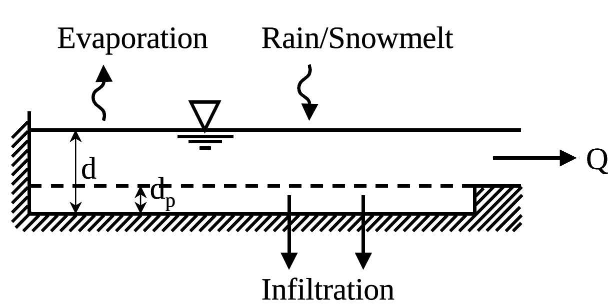
where

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

Table 3-8. Green-Ampt Parameters

Soil Texture Class	Saturated Hydraulic Conductivity (in./hr)	Suction Head (in.)	Porosity (Fraction)	Field Capacity (Fraction)	Wilting Point (Fraction)
Sand	4.74	1.93	0.437	0.062	0.024
Loamy Sand	1.18	2.40	0.437	0.105	0.047
Sandy Loam	0.43	4.33	0.453	0.190	0.085
Loam	0.13	3.50	0.463	0.232	0.116
Silt Loam	0.26	6.69	0.501	0.284	0.135
Sandy Clay Loam	0.06	8.66	0.398	0.244	0.136
Clay Loam	0.04	8.27	0.464	0.310	0.187
Silty Clay Loam	0.04	10.63	0.471	0.342	0.210
Sandy Clay	0.02	9.45	0.430	0.321	0.221
Silty Clay	0.02	11.42	0.479	0.371	0.251
Clay	0.01	12.60	0.475	0.378	0.265

Source: Rawls et al. 1983



Source: Rossman 2005

Figure 3-3. Conceptual view of surface runoff.

Subwatershed width (W) can be estimated by dividing the subwatershed area by the length of the representative flow path. The depth of water over the subwatershed is continuously updated with time by solving a water balance Equation (3-9) for the subwatershed.

$$\frac{dd}{dt} = i_e - \frac{1.49W}{A \cdot n}(d - d_p)^{5/3} S^{1/2} = i_e + WCON(d - d_p)^{5/3} \quad (3\text{-}9)$$

$$WCON = -\frac{1.49 \cdot W \cdot S^{1/2}}{A \cdot n} \quad (3\text{-}10)$$

where

WCON = parameter for overland flow routing,
d = water depth (ft),
t = time (sec),
W = subwatershed width (ft),
A = surface area of subwatershed (ft^2),
n = Manning's roughness coefficient,
i_e = rainfall excess (ft/s),
d_p = depth of depression storage (ft), and
S = subwatershed slope (ft/ft).

Groundwater Flow

Accounting for groundwater inputs is of greater significance with larger watersheds for the purpose of accounting for baseflow in streams. Groundwater simulation provides an important link between surface and subsurface flow. In *SUSTAIN*, groundwater flow is simulated using the SWMM formulation (Rossman 2005). It also employs some modifications based on HSPF techniques for simulating the interaction between saturated soil water and unsaturated soil water when the water table approaches or rises above the ground (Bicknell et al. 2001). Those modifications were made to smooth out the groundwater outflow response to account for the interaction of rising groundwater storage with the unsaturated zone storages, cohesive water storage, and gravity water storage. Without those modifications, the groundwater level is a function of gravity storage only. The water in cohesive water storage is not available for groundwater outflow but is subject to evapotranspiration. It is assumed in *SUSTAIN* that there is no interaction between land groundwater and BMP deep percolation. Deep percolation water from BMPs is lost from the system.

Two-zone Groundwater Model from SWMM

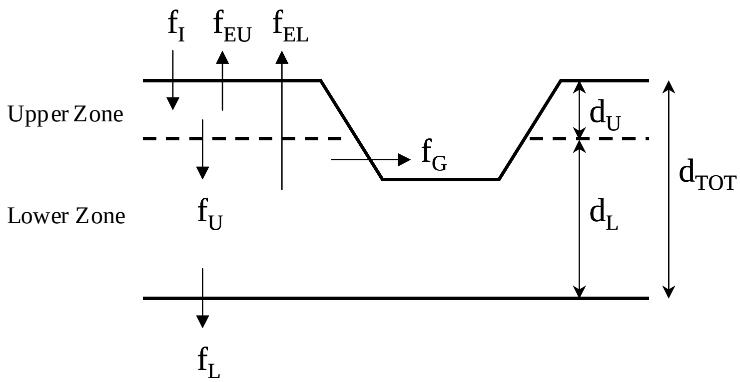
In this formulation, groundwater flow is a function of groundwater and surface water heads in the discharge channel, as shown in Equation (3-11).

$$Q_{gw} = A_1 (H_{gw} - E)^{B_1} - A_2 (H_{sw} - E)^{B_2} + A_3 H_{gw} H_{sw} \quad (3\text{-}11)$$

where

Q_{gw} = groundwater flow (cfs),
H_{gw} = elevation of groundwater table (ft),
H_{sw} = elevation of surface water at receiving node (ft),
E = elevation of node invert (ft),
A_1 = groundwater flow coefficient,
B_1 = groundwater flow exponent,
A_2 = surface water flow coefficient,
B_2 = surface water flow exponent, and
A_3 = surface-groundwater interaction coefficient.

The SWMM's two-zone groundwater model is shown in Figure 3-4. The upper zone is unsaturated at varying moisture content, which is updated at each time step of infiltration and regeneration of infiltration capacity simulation. The lower zone is saturated, and hence its moisture content is fixed at the soil porosity.



Source: Rossman 2005

Figure 3-4. Two-zone groundwater model adapted from SWMM.

The fluxes shown in Figure 3-4 are expressed as volume per unit area per unit time and consist of the following:

f_I = infiltration from the surface;
f_{EU} = evapotranspiration from the upper zone, which is a fixed fraction of the unused surface evaporation;
f_U = percolation from the upper to lower zone, which depends on the upper zone moisture content θ and depth d_U**;**
f_{EL} = evapotranspiration from the lower zone, which is a function of the depth of the upper zone d_U**;**
f_L = percolation from the lower zone to deep groundwater, which depends on the lower zone depth d_L; and
f_G = lateral groundwater interflow to the conveyance network, which depends on the lower zone depth d_L as well as depths in the receiving channel.

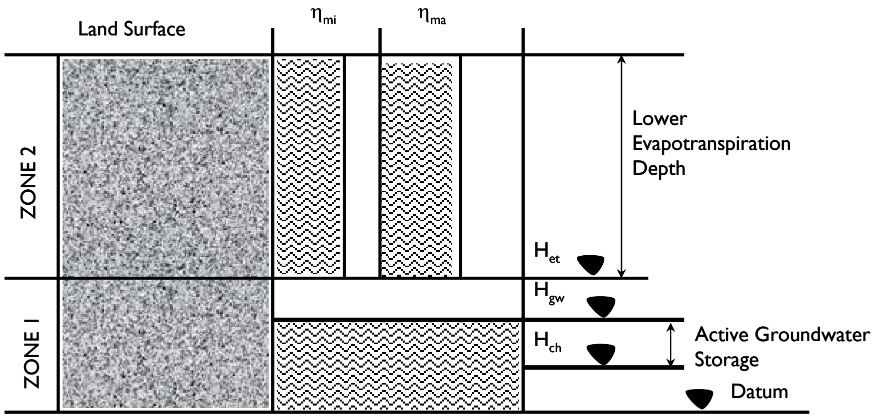
Two-zone Groundwater Interaction from HSPF

The effects of a rising water table differ under low water table and high water table conditions. A modified, two-zone groundwater representation in Figures 3-5 and 3-6 provides a higher-resolution option for characterizing subsurface conditions and improvements to runoff computation. Figure 3-5 shows the schematic of a two-zone soil moisture storage layer under low water table conditions, while Figure 3-6 illustrates that under high water table conditions.

The saturated and unsaturated zone interactions are a function of water transfer rates, existing saturation levels, and physical characteristics of the soils such as porosity. For modeling purposes, the total porosity is divided into two parts: porosity in micropores (η_{mi}, cohesion water) and porosity in macropores (η_{ma}, gravitational water). Cohesion water is bonded in soil by capillary forces, and it is roughly equal to the difference between the wilting point and field capacity. Gravitational water drains from soils in the unsaturated zone by gravity forces.

The groundwater level is the elevation of the saturated zone above an arbitrary datum such as mean sea level. The active groundwater storage is gravity water stored above the water elevation of a channel that is within or adjacent to the land. A *lower elevation* is the maximum depth where soil moisture varies seasonally due to evapotranspiration.

When the groundwater elevation is below the lower elevation (within the saturated Zone 1 as shown in Figure 3-5), there is no interaction between the saturated and the unsaturated zones. Groundwater elevation in this zone is computed as a function of the groundwater storage and the total porosity (the sum of macropores and micropores).



Source: Bicknell et al. 2001

Figure 3-5. Two-zone soil moisture storage under low water table condition.

The groundwater elevation in this zone is calculated as:

$$H_{gw} = \frac{S_{gw}}{(\eta_{mi} + \eta_{ma})} \qquad (3\text{-}12)$$

where

H_{gw} = groundwater elevation (ft),
S_{gw} = total groundwater storage (ft),
η_{mi} = soil porosity in micropores (large pores for cohesive water), and
η_{ma} = soil porosity in macropores (large pores for gravitational water).

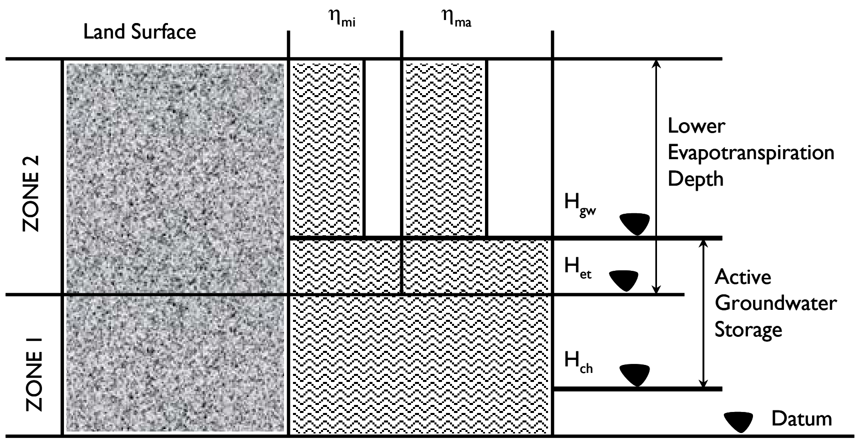
When the groundwater elevation reaches the higher elevation (within the unsaturated Zone 2 as shown in Figure 3-6), the groundwater storage starts interacting with the upper zone storages. Rising groundwater that occupies micropores is reassigned to the upper zone cohesive water storage. Groundwater storage shares macropores with the upper zone gravity water storage and is subject to evapotranspiration. Changes in groundwater storage are distributed between upper zone storages and groundwater storage, according to their relative saturation levels. Groundwater elevation in this zone is a function of upper zone water in macropores and groundwater storages and is calculated as:

$$H_{gw} = \frac{H_{et} + \left[S_{uz} + \left(S_{gw} - S_{lz}\right)\right]}{\eta_{ma}} \qquad (3\text{-}13)$$

where

H_{et} = elevation at the maximum depth due to seasonal evapotranspiration (ft),
S_{gw} = total groundwater storage (ft), including all water in the lower saturated zone and in macropores of the upper zone saturated soil,

S_{uz} = upper zone water storage in macropores of the unsaturated soil (ft), and
S_{lz} = groundwater storage below H_{et} (ft), which is equal to $H_{et} \times (\eta_{mi} + \eta_{ma})$.



Source: Bicknell et al. 2001

Figure 3-6. Two-zone soil moisture storage under high water table conditions.

When the groundwater elevation is below H_{ch}, the channel water elevation, there will be no outflow from the groundwater storage. When the groundwater elevation is above H_{ch}, the groundwater outflow is computed as a function of the active groundwater storage, i.e., the gravity water storage above the channel water level.

3.2.3. Water Quality Component

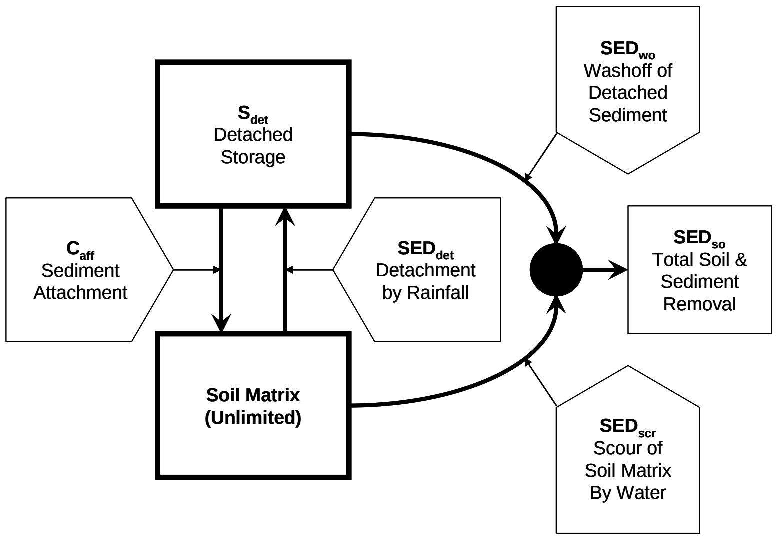
The water quality component performs the transport of pollutants on the basis of total flow (runoff and/or infiltrated groundwater outflow) computed in the hydrology component. The simulation methods included for routing of sediments and pollutants are adapted from the SWMM land surface compartment (Rossman 2005) and from HSPF for sediment production and removal from pervious lands (Bicknell et al. 2001). *SUSTAIN* can simulate the generation and transport of any number of user-defined pollutants and divides them into two major groups: sediment and non-sediment pollutants. To facilitate sediment routing, the total sediment load is divided into three sediment classes—sand, silt, and clay—and the model allows users to define their distribution fractions. For pollutants that are associated with sediment, co-fractions are used to quantify the mass of pollutant as a direct proportion of sediment mass. The total sediment/non-sediment load is simulated for each defined land use category, and then the total is summed within each subwatershed or BMP drainage area for routing to a BMP or conduit component.

Pervious Land Segment

SUSTAIN computes the sediment load using the HSPF sediment algorithms (SEDMNT) and all non-sediment pollutant loadings using the SWMM buildup and washoff algorithms for pervious land segments (Lai et al. 2007).

Production and Removal of Sediment

HSPF simulates sediment production as a function of detachment/washoff or direct scour from a soil matrix. It assumes that the soil matrix contains an unlimited supply of sediment. User-specified, physically based model parameters are used to determine the specific rates and modes of how sediment is made available for transport with runoff. For example, the supporting management practice factor in the soil detachment by rainfall equation was based on the P factor in the Universal Soil Loss equation (USLE) (Wischmeier and Smith 1965). It is introduced to better evaluate agricultural conservation practices on reducing erosion potential. Figure 3-7 represents the storages and fluxes used to simulate the detachment, attachment, and removal involved in the erosion processes on the pervious land surface.



Source: Bicknell et al. 2001

Figure 3-7. **Schematic of sediment production and removal processes.**

Removal of sediment by water is simulated as washoff of detached sediment in storage (SED_{wo}) and scour of matrix soil (SED_{scr}). The washoff process involves two parts: the detachment/attachment of sediment from/to the soil matrix and the transport of this sediment. Detachment (SED_{det}) occurs by rainfall. Attachment occurs only on days without rainfall; the rate of attachment is specified by parameter C_{affix}. Transport of detached sediment is by overland flow. The scouring of the matrix soil is simplified into one process by combining both pickup and transport by overland flow.

Sediment Detachment by Rainfall

Kinetic energy from rain falling on the sediment detaches particles which are then available to be transported by overland flow. The equation that simulates detachment is:

$$SED_{det} = \Delta t \times (1 - C_r) \times P \times K_r \times \left(\frac{P_{cp}}{\Delta t} \right)^{J_r} \qquad (3\text{-}14)$$

where

SED_{det} = sediment detached from the soil matrix by rainfall (tons/acre/interval),
Δt = number of hours/interval,
C_{r} = fraction of the land covered by snow and vegetation,
P = supporting management practice factor,
K_{r} = coefficient for detachment of soil by rainfall,
P_{cp} = rainfall (in./interval), and
J_r = exponent for detachment of soil by rainfall.

Sediment Removal by Overland Flow

When simulating the washoff of detached sediment, the transport capacity of the overland flow is estimated and compared to the amount of detached sediment available. The transport capacity is calculated by the equation:

$$SED_{cap} = \Delta t \times K_s \times \left(\frac{q_s}{\Delta t} \right)^{J_s} \tag{3-15}$$

where

SED_{cap} = transport capacity of detached sediment in overland flow (tons/acre/interval),
Δt = number of hours/interval,
K_s = coefficient for detached sediment by overland flow,
q_s = overland flow (in./interval), and
J_s = exponent for detached sediment by overland flow.

When SED_{cap} is more than the amount of detached sediment in storage (S_{det}), the flow washes off all the detached sediment storage, and SED_{wo} becomes equal to S_{det}. However, when SED_{cap} is less than S_{det}, the situation is transport limiting, so SED_{wo} is equal to SED_{cap}.

Direct detachment and transport of the soil matrix by scouring (e.g., gullying) is simulated with the equation:

$$SED_{scr} = \Delta t \times K_g \times \left(\frac{q_s}{\Delta t} \right)^{J_g} \tag{3-16}$$

where

SED_{scr} = scour of matrix soil (tons/acre/interval),
Δt = number of hours/interval,
K_g = coefficient for scour of the matrix soil,
q_s = surface flow (in./interval), and
J_g = exponent for scour of the matrix soil.

The sum of the two fluxes, SED_{wo} and SED_{scr}, represents the total sediment outflow (SED_{so}) from the land segment.

Re-attachment of Detached Sediment

Sediment attachment to the soil matrix is simulated by changes in SED_{det}. Because the soil matrix is considered to be unlimited, no addition to the soil matrix is necessary when this occurs. S_{det} is diminished at the start of each day following a day without precipitation. This decrease is calculated by multiplying S_{det} by ($1.0 - C_{affix}$), where C_{affix} is the fraction by which detached sediment storage decreases each day as a result of soil compaction. This fraction is a calibration parameter.

Pervious Land Sediment Input Parameters

Table 3-9 shows the recommended ranges of input parameters for simulating the pervious land segment. The minimum and maximum ranges given in Table 3-9 are for the numerical stability of the model. The actual values fall within those ranges and are typically defined by calibration and user experience. Additional HSPF parameterization guidance is available as part of the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) technical note series at http://www.epa.gov/waterscience/basins/docs/tecnote8.pdf (USEPA 2006).

Table 3-9. List of Sediment Input Parameters for Pervious Land

Parameters	Default Value	Min. Value	Max. Value	Units
P	1.0	0.001	1.0	none
K_r	0.0	0.0	none	-
J_r	none	none	none	-
C_{affix}	0.0	0.0	1.0	per day
C_r	0.0	0.0	1.0	none
K_s	0.0	0.0	none	-
J_s	none	none	none	-
K_g	0.0	0.0	none	-
J_g	none	none	none	-

Source: Bicknell et al. 2001

Pervious Land Sediment Erosion Calibration

The erosion process on pervious land areas is represented as the net result of detachment of soil particles by raindrop impact on the land surface and subsequent transport of the fine particles by overland flow. The primary sediment erosion calibration parameters are as follows:

K_r = coefficient in soil detachment equation (pervious area)
K_s = coefficient in sediment washoff equation (pervious area)

Although a number of additional parameters are involved in sediment erosion calibration, such as those related to vegetation cover, agricultural practices, rainfall, and overland flow intensity, K_r and K_s are the primary parameters controlling sediment loading rates. K_r is usually estimated as equal to the erodibility factor, K, in the USLE (Wischmeier and Smith 1965) and then is adjusted in calibration. K_s is primarily evaluated through calibration and past experience.

While Table 3-9 presents possible parameter ranges to ensure model stability, Table 3-10 lists the sediment parameters along with typical and possible minimum and maximum ranges of values based on application experience over the past 20 years. In addition, the HSPFParm database (USEPA 1999) provides calibrated parameter values for numerous watersheds across the United States. Additional guidance in sediment erosion calibration is provided in the HSPF Application Guide (Donigian et al. 1984).

Pollutant Buildup

In *SUSTAIN*, the amount of pollutant buildup over land is computed using one of the following functions available in SWMM, as a function of the number of preceding dry-weather days (Rossman 2005).

Power Function

Pollutant buildup, B, is accumulated proportional to time, t, raised to defined power C_3 until a maximum limit is achieved:

$$B = min\left(C_1, C_2 \times \Delta t^{C_3}\right) \tag{3-17}$$

where

B = pollutant buildup (mass per unit area, e.g., lbs/acre),
C_1 = maximum buildup possible (mass per unit area, e.g., lbs/acre),
C_2 = buildup rate constant (mass per unit area per unit time, e.g., lbs/acre/day),
C_3 = time exponent, and

Δt = time, e.g., number of days.

Table 3-10. Range of Values for Sediment Erosion Parameters for Pervious Land

Name	Definition	Units	Range of Values				Function of...	Comments
			Typical		Possible			
			Min	Max	Min	Max		
P	Management practice factor from USLE	None	0.0	1.0	0.0	1.0	Land use, agricultural practices	Use the P factor from USLE
K_r	Coefficient in the soil detachment equation	--	0.15	0.45	0.05	0.75	Soils	Estimate from the soil erodibility factor (K) in USLE
J_r	Exponent in the soil detachment equation	None	1.5	2.5	1.0	3.0	Soils, climate	Usually start with value of 2.0
C_{affix}	Daily reduction in detached sediment	Per day	0.03	0.1	0.01	0.5	Soils, compaction, agricultural operations	Reduces fine sediments following tillage
C_{sv}	Fraction land surface protected from rainfall	None	0.0	0.9	0.0	0.98	Vegetal cover, land use	Seasonal/ monthly values are often used
K_s	Coefficient in the sediment washoff equation	--	0.5	5.0	0.1	10.0	Soils, surface conditions	Primary sediment calibration parameter
J_s	Exponent in the sediment washoff equation	None	1.5	2.5	1.0	3.0	Soils, surface conditions	Usually use value of about 2.0
K_g	Coefficient in soil matrix scour equation	--	0.0	0.5	0.0	10.0	Soils, evidence of gullies	Calibration, used only if there is evidence of gullies
J_g	Exponent in soil matrix scour equation	None	1.0	3.0	1.0	5.0	Soils, evidence of gullies	Usually use value of about 2.5

Source: Donigian and Love 2003

Exponential Function

Pollutant buildup, B, follows an exponential growth curve that approaches a maximum limit asymptotically:

$$B = C_1 \times \left(1 - e^{-C_2 \times \Delta t}\right) \tag{3-18}$$

where

B = pollutant buildup (mass per unit area, e.g., lbs/acre),
C_1 = maximum buildup possible (mass per unit area, e.g., lbs/acre),
C_2 = buildup rate constant (per time, e.g., per day), and

Δt = time, e.g., number of days.

Saturation Function

Pollutant buildup, *B*, begins at a linear rate then slows down over time until a saturation value is reached:

$$B = \frac{C_1 t}{C_2 + t} \tag{3-19}$$

where

B = pollutant buildup (mass per unit area, e.g., lbs/acre),
C_1 = maximum buildup possible (mass per unit area, e.g., lbs/acre),
C_2 = half-saturation constant (days to reach half of the maximum buildup), and
t = time, e.g., number of days.

Pollutant Washoff

The accumulated pollutants on a pervious land surface are washed off during runoff periods from a choice of available SWMM functions (Rossman 2005), which are all supported by *SUSTAIN*. These functions include the exponential washoff, rating curve washoff, and an event mean concentration (EMC).

Exponential Washoff

The washoff load, *W*, is proportional to the product of runoff raised to the defined power C_2 and to the amount of pollutant buildup remaining at each simulation timestep:

$$W = C_1 \times q_s^{C_2} \times B \tag{3-20}$$

where

W = pollutant washoff load (mass per unit area per time, e.g., lbs/acre/hr),
C_1 = washoff coefficient,
C_2 = washoff exponent,
q_s = runoff rate per unit area (e.g., in./hr), and
B = pollutant buildup (mass per unit area, e.g., lbs/acre).

Rating Curve Washoff

The rate of pollutant washoff, *W*, is proportional to the runoff rate raised to the defined power C_2:

$$W = C_1 \times q_s^{C_2} \tag{3-21}$$

where

W = pollutant washoff load (mass per unit area per time, e.g., lbs/acre/hr),
C_1 = washoff coefficient,
C_2 = washoff exponent, and
q_s = runoff rate (user-specified flow units, e.g., in./hr).

Event Mean Concentration (EMC)

This is a special case of Rating Curve Washoff where the exponent is 1.0 and the coefficient C_1 represents the washoff pollutant concentration in mass per volume. The typical EMCs for selected pollutants in urban runoff are shown in Table 3-11.

Table 3-11. Typical EMCs in Urban Runoff

Pollutant	EMC
TSS (mg/L)	180–548
BOD (mg/L)	12–19
COD (mg/L)	82–178
Total P (mg/L)	0.42–0.88
TKN (mg/L)	1.90–4.18
NO_2/NO_3-N (mg/L)	0.86–2.2
Total Cu (µg/L)	43–118
Total Pb (µg/L)	182–443
Total Zn (µg/L)	202–633

Source: USEPA 1983

Impervious Land Segment

SUSTAIN computes sediment and all other pollutant loadings from the impervious land segment using the pollutant buildup and washoff algorithms as defined in the previously described Pervious Land Segment section. For impervious land segments, *SUSTAIN* supports a street-sweeping algorithm adopted from SWMM (Rossman 2005). The user can specify days between sweeping, days since the last sweeping at the start of the simulation, the fraction of buildup of all sediment types (sand, silt, and clay) available for removal by sweeping, and the fraction of available buildup for each sediment type removed by sweeping. The parameters can differ by type of land use.

3.2.4. Important Considerations and Limitations: Land Module

Rainfall-runoff time series data are the drivers for BMP simulation and network routing in *SUSTAIN*. The relative modeled response from one land use to another is influenced by the physical characteristics of the land as defined by the model setup. In any modeling application, many important factors must be considered. A few of these considerations are highlighted for guidance on configuration and interpretation of results when applying the land module. They include model testing considerations and land segmentation.

Model Testing: Calibration and Validation

Calibration and validation is a process during which monitoring data are split into two independent periods: calibration and validation. Ideally, those are two typical periods (not extreme conditions) within a typical range of flow conditions. During the calibration period, key parameters are adjusted within reasonable ranges until the best fit with the observed data is determined. The performance of the *calibrated* model is then tested with data from a separate validation period.

The SWMM-based method available in *SUSTAIN*, as well as similar rainfall-runoff models and methods used for externally generating time series, though physically based, are empirical in how they are applied. The models require calibration and validation of estimated model results with observed data. Observed data that are used for calibration are often collected at locations that drain multiple land use types. Because individual modeled land use time series are the fundamental units for runoff generation in

SUSTAIN, there is a need to ensure with reasonable confidence that modeled results are meaningful and applicable.

An ideal modeling data set for calibration includes monitoring several smaller watersheds, each with relatively homogeneous land uses (i.e., low-density urban, high-density urban, forest) for a range of storm conditions. For each monitored storm event, the recommended data includes high-resolution precipitation, flow hydrograph, and discrete or composite water quality sampling for pollutants of concern. Using the observed precipitation, flow, and water quality data, the model is developed and tested for each land use type on the basis of physical characteristics of the drainage area. Standard calibration techniques are typically applied to assess how well the observed and the modeled time series data match.

A limitation of any modeling effort is the inability to represent 100 percent of nature's heterogeneity; the recognition of that fact influences the interpretation and application of calibrated model results. The setup of *SUSTAIN* is based on building representative land use times series data that allow users to make comparisons and extrapolate responses for current and potential future land use and management conditions. Testing each land use and the combined behavior of mixed land use watersheds against observed data is used to adjust model parameters for the best fit and to confirm model results. One common use of the calibrated data set is the extrapolation of results at one location to represent a response at other similar but ungaged locations. *SUSTAIN* includes land use reclassification to facilitate the application of models to various future or managed conditions and can be used to develop locally *homogenized* responses of similar land units. The primary objective of the model is to capture the unique essence of one type of land-use response relative to other types. When the available calibration data are limited, that objective becomes even more important for either extrapolating time series response from one calibrated area to another, or adopting loading estimates for various land uses from literature.

Particle Size Distribution

Most land-based erosion and sediment simulation techniques compute total eroded sediment load. Because the simulation land segments are discretized by the land use category, erosion is simulated uniquely and is characteristic of that land use category. For sediment produced by each land use, particle size distribution is represented as fractional distribution of the total sediment. That means that the total land-based sediment load, multiplied by the corresponding size fraction, gives the actual amount of sediment computed for each sediment size class. The user can allocate sediment into three classes (sand, silt, and clay). The three sediment classes are used to represent sediment response behavior during transport in subsequent BMP or conduit modules or both.

Particle size distribution and associated pollutant concentrations provide an important linkage to BMP simulation algorithms. For example, BMPs that remove pollutant through trapping and settling of sediments will be especially sensitive to the user-specified particle size distributions. If residence time within the BMP is short, only larger particles might be removed effectively. For externally generated time series data, *SUSTAIN* supports the option to specify each sediment class as an independent time series rather than apply a size distribution to a bulk sediment mass. This approach might be desirable in cases where particle size distribution changes dramatically during the course of a single storm event and detailed sediment monitoring data are available to justify the modeling approach.

Land Segmentation

Finally, depending on the size of the watershed being modeled, regional considerations can influence the robustness and utility of the modeled land units. In fact, the way land units are classified from the onset can have a strong bearing on how representative or portable the modeled land unit response will be. For example, in some places, it might be sufficient to model land units on land use alone; whereas, in others, the use of a hydrologic response units (HRUs) approach might provide a better representation. An HRU is a combination of multiple physiographic characteristics, such as land use, soils, or slope. In flat regions where soils are relatively homogeneous, it might be sufficient to use a purely land-use-based classification approach. However, if soils or slopes are heterogeneous across multiple land units, the HRU approach might be a better way of organizing land units.

3.3. BMP Module

The BMP module is designed to provide a process-based simulation of flow and pollutant transport routing for a wide range of structural BMPs. It is designed so that new BMPs and alternative solution techniques can be added over time. The BMP module performs the following hydrologic processes to reduce land runoff volume and attenuate peak flows: evaporation of standing surface water, infiltration of ponded water into the soil media, deep percolation of infiltrated water into groundwater, and outflow through weir or orifice control structures. Figure 3-8 shows a schematic of the BMP simulation processes.

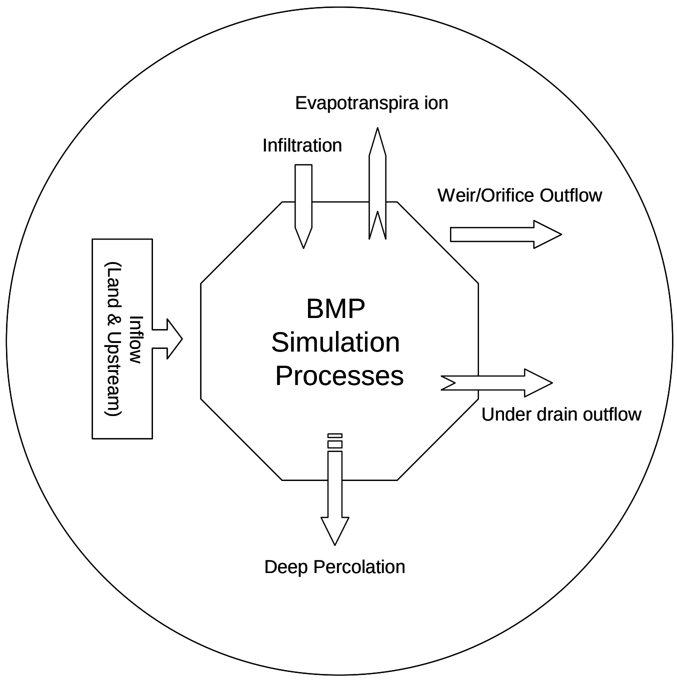


Figure 3-8. A schematic showing the BMP simulation processes modeled in *SUSTAIN*.

Table 3-12 provides an overview of the required inputs, the methods used to manage and process the inputs, and the resulting outputs of the BMP module.

Table 3-13 provides a summary of the key BMP simulation processes included in *SUSTAIN*. Option 1 is the default option. Option 2 provides a more data intensive alternative that simulates additional physical processes in the BMP. With regard to pollutant removal, Option 1 differs from Option 2 in that it does not include background concentration C*. Users can select processes from either option depending on the available data and level of detail required.

Table 3-14 lists the BMP types and the associated applicable simulation methods. The BMP simulation techniques are chosen and implemented to provide a reasonable representation of the physical processes associated with detention, retention, and infiltration.

Table 3-12. Summary of Inputs, Methods, and Outputs in the BMP Module

BMP Module
Inputs
– Define BMP dimensions
– Define substrate (soil and underdrain media) properties
– Define sediment settling and transport parameters
– Define pollutant removal and routing parameters
– Define cost for each functional component of a BMP
– Hourly inflow time series
– Hourly sediment (sand, silt, and clay) concentration time series
– Hourly pollutant concentration time series
Methods
– Evapotranspiration is calculated (user-selected constant, monthly, or daily values; derived from daily temperature using Hamon method)
– Infiltration is computed using the Green-Ampt or Holtan methods
– Deep percolation is calculated according to user-specified background infiltration rate
– Surface outflow is computed using weir or orifice equations
– Underdrain outflow is computed using orifice equation
– Sediment (sand, silt, and clay) settling and routing is computed using the processed based algorithms adopted from the HSPF model
– Pollutant removal is calculated using 1^{st} order decay or k-C* method
– Pollutant routing is computed by using completely mixed or CSTR in series method
Outputs
– Sub-hourly outflow time series
– Sub-hourly sediment (sand, silt, and clay) concentration time series
– Sub-hourly pollutant concentration time series

Table 3-13. Available Optional Methods for BMP Simulation Processes

Processes	Option 1	Option 2
Flow Routing	Stage-outflow storage routing using weir or orifice equations	For swale: kinematic routing by solving the coupled continuity equation and Manning's equation
Infiltration	Green-Ampt method	Holtan-Lopez equation
Evapotranspiration	Constant ET rate or monthly average value, or daily values	Calculate potential ET using Hamon's method
Pollutant Routing	Completely mixed, single CSTR	CSTRs in series
Pollutant Removal	1^{st} order decay	k'-C* method
Buffer Strip (Sheet Flow) Flow Routing	Kinematic wave overland flow routing	--
Buffer Strip Sediment Trapping	Process-based Univ. of Kentucky sediment interception simulation method as applied in VFSMOD	--
Buffer Strip (Sheet Flow) Pollutant Removal	1^{st} order decay	--

Table 3-14. Representative BMPs and Recommended Simulation Methods

BMP	Recommended Simulation Methods
Detention pond	Constant ET rate or monthly average value, or daily values Calculate potential ET using Hamon's method Stage-outflow storage routing using weir or orifice equations Completely mixed pollutant routing CSTR in series pollutant routing First order decay (k'-C* method) Sediment settling and transport
Constructed wetland	Green-Ampt method Holtan-Lopez equation Constant ET rate or monthly average value, or daily values Calculate potential ET using Hamon's method Stage-outflow storage routing using weir or orifice equations Completely mixed pollutant routing CSTR in series pollutant routing First order decay (k'-C* method) Sediment settling and transport
Bioretention	Green-Ampt method Holtan-Lopez equation Constant ET rate or monthly average value, or daily values Calculate potential ET using Hamon's method Stage-outflow storage routing using weir or orifice equations Completely mixed pollutant routing, single CSTR 1^{st} order decay, no C* Underdrain percent reduction (user defined)
Infiltration trench	Green-Ampt method Holtan-Lopez equation Constant ET rate or monthly average value, or daily values Calculate potential ET using Hamon's method Stage-outflow storage routing using weir or orifice equations Completely mixed pollutant routing, single CSTR 1^{st} order decay, no C*
Hydrodynamic storage device	Stage-outflow storage routing using weir or orifice equations Completely mixed pollutant routing 1^{st} order decay, no C* Sedimentation
Grassed swale	Kinematic flow routing by solving the coupled continuity equation and Manning's equation Completely mixed pollutant routing, single CSTR 1^{st} order decay, no C* Sediment settling and transport using user defined settling velocity and critical shear stress
Vegetated filterstrip	Kinematic wave overland flow routing Process-based sediment interception simulation method (VFSMOD) 1^{st} order decay pollutant removal, no C*

The following describes in more detail the methods and algorithms implemented in the BMP simulation module. Section 3.3.1 describes the BMP simulation component, Section 3.3.2 the buffer strip component, Section 3.3.3 the aggregate BMP component, and Section 3.3.4 the cost database component.

3.3.1. BMP Simulation Component

BMPs in *SUSTAIN* are simulated using a combination of fundamental algorithms to represent the processes of storage, routing, infiltration, evapotranspiration, underdrain infiltration, and pollutant routing and removal. The fundamental algorithms associated with each method are shown below.

Storage Routing Method

Water balance storage routing is a commonly used method for flow routing in ponds and impoundments.

$$\Delta V/\Delta t = I - O \qquad (3\text{-}22)$$

where

ΔV = change in storage (volume),
Δt = time interval (time),
I = inflow (volume per unit time), and
O = outflow (volume per unit time).

Stage-outflow relationships are widely used for flow routing through an orifice or over a weir as shown in Figure 3-9.

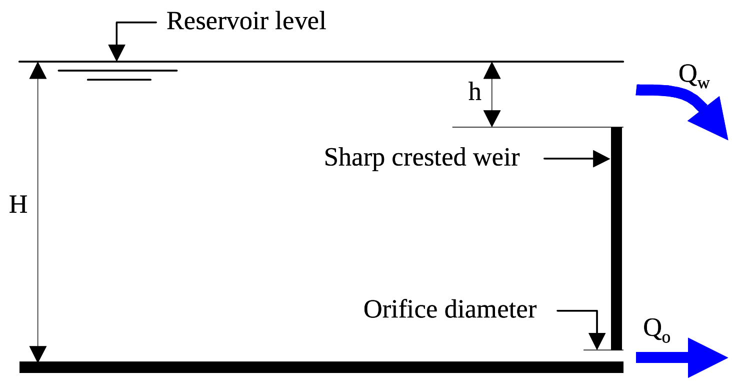


Figure 3-9. **Wetland/lake/reservoir weir and orifice outflow.**

Weir Outflow

Three commonly used weir types (i.e., sharp-crested rectangular weir, sharp-crested triangular weir, and broad-crested rectangular weir) are supported in *SUSTAIN*.

The equation for the rectangular, sharp-crested weir overflow is (Linsley et al. 1992):

$$Q_w = C_w L_w h^{3/2} \qquad (3\text{-}23)$$

where

Q_w = outflow over sharp-crested weir (ft^3/s),
C_w = coefficient of discharge,
L_w = length of weir crest (ft), and
h = depth of the water above weir crest (ft).

Values of C_w (English units) for sharp-crested rectangular weirs are given in Table 3-15.

Table 3-15. Coefficient *Cw* (English units) for Rectangular Sharp-Crested Weirs

	Head *h* on Weir, ft						
H_d/h	0.2	0.4	0.6	0.8	1.0	2.0	5.0
0.5	4.18	4.13	4.12	4.11	4.11	4.10	4.10
1.0	3.75	3.71	3.69	3.68	3.68	3.67	3.67
2.0	3.53	3.49	3.48	3.47	3.46	3.46	3.45
10	3.36	3.32	3.30	3.30	3.29	3.29	3.28
∞	3.32	3.28	3.26	3.26	3.25	3.25	3.24

Source: Linsley et al. 1992
H_d = Height of the weir

The equation for the triangular (V-notch) sharp-crested weir overflow is (Linsley et al. 1992):

$$Q_w = C_w'' \frac{8}{15}\sqrt{2g}\, h^{5/2} tan\left(\frac{\theta}{2}\right) = 4.28 C_w'' h^{5/2} tan\left(\frac{\theta}{2}\right) \qquad (3\text{-}24)$$

where

Q_w = outflow over sharp-crested weir (ft^3/s),
C_w'' = coefficient of discharge, default value is 0.58 for English units,
h = depth of the water above weir crest (ft),
θ = vertex angle of the V-notch, and
g = acceleration of gravity (32.2 ft/s^2).

True broad-crested weir flow occurs when the upstream head above the crest is between about 1/20 and 1/2 the crest length in the direction of flow (USBR 2001). Equation (3-25) is applicable to broad-crested weirs, and it is recommended that weir coefficient C_w be determined by measuring the flow at various flow rates (Linsley et al. 1992). The value of the weir coefficient varies with h/H_d. One way of estimating C_w is to use the equation derived by Fox (University of British Columbia Department of Mechanics (No date) Fluid Dynamics Course Notes):

$$C_w = \frac{0.65}{\left(1 + \frac{h}{H_d}\right)^{1/2}} \frac{2}{3}\sqrt{2g} \qquad (3\text{-}25)$$

where

h = depth of the water above the weir crest (ft),
H_d = height of the weir (ft), and
g = acceleration of gravity (32.2 ft/s^2).

Orifice outflow

The equation for the orifice flow is:

$$Q_o = C_o A_o \sqrt{2gH} \qquad (3\text{-}26)$$

where

Q_o = outflow through orifice (ft^3/s),
C_o = orifice coefficient of discharge,
A_o = orifice cross sectional area (ft^2),

g = acceleration due to gravity (ft/s^2), and
H = depth of the water level above the orifice (ft).

Infiltration/Filtration

SUSTAIN supports two options for the simulation of infiltration in BMPs: (1) the Holtan-Lopez equation adopted from the Prince George's County BMP module (Tetra Tech 2001) and (2) the Green-Ampt equation (for details, see Section 3.2.2) as is applied in the SWMM (Rossman 2005).

Holtan-Lopez Empirical Model

The Holtan-Lopez empirical model computes the infiltration rate as a function of the actual available soil water storage, S_a, of the surface soil layer, as shown below (Maidment 1993):

$$f = GRI \times A \times S_a^{1.4} + f_c \quad (3\text{-}27)$$

where

f = infiltration rate (in./hr),
GRI = growth index of vegetation in percent maturity, varying from 0.1 to 1.0,
A = infiltration capacity (an index representing surface-connected porosity and density of plant roots),
S_a = available storage in the surface layer (in.), and
f_c = constant final infiltration rate (in./hr).

In Equation (3-27), A is the vegetative parameter that characterizes surface-connected porosity and the density of plant roots, which affect infiltration (a value of 0.8 is a typical number for sod or vegetation that would be found in a BMP). f_c is the final constant infiltration rate (in./hr), which is a function of the hydrologic soil group. The value of f_c ranges from 0.3 in./hr for group-A soils to between 0.0 and 0.05 in./hr for group-D soils (Maidment 1993). In a continuous calculation, the available soil storage (S_a) and infiltration rate (f) are computed at each simulation time step. Available soil storage is updated each time increment and the infiltration is calculated.

This method was developed using the premise that soil moisture storage, surface-connected porosity, and the effect of root density of the control soil layer are the dominant factors influencing the infiltration process.

A difficulty with using this method is estimating the control soil layer depth. For simulating the infiltration process, it is assumed that the soil column depth is the control depth because BMP devices normally have a confined soil/substrate layer.

Green-Ampt Infiltration Equation

This method is discussed in Section 3.2.2 in the hydrology component of land simulation module. The Green-Ampt equation can be applied to both surface runoff and BMP simulation.

When performing BMP infiltration simulation, the impact of the underdrain layer, the impermeable bottom layer, or both, on the infiltration process needs to be considered in the simulation. Because the Green-Ampt method can be applied to a layered soil column, the underdrain layer can be represented as a separate layer under the soil column. In cases where an impermeable layer is present at the bottom of the soil column, the infiltration rate ceases when the soil storage capacity is reached.

A drawback of the Green-Ampt method is that it does not include a parameter to explicitly reflect the effect of the vegetation root zone on the infiltration rate.

Evapotranspiration

Potential evapotranspiration (PET) time series can be estimated on the basis of the U.S. Weather Bureau Class A pan records with adjustment. For instance, the HSPF WDM utility estimates PET using the pan records, then the HSPF simulation model is used to adjust the time series for snow accumulation and melt (Bicknell et al. 1997). When snow conditions are absent, only PET and precipitation are required. However, when snow conditions are considered, air temperature, rainfall, snow cover, water yield, and ice content of the snowpack are also required, and the evaporation data are adjusted. The input evaporation values are reduced to account for the fraction of the land segment covered by the snowpack.

Several methods are available to estimate PET. The Penman-Monteith method (Maidment 1993) requires values for solar radiation, air temperature, relative humidity, and wind speed. The Priestley-Taylor method (Maidment 1993) requires solar radiation, air temperature, and relative humidity. The third, Hargreaves method (Maidment 1993) requires air temperature only.

SUSTAIN provides three options to estimate PET: (1) rely on the user-supplied monthly PET rate (2) calculate PET from the user-supplied pan evaporation time series input and monthly pan coefficients, and (3) calculate the PET rate using Hamon's method (1961).

Hamon's (1961) method generates daily PET using air temperature, a monthly variable coefficient, the number of hours of sunshine (computed from latitude), and absolute humidity (computed from air temperature).

$$PET = C_{TS} \times D_{hr}^{\ 2} \times \rho_{ws} \tag{3-28}$$

where

PET = daily PET (in.),

C_{TS} = monthly variable coefficient, and

D_{hr} = possible hours of sunshine computed as a function of latitude and time of year.

$$\rho_{ws} = \frac{216.7 \times p_{ws}}{T_{av} + 273.3} \tag{3-29}$$

where

ρ_{ws} = saturated water vapor density (absolute humidity) at daily mean air temperature (g/cm^3) and

T_{av} = mean daily air temperature ($^{\circ}$C).

$$p_{ws} = 6.108 \times exp\left[\frac{17.26939 \times T_{av}}{T_{av} + 273.3}\right] \tag{3-30}$$

where

p_{ws} = saturated vapor pressure at the air temperature.

Hamon (1961) suggests a constant value of 0.0055 for C_{TS}. However, monthly values can be specified to avoid underestimating PET in some areas, especially for the winter months.

Calculate Actual Evapotranspiration

Once PET is determined, the actual evapotranspiration (ET) is calculated as a function of PET and soil moisture storages. While PET represents the maximum possible achievable ET on the basis of atmospheric conditions alone, actual ET is determined using an accounting of the status of the various components of the hydrologic budget. The actual ET is equal to PET when the soil moisture is greater than or equal to the moisture at the field capacity and there is no actual ET if the moisture content is less than or equal to the moisture at the wilting point.

Underdrain Method

Underdrain Outflow

The underdrain outflow in a BMP is modeled using a simple water balance concept. The available underdrain storage is represented as the total of void spaces beneath the upper soil layer. Inflow into underdrain storage is limited by the final infiltration rate of the upper soil layer. Because the primary function of the underdrain is to provide additional water storage and to delay outflow, the outflow pipe draining the underdrain layer is placed at the interface between the upper soil layer and the underdrain layer. Figure 3-10 illustrates the function of underdrain together with other substrate model components.

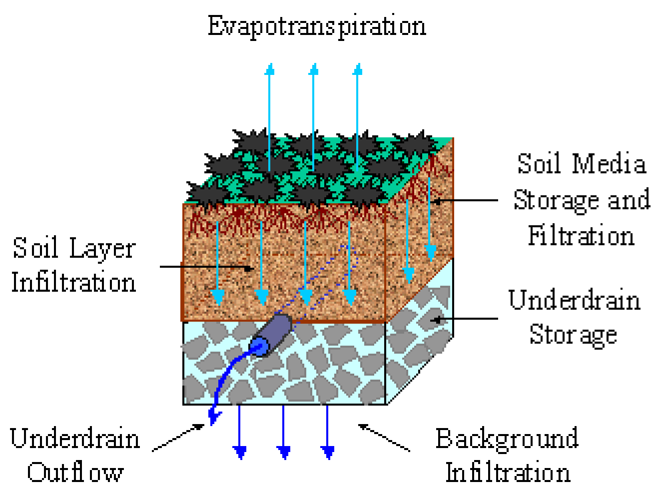


Figure 3-10. Processes considered in an underdrain structure.

Outflow from the underdrain layer is assumed to be unrestricted; therefore, no pipe outflow is required. Underdrain outflow is part of the modeled BMP effluent and occurs when all available underdrain storage is used up, when the water level meets or exceeds the underdrain level, or when both occur. Each infiltration management practice can be modeled with or without underdrain outflow. If underdrain outflow is enabled, the user must specify the thickness of the underdrain storage layer, the media void fraction, and the background infiltration rate (Figure 3-10). Water and pollutants are removed from the system entirely through background infiltration.

Underdrain Filtration of Pollutant

If underdrain is specified in the *soil properties* of a BMP, additional reduction in pollutant concentration from underdrain routing is simulated in the module using the *underdrain percent removal*, which is a user-supplied parameter. This option allows users the flexibility in estimating pollutant removals through the soil media of a BMP.

Pollutant Routing and Removal Methods

The methods of pollutant routing to achieve pollutant reduction are described in this subsection for a completely mixed system and a multiple impoundments in series. The flow through a plug flow reactor (PFR), as a series of infinitely thin coherent *plugs*, each with a uniform composition, is perfectly mixed in the cross direction but not in the longitudinal direction (direction of flow). Each plug of differential volume is considered as a separate entity, with an infinitesimally small volume and requires a very small time steps (in seconds). *SUSTAIN* uses one minute to hourly time step to simulate flow and pollutant routing and does not support plug flow option in the current version. However, it can be seen that an infinite number of small continuously stirred tank reactors (CSTRs) operating in series would be equivalent to a PFR.

First-Order Decay with Complete Mixing

This method is commonly used and suitable for small ponds when complete mixing is likely.

$$\frac{d(VC)}{dt} = I(t)C_I(t) - O(t)C(t) - KC(t)V(t) \tag{3-31}$$

where

V = reservoir volume (ft^3),
C_I = influent pollutant concentration (mg/L),
C = effluent and reservoir pollutant concentration (mg/L),
I = inflow rate (ft^3/s),
O = outflow rate (ft^3/s),
t = time (sec), and
K = decay coefficient (1/s).

Continuously Stirred Tank Reactors in Series and Kadlec and Knight's Model

CSTRs in series are used to represent a hydraulic condition intermediate between completely mixed and plug flow (Wong et al. 2001, 2002). That method is applied for simulating first-order pollutant removal processes (e.g., settling, decay) that occur in ponds, wetlands, and other similar BMPs. The calculation begins by estimating the number of reactors in series to be selected to represent the shape of the BMP, followed by applying first order kinetics with nonreactive background concentration (the *k*-*C** model; Kadlec and Knight 1996).

Step 1: Estimate *N*, the number of CSTRs in series.

N, the number of CSTRs in series, can be approximated on the basis of BMP shape (Persson et al. 1999; Wong et al. 2001, 2002). Values of *N* for the various pond shapes, shown in Figure 3-11, are presented in Table 3-16. Highest *N* values are for ponds with a distributed inflow (pond E), baffles (pond G), and very elongated flow or high length to width ratio (pond J).

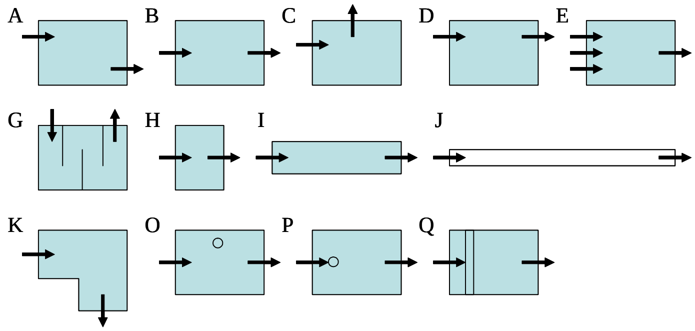


Figure 3-11. **Conceptual pond shapes simulated by Persson et al. (1999).**

Table 3-16. **Quality Ratings of Conceptual Pond Shapes Simulated by Persson et al. (1999)**

Pond	**N≈1/(1-λ)**	**Qualitative Rating**
J	10.0	Good
G	4.2	
E	4.1	
P	2.6	Satisfactory
Q	2.5	
I	1.7	Poor
K	1.6	
A	1.4	
B	1.4	
O	1.3	
D	1.2	
H	1.1	
C	1.1	

Step 2: Apply first-order decay *(k′ - C** model) to each CSTR.

After selecting the number of reactors, pollutants are modeled for each tank at each time step using the first-order kinetic model, described in Equation (3-32).

$$(C_{out} - C^*)/(C_{in} - C^*) = e^{-k'/q} \tag{3-32}$$

where

C^* = background concentration (mg/L),
C_{in} = input concentration (mg/L),
C_{out} = output concentration (mg/L),
q = hydraulic loading or overflow rate (m/yr),
$k' = k \cdot h$ = rate constant (m/yr),
k = first order decay rate (1/yr), and
h = pond depth (m).

This equation is computed separately for each time step at each CSTR. The main difference between this equation and ordinary first-order decay modeling for a CSTR is the inclusion of C^*, the background concentration, below which the effluent cannot fall. Another advantage of this method is that using an *areal* rate constant (units of depth/time) instead of a *volumetric* one (units of inverse time) helps avoid having to specify an average depth or the volume for odd natural configurations; instead, only the pond surface area is required to compute the hydraulic loading rate *q*.

Wong et al. (2002) recommend some k' and C^* values as shown in Table 3-17, on the basis of limited model calibration for total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN) in urban areas near Melbourne. Those values should be used with caution. However, they could be used as a starting point in the absence of local data.

Table 3-17. Recommended *k'* and *C Values**

	***k'* (m/yr)**			***C** (mg/L)**		
Treatment Measures	TSS	TP	TN	TSS	TP	TN
Sedimentation Basins	15,000	12,000	1,000	30	0.18	1.7
Ponds	1,000	500	50	12	0.13	1.3
Vegetated Swales	15,000	12,000	1,000	30	0.18	1.7
Wetlands	5,000	2,800	500	6	0.09	1.3

Localized calibration can be performed to customize the simulation technique for specific areas. The C^* and k' values can be determined or calibrated using monitoring data (particle size distribution in particular) and treatment measure design specifications.

3.3.2. Overland Flow Routing and Pollutant Interception

The following algorithms for overland flow routing and pollutant interception simulation are employed in *SUSTAIN* for buffer strip simulation.

Kinematic Wave Overland Flow Routing Method for Filter Strip Simulation

Overland flow through filter strips can be simulated using a kinematic wave method and solving the coupled continuity and Manning's equations.

Mathematical Model

Continuity equation

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = i_e(t) \tag{3-33}$$

Manning's equation

$$q = q(h) = \frac{\sqrt{S_o}}{n} h^{5/3} \tag{3-34}$$

where

h = overland flow depth (ft),

q = overland flow per unit width of the subcatchment (ft^2/s),
n = Manning's roughness coefficient,
i_e = rainfall excess depth (ft/s),
t = time (s), and
S_o = subcatchment slope.

Initial condition

$$h = 0; \quad 0 \le x \le L; \qquad t = 0$$

Boundary condition

$$h = h_0; \quad x = 0; \qquad t > 0$$

where, h_0 can be 0, a constant, or a time-dependent function, such as the incoming hydrograph from the adjacent subcatchment. The rainfall excess, i_e, can be calculated from the hyetograph and Green-Ampt infiltration method at each time step.

Numerical Solution

The coupled continuity equation and Manning's equation are solved using Petrov-Galerkin (PG) formulation to compute the flow rate (q), velocity (v), and depth (h) throughout the plane for each time step. Kinematic shocks (oscillations in the solution) are introduced when a sudden change in conditions (e.g., slope, roughness, and inflow) occurs. For filter strip simulation, as the soil surface conditions are updated for each time step, the potential for kinematic shocks is further increased. The PG finite element method was found to reduce the amplitude and frequency of oscillations compared to a conventional Bubnov-Galerkin finite element solution, thus improving the model stability for situations that are subject to kinematic shocks (Muñoz-Carpena et al. 1993).

VFSMOD Algorithms for Sediment Interception

The sediment interception algorithm used in VFSMOD considers that when runoff reaches the upstream edge of the filter, the vegetation provides a sudden increase in hydraulic resistance, which slows the flow, lowers its transport capacity, and causes deposition of the coarse material (particle diameter $d_p > 0.0037$ cm), which is carried mostly as bed-load transport. The sediment trapped in the first section of the filter forms a geometrical shape (the wedge zone), which is either triangular when $Y(t) < H$ or trapezoidal after $Y(t) = H$, where $Y(t)$ is the thickness of the deposited sediment layer and H is the effective height of the vegetation.

The wedge zone is characterized by three well-defined zones: O, A, and B (Figure 3-12). The sediment loads at points 1 and 2 (g_{s1} and g_{s2}) are calculated using the flow values provided by the overland flow routing module at points 1 and 2, and Einstein's sediment bed-load transport function. After solving the sediment transport equations for a time step, new values of roughness and/or slope are selected as nodal values for the finite element grid in zones A(t) and B(t); while values for the grids in zones C(t) and D(t) remain unchanged. Changes in surface saturated hydraulic conductivity values are assumed to be negligible. The new surface parameters are fed back into the hydrology model for the next time step. The changes in the surface condition (i.e., slope and roughness) due to sediment deposition are recorded and passed back to the flow module.

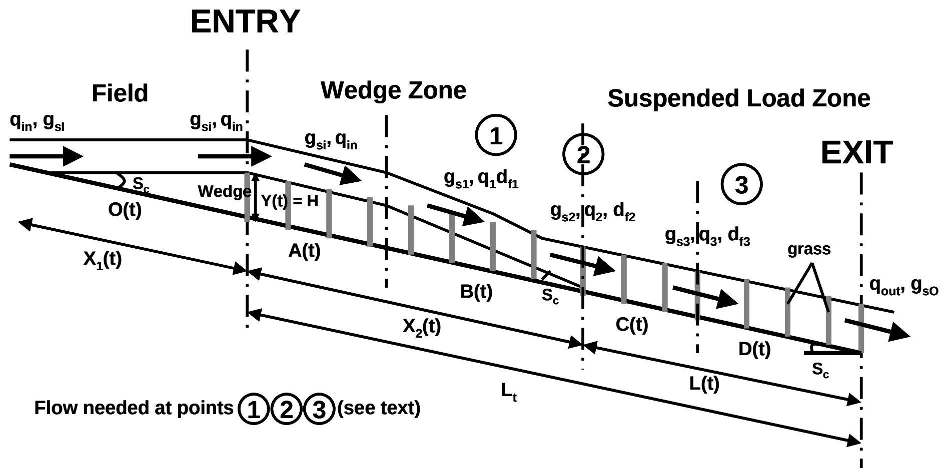


Figure 3-12. **Filter description for the sediment transport algorithm.**

Einstein's bed-load transport Equation (3-35) is solved using the method proposed by Barfield (Muñoz-Carpena 1993) to compute the sediment transport capacity.

$$\frac{\gamma_s - \gamma}{\gamma} \frac{d_p}{R_{sk} S_k} = 1.08 \left(\frac{g_{sk}}{\gamma_s \sqrt{\frac{\gamma_s - \gamma}{\gamma} g d_p^3}} \right)^{-0.28} \tag{3-35}$$

where

γ = water density (g/cm^3),
γ_s = sediment density (g/cm^3),
d_p = particle diameter (cm),
g_{sk} = sediment load (g/cm-s) at point k (k = 1, 2),
S_k = slope at point k,
g = gravitational constant (cm/s^2),
R_{sk} = spacing hydraulic radius at point k, defined as $\frac{S_s d_{fk}}{2 d_{fk} + S_s}$,
S_s = grass spacing (cm),
d_{fk} = modified flow depth (cm) at point k, defined as $\frac{q_k n}{R_{sk}^{2/3} \sqrt{S_k}}$, and
q_k = unit width flow rate (cm^2/s) at point k.

It was assumed that only sediment at the fine sand/silt threshold (diameter > 0.0037 cm) is considered in the wedge zone sediment routing and that fine sediment (diameter < 0.0037 cm) runs through to the suspended zone (Muñoz-Carpena 1993). Therefore, the user is required to input the percentage of coarse particles from incoming sediment that will be routed through the wedge. The calculated sediment transport capacity is compared with incoming sediment concentration. If the incoming sediment concentration is higher, deposition at the wedge will occur; if lower (meaning that there is enough energy to transport sediment through the wedge and no deposition occurs), all sediment is transported to the suspended sediment zone (zones C(t) and D(t)).

After the downside of the wedge, two zones, C and D, form the *suspended load zone*. It was assumed that on zone C, sediment has covered the indentations of the surface so that bed-load transport and deposition occur, but the soil slope is not significantly changed. All bed-load transported sediment is captured before reaching zone D so only suspended sediment is transported and deposited in this zone until the flow reaches the end of the filter. Flow values at point 3 and the exit point are needed for the calculation and are provided by the flow module. The trapping capacity (T_r) Equation (3-36) developed by Tollner et al. (1976) is used to simulate the sediment trapping for the suspended load zone:

$$T_r = \frac{g_{s2} - g_{so}}{g_{s2}} = e^{\left[-1.05\times 10^{-3}\left(\frac{V_3 R_{s3}}{v}\right)^{0.82}\left(\frac{V_f L}{V_3 h_3}\right)^{-0.91}\right]} \tag{3-36}$$

where

g_{s2} = sediment load at point 2 (g/cm-s),
g_{so} = sediment load at the output point (g/cm-s),
V_3 = mean velocity at point 3 (cm/s),
V_f = fall velocity (cm/s),
v = kinematic viscosity of water (cm^2/s), and
L = effective filter length (cm).

Particle Deposition and Sediment Transport

On the basis of the laboratory study by Deletic (2001) the particle deposition or trapping efficiency for sediment fraction s (particle with diameter of d_s) can be estimated as a function of the particle fall number, $N_{f,s}$, which is calculated as:

$$N_{f,s} = \frac{lV_s}{hV} \tag{3-37}$$

where l is the flow length, V_s the Stokes' settling velocity of particle size d_s, and V is the average mean flow velocity between grass blades. The sediment trapping efficiency $T_{r,s}$ is expressed as:

$$T_{r,s} = \frac{N_{f,s}^{0.69}}{N_{f,s}^{0.69} + 4.95} \tag{3-38}$$

The suspended sediment transport equation is expressed as:

$$\frac{\partial(hq_{s,s}/q)}{\partial t} + \frac{\partial q_{s,s}}{\partial x} = Dis\frac{\partial^2(hq_{s,s}/q)}{\partial x^2} - \lambda_s q_{s,s} \tag{3-39}$$

where $q_{s,s}$ is the sediment loading rate of fraction *s* per unit width, *Dis* is the dispersion coefficient, and λs is the trapping efficiency for fraction *s* per unit length calculated as $\lambda s = T_{r,s}/l$.

Terrain Surface Level and Slope Changes

The rise in the surface level, z, is modeled as the integral of trapped particles of all fractions of particle sizes and is expressed as:

$$\frac{\partial z(x,t)}{\partial t} = \frac{1}{1-p}\int_s \frac{1}{\rho_s}\lambda_s q_{s,s} ds \tag{3-40}$$

where p is the porosity of deposited sediment.

The water quality for the pollutant (other than suspended sediment) is simulated by applying the most commonly used first order decay model. A first order decay is equivalent to an exponential decay, represented by the Equation (3-41).

$$C_t = C_0 \, e^{-kt} \tag{3-41}$$

where

C_t = concentration at time t (mass per volume),
C_0 = initial concentration at time zero (mass per volume), and
k = reaction rate (per timestep).

For the current phase of *SUSTAIN* development, the decision was made to include this complex, process-based simulation for filter strip simulations. This model is CPU intensive and, thus, is not used during the optimization process. Its purpose in *SUSTAIN* is for evaluation of filter strip performance only (see Section 3.3.6). Future phases will include a simplified method that can be incorporated into the optimization module.

3.3.3. Aggregate BMP Component

The aggregate BMP component provides an optional method for assessing the combined impact of multiple BMPs on the watershed runoff and pollutant load. The formulation was developed to represent the *aggregate* characteristics of distributed BMP, while reducing the user effort for model setup and computation time needed for simulation and optimization. While the BMP module in *SUSTAIN* performs explicit simulation of individual BMP practices for a defined management area, the aggregate BMP component evaluates storage and infiltration characteristics for multiple BMPs simultaneously without explicit recognition of their spatial distribution and routing characteristics in the selected watershed.

As illustrated in Figure 3-13, an aggregate BMP consists of a series of process-based components, including on-site interception, on-site treatment, routing attenuation, and regional storage/treatment. For the aggregate BMPs, users are asked to input design drainage area and number of units for each aggregate BMP component. Each component can be used to represent one of a number of individual BMPs. For example, on-site interception can be represented as a cistern, rain barrel, or green roof, while on-site treatment can be bioretention, porous pavement, or an infiltration trench. Each individual component can be enabled or disabled according to the desired functionality and sized and parameterized using the BMP templates that are identical to that of the individual BMPs.

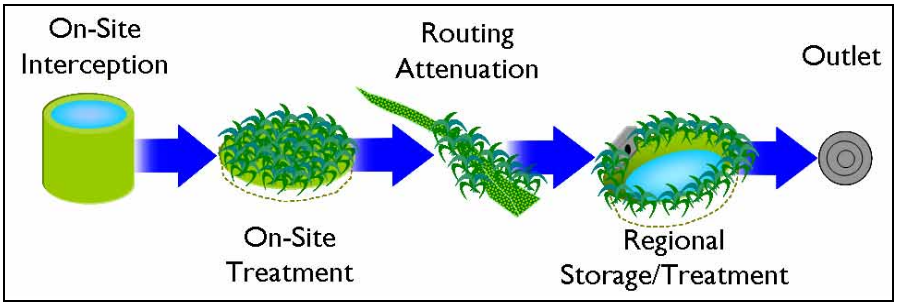


Figure 3-13. Generic aggregate BMP schematic.

Aggregate BMPs can be applied to a user-defined drainage area. The land use distribution of the drainage area is automatically calculated on the basis of the land use map and populated into the land use distribution/assignment table as shown in Figure 3-14. Users then assign the percentage of each land use that contributes to each of the aggregate BMP components (Figure 3-14). Runoff and pollutant loads from the total drainage area of each component are lumped and routed through the respective component. The relative scales and sizes of individual BMPs are preserved in the aggregate representation.

Landuse Group/Info Type	Area (ac.)	RainBarrel1 (%)	BioRetentionBasin1 (%)	Outlet (%)
BMPID		5	6	0
Category		On-Site Interception	On-Site Treatment	Outlet
BMPType		RainBarrel	BioRetentionBasin	Outlet
High-Density-Residential_Impervious	8.95	25	75	0
High-Density-Residential_Pervious	2.24	0	0	100
Downstream ID		6	0	0

Figure 3-14. Illustration of land use area assignment to aggregate BMP components.

To investigate the applicability of the aggregate BMP approach, a test case was conducted to compare the results of a *SUSTAIN* simulation using the aggregate approach to one using the distributed approach representing the same BMP scenarios. The distributed approach represents a fully articulated BMP and routing network, whereas the aggregate approach represents the component responses. Because of the *lumped* representation, the aggregate approach does not consider detailed routing between components. It is assumed that for small basins, the associated short time of concentration means that a fully articulated routing simulation is not necessary. Similarly, there is presumably some watershed size threshold, above which the lumped routing assumption might no longer be appropriate.

That presumption was evaluated by developing five test simulation drainage areas of different sizes (1.3 acres, 7.8 acres, 31.2 acres, 128 acres, and 256 acres). For each size, three simulation scenarios were applied: (1) an aggregate BMP representation, (2) a fully articulated network with conduit routing, and (3) a fully articulated network without conduit routing (conduit dimensions were set equal to zero). In this way, the test was designed to highlight the relative importance of the routing component to overall simulation results. Figure 3-15 illustrates the testing concept, showing the relative complexity of the distributed routing network scenarios as they increase in size vs. that of the aggregate representation. One-year simulations were conducted for each scenario with each drainage area size. Three factors were computed and summarized for each run: total annual flow volume, peak flow rate, and total annual TSS load.

Table 3-18 summarizes the results of the comparison. Among the three factors examined, peak flow rate is most sensitive to drainage area size. For example, at 128 acres, the peak flow rate values of the aggregate representation are significantly different from the distributed representations even though total flow volume and total TSS load values remain relatively constant.

At the drainage area size of 256 acres, the total TSS load of the aggregate representations were drastically different from the distributed ones; however, the differences are much smaller for drainage areas less than 256 acres (less than 2 percent difference). Simulation run times for various scenarios are listed in Table 3-19, showing that on the basis of this initial testing and as expected, the distributed representation requires a much longer run time than the aggregate representation.

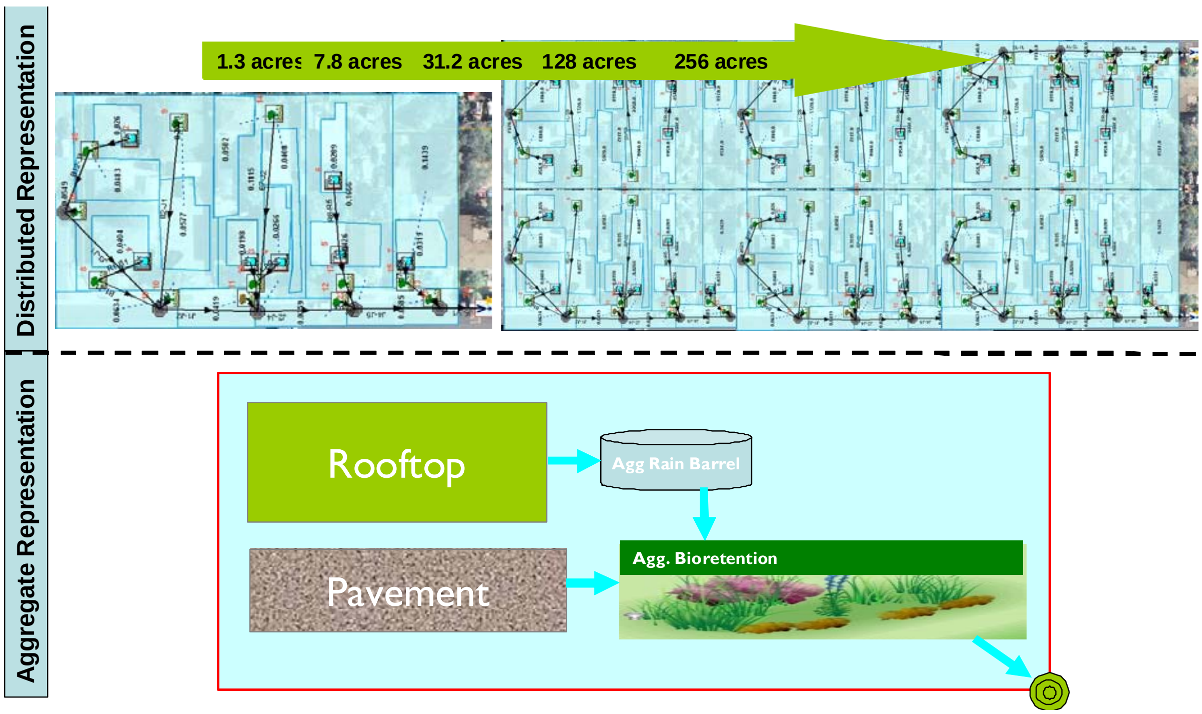


Figure 3-15. Aggregate BMP testing configuration.

3.3.4. BMP Cost Database Component

The BMP module costing component provides the underlying cost database used by the optimization component in evaluating BMP scenarios. The compilation of cost information was predicated on obtaining cost data in a format that could be input into a uniform database. This compilation was constrained by the non-uniformity with which available cost information for BMP construction is reported. As a result, it was determined that the best approach for building *SUSTAIN's* cost database was to determine unit costs (i.e., cost per square foot) for individual construction components of the overall BMP. Construction components include excavation, grading, filter fabric, and so forth. Basing the cost estimation routines on basic construction components rather than the whole BMP installation is aimed to minimize differences encountered because of site or locality factors. Users have the ability to override the data with their own locally derived information.

The cost database was developed by identifying individual construction components for each BMP technique simulated by *SUSTAIN*. Table 3-20 outlines the construction components for which data were compiled, the assumptions governing the general characteristics of the construction component (e.g., hardwood mulch versus pine straw mulch), and the associated BMP techniques. Unit costs for each component were compiled from retail sources and from reference documents and programs involved in BMP implementation at the local, state, and federal levels.

Table 3-18. Comparison of Aggregate vs. Distributed BMP Results

Scenario	Aggregate Representation	Distributed Representation		% Difference vs. Aggregate Representation	
		w/o Routing	Routing	Distributed w/o Routing	Distributed with Routing
Total flow volume (ft^3/yr)					
1.3 acre with BMPs	32,845	33,401	33,924	1.69	3.29
7.8 acre with BMPs	197,038	200,408	203,956	1.71	3.51
31.2 acre with BMPs	787,793	808,312	822,903	2.60	4.46
128 acre with BMPs	3,150,904	3,233,250	3,280,110	2.61	4.10
256 acre with BMPs	6,301,805	6,466,500	6,563,871	2.61	4.16
Peak Flow Rate (cfs)					
1.3 acre with BMPs	0.7	0.7	0.7	2.00	-0.59
7.8 acre with BMPs	4.0	4.1	3.9	1.75	-1.75
31.2 acre with BMPs	15.2	16.3	15.7	6.83	3.09
128 acre with BMPs	58.3	65.1	60.4	11.58	3.52
256 acre with BMPs	120.8	175.7	91.7	45.41	-24.09
TSS load (lb/yr)					
1.3 acre with BMPs	280	282	281	0.57	0.20
7.8 acre with BMPs	1,679	1,690	1,669	0.63	-0.60
31.2 acre with BMPs	6,727	6,817	6,725	1.34	-0.03
128 acre with BMPs	26,907	27,269	26,925	1.35	0.07
256 acre with BMPs	53,814	68,794	67,685	27.84	25.78

Table 3-19. Simulation Run-Time Comparison: Aggregate vs. Distributed

Scenario	Aggregate Representation	Distributed w/o Routing	Distributed w/ Routing	Notes
1.3 acre with BMPs	< 0.3 sec	1 sec.	14 sec	19 BMPs, 5 conduits
7.8 acre with BMPs	< 0.3 sec	12 sec.	90 sec.	114 BMPs, 30 conduits
31.2 acre with BMPs	< 0.3 sec	60 sec	7 min	456 BMPs, 120 conduits
128 acre with BMPs	< 0.3 sec	7 min	30 min	1,824 BMPs, 480 conduits
256 acre with BMPs	< 0.3 sec	12 min	50 min	3,648 BMPs, 961 conduits

Table 3-20. BMPs and Associated Construction Components

Construction Component	Description	Applicable BMP Techniques
Excavation	Using light equipment	Bioretention Basin; Vegetated Swale; Porous Pavement; Wet Pond; Dry Pond; Wetland; Infiltration Basin
Grading/finishing	Generally using light equipment or hand tools to minimize compaction except in the case of the creation of detention ponds where compaction is necessary	Bioretention Basin; Vegetated Swale; Porous Pavement; Wet Pond; Dry Pond; Wetland; Infiltration Basin; Buffer Strip
Backfilling	Replacing excavated area with soil/planting media; required when using amended growing media	Bioretention Basin; Wetland; Infiltration Basin
Soil/Planting Media	A typical mix is 50% sand, 30% planting soil (low clay content), and 20% shredded hardwood mulch	Bioretention Basin; Wetland; Infiltration Basin; Green Roof
Filter Fabric	Often placed between gravel reservoir and underlying/overlying soil to reduce clogging of the reservoir void spaces	Bioretention Basin; Porous Pavement; Infiltration Basin
Gravel 1	Porous pavement filter course, smaller particle sizes	Porous Pavement
Gravel 2	Reservoirs; slightly larger particle sizes, no fines	Bioretention Basin; Porous Pavement; Infiltration Basin
Gravel 3	Erosion control (rocks/riprap)	Wet Pond; Dry Pond; Wetland
Underdrain Pipe	4-in. perforated PVC	Bioretention Basin; Porous Pavement
Mulch	Shredded hardwood	Bioretention Basin; Wetland; Infiltration Basin
Rain Barrel		Rain Barrel
Green Roof System		Green Roof
Grass	Framework assumes use of sod	Bioretention Basin; Vegetated Swale; Wet Pond; Dry Pond; Infiltration Basin; Buffer Strip; Wetland
Perennials	Assumes planting density of 1 ft o.c. for 1-gal plants	Bioretention Basin; Infiltration Basin; Wetland
Small Trees	Assumes planting densities of 15 ft o.c.	Bioretention Basin
Woody Shrubs	Assumes planting densities of 3 ft o.c.	Bioretention Basin
Inlet Structure		Wet Pond; Dry Pond; Wetland
Outlet Structure		Wet Pond; Dry Pond; Wetland
Observation Well	4-in. PVC pipe	Infiltration Basin
Seal	Bentonite (as opposed to geotextile)	Wet Pond
Porous Paving Material		Porous Pavement

Unit Cost Data Sources

Costs for BMP construction components were obtained from the following sources.

Wholesale/Retail Bulk Material Pricing

Several wholesale or retail companies were inventoried to provide bulk material pricing. Retailers were contacted to provide unit pricing for various raw materials such as mulch, sand, stone, and other commercial landscape materials. Retailers were also contacted to provide pricing for rain barrels. Unit cost data were compiled in 2007.

EPA Stormwater Technology Fact Sheets

EPA's Office of Water Municipal Technology Assessment Program supports innovative and alternative technology development through a number of efforts and partners. In 1999 the program produced a series of Stormwater Technology Fact Sheets (832-F-99-001 to 048), which are at http://www.epa.gov/owmitnet/mtb/mtbfact.htm. The series provides information on advantages and disadvantages, design criteria, operations and maintenance, performance, and cost estimates regarding a range of management technologies including bioretention, catch basins, flow diversion, infiltration trenches, modular systems, porous pavement, and others.

California Department of Transportation (CALTRANS)

In the late 1990s, CALTRANS began a study to evaluate structural BMPs for stormwater treatment. Among other things, the study evaluated removal efficiencies, capital costs, and annual operation and maintenance (O&M) costs of individual applications.

Fairfax County BMP Fact Sheets

Fairfax County, Virginia, developed 25 fact sheets for inclusion in the county's *Public Facilities Manual* that present an overview of the management strategies and technologies for various current or potential BMP/LID techniques used in the county. The fact sheets address seven different BMP categories including: (1) bioretention systems, (2) filtering technologies, (3) permeable pavements, (4) site design strategies, (5) soil amendments, (6) vegetative systems, and (7) water conservation/reuse. The information in each fact sheet is consistent so that relative comparisons can be made on the critical design, construction, and maintenance issues. Information includes a general description of the BMP, water quality and quantity controls, location; design construction and materials, cost, maintenance, performance and inspection, and potential LEED (Leadership in Energy and Environmental Design) credits. The fact sheets are at http://www.lowimpactdevelopment.org/fairfax.htm#ffx_factsheet.

Natural Resources Conservation Service (NRCS) Cost Share Data

The U.S. Department of Agriculture's (USDA's) NRCS program Web site provides cost lists and tools developed by NRCS field office staff to support BMP cost-sharing programs under the department's Environmental Quality Incentives Program and other programs. Documents containing unit cost data for BMP components are available for various years for 34 states.

Michigan Department of Environmental Quality's (DEQ's) 319 BMP Cost Database

The Michigan DEQ's Nonpoint Source Program administers the CWA section 319 grant program for the state. It requires grantees to submit BMP cost share information for purposes of tracking the cost and location of BMPs installed with DEQ Nonpoint Source grant funding and documenting expenses for cost-share practices. DEQ is required to produce annual reports for the EPA and the Michigan legislature to detail the use of state and federal grant funds. In addition, the data are also used to share information about specific practices with current and potential grant recipients. The *SUSTAIN* cost database adapted cost data for certain practices such as green roofs and porous pavement because they were reported in the same units as the cost module database. Costs for other relevant BMPs are reported in the DEQ BMP Cost Share database; however, component costs are not broken down. As a result, these data were not used.

Green Roofs

EPA's Heat Island Web site and the Great Lakes Water Institute's Web site provide installation and maintenance costs per unit for green roofs in urban areas. The Web sites are http://www.epa.gov/heatisland/mitigation/greenroofs.htm http://www.glwi.uwm.edu/research/genomics/ecoli/greenroof/roofinstall.php#costs.

Minnesota Stormwater Manual (version 1.1)

The Minnesota Stormwater Manual (Minnesota Pollution Control Agency 2005) provides unit costs for several BMPs. The Stormwater Manual discusses a variety of BMP approaches designed to lessen the impacts of urban development. The Manual explores an array of BMPs that can be implemented to control sediment and reduce runoff in a practical and flexible manner.

Cost Database

The cost database in the BMP module is a Microsoft Access database containing records related to unit costs of BMP construction components relevant to the techniques simulated by *SUSTAIN*. In addition to the unit cost per component, each record contains information related to the source of the data and, to the extent possible, the year or general time period from which the cost data were recorded. In addition, O&M cost estimates were available for a limited number of records. All unit cost data were entered into the unit cost table using the unit in the original source; conversions to a consistent unit of measure take place in the system using appropriate conversion factors.

Using the Cost Component

The Cost Component provides the flexibility of choosing the construction components and the associated costs for estimating the total cost of the BMP.

User Data

Users also have the option to enter their own cost data as well as operations and maintenance costs.

Selection of Data

Cost estimates in the database are taken from sources across the country; however, not all states and regions are represented. Users can choose to base cost estimates on an average of all data in the database or they can choose to use only select sources of data if they deem specific sources to be adequately representative. In addition, the interface allows users the option of not including specific components when calculating the unit cost of a BMP. For example, in an area where it is not necessary to include an impermeable seal on the bottom of a wet detention pond, the cost component can be turned off. O&M data were limited and, thus, are not included in the cost database.

Table 3-21 through Table 3-26 provide additional information related to fields and tables that compose the database.

Table 3-21. Components

Column	Details	Type
Components_ID	Component ID number	Numeric
Components_txt	Construction component	Text
Components_Desc	General description of the component	Text

Table 3-22. BMP Types

Column	Details	Type
BMPType_ID	BMP Type ID number	Numeric
BMPType_Code	Lookup code (no spaces) (e.g., Bioretention Basin)	Text
BMPType_Desc	Description of the BMP Type (e.g., Bioretention Basin)	Text

Table 3-23. BMP Components

Column	Details	Type
BMP_Component_ID	Unique record identifier	Numeric
Component_ID	Component ID number as in components table	Numeric
BMP Type_ID	BMP Type ID number as in BMP Types table	Numeric

Table 3-24. Component Costs

Column	Details	Type
Component_Cost_ID	Unique record identifier	Numeric
Component_ID	Construction Component	Numeric
Unit	Unit on which cost estimate is based (e.g.,, ft, ft^2, ft^3, etc.)	Text
Cost	Cost in dollars	Numeric
Year	Year in which the construction cost estimate was developed for conversion and baseline comparisons	Numeric
Source_ID	Code for the reference from which unit cost data were taken	Text
Locale	Geographic area for which cost estimate is applicable (e.g., national, state, city specific)	Text
UseFlag	Flag to differentiate useable records	Numeric
Note	Notes regarding the data	Text
Orig_Unit	Original unit on which cost estimate is based, before conversion to standard units	Text
Orig_Cost	Original cost in dollars, before standardizing units	Numeric

Table 3-25. Unit Types

Column	Details	Type
UnitType_ID	Unit Type ID number	Numeric
UnitType_Code	Code for the unit of cost data used for specific BMP component costs (e.g., ft^2)	Text
UnitType_Desc	Text description of unit of cost data for BMP component cost (e.g., square feet)	Text

Table 3-26. Reference Sources

Column	Details	Type
Reference_Source_ID	Unique record identifier	Numeric
Source_Type	Assigned code for the reference/source from which unit cost data were taken	Text
Title	Title of reference	Text
Year	Year reference was published	Numeric
Author	Agency under whose name the reference was developed and distributed	Text
Publication_Street	Mailing street address, if listed	Text
Publication_City	City listed for publishing agency/author; NOT city for which data are derived	Text
Publication_State	State listed for publishing agency/author; NOT state for which data are derived	Text
Publication_ZIP	ZIP Code listed for publishing agency/author; NOT the ZIP Code for which data are derived	Numeric
Reference_Number	Any code listed on the report title page used by author/issuing agency to identify and track official publications	Text
Prepared_by	Developer of the reference (if work was completed on behalf of public agency by contractor)	Text
Note	Notes regarding the source and/or data	Text

Factors Affecting Development of Cost Database and Implications for Use

Format of available cost data

All data used to populate the cost database are from nonproprietary sources. It is important to note that the nature of database construction requires that information be consistent and uniform. Unfortunately, a wide variety of formats are used in which cost data for BMP and construction components are reported. That presents a serious limitation to the amount of cost data available for the current phase of *SUSTAIN* development. To maximize the utility of the optimization functions of *SUSTAIN*, future development phases must include development of additional unit cost data.

A limited number of estimates were available for O&M costs. If a range of costs was given in the original source, such as 5 through 7 percent of construction costs, the average was used in the database (e.g., 6 percent).

NRCS data

The NRCS unit cost data represents a significant portion of the cost records in the *SUSTAIN* cost database. The information available from the NRCS includes cost lists and various tools (such as spreadsheets) developed by NRCS field office staff to support BMP cost-sharing programs under the USDA's Environmental Quality Incentives Program and other programs. In general, the BMPs and cost data represented in the NRCS data are focused on rural, agricultural applications; however, several projects have data available in counties with both urban and rural areas. Project and construction component costs are obviously reflective of local and regional economic factors.

Note, too, that different states have adopted different approaches to developing this information; while some state NRCS field offices responsible for developing this information employ economists, some do not. In Virginia, for example, costs are based on either real project numbers or on bids submitted by local contractors for typical applications. Atypical (expensive, technically complicated, or unusual) projects are generally excluded from the universe of estimates used to generate average cost lists.

The cost share data for 28 states were accessed and reviewed during development of the database, and appropriate records were selected for inclusion on the basis of consistency with the BMPs and components represented in *SUSTAIN*, as well as the applicability of units for which costs were reported. The potential exists that cost estimates derived from the NRCS data are low, relative to costs for projects in more urban areas, which might be expected to have higher unit costs because of higher operating, equipment rental, land, and other costs. Efforts were made to select data for inclusion in the database to address this potential for underestimation. For example, the Alabama cost estimator spreadsheet includes four records related to unit costs for the *SUSTAIN* component *backfill*. The analogous component in the Alabama Cost Estimator spreadsheet is called *Earthfill*. Cost estimates are available for < 3,000 yd^3; 3,000–10,000 yd^3; 10,000–30,000 yd^3; and 30,000+ yd^3. Unit costs for the smallest volume (< 3,000 yd^3) are highest; therefore, it was the estimate selected for inclusion in the *SUSTAIN* cost estimate database. Where the NRCS data provide multiple unit costs for a component, the highest cost is used.

Because the NRCS data represent such a significant proportion of the publicly available unit cost data related to implementation and construction of BMPs, they were included in the cost database for *SUSTAIN*. However, in recognition of the potential limitations associated with applying those data to urban areas, users may opt to exclude all NRCS data from cost calculations. Note that excluding NRCS data will result in a more restricted data set from which the model's cost estimates will be based.

3.3.5. Summary of Management Practices and Treatment Processes in SUSTAIN

SUSTAIN provides multiple ways for simulating management practices that are widely used to treat runoff and mitigate flow volumes. Treatment processes may be grouped into the following categories:

- Storage/detention or flow attenuation (i.e., those detaining and/or attenuating water)
- Infiltration (i.e., those infiltrating water to the ground)
- Filtration (i.e., those passing water through a porous medium)
- Evapotranspiration (i.e., those losing water from surface and/or soil column)
- Water quality (i.e., those performing pollutant removal)

Table 3-27 lists the structural BMP types handled by *SUSTAIN* and the associated treatment processes.

3.3.6. Important Considerations and Limitations of the BMP Module

Selecting an Appropriate Simulation Method

The BMP module provides an array of simulation options with varying degrees of sophistication in the required input and computational rigor. Such options provide flexibility for users to customize their problem formulations to suit the project needs. The user should carefully select the method or approach considering the overall problem formulation, availability of supporting data, and expected outcomes. For example, users can choose between the two infiltration options provided: the simple Holtan infiltration method or the iterative Green-Ampt infiltration method. To optimize BMP selection for a large study area having several infiltration BMPs, it might be advantageous to select the Holtan method over the Green-Ampt method because it might result in shorter computation time (e.g., reduced runtime for a single run by several seconds). Because it might be required to perform hundreds or thousands of BMP simulations during an optimization analysis, the accumulated run time savings of a few seconds per run could be significant. On the other hand, users should also consider simulation accuracy and localized investment in model simulation in determining the appropriate technique. For example, if the Green-Ampt method has already been parameterized and successfully applied for land simulation (in SWMM), it would be wise to use the same method for simulating infiltration in the Land and BMP modules.

Table 3-27. Structural BMPs and Major Treatment Processes

Structural BMP Types	Storage/Detention or Flow Attenuation	Infiltration	Filtration	Evapotranspiration	Water Quality
Bioretention	o	+	o	o	+
Cistern	+	-	-	-	-
Constructed Wetland	+	(o)	-	+	+
Dry Pond	+	(o)	-	+	o
Grassed Swale	o	+	(o)	-	o
Green Roof	(o)	-	(o)	+	-
Infiltration Basin	(o)	+	o	-	o
Infiltration Trench	(o)	+	o	-	o
Porous Pavement	-	+	(o)	-	o
Rain Barrel	+	-	-	-	-
Sand Filter (non-surface)	(o)	o	+	-	+
Sand Filter (surface)	(o)	o	+	-	+
Vegetated Filterstrip	(o)	o	+	o	+
Wet Pond	+	(o)	-	o	o

Note: ( ) optional function; + major function; o secondary function; - insignificant function

Nonstructural BMP Representation

The previous discussions focused on the simulation methods for structural BMPs, but viable nonstructural BMPs are potentially effective. For example, street sweeping is a nonstructural BMP; however, it is handled as part of the land simulation module because it directly reduces pollutant sources upstream of structural BMPs. Other pollutant source control practices, like fertilizer or pet waste management, are BMPs; but for a similar reason, they are accounted for through the land module. With the exception of street sweeping, *SUSTAIN* does not provide explicit representation for source control actions. Using standard modeling practices, land use characteristics in the land module or in an external model can be modified to represent changes in land management. The user can create alternative land use categories that represent areas with and without nonstructural BMPs. Note that *SUSTAIN* does not support the use of land uses as a decision variable in cost-optimization.

Using VFSMOD in *SUSTAIN*

The VFSMOD component for the simulation of vegetated filter strips has limitations in terms of how it is integrated within *SUSTAIN*. While VFSMOD has a detailed representation of sediment transport through a filter strip, it uses a simple first-order decay representation for water quality constituents and does not address sediment-associated pollutants. In addition, *SUSTAIN* acts as a pre-processor for generating an input file for VFSMOD, and data flow to VFSMOD is one-directional. For that reason, a filter strip modeled in VFSMOD cannot be integrated with other BMPs or be included in an optimization formulation. Consequently, VFSMOD is primarily used as a BMP evaluation component for assessing filter strip performance.

Using the Aggregate BMP

The behavior of an aggregated BMP type in a treatment train conceptually represents the collected behavior of all BMPs of the same type in the watershed. No attenuation of flow and pollutants, such as from routing through a reach or a conduit, occurs from one upstream aggregated BMP to the one downstream. For small drainage areas, that assumption usually has less impact because the routing effect is small and the travel time or time of concentration is short. As drainage area increases, so does the compounded impact of routing through a large conveyance network. The aggregate BMP simulation results will begin to diverge from the detailed distributed simulation. In summary, the aggregate BMP option tends to work best in watersheds that have a time of concentration similar to the simulation time step. Given a one-hour time step simulation, a good size for watershed with a low- to moderate slope is between 50 and 150 acres. The aggregated BMP is probably best used for screening-level analysis to determine the treatment potential of a watershed. Once treatment targets have been established, further analysis can be perform on a more fully articulated and detailed BMP network.

Operation and Maintenance Assumptions and Costs

The BMP cost database does not include O&M costs, and provisions are made to allow users to enter values in terms of a fraction of construction costs or as an added fixed cost. Because of the limited and highly variable nature of the O&M cost information, the cost is assumed to be evenly distributed over the entire life cycle of the BMP. In addition, the BMPs are assumed to be maintained to perform as designed and that performance does not degrade over time.

3.4. Conveyance Module

The conveyance module performs routing of flow and water quality through a conduit. In *SUSTAIN*, conduits are pipes or one-dimensional open channels that move water from one node to another in a watershed routing network. The cross-sectional shapes of a conduit can be selected from a variety of standard open and closed geometries. Irregular, natural, cross-section shapes are supported, as are user-defined, closed shapes. Flow and pollutant routing are simulated using algorithms from SWMM (version 5) transport compartment (Rossman 2005). Sediment routing is simulated using reach sediment transport algorithms from HSPF (Bicknell et al. 2001). Table 3-28 provides an overview of the required inputs, the methods used to manage and process the inputs, and the resulting outputs of the conveyance module.

3.4.1. Methodology

This section discusses the methodologies applied by the conveyance module to handle flow routing, sediment settling and routing, pollutant removal, and pollutant routing.

Flow Routing

SUSTAIN uses the kinematic wave method to perform flow routing simulation. This method solves the continuity equation along with a simplified form of the momentum equation. Kinematic wave routing allows flow to vary both spatially and temporally in a conduit and results in attenuated and delayed outflow hydrographs as inflow is routed (Rossman 2005). The maximum flow that can be conveyed through a conduit is the full-flow Manning equation value. Any flow in excess of this conduit capacity is bypassed to the downstream node as an untreated overflow. The typical Manning's roughness coefficients for closed pipes and open channels are shown in Table 3-29 and Table 3-30, respectively.

Table 3-28. **Summary of Inputs, Methods, and Outputs of the Conveyance Module**

Inputs – Define conduit dimensions – Define conduit initial condition parameters – Define reach cross-section for irregular shape – Define sediment settling and transport parameters – Define pollutant removal and routing parameters – Hourly inflow time series – Hourly sediment (sand, silt, and clay) concentration time series – Hourly pollutant concentration time series
Methods – Flow routing is computed using kinematic wave method – Sediment (sand, silt, and clay) settling and routing is computed using the process-based algorithms adopted from the HSPF model – Pollutant removal is calculated using the 1st order decay method – Pollutant routing is computed using the CSTR method
Outputs – Sub-hourly outflow time series – Sub-hourly sediment (sand, silt, and clay) concentration time series – Sub-hourly pollutant concentration time series

Table 3-29. **Typical Manning's Roughness Coefficient for Closed Pipes**

Conduit Material	**Manning's Roughness**
Asbestos-cement pipe	0.011–0.015
Brick	0.013–0.017
Cast iron pipe	
Cement-lined and seal coated	0.011–0.015
Concrete (monolithic)	
Smooth forms	0.012–0.014
Rough forms	0.015–0.017
Concrete pipe	0.011–0.015
Corrugated-metal pipe (1/2-in. x 2-2/3-in. corrugations)	
Plain	0.022–0.026
Paved invert	0.018–0.022
Spun asphalt lined	0.011–0.015
Plastic pipe (smooth)	0.011–0.015
Vitrified clay	
Pipes	0.01 –0.015
Liner plates	0.013–0.017

Source: ASCE 1982

Table 3-30. Typical Manning's Roughness Coefficient for Open Channels

Conduit Material	Manning's Roughness
Lined Channels	
Asphalt	0.013–0.017
Brick	0.012–0.018
Concrete	0.011–0.020
Rubble or riprap	0.020–0.035
Vegetal	0.030–0.40
Excavated or dredged	
Earth, straight and uniform	0.020–0.030
Earth, winding, fairly uniform	0.025–0.040
Rock	0.030–0.045
Unmaintained	0.050–0.140
Natural channels (minor streams, top width at flood stage < 100 ft)	
Fairly regular section	0.030–0.070
Irregular section with pools	0.040–0.100

Source: ASCE 1982

Sediment Transport

This section describes the transport, deposition, and scour of inorganic sediment in free-flowing reaches using the HSPF algorithms (Bicknell et al. 2001). Figure 3-16 shows the principal state variables and fluxes involved in the sediment transport processes.

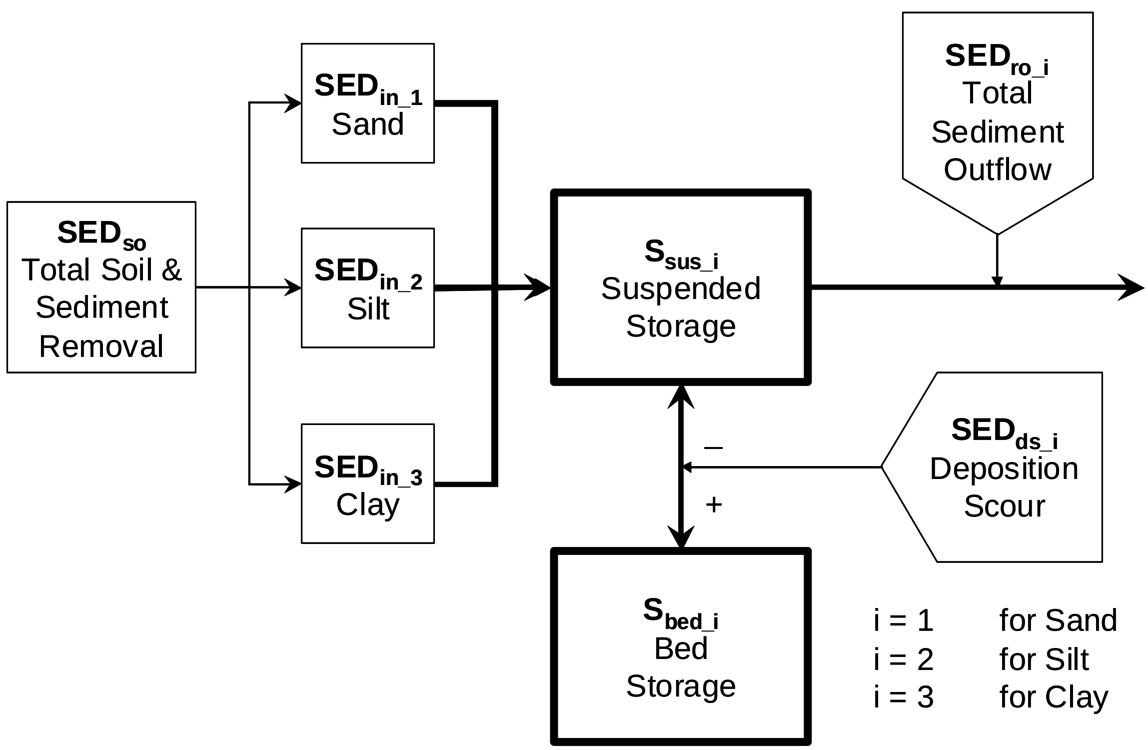


Figure 3-16. Schematic of sediment transport, deposition, and scour in conduits.

Both the migration characteristics and the adsorptive capacities of sediment vary significantly with particle size. To facilitate analyses to account for the effects of particle sizes, *SUSTAIN* divides the inorganic sediment load into three components (sand, silt, and clay), each with its own properties. Sand has a particle size ranging from 0.05 millimeter (mm) to 2.0 mm in diameter, silt from 0.002 mm to 0.05 mm in diameter, and clay smaller than 0.002 mm.

The system assumes that scour or deposition of inorganic sediment does not affect the hydraulic properties of the conduit. Furthermore, it is assumed that sand, silt, and clay deposit in different areas of the conduit bed so that the deposition or scour of one material is not linked to the changes of others. Longitudinal movement of bed sediments by flow shear stress is not modeled.

First, the volume occupied by each component of bed sediment is calculated as shown in Equation (3-42).

$$V_{bed\_i} = \frac{S_{bed\_i}}{\rho_{\_i}} \tag{3-42}$$

where

V_{bed_i} = volume occupied by component *i* of bed sediment (ft^3),
S_{bed_i} = bed storage of component *i* of sediment (lb), and
$\rho_{\_i}$ = particle density of component *i* (lb/ft^3).

The volumes of the three components of bed sediment are summed, and the total bed volume is adjusted to account for voids in the sediment (i.e., the porosity):

$$V_b = \frac{\sum_{i=1}^{i=3} V_{bed\_i}}{1-\eta} \tag{3-43}$$

where

V_b = volume of bed (ft^3),
V_{bed_i} = volume of sediment contained in the bed (sand, silt, and clay) (ft^3), and
η = porosity of bed sediment (ratio of pore volume to total volume).

Finally, the depth of bed sediment is calculated as:

$$d_b = \frac{V_b}{L_r \times W_b} \tag{3-44}$$

where

d_b = depth of bed (ft),
V_b = volume of bed (ft^3),
L_r = length of conduit (ft), and
W_b = effective width of bed (ft).

Cohesive sediments

Two steps are used to model the deposition, scour, and transport processes of cohesive sediments (silt and clay). The first step computes the advective transport and the second step calculates the amount of deposition or scouring on the basis of the bed shear stress.

Advective Transport of Constituent

This section computes the concentration of material in a conduit and the quantities of material that leave the conduit due to longitudinal advection. Two assumptions are made in the solution technique for normal advection: each constituent is uniformly dispersed throughout the waters of the conduit and is completely entrained by the flow—that is, the material moves at the same horizontal velocity as the water.

The equation of continuity can be written as:

$$SED_{in} - SED_{ro} = (C \times V) - (C_s \times V_s) \tag{3-45}$$

where

SED_{in} = total inflow of sediment over the interval (lb),
SED_{ro} = total outflow of sediment over the interval (lb),
C_s = sediment concentration at the start of the interval (lb/ft^3),
C = sediment concentration at the end of the interval (lb/ft^3),
V_s = volume of water stored at the start of the interval (ft^3), and
V = volume of water stored at the end of the interval (ft^3).

The other basic equation states that the total outflow of material over the time interval is a weighted mean of two estimates; one based on conditions at the start of the interval, the other on ending conditions:

$$SED_{ro} = (C_s \times Q_s \times js) + (C \times Q \times cojs) \tag{3-46}$$

where

Q_s = outflow rate at the start of the interval (ft^3/time interval),
Q = outflow rate at the end of the interval (ft^3/time interval),
js = weighting factor, and
$cojs = 1 - js$.

By combining Equations (3-45) and (3-46) we can solve for the concentration C:

$$C = \frac{SED_{in} + C_s \times (V_s - Q_s \times js)}{V + Q \times cojs} \tag{3-47}$$

The total amount of material leaving the conduit during the interval is calculated using Equation (3-46). If the conduit goes dry during the interval, the total amount of material leaving the conduit is the sum of the material coming in and the material leaving based on the concentration at the start of the interval:

$$SED_{ro} = SED_{in} + (C_s \times Q_s \times js) \tag{3-48}$$

Deposition and Scouring

Exchange of cohesive sediments with the bed is dependent upon the shear stress exerted on the bed surface. When the shear stress (τ) in the conduit is less than the user-supplied, critical, shear stress for deposition (τ_{cd}), sediment deposition occurs. On the other hand, when the shear stress is greater than the user-supplied, critical, shear stress for scour (τ_{cs}), scouring of cohesive bed sediments takes place. The rate of deposition for a particular fraction of cohesive sediment is based on a simplification of Krone's (1962) equation in the following form:

$$D = \omega \times C \times \left(1 - \frac{\tau}{\tau_{cd}}\right) \tag{3-49}$$

where

D = rate at which sediment settles out of suspension (lb/ft^2 interval),
ω = settling velocity for cohesive sediment (ft/interval),
C = concentration of suspended sediment (lb/ft^3),
τ = shear stress (lb/ft^2), and
τ_{cd} = critical shear stress for deposition (lb/ft^2).

The rate of change of suspended sediment concentration in the conduit due to deposition can be expressed as:

$$\frac{dC}{dt} = -\frac{D}{d_{av}} \tag{3-50}$$

where

d_{av} = average depth of water in the conduit (ft).

By substituting the expression for deposition rate (D) from Equation (3-49), and integrating and rearranging Equation (3-50), a solution can be obtained for the concentration of suspended sediment lost to deposition during a simulation interval (C_{dep}):

$$C_{dep} = C \times \left[1 - exp\left\{\left(-\frac{\omega}{d_{av}}\right) \times \left(1 - \frac{\tau}{\tau_{cd}}\right)\right\}\right] \tag{3-51}$$

where

C = concentration of suspended sediment at the start of interval (lb/ft^3),
ω = settling velocity for sediment fraction (ft/interval),
d_{av} = average depth of water in conduit (ft),
τ = shear stress (lb/ft^2), and
τ_{cd} = critical shear stress for deposition (lb/ft^2).

The user must supply values for settling velocity (ω) and critical shear stress for deposition (τ_{cd}) for silt and clay fractions in cohesive sediment.

The amount of sediment in suspension (S_{sus}) is updated by subtracting the amount settled. Likewise, the amount of sediment in bed (S_{bed}) is updated by adding the amount settled on it.

The rate of resuspension, or scour, of cohesive sediments from the bed is derived from a modified form of Partheniades' (1962) equation:

$$S = \mu \times \left(\frac{\tau}{\tau_{cs}} - 1\right) \tag{3-52}$$

where

S = rate at which sediment is scoured from the bed (lb/ft^2 interval),

μ = erodibility coefficient for the sediment fraction (lb/ft^2 interval), and
τ_{cs} = critical shear stress for scour (lb/ft^2).

The rate of change of suspended sediment fraction concentration in the conduit due to scour can be expressed as:

$$\frac{dC}{dt} = -\frac{S}{d_{av}} \tag{3-53}$$

By substituting the expression for scour rate *(S)* from Equation (3-52) and integrating and rearranging Equation (3-53), a solution can be obtained for the concentration of suspended sediment added to suspension by scour during a simulation interval (C_{scr}):

$$C_{scr} = \frac{\mu}{d_{av}} \times \left[\frac{\tau}{\tau_{cs}} - 1 \right] \tag{3-54}$$

where
μ = erodibility coefficient (lb/ft^2 interval), and
d_{av} = average depth of water (ft).

The user is required to supply values for the erodibility coefficient (μ) and critical shear stress for scour (τ_{cs}) for each fraction of cohesive sediment (silt and clay) that is modeled.

The amount of sediment in suspension (S_{sus}) is updated by adding the scoured mass, as is the amount of sediment in bed (S_{bed}) by subtracting the scoured mass.

If the amount of scoured sediment is greater than the original sediment in the bed, all sediment in the bed will be resuspended and the amount of sediment in the bed is set to zero.

Non-cohesive Sediment

Erosion and deposition of sand, or non-cohesive sediment, is affected by the amount of sediment that the flow is capable of carrying. If the amount of sand being transported is less than the flow can carry for the hydrodynamic conditions of the conduit, sand is scoured from the bed. This occurs until the actual sand transport rate becomes equal to the carrying capacity of the flow or until the available bed sand is all scoured. Conversely, deposition occurs if the sand transport rate exceeds the flow's carrying capacity.

The sand transport capacity for a conduit is calculated by using an input power function of the velocity. The potential sand concentration (C_p) is determined by the following conversion:

$$C_p = k \times \upsilon_{av}{}^{j} \tag{3-55}$$

where
C_p = potential sand concentration (lb/ft^3),
k = coefficient in the sandload suspension equation (input parameter),
j = exponent in sandload suspension equation (input parameter), and
υ_{av} = average velocity (ft/s).

The potential outflow of sand (SED_{pro}) is calculated as:

$$SED_{pro} = \left(C_s \times Q_s \times js\right) + \left(C_p \times Q \times cojs\right) \tag{3-56}$$

where C_s, Q_s, js, Q, and $cojs$ are as previously defined for Equations (3-45) and (3-46).

The potential scour from, or deposition to, the bed storage is found using the continuity equation:

$$SED_{pds} = \left(V \times C_p\right) - \left(V_s \times C_s\right) + SED_{pro} - SED_{in} \tag{3-57}$$

where

- SED_{pds} = potential scour (+) or deposition (-) (lb),
- C_p = potential sand concentration at the end of the interval (lb/ft^3),
- C_s = sand concentration at the start of the interval (lb/ft^3),
- SED_{pro} = potential outflow of sand over the interval (lb), and
- SED_{in} = inflow of sand during the interval (lb).

The potential scour is compared to the amount of available sand for resuspension. If scouring potential is less than the available sands, the demand is satisfied in full and the bed storage is adjusted accordingly. If the potential scour cannot be satisfied by bed storage, all the available bed sand is suspended, and the bed storage is exhausted. The concentration of suspended sand (C) is calculated as:

$$C = \frac{SED_{in} + SED_{ds} + C_s \times \left(V_s - Q_s \times js\right)}{V + Q \times cojs} \tag{3-58}$$

where

- C = concentration of sand at end of interval (lb/ft^3),
- C_s = concentration of sand at start of interval (lb/ft^3),
- SED_{in} = inflow of sand during the interval (lb), and
- SED_{ds} = sand scoured from, or deposited to, the bottom (lb).

The total amount of sand leaving the conduit during the interval is calculated using Equation (3-58). If a conduit goes dry during an interval, or if there is no outflow from the conduit, all the sand in suspension at the beginning of the interval is assumed to settle out, and the bed storage is correspondingly increased.

Sediment Transport Input Parameters

Parametric information required for silt and clay includes particle diameter (ϕ), particle settling velocity in still water (ω), particle density (ρ), critical shear stress for deposition (τ_{cd}), critical shear stress for scour (τ_{cs}), and erodibility coefficient (μ). Parameter values required for sand include median bed sediment diameter (ϕ_{50}) and particle settling velocity (ω). Table 3-31 shows the range of input parameters that are recommended.

Sediment Transport Calibration

Sediment transport parameters are typically derived by calibration. The calibration process involves establishing initial parameter values and a subsequent adjustment process. The eroded material from each land use category is fractionated into sand, silt, and clay before entering a conduit using available soils information; typically, a single fractionation scheme is used for all conduits. The fraction should reflect the relative percent of the surface material (i.e., sand, silt, clay) available for input to the conduit.

Investigation of the bed material composition will also help provide insight into appropriate fractionation values.

The initial sediment parameters—such as particle diameter, particle density, settling velocity, and bed depth and composition—and beginning calibration parameters can be evaluated from sources such as local/regional data, past experience, and handbooks or literature. The parameter values can then be adjusted on the basis of available site-specific data and calibration.

Table 3-31. List of Sediment Input Parameters for the Reach

Parameters	Default Value	Min. Value	Max. Value	Units
ϕ	0.0	0.0	0.003	in.
ϕ_{50}	0.01	0.0001	100.0	in.
ω	none	0.02	500.0	in./s
μ	0.0	0.0	none	lb/ft^2/day
ρ	2.65	1.0	4.0	lb/ft^3
τ_{cd}	1.0E10	1.0E-10	none	lb/ft^2
τ_{cs}	1.0E10	1.0E-10	none	lb/ft^2
k	0.0	0.0	none	--
j	0.0	0.0	none	--

Source: Bicknell et al. 2001

Pollutant Transport

The conveyance module simulates pollutant routing assuming that the conduit behaves as a CSTR. The algorithms are adopted from SWMM (version 5) transport compartment (Rossman 2005). The pollutant concentration exiting the conduit is determined by integrating the conservation of mass equation, using average values for quantities that might change over the time step such as flow rate and volume. *SUSTAIN* simulates sediment as a primary pollutant and assumes that all other pollutants follow the 1st order decay in a conduit as shown in Equation (3-41).

3.4.2. Important Considerations and Limitations of the Conveyance Module

Use of Kinematic Wave Routing Method

Several issues are important to consider when applying the conveyance module to perform stream routing. The desire to maintain a high resolution of spatial detail must be balanced with the need to preserve time of concentration along the in-stream flow network in the watershed. In-stream travel time can have a significant influence on model stability and accuracy. *SUSTAIN* incorporates two types of routing algorithms: storage routing and kinematic wave. Those algorithms are most accurate when the flow time of the flood wave through individual reaches approximates the simulation time step. This is achieved during model configuration by either: (1) selecting a simulation time step that is as small as the travel time through the smallest transport segment in the network, or (2) sizing the transport segments in the network to have travel times that are at least greater than or equal to the simulation time step.

In cases most likely encountered in the context of *SUSTAIN* applications, a kinematic wave routing method can usually maintain numerical stability with time steps on the order of 5 to 15 minutes. If those effects are not expected to be significant, kinematic wave routing can be an accurate and efficient method, especially for long-term simulations. Finally, it is important to recognize that kinematic wave routing does not account for backwater effects, entrance/exit losses, flow reversal, or pressurized flow and is restricted to dendritic network layouts.

Simulation Time and Number of Conveyance Elements

Another aspect to consider in setting up a conveyance network for simulation is to determine the number of conveyance elements. The conveyance system is found to be the most computationally intensive component of the network. It often needs an order of magnitude more time to run water through a conveyance than through a BMP. For this reason, the strategic selection and sizing of conveyances (i.e., using one representative pipe in place of several actual pipes in a section of the network) can have significant benefit in terms of computation time savings. If a conveyance network is a part of an optimization formulation, a saving of several seconds per simulation run will translate into a significant reduction in computational time because hundreds or even thousands of optimization runs are often required to arrive at optimal solutions.

3.5. Optimization Module

SUSTAIN includes an optimization module to develop cost-effective BMP placement and selection strategies on the basis of a pre-selected list of potential sites and applicable BMP types and size ranges. The module uses evolutionary optimization techniques to perform the searches for optimal combinations of BMPs that meet the user-defined decision criteria. Table 3-32 summarizes the required inputs, methods used, and outputs and Figure 3-17 presents a conceptual overview of the module.

The optimization module works hand-in-hand with the BMP, land, and conveyance modules during the search process in an iterative and evolutionary fashion. The simulation modules evaluate the BMP performance, as defined via evaluation factors, and cost data of a set of chosen BMP options and pass that information to the optimization engine. The optimization engine synthesizes the information, modifies the search path, and generates new solutions that are repeatedly evaluated using the simulation modules. Through this evolutionary search process, the module will progressively march toward the identification of the best or most cost-effective BMP solutions that meet the user's specific conditions and objectives.

Table 3-32. Summary of Inputs, Methods, and Outputs in the Optimization Module

Inputs
– Define decision variables (the size ranges of potential BMPs)
– Define assessment point(s) and evaluation factor(s)
– Define management targets (for the *minimize cost* option)
– Define BMP cost functions
Methods
– For the *minimize cost* option, optimization search is performed using Scatter Search technique
– For the *generate cost-effectiveness curve* option, optimization search is performed using NSGAII technique
Outputs
– For the *minimize cost* option, the optimization process outputs optimal solutions that meet the specified treatment targets
– For the *cost-effectiveness curve* option, the optimization process outputs the optimal solutions along the cost-effectiveness curve

3.5.1. Problem Formulation

The objective of the optimization module is to determine BMP locations, types, and design configurations that minimize the total cost of management while satisfying water quality and quantity constraints. To formulate an optimization problem, *SUSTAIN* requires the user to specify three sets of information: decision variables, assessment points and evaluation factors, and management targets.

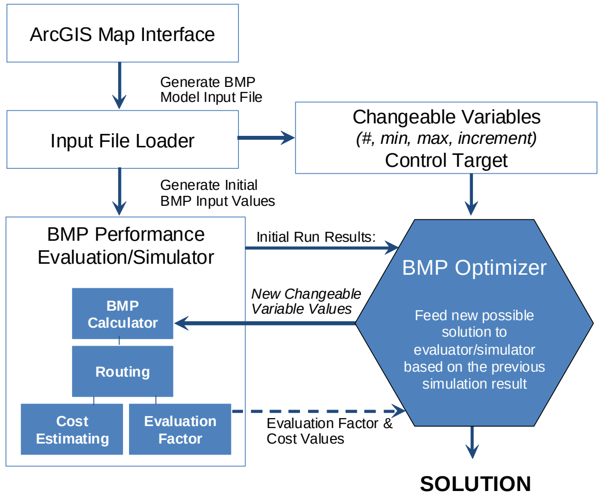


Figure 3-17. Conceptual overview of the optimization module.

Decision Variables

Placing BMPs at different spatial levels or locations (or both) affects the overall cost-effectiveness of the stormwater control system (Zhen 2004). Therefore, BMP location represents one important decision variable for optimization. The possible BMP locations are typically pre-selected on the basis of multiple factors, including availability of space site characteristics (slope, soil infiltration rates, and water table elevation) and other logistical considerations. Another important decision variable involves BMP configuration. At a given feasible location of a BMP type, the configuration parameters can be treated as decision variables with the specified minimum, maximum, and discreet search interval values.

Assessment Point(s) and Evaluation Factor(s)

An assessment point is a location where the water quality or quantity parameters or both are evaluated. Figure 3-18 shows an example of assessment points that can be at the watershed outlet, key tributary outlets, and the downstream node of a stream segment.

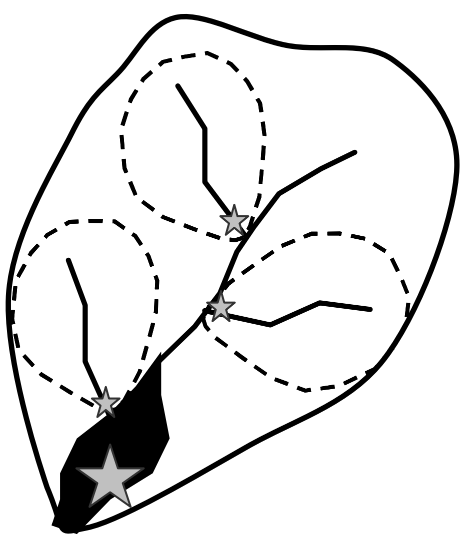


Figure 3-18. Illustration of assessment points.

SUSTAIN provides the user an evaluation factor selection menu when defining the optimization problem. The framework allows for various averaging periods and frequencies consistent with that for typical water quality criteria and TMDL related allocations. Table 3-33 lists the evaluation factor options in *SUSTAIN*.

Table 3-33. Example Control Targets for Typical Evaluation Factor Assessment in *SUSTAIN*

Control Target	Target Value		Note
Flow			
Peak Discharge	cubic feet per sec	--	Parameters related to increased runoff from urbanization
	percent reduction of the existing condition	0–100	
	fraction between existing and pre-developed conditions	0–1	
Annual Average Volume	cubic feet per year	--	
	percent reduction of the existing condition	0–100	
	fraction between existing and pre-developed conditions	0–1	
Exceeding Frequency	times per year of a given threshold flow rate (cfs)	--	
	percent reduction of the existing condition	0–100	
	fraction between existing and pre-developed conditions	0–1	
Sediment			
Annual Average Load	pounds per year value	–	Parameters to meet the water quality standards or biologically derived parameters to meet designated uses in waterbody of concern
	percent reduction of the existing condition	0–100	
	fraction between existing and pre-developed conditions	0–1	
Annual Average Concentration	milligram per liter value	--	
	percent reduction of the existing condition	0–100	
	fraction between existing and pre-developed conditions	0–1	
Maximum Days Average Concentration	milligram per liter value of given days	--	
	percent reduction of the existing condition	0–100	
	fraction between existing and pre-developed conditions	0–1	
Pollutants (TN, TP, or User Defined)			
Annual Average Load	pounds per year value	--	Parameters to meet the pollutant criteria (numeric concentration or frequency of exceedance) or TMDL (load allocation) or other locally defined water-protection goals
	percent reduction of the existing condition	0–100	
	fraction between existing and pre-developed conditions	0–1	
Annual Average Concentration	milligram per liter value	--	
	percent reduction of the existing condition	0–100	
	fraction between existing and pre-developed conditions	0–1	
Maximum Days Average Concentration	milligram per liter value of given days	--	
	percent reduction of the existing condition	0–100	
	fraction between existing and pre-developed conditions	0–1	

Management Targets

Management targets can be related to either water quality or quantity. The user specifies the water quality or water quantity target value or range for each assessment point.

3.5.2. Optimization Algorithms

Evolutionary search techniques have shown great promise in their ability to solve nonlinear, multiobjective, complex optimization problems such as the one above (Zhen and Yu 2004; Dorn and Ranjithan 2003; Harrell 2001; Perez-Pedini et al. 2005). Though such techniques demand extensive computing time, rapid advances in computing power and speed make the techniques more practical and applicable than ever before.

Numerous evolutionary algorithm-based multiobjective optimization procedures are available. Generally, the search techniques can be classified into two categories, i.e., (1) constraint method-based evolutionary algorithms, which use single-objective evolutionary algorithms to solve multiobjective optimization problems by transforming the multiobjective problem to a single-objective problem via the constraint method, and then solving it iteratively; (2) multiobjective evolutionary algorithms, which solve the problem in a single pass, where the population represents the set of nondominated solutions. In the *SUSTAIN* framework, two search techniques are implemented: Scatter Search and Nondominated Sorting Genetic Algorithm-II (NSGA-II)). Scatter Search is a single-ojective evolutionary algorithm, and NSGA-II is a multiobjective evolutionary algorithm.

Scatter Search is introduced by Glover (1977) as a heuristic for integer programming that expanded on the concept of surrogate constraints. The Scatter Search method is an evolutionary search technique that has been explored and used in optimizing complex systems (Glover et al. 2000). Scatter Search shares some commonalties with the widely applied single-objective genetic algorithms (GAs) because both techniques are *population-based* approaches. However, Scatter Search and GA have a number of distinct features of their own. GA approaches are predicated on the idea of choosing parents randomly to produce offspring and then introduce randomization to determine which components of the parents should be combined. By contrast, the Scatter Search approach does not emphasize randomization or being indifferent to choices among alternatives. Instead, it is designed to incorporate strategic responses, both deterministic and probabilistic, that take account of evaluation history. Scatter Search focuses on generating relevant outcomes without losing the ability to produce diverse solutions (Laguna and Marti 2002). Because of that feature, it serves as a better optimization technique for identifying the near-optimal solution with a specific target value.

NSGA-II is one of the most efficient, multiobjective, evolutionary algorithms using the elitist approach (Deb et al. 2002). In NSGA-II, solutions are sorted on the basis of the degree of dominance within the population (i.e., if a given solution is not dominated by any other solution, that solution has the highest possible fitness). In addition, the algorithm seeks to preserve diversity along the first non-dominated front so that the entire Pareto-optimal region is found. NSGA-II has gained popularity in recent years and showed superiority over other multiobjective evolutionary algorithms, e.g. Pareto-Archived Evolution Strategy and Strength-Pareto EA, when applied to solve optimization problems associated with watershed management (Dorn and Ranjithan 2003).

Comparison of Scatter Search and NSGA-II

Both Scatter Search and NSGA-II are population-based evolutionary optimization techniques; however, they employ different search strategies. Scatter Search refines a scatter pattern around the targeted objectives by replacing members of a reference population, while NSGA-II defines a population as individual solutions along a cost-effectiveness curve and refines the entire population with better solutions until the final solution approaches the true Pareto frontier. Pareto optimality is a concept commonly applied in economics and engineering. At any cost or reduction level, a solution is said to be Pareto optimal when no further improvements can be made. Figure 3-19 is a conceptual representation of the two search routines. In Figure 3-19, the Pareto optimum frontier is represented in two-dimensional space as the solid cost-benefit arc in both graphs. A new dimension would be added for each additional pollutant reduction target in the objective function. The concentric circles in the Scatter Search graph illustrate progressively better (narrower) reference populations, until the final set of best solutions are found clustered around the point along the Pareto frontier. The dashed lines in the NSGA-II graph illustrate progressively improving cost-benefit relationships with each new generation of solutions until the true Pareto frontier is realized in the last generation. Scatter Search clusters solutions around the defined objective on the Pareto frontier, while NSGA-II distributes the solutions along the entire trade-off frontier. Increasing the resolution for NSGA-II means increasing the number of individuals in the population, which increases the number of generations needed to find the Pareto optimal frontier.

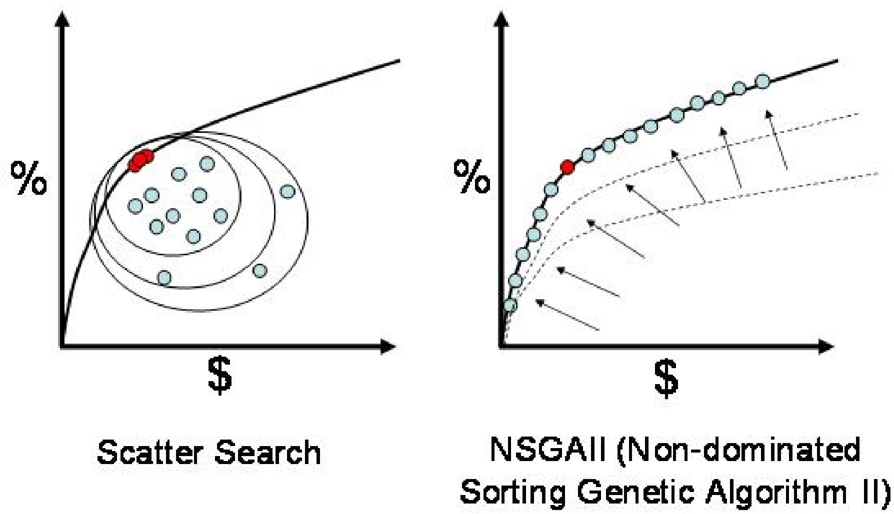


Figure 3-19. **Comparison of Scatter Search and NSGA II optimization techniques.**

For the *minimize cost* option, Scatter Search is more efficient (finding the best solutions with fewer runs of the simulation module) because the search is more focused around the target. For the *cost-effectiveness curve* option, NSGA-II (genetic algorithm) is more efficient because it applies the non-dominated sorting technique and the search proceeds in a manner of fronts.

Scatter Search

The major operation steps of Scatter Search are described below.

Generating a starting set of diverse points

Generating a starting set of diverse points is accomplished by dividing the range of each variable into four sub-ranges of equal size. Next, a solution is constructed in two steps: a sub-range is first randomly selected and then a value is randomly chosen from the selected sub-range. The starting set of solution points also includes all variables at their lower bound, all variables at their upper bound, all variables at their midpoints, and other solution points suggested by the user.

Choosing a subset of diverse points as the reference set

The reference set (RefSet), is a collection of both high-quality solutions and diverse solutions that are used to generate new solutions. Specifically, the RefSet consists of the union of two subsets, *RefSet1* and *RefSet2*, of size b_1 and b_2, respectively. That is, $|RefSet| = b = b_1 + b_2$. The construction of the initial reference set starts with the selection of the best b_1 solutions from the starting set of diverse points (P). The notion of *best* in this step is a measure given by the evaluation of the objective function. These solutions are added to RefSet and deleted from *P*. For each improved solution in *P – RefSet*, the minimum of the Euclidean distances to the solutions in RefSet is computed. Euclidean distance is the straight line distance between two points. For example, in a two-dimensional plane, the Euclidean distance is the straight line between point 1 at (x_1, y_1) and point 2 at (x_2, y_2) and is equal to $\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$.

Then, the solution with the maximum of these minimum distances is selected. This solution is added to RefSet and deleted from *P* and the minimum distances are updated. This process is repeated b_2 times. The resulting reference set has b_1 high-quality solutions and b_2 diverse solutions.

Starting the search for the optimal solution by using a linear combination method to construct new solution points from the reference solution points

The linear combination is based on the three types of formulation, in which x' and x'' are reference solution points, and $x_{1\text{–}3}$ is the newly generated solution points:

$$x_1 = x' - d$$
$$x_2 = x'' - d$$
$$x_3 = x' + d$$

where $d = r\dfrac{x'' - x'}{2}$ and *r* is a random number in the range of (0, 1).

Updating the RefSet

In the course of searching for a global optimum, the RefSet is continuously updated. The solutions having better quality, or ones that can improve the diversity of the reference set, replace the old points in the set.

Stop the search if the stopping criteria are met

The *stopping* criteria can be defined, at the user's option, either as the maximum number of iteration runs, or the minimum improvement between updates of the reference set, or both, in which case, the search process will be stopped when either of the criteria is met.

NSGA-II

The major operation steps of NSGA-II are described below.

Creation of first generation

When applying the NSGA-II, a random parent population (P_0) consisting of *N* solutions is first created. The population is then sorted by the non-dominant level. A solution $x^{(1)}$ is non-dominant to another solution when $x^{(1)}$ performs no worse than the other solution in all objectives, and $x^{(1)}$ performs better than the other solution in at least one objective. At the end of the sorting, each solution is assigned a fitness (or rank) equal to its non-dominant level, with a smaller value indicating that the solution is dominated by fewer other solutions.

The processes of tournament selection, crossover, and mutation are used to create a child population (Q_0), which has a same size of P_0 with *N* solutions.

Main loop

In the first step of the main loop, the parent population and the child population are combined (R_0). The population of R_0 will have 2*N* solutions. The 2*N* solutions in R_0 are then sorted according to non-domination. Elitism is ensured in this step because both the parent and the child population are used in the sorting. The sorted 2*N* solutions will form various best non-dominated subsets (in which all the solutions are non-dominant to each other, but overall they dominate other subsets). The first *N* solutions from the ranked best non-dominant subsets, $F_1,\ldots, F_i$, are then selected to form a new parent population (P_1). The new parent population is used to create a new child population (O_1), and the process continues until the stopping criteria are met.

The NSGA-II uses the crowding distance (the size of the largest cuboid enclosing solution $x^{(1)}$ without including any other solution in the population) concept to maintain solution diversity. That is, in cases where two solutions have the same non-domination rank, the solution with larger crowding distance is always preferred.

Stopping criteria

The user can make the NSGA-II stop when the new parent population does not change for two consecutive loops. The stopping criterion can also be that the fitness function does not improve after a certain number of iterations.

Optimization Options

SUSTAIN provides two optimization options: (1) cost minimization, and (2) cost-effectiveness curve. In the cost-minimization option, the optimization search process identifies the near-optimal solutions that meet the user-specified management targets. With the cost-effectiveness curve option, the optimization process reveals all the cost-effective solutions within the user-specified management target range.

Cost-Minimization Option

With the objective of minimizing cost subject to desired water quality or water quantity objectives (or both) at a specified location (assessment point), the optimization problem formulation can be mathematically expressed as below. In the formulation, a group of BMP_i (i = 1,…, n) forms the decision matrix, which defines the optimization engine's search domain. For each potential location, the user defines the feasible range of BMP type and configuration parameters.

The objective is to:

$$\text{Minimize } \sum_{i=1}^{n} Cost(BMP_i)$$

subject to:

$$Q_j \leq Qmax_j \quad \text{and}$$

$$L_k \leq Lmax_k$$

where

BMP_i = a set of BMP configuration decision variables associated with location i,
Q_j = the computed amount of water quantity factor at the assessment point j,
$Qmax_j$ =the maximum value of the water quantity factor targeted at the assessment point j,
L_k = the computed amount of water quality loading factor at the assessment point k, and
$Lmax_k$ = the maximum value of the water quality loading targeted at the assessment point k.

Cost-Effectiveness Curve Option

Under the cost-effectiveness curve option, the search aims at identifying the cost-effective solutions within the specified management target range. The multiobjective problem can be expressed as follows:

$$\text{Minimize } \sum_{i=1}^{n} Cost(BMP_i) \text{ and}$$

$$\text{Minimize } EF$$

where

BMP_i = a set of BMP configuration decision variables associated with location *i* and
EF = the management evaluation factor (*EF*) at one given assessment point, and the *EF* can be any of the options listed in Table 3-33.

3.5.3. Regional Application

SUSTAIN is able to evaluate management practices at multiple scales, ranging from local to watershed applications. Placement of BMPs at different spatial levels (i.e., on-site, subregional, and regional) affects the overall cost-effectiveness of the stormwater control system (Zhen and Yu 2004). Management plans often need to evaluate the cumulative benefit of management practices at multiple- scale watersheds on downstream water quality in rivers, lakes, or estuaries. The site or local-scale evaluation involves simulation and analyses of individual BMPs and various combinations of practices and treatment trains to derive local runoff quantity and quality. For a larger-scale watershed, there could be hundreds or thousands of individual management practices that are implemented to achieve a desired cumulative benefit. *SUSTAIN* incorporates an innovative, tiered approach that allows for cost-effectiveness evaluation of both individual and multiple nested watersheds to address the needs of both regional and local-scale applications (Figure 3-20). This section describes the procedures of the tiered optimization analysis approaches in *SUSTAIN* for sequentially identifying cost-effective BMPs on a regional scale.

A relatively large watershed can usually be subdivided into several smaller subwatersheds as shown in Figure 3-20. Users need to select, with, say, the use of the siting tool in *SUSTAIN*, an appropriate suite of feasible BMP options (types, configurations, and costs) at strategic locations for each subwatershed. *SUSTAIN* then generates the time series rainfall-runoff data from BMP drainage areas and routes them through BMPs, in parallel or in series, to produce the quantity and quality data at downstream assessment points. *SUSTAIN* uses the cost and effectiveness data to derive the cost-effectiveness curve that relates flow or pollutant-load reductions with costs. Each point on the cost-effectiveness curve represents an optimal combination of BMPs that will collectively remove the targeted amount of pollutant load at the least cost.

The tiered optimization procedures implemented in *SUSTAIN* provides an efficient and manageable means for large-scale applications and allows users to evaluate and optimize on the basis of the hydrologic and water quality characteristics at the specified assessment points. Tier-1 performs the optimization search to develop cost-effectiveness curves for each tier-1 subwatershed. In a tier-2 analysis, the tier-1 solutions are used to construct a new optimization search domain and run the transport module, if needed, with solutions from all the tier-1 subwatersheds to develop the combined cost-effectiveness curve for the entire watershed.

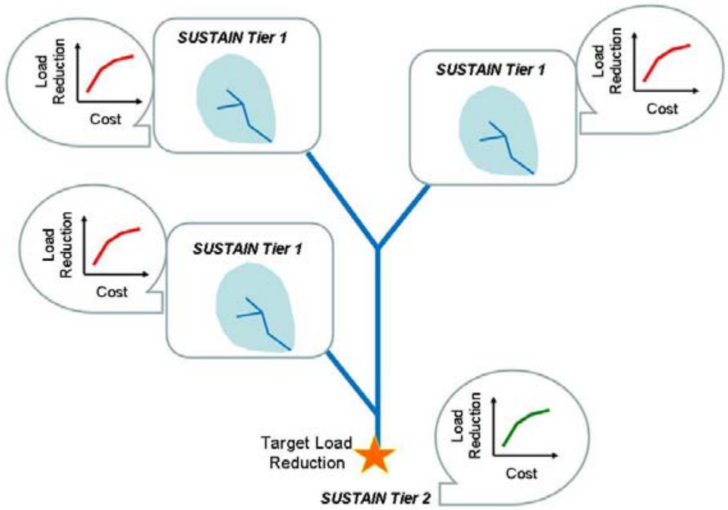


Figure 3-20. **Tiered application of *SUSTAIN* for developing cost-effectiveness curves.**

Figure 3-21 illustrates the tiered application process in more detail. At the first step (tier-1) of the tiered optimization analysis, the cost-effectiveness curve for each subwatershed is generated by performing continuous multiple optimization runs at incremental flow/pollutant reduction targets. In the second step (tier-2), the search domain is constructed using the tier-1 results. As shown, the search domain for tier-2 contains the discrete solutions on the tier-1 cost-effectiveness curves at assessment points *i* and *j*. The third step is to perform the tier-2 optimization for the search domain constructed. The optimization engine strategically samples the discrete options in the search domain. The cost-effectiveness of each sample is measured, stored, and analyzed to guide the next search direction.

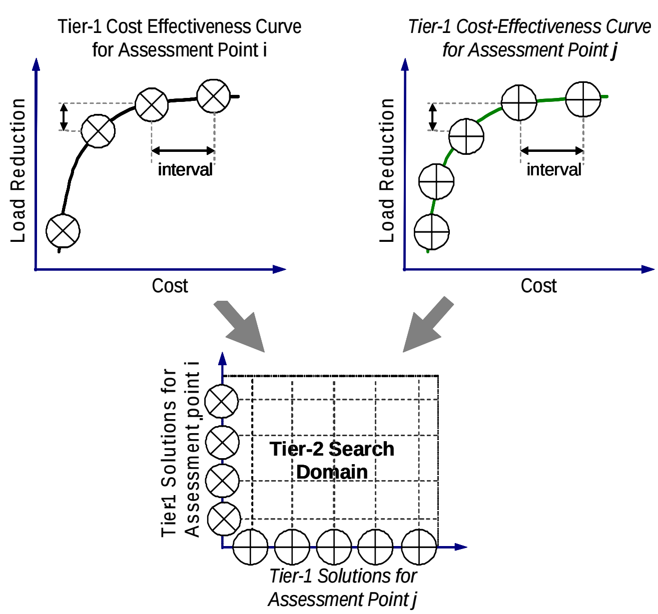


Figure 3-21. **Construction of the tier-2 search domain using tier-1 results.**

Figure 3-22 illustrates the simulation process used to generate the results for measuring the cost-effectiveness of each iteration in the tier analysis. The simulated time series outputs for all discrete points on the tier-1 cost-effectiveness curve are stored and used when a point, hence the BMP options associated with it, is chosen in the tier-2 analysis. Similarly, the time series runoff data of the watershed area that is not part of the tributary areas of the tier-1 assessment points is generated and stored before the tiered analysis. This data, however, might also be generated during the tier-2 search process. The transport module is often required to perform routing of the time series data from the upstream tier-1 subwatershed to merge with that for the downstream tier-1 subwatershed. In such a manner, the tiered approach is applied to a large watershed which contains subwatersheds or to a small watershed that requires the development of a detailed management plan at a parcel- or a street-block-level.

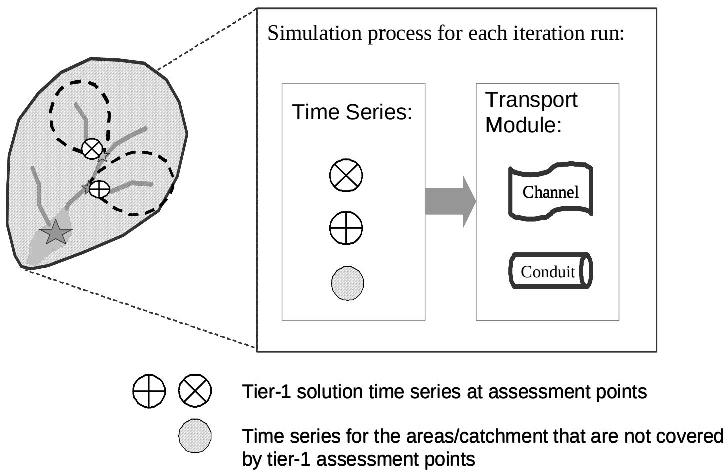


Figure 3-22. **Simulation process for each iteration run.**

3.5.4. Important Considerations and Limitations: Optimization Module

Importance of Calibration

The optimization engine performs iterative searches to identify cost-effective solutions. The search process is dependent on the cost and BMP treatment effectiveness values of each BMP or a combination of BMPs evaluated. Therefore, it is crucial to have calibrated watershed and BMP simulation modules, as well as good BMP cost data, to ensure meaningful results. The cost-effective solutions from evolutionary search techniques should be considered only near-optimal solutions, meaning that the solutions are not guaranteed to be the absolute best but are believed to be close to it.

Minimizing Run-time and Computational Effort

The approximate number of iterative runs to reach the near-optimal solutions is dependent on the number of decision variables, the number of discrete options of a decision variable, and the complexity of the problem. In general, the number of runs needed is reduced with a reduced number of decision variables, number of discrete options for a decision variable, and complexity of the problem. Experience gained from performing experiments is usually useful for estimating the number of runs needed for reaching near-optimal solutions.

The optimization process based on long-term continuous simulation can require a large amount of computation time especially for a large watershed that has many feasible BMP sites and reaches/conduits. To achieve computational efficiency, it is advantageous to minimize the number of non-dummy conduits, decision variables, and search steps.

When using the cost-minimization option, the user is asked to set a treatment (e.g., pollutant reduction) target. To avoid setting an unreachable target, one can perform a simulation that maximizes treatment scenario by setting the BMP sizes to maximum for a site for estimating the maximum treatment effectiveness.

Tiered Analysis Interface

Although the *SUSTAIN* engine is capable of performing tiered optimization, the related interface is yet to be developed. Users must manually create all the input files to perform the tiered optimization analysis. A more robotic and automated interface will be developed to guide the users through the tiered analysis processes.

3.6. Post-Processor for Results Interpretation

The *SUSTAIN* post-processing module provides a centralized location for analyzing and interpreting simulation outputs at multiple locations, and for scenarios (e.g., existing development with and without BMPs, and pre-development conditions) and parameters of interest (e.g., inflows, outflows, and pollutant loads and concentrations). The framework allows users to evaluate simulation results that are highly variable in magnitude, duration, intensity, treatment containment volume, attenuation, and pollutant-removal effectiveness. The simulation outputs contain hourly or subhourly data, and can span several years, depending on the length of simulation.

The primary objective of the post-processor is to mine the model results to derive meaningful information that best characterizes the effectiveness of the modeled management strategies. This is achieved by the use of specific graphical and tabular reports. Four components are in the post-processor: storm event classification, storm event viewer, storm performance summary, and cost-effectiveness curve. Table 3-34 provides an overview of the required inputs, the methods used to manage and process the inputs, and the resulting outputs from *SUSTAIN*'s post-processor.

3.6.1. Storm Event Classification

Storms with identical hyetographs (i.e., precipitation pattern) can produce very different runoff responses depending on prior moisture conditions, seasonality, and geographic location. For example, if one storm follows a long, dry period, and another follows shortly after a relatively wet period, the runoff responses would be different. BMP performance is similarly affected by antecedent conditions. As a result, accurate interpretation of modeled BMP performance requires an understanding of prior precipitation and soil moisture. *SUSTAIN's* post-processor facilitates this through its storm event classification method, whereby the time interval between storms (storm interval) is specified in order to define a *storm event* from a precipitation time series.

The storm interval is the number of dry days between storms necessary to restore near-equilibrium soil moisture conditions. The interval varies by geographic region and can be selected using statistical evaluation of precipitation time series. For example, in regions such as Seattle, Washington, where rainfalls are frequent but of low intensity, a shorter storm event interval is more appropriate. Longer dry intervals, say, 3 days, are typically used in drier regions that rarely get rain, such as Southern California. Figure 3-23 shows how the derived set of storm events changes with the number of dry hours between storms. For each storm event, the graphs in Figure 3-23 show the total precipitation and the peak precipitation intensity during an interval, relative to other intervals. As expected, the number of events decreases as the dry interval (number of dry hours between storms) increases.

Table 3-34. Post-processor Inputs, Methods, and Outputs

Post-Processor
Inputs – Storm event classification – Rainfall time series file – Number of dry days between storm events – Evaluation period (start and end dates) – Time series files for storm viewer and performance summary – Development conditions: pre-developed, with, and without BMPs – Cost-effectiveness curve – Best solutions and all solutions – Associated model input file
Methods – Storm event classification: divide time series into discrete storm events, separated by a user-defined minimum number of days for the entire evaluation period – Storm event viewer: browse and display modeled time series comparisons for three scenarios (with and without BMPs and pre-developed condition) for a user-selected storm event – Storm performance summary: display summary comparisons for scenarios (with BMPs and pre-developed condition, relative to the scenario without BMPs) for all storm events – Cost-effectiveness curve: superimpose cost-effective solutions on all solutions – Upon request, generate model results for a selected cost-effective solution
Outputs – Storm event classification: browsable and sortable list of storm events – Storm event viewer: time series comparison graphs – Storm performance summary: load comparison graphs for all storm events and EMC graphs for all storms – Cost-effectiveness curve: cost distribution by BMP type and storage distribution by cost interval

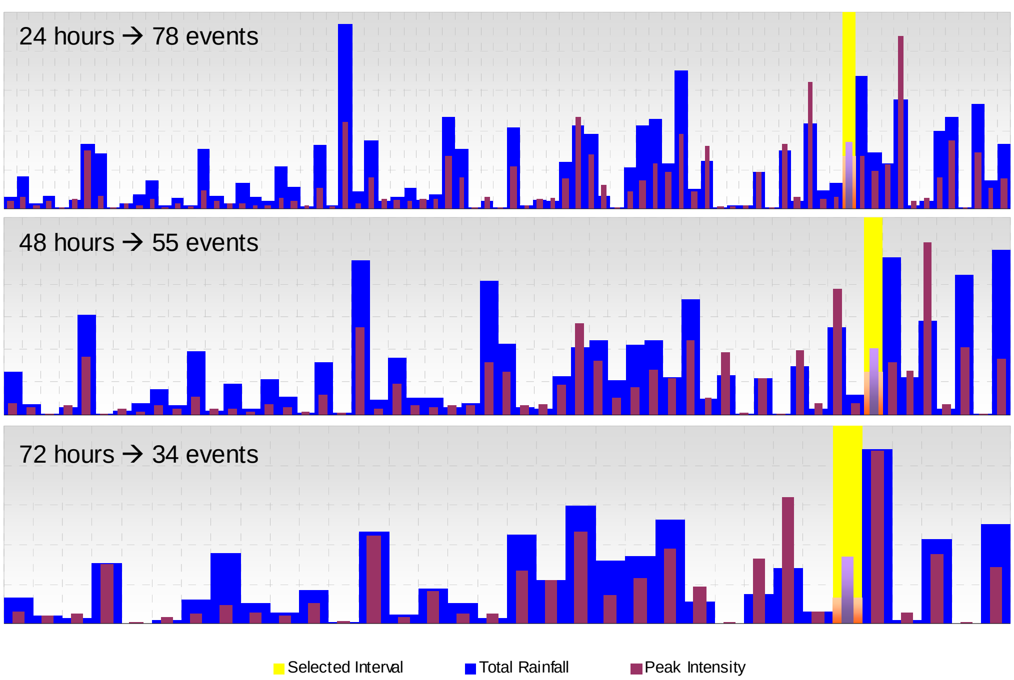


Figure 3-23. Number of storm events and total precipitation and peak intensity as a function of dry hours between storms.

In the *SUSTAIN* post-processor, once the storm events are defined, the user has the option of sorting the events by total precipitation volume or by peak intensity, as shown in Figure 3-24. Note that the same event (August 9, 2001, 6:00 p.m.) has been highlighted in both Figure 3-23 and Figure 3-24. The event sorting provides additional insight into the details of the selected event relative to other events. For example, in terms of total rainfall volume, the selected event is in the 53rd percentile; however, in terms of peak intensity, it is in the 82nd percentile for the selected year. The derived storm event information is further explored by the storm event viewer and storm performance summary analysis as described in the next two sections.

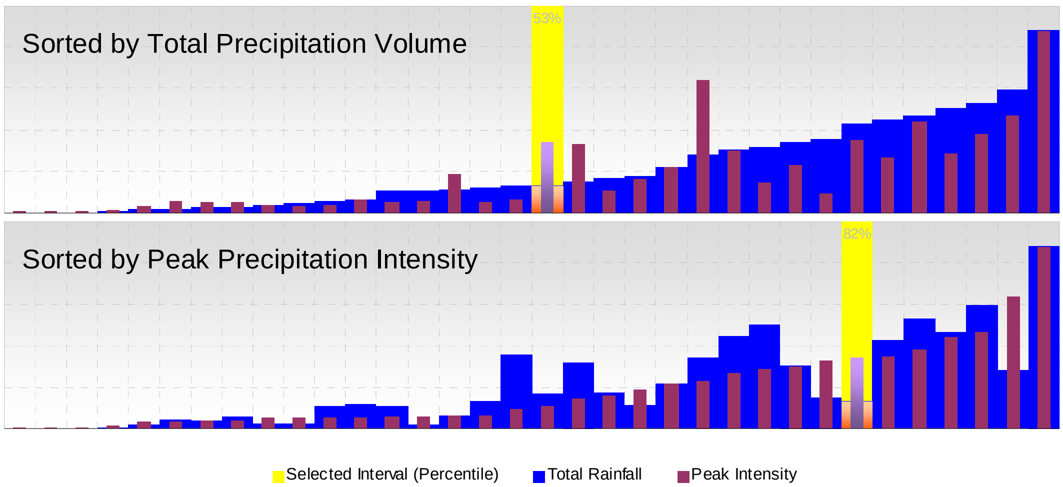


Figure 3-24. **Precipitation events sorted by total precipitation volume and peak intensity.**

3.6.2. Storm Event Viewer

Once the storm events are defined, the user can select a specific storm event to visualize its detailed time series responses. The storm event viewer plots the time series data for comparison under the following three conditions: (1) existing development without BMPs, (2) existing development with BMPs, and (3) before development. The viewer illustrates how BMP performance changes with increasing or decreasing storm size. Four example storms are shown below for illustration the use of the viewer. Those storm events were derived using 24 dry hours as the storm separation criterion. Storm event 1 (Figure 3-25) is the selected interval highlighted previously in the storm classification figures.

In each of the storm viewer graphs, the blue shaded area represents the developed condition without BMPs (post-developed), the brown line represents the BMP scenario, and the green line represents the pre-developed condition. Storm event 1 in Figure 3-25 shows excellent BMP performance because the outflow from the BMP scenario (brown line) is significantly reduced from the post-developed condition, indicating that the storm runoff was well controlled by the BMP installed. Figure 3-26 shows a slightly different response. Although the peak flow for this event is similar to that of the first one (slightly lower), the storm interval 2 generates significantly more outflow than storm event 1. This is because the peak precipitation came after 2 hours of steady rainfall causing the ground to be saturated and thus more bypass flow through the BMPs. After the storm has ended, outflow persists for a number of hours because of the attenuation by BMPs in the drainage area.

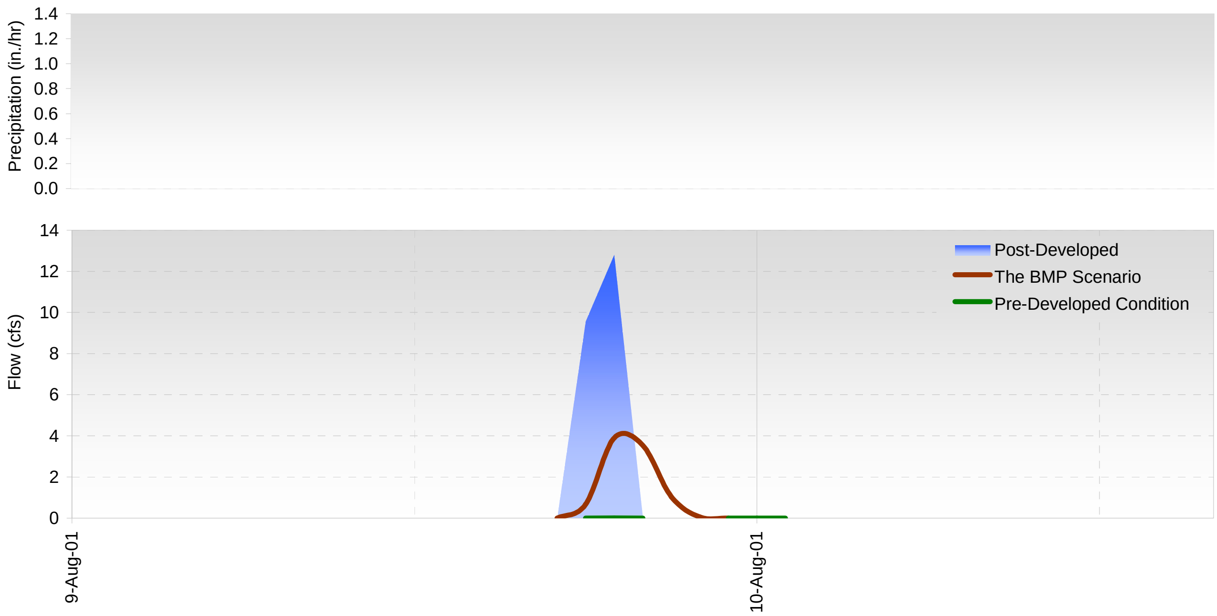


Figure 3-25. Storm event 1: August 9, 2001 6:00 p.m. to August 9, 2001 8:00 p.m. (0.66 in. to 2 wet hours, peak: 0.48 in.).

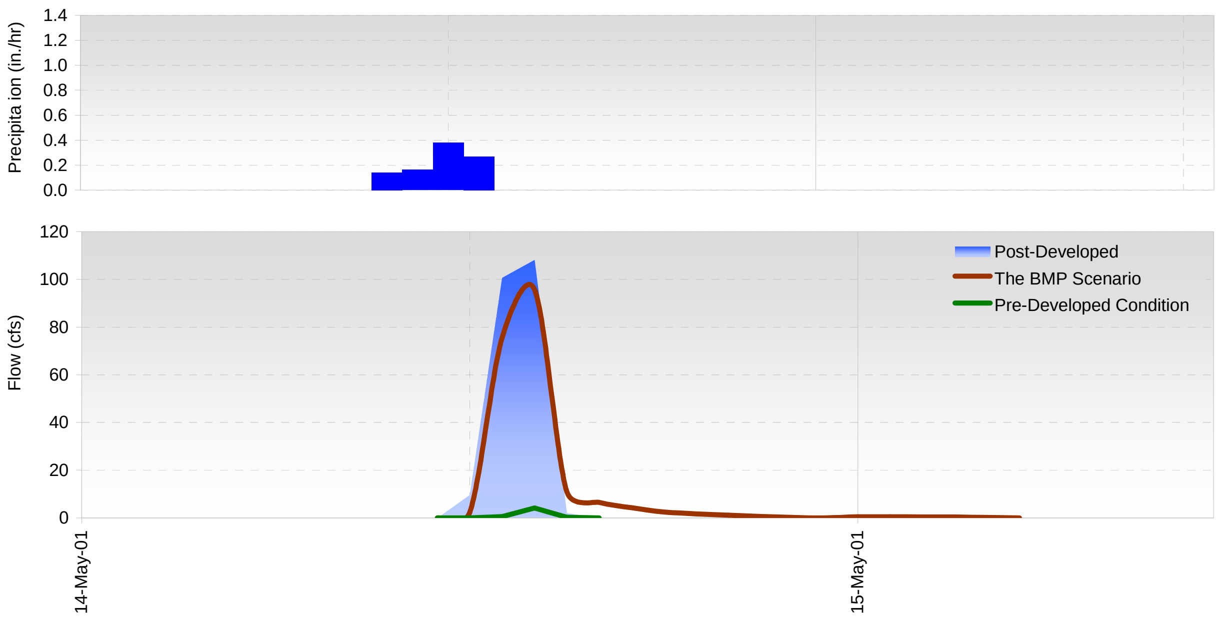


Figure 3-26. Storm event 2: May 14, 2001 11:00 a.m. to May 14, 2001 1:00 p.m. (0.95 in. to 4 wet hours, peak: 0.38 in.).

The dry-interval criterion is applied after the last precipitation. For a 24-hour dry interval criterion, a storm event begins with the first non-zero precipitation and ends at a minimum of 24 hours after the end of the last precipitation. The storm duration as is defined allows the runoff to be rightly associated with the storm that caused it. Storm event 3 in Figure 3-27 consists of two storms because the second storm began less than 24 hours after the end of the first storm. By definition, the second storm cannot be evaluated independently of the first storm because antecedent moisture conditions were not stabilized following the first storm. This approach of defining a storm event will reduce the *noise* associated with a time series response. Had those two storms been considered independently, the second storm in the interval—which has a slightly lower total precipitation, longer duration, and lower peak precipitation—would have appeared much worse than storm event 1 because of the antecedent conditions.

It is also interesting to note that only the second storm generated measurable surface runoff for the pre-developed condition. This further illustrates the impact of antecedent moisture conditions on BMP performance.

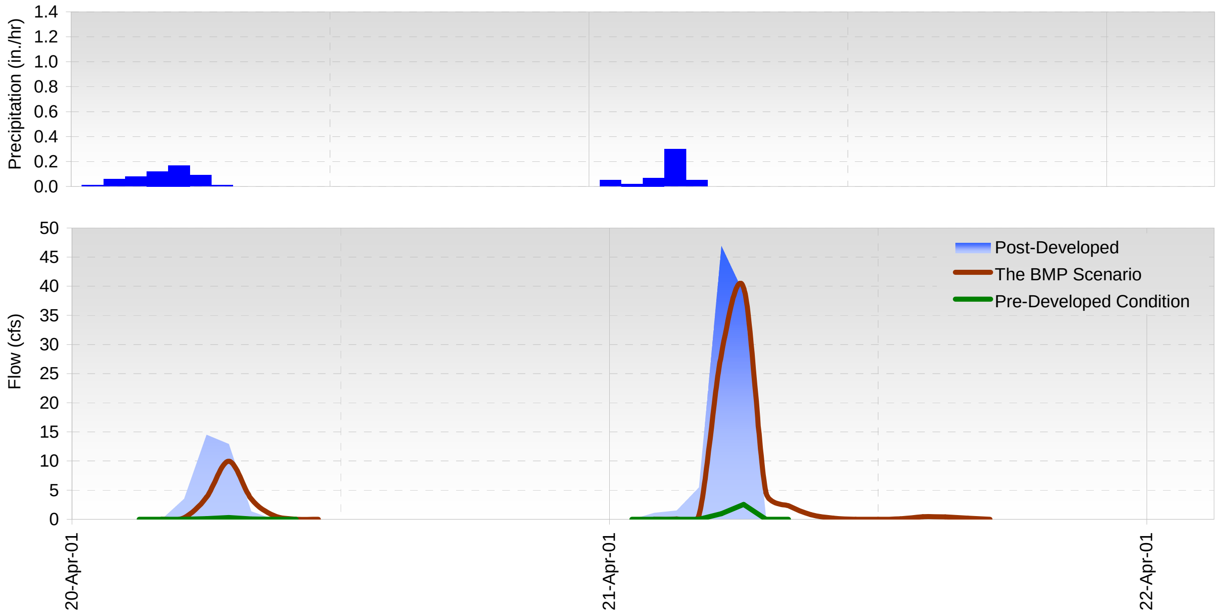


Figure 3-27. **Storm event 3: April 20, 2001 2:00 a.m. to April 21, 2001 5:00 a.m. (1.03 in. to 12 wet hours, peak: 0.30 in.).**

Finally, storm event 4 in Figure 3-28 is the largest total precipitation volume of storms considered. It consists of a series of intermittent precipitation occurrences scattered over a 2-day period. By grouping the events into the same storm event, their effects are evaluated together because they are not independent hydrologically.

3.6.3. Storm Performance Summary

The derived storm events are used to generate a BMP performance summary for the simulation period. The graph (as shown in Figure 3-29) displays summary comparisons of three scenarios (with and without BMPs and pre-development condition). The graph shows three series. The first series (circles) shows percent reduction by storm interval for the BMP scenario relative to the post-developed (with no BMPs) scenario. The second series (horizontal hashes) shows percent reduction for the pre-developed condition relative to the post-developed (with no BMPs). The series is plotted for reference purposes. If the BMP scenario (circle) is at or below the series (hash line), it indicates that BMP performance for that storm event is not performed at the level of pre-developed conditions. The final series is a bar graph, which follows the right axis. For each output constituent, the series computes the pollutant contribution (in percent) of each storm event with respect to the total rainfall series. Figure 3-29 shows a sediment removal summary for 34 storm events sorted by sediment load on the y-axis and storm event volume on the x-axis.

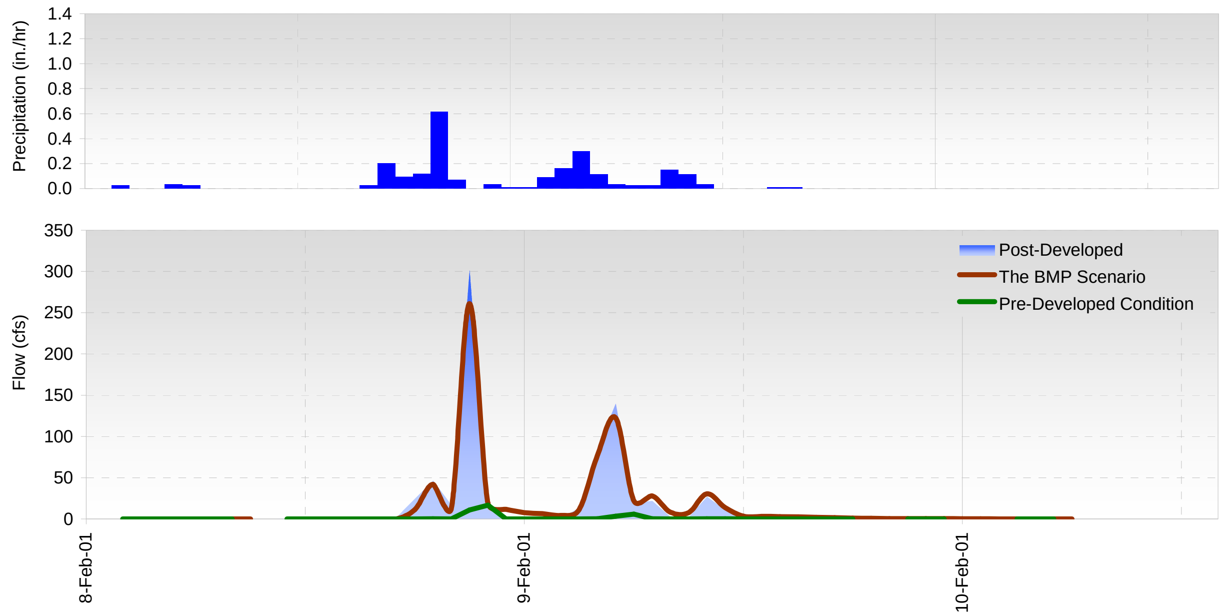


Figure 3-28. **Storm event 4: February 8, 2001 12:00 a.m. to February 9, 2001 4:00 p.m. (2.34 in. to 25 wet hours, peak: 0.61 in.).**

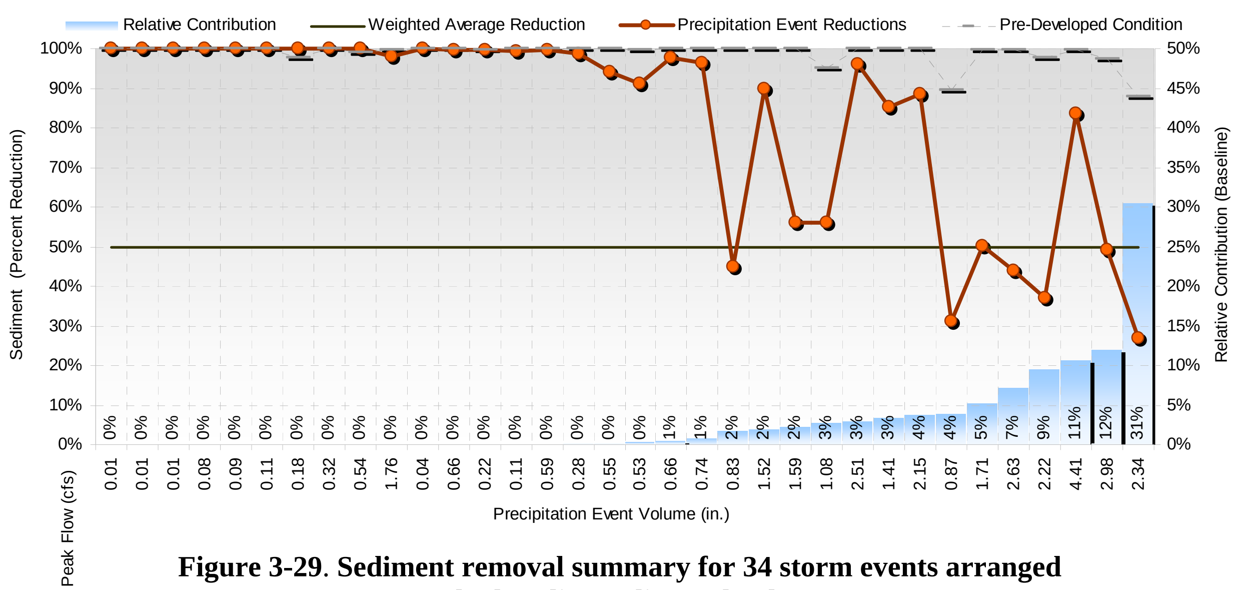


Figure 3-29. **Sediment removal summary for 34 storm events arranged by baseline sediment load.**

As shown in Figure 3-29, sediment load increases generally with increase in precipitation volume and smaller storms can be better managed by BMPs than the larger storms. In the example, the weighted average percent reduction is around 50 percent, which illustrates the influence of the larger load-producing storms on the long-term average reduction. While the pre-development condition (horizontal hashes series) would contain close to 100 percent of the current baseline flow and load under the existing development condition, some large storms produce runoff and loads. For example, the largest load producing storm (2.34 in., which was also previously featured in Figure 3-28) shows the poorest BMP performance at 13 percent removal. This storm generated measurable sediment load even under the pre-developed condition.

Figure 3-30 shows the summary results of peak flow-reduction performance for this same storm series. The overall results are similar to that for sediment load reduction. For both sediment load and peak flow reductions, the 4.41-in. storm event performs among the highest because of its relatively low intensity. This storm event consists of four individual small storms with relatively high peak flow rates over an 11-day period, and hence the runoff is largely contained by the BMPs.

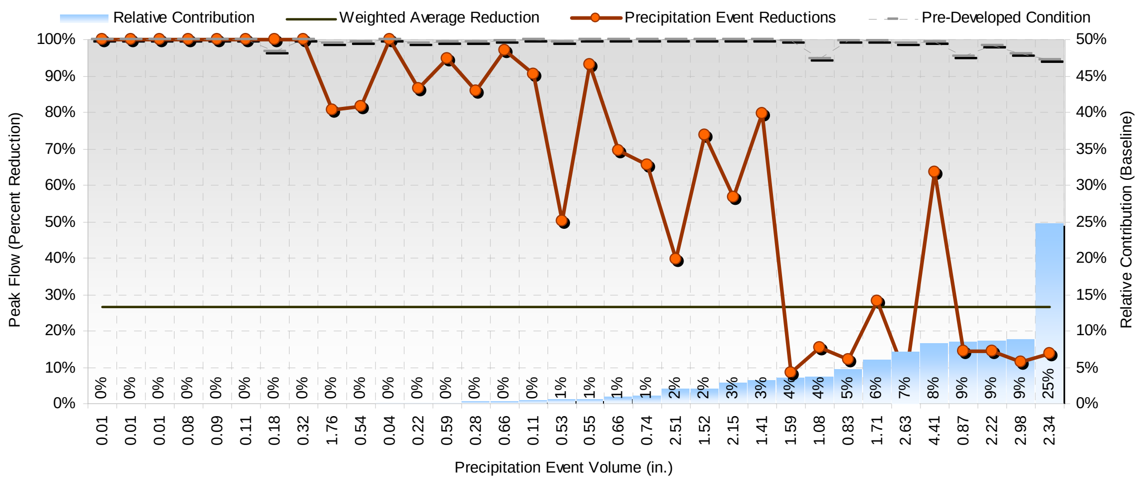


Figure 3-30. Peak flow reduction summary for 34 storm events arranged by peak flows.

Additionally, the post-processor is designed to produce a different graph to show a summary comparison of peak flows or water quality constituents for the same three scenarios. For water quality constituents, it uses the EMC, which is computed as the total pollutant load divided by the total outflow volume of the storm. Figure 3-31 shows a peak flow comparison of three scenarios by storm event arranged by increasing peak flows for the existing development (baseline). Similarly, Figure 3-32 shows the EMCs of sediment for the corresponding storm events in Figure 3-30. It is interesting to note from Figure 3-32 that sediment EMC in pre-developed condition can be larger than the other two scenarios because of low runoff volumes when the watersheds are not yet developed. Depending on the study nature, attaining a specified EMC might be an important goal to achieve.

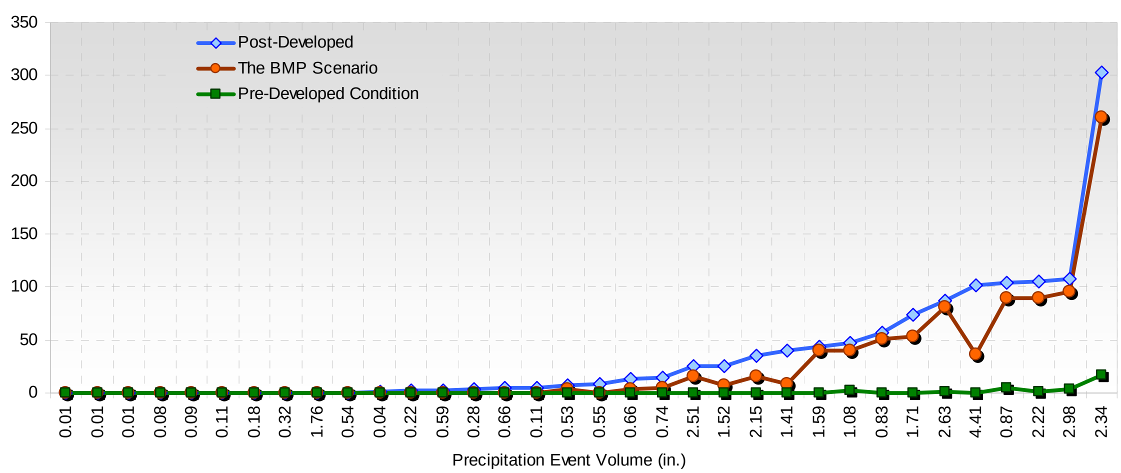


Figure 3-31. Peak flow comparison by storm event arranged by post-developed peak flows.

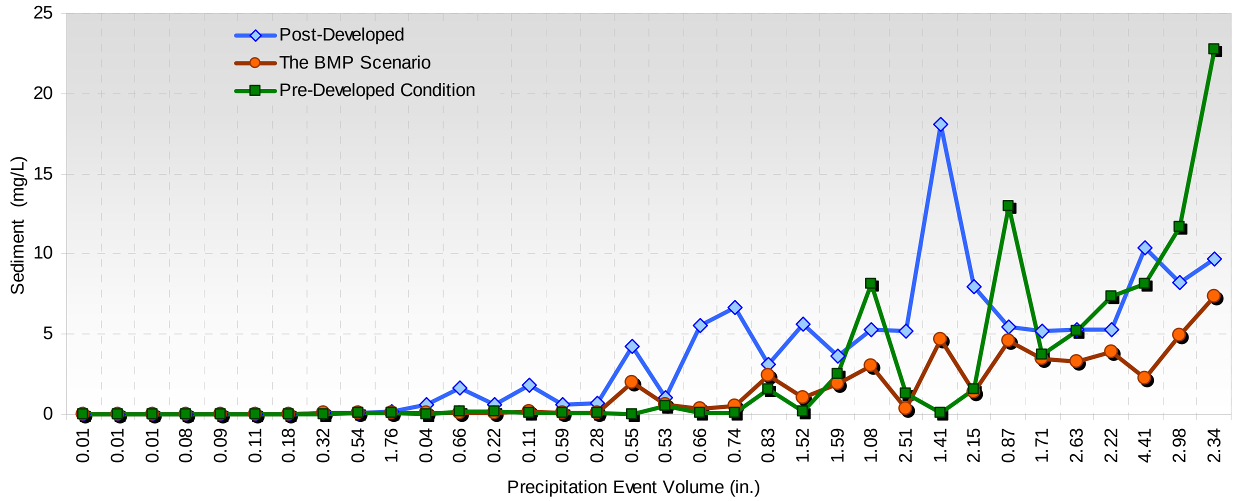


Figure 3-32. **EMC of sediment for the corresponding storms.**

3.6.4. Cost-effectiveness Curve

The final analysis component of the post-processor is creating a cost-effectiveness curve to facilitate decision making. The post-processor can generate and display this curve directly from the output only when the NSGA-II search method is used in the optimization module. It displays the curve one pollutant constituent at a time; however, the post-processor still allows a user to evaluate the resulting benefit to other constituents gained from optimizing performance for a single constituent. For example, one can evaluate how optimizing flow reductions impacts sediment reductions. Each optimization run generates two files from which the post-processor derives the cost-effectiveness curve: (1) *AllSolutions.out*, which contains cost-benefit summaries for each intermediate optimization run, and (2) *BestSolutions.out*, which contains cost-benefit summaries for the final population of points that constitutes the optimum frontier. Figure 3-33 shows an example of a cost-effectiveness curve for sediment load reduction.

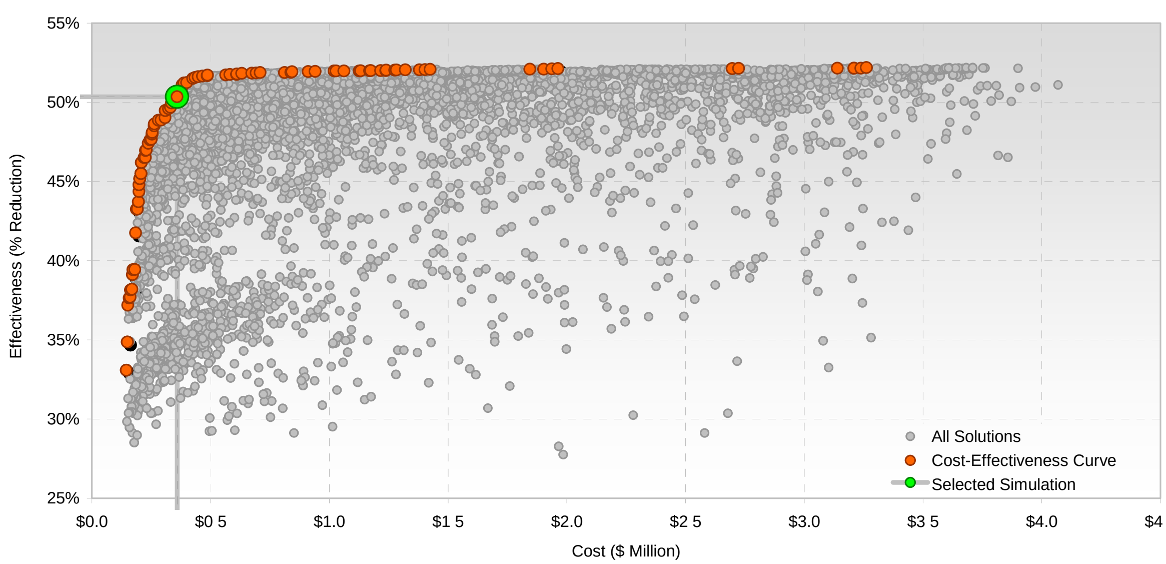


Figure 3-33. **Example cost-effectiveness curve for sediment load reduction.**

In Figure 3-33, cost (dollars in millions) is plotted on the x-axis, while effectiveness (% sediment load reduction) is plotted on the y-axis. All the intermediate solutions are plotted as smaller circles, while the optimum cost-effectiveness curve solutions that form the left- and upper-most boundaries of the search domain use more pronounced circles.

The data in a cost-effectiveness curve is related to the data generated in all the previously described post-processor components described thus far. In Figure 3-33, as an example, the most cost-effective solution (at a cost of around $340,000) for 50% load reduction is highlighted. The cost, performance, and time series data associated with the BMPs that collectively provide 50% sediment load reduction can be retrieved from the information presented in Figure 3-29, in the rest of the storm performance graphs shown in Section 3.6.3, and the storm viewer graphs shown in Section 3.6.2. Using the post-processor, the user can navigate along points on the cost-effectiveness curve, generate individual runs for individual solutions on the fly, and toggle between the storm summary/individual storm viewers and the cost-effectiveness curve to see BMP performance at multiple temporal levels of resolution.

The post-processor can produce two additional types of information from the *BestSolutions.out* file: cost distribution by BMP type for a given point on the cost-effectiveness curve and BMP storage distribution by cost interval. Figure 3-34 shows the data of BMP cost distribution versus sediment reduction effectiveness on the cost-effectiveness curve and the 50% reduction point shown on Figure 3-32 is highlighted. For each effectiveness curve, the figure also shows the costs associated with the selected BMP types. The inset pie chart shows the distribution of cost by BMP type associated with 50 percent effectiveness. Note that the porous pavement option is not in the pie chart because it is not an optimal option to achieve the 50% reduction line to the right of the selected point in Figure 3-33. That means that porous pavement option is likely feasible but not cost-effective for that level of load reduction. However, it would be a cost-effective choice to achieve 52% or more reduction of sediment load as shown in Figure 3-33.

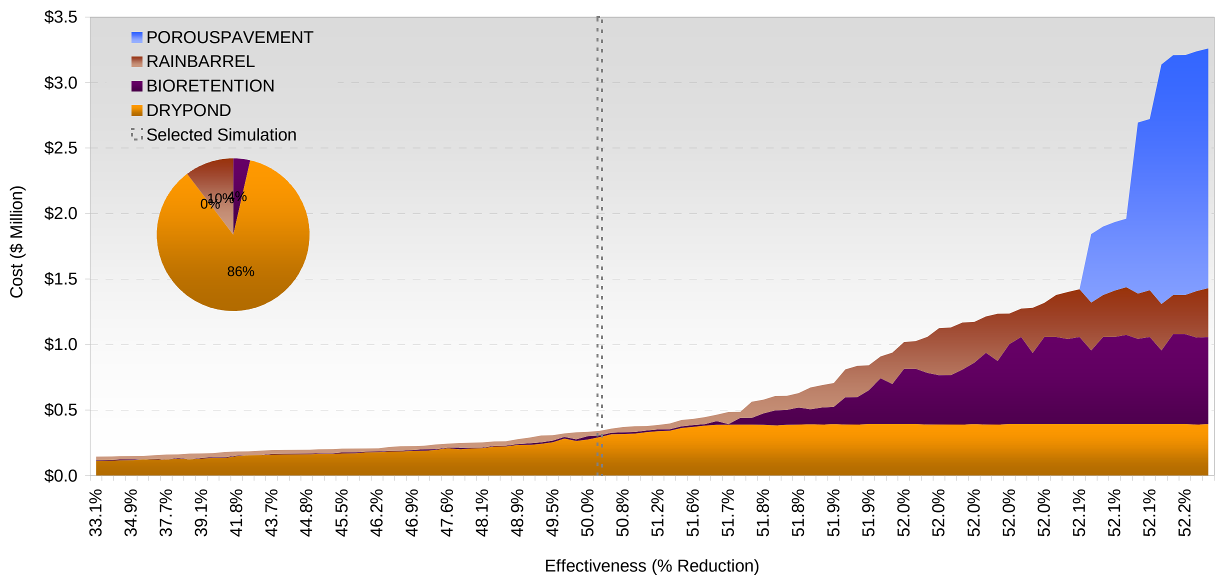


Figure 3-34. BMP cost distribution by effectiveness for sediment load reduction on the cost-effectiveness curve.

In the optimization process, the feasible BMP types are compared and screened based on simulation modeling, cost, and optimization input specification, to develop an order of cost-effective options for maximizing their use. Figure 3-34 implies that to achieve sediment removal from runoff, dry ponds are the most cost-effective option, while porous pavement is the least. In some places, rain barrels are used in conjunction with bioretention, and the use of those two BMP types in the same space results in some variability that exhibits itself as *noise* in the graphs. In this example, there is no clear choice for maximizing one technique over the other because both rain barrels and bioretention were selected at all levels along the cost-effectiveness curve. Figure 3-35 provides detail about a point along the curve where BMP selection is fairly well distributed among the four broad categories of BMPs. However, the point represents a $2 million investment, which is well above the point of diminishing returns; similar performance can be achieved for less than $0.5 million.

The cost distribution by BMP types as described represents the total cost for a given type in the drainage area that meets the goals set at the assessment point. While that cost distribution does not provide specific information about the spatial locations of actual BMPs, knowing the types of practices associated with each point along the cost-effectiveness curve provides insight into the reasoning and order of selecting individual practices.

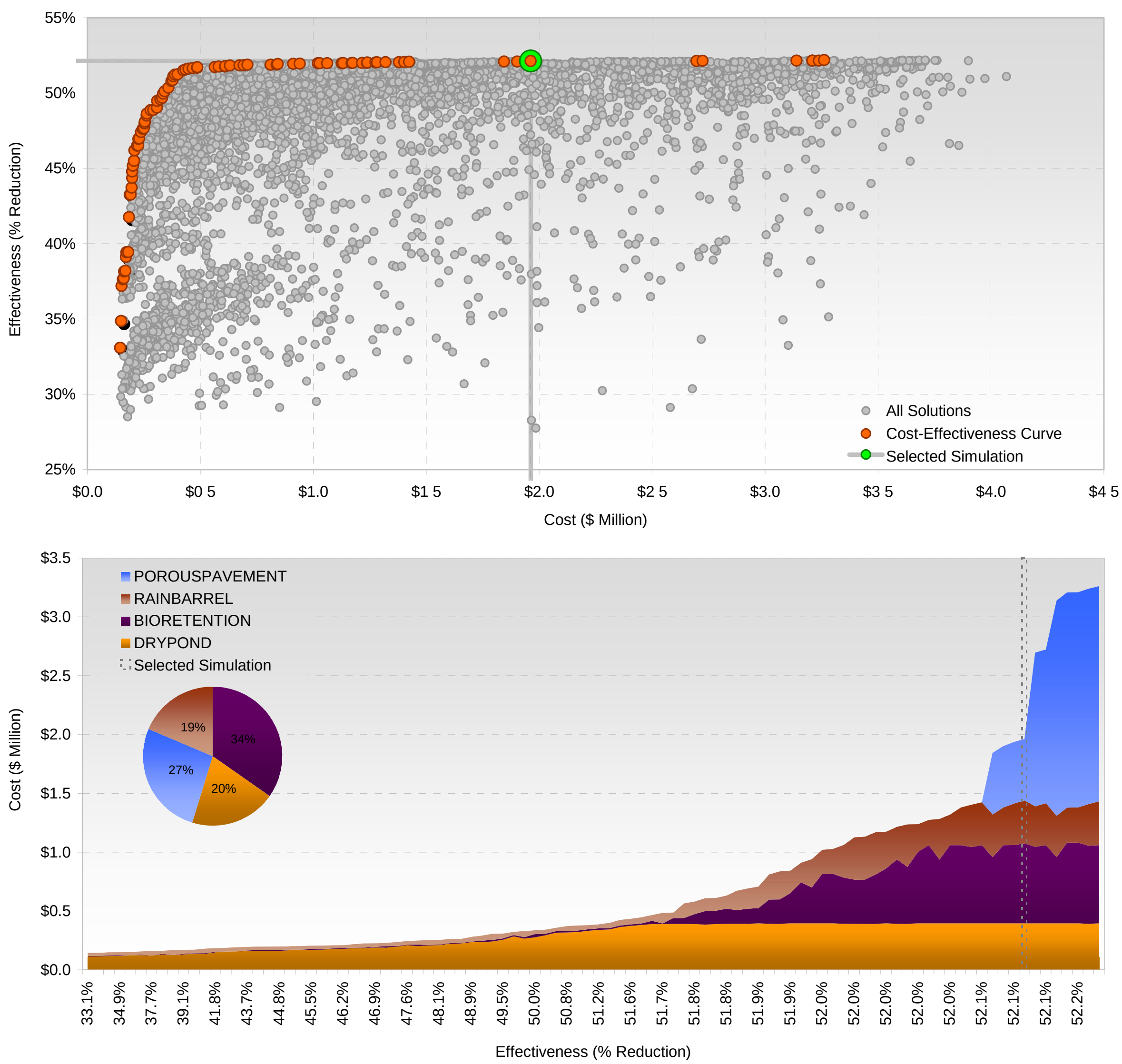


Figure 3-35. Example cost-effectiveness and cost-distribution pair.

SUSTAIN provides another way to look at the preference of BMP types across a cost-effectiveness curve. Figure 3-36 shows BMP storage distribution by cost and effectiveness interval. The horizontal axis is cost, while the left vertical axis and line graph are effectiveness in terms of the percent of sediment reduction. The right vertical scale is the amount of storage (in acre-feet), associated with surface, soil, and underdrain storages. The graph shows which of the physical treatment processes is responsible for providing the effectiveness. For instance, the contribution from soil/underdrain storage is relatively small until around the $0.3 million interval (or 47% removal efficiency). At this point on the cost-effectiveness curve shown in Figure 3-33, the primary mode of pollutant removal is the use of dry ponds. Subsurface storage increases as bioretention plays a larger role and when porous pavement is used.

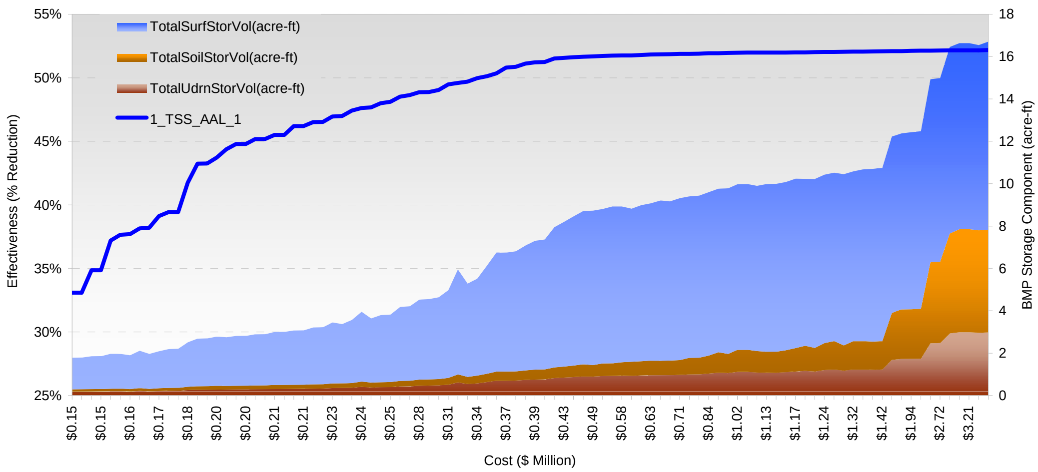


Figure 3-36. **BMP storage distribution by cost-effectiveness interval.**

3.6.5. Important Considerations and Limitations: Post-Processor

Microsoft Excel Macros Security Setting

The post-processor uses Microsoft Excel 2003 Visual Basic Applications (VBA) to perform summary and analysis. VBA requires that the user's Microsoft Excel security setting be set to at least medium. The default setting is high, which will disable all macros without notifying the user. The medium setting will prompt the user when a spreadsheet is opened that has macros and requires a response of enable or disable from the user to proceed. The low setting always enables macros without prompting the user for a decision. The medium setting is recommended because the user has the option of disabling the macros if the spreadsheet is not from a trusted source.

Functional Limitations

The post-processor is designed to perform analysis in conjunction with cost-effectiveness curves. The curves can be produced using only the NSGA-II optimization method. While it is possible to use the post-processor to visualize individual storms and time series data generated by the Scatter Search method, cost-effectiveness curve evaluation uses the full functionality. Another limitation of the post-processor with regard to time series evaluation is that it shows only total inflow versus total outflow through a given node in the network. If an assessment point is also a BMP site, the post-processor does not have the ability to summarize the complete history of surface and subsurface interactions (e.g., infiltration capacity exceedence, underdrain outflow, weir and orifice outflow). In addition, the post-processor has the ability to select and run only those solutions that appear along the cost-effectiveness curve. It cannot be used to directly select, run, and visualize information associated with a specific point that falls below the cost-effectiveness curve.

Chapter 4 Case Studies

To best demonstrate the functionality and help users visualize how they can apply *SUSTAIN*, two case studies were developed for metropolitan areas that represent typical settings for applying the framework. Case studies provide an excellent opportunity to explore the capabilities of *SUSTAIN* as described in this document in the context of a *real life* scenario and demonstrate the application process beginning with data collection, problem setup, optimization, and results interpretation. The examples were specifically developed to highlight the core functions of BMP placement and selection and the associated development of the *best solution* for the user-defined problem. The case studies also demonstrate how to apply key functions such as the multi-scale, tiered analysis, and the use of multiple control targets for optimization.

Ideal case studies for testing *SUSTAIN* should be consistent with the design requirements and the placement and selection of BMPs in urban areas. For effective demonstration, the case studies also need to build on a history of monitoring data collection and analysis. The ideal case studies also have recent watershed-based studies that have resulted in calibrated and validated models that can be used for setup and comparison. The case studies were selected using the following criteria:

- Dominantly urban land use
- Water quality management needs
- History of data collection
- Calibrated/validated model application

Two locations fit the criteria and were available for use—the Milwaukee Metropolitan Sewer District (MMSD) in Milwaukee, Wisconsin (the Oak Creek watershed), and Fairfax County, Virginia (the Little Rocky Run watershed). For each case study, locally derived data were used to develop the project setup and analysis. Next, specific problem objectives were identified that highlighted some important functions of *SUSTAIN*. For the Oak Creek watershed, the case study focuses on placement and selection of BMPs, using a single pollutant with a tiered approach, for effectiveness evaluation at several targeted pollutant reduction goals. It also demonstrates how to integrate external model time series from an existing watershed model. For the Little Rocky Run watershed, the case study focused on placement and selection of BMPs on the basis of the evaluation of two concurrent control targets of peak flow and TSS reduction. It also demonstrates using the internal SWMM model for generating runoff and pollutant load time series. This chapter describes the project setup, analysis process, and results interpretation for each case study.

Through the demonstrations, the flexibility and potential of the framework is shown. Future demonstrations and applications throughout the user community will provide valuable experiences and insights on both the full potential of the existing framework and recommendations for the continued improvement of *SUSTAIN*.

4.1. Upper North Branch Oak Creek Watershed

Milwaukee is on the southwestern shore of Lake Michigan and is the largest city in Wisconsin and 23rd largest (by population) in the nation. Milwaukee is the main cultural and economic center of the seven-county Greater Milwaukee Area, with an estimated population of 2,014,032 as of 2008. Four major river systems (Menomonee River, Kinnickinnic River, Oak Creek, and Root River) drain an area of more than 1,100 square miles that ultimately discharges through the Milwaukee River, in downtown Milwaukee, to the harbor and Lake Michigan. Upstream areas are predominantly rural and agricultural including dairy farms and crops such as corn, soybeans, and alfalfa. Nearer to the metropolitan area are suburban areas and commuter communities. The downtown region is densely urbanized and drained by a combined sewer system. Over the past 20 years the city and the Milwaukee Metropolitan Sewerage District (MMSD) have taken significant steps to address CSOs by constructing a major storage tunnel. The 7.1-mile long Northwest Side Relief Sewer is a deep tunnel that can hold up to 89 million gallons of wastewater. The region has also led the way with various green programs such as the Greenseams program and been an advocate of innovative stormwater management techniques such as rain gardens, rain barrels, and downspout disconnections. Major environmental issues in the region include increased loadings of sediment, nutrients, and pathogens associated with urbanization and agriculture, and in the urban center CSOs.

Regional water quality and environmental protection continue to be a priority in the area. Recognizing this need, the MMSD has led a long-range planning effort to identify improvements needed for its facilities to accommodate growth and protect water quality through the year 2020. This effort is known as the MMSD 2020 Facility Plan. A related planning effort, known as the Regional Water Quality Management Plan Update (RWQMPU), was also conducted in coordination with the MMSD by the Southeastern Wisconsin Regional Planning Commission (SEWRPC) to update the regional water quality management plan for all the major watersheds draining through the greater Milwaukee area (SEWRPC 2007).

As part of the planning process, a comprehensive suite of models was applied to the four major tributaries to assess current conditions and evaluate a range of management scenarios. Those models allowed planners to evaluate the potential water quality benefits of a range of implementation measures, including facility improvements and urban, suburban, and rural stormwater BMPs. The watershed modeling component was developed using LSPC (Tetra Tech and USEPA 2002). Hydrology and water quality models were developed and calibrated to provide a basis for modeling current conditions versus potential implementation scenarios. The modeling application was developed and tested using an extensive record of precipitation, flow, and water quality sampling. Calibration of the watershed models followed a sequential, hierarchical process that began with hydrology, followed by sediment erosion and transport, and, finally, calibration of chemical water quality.

The Kinnickinnic River, Menomonee River, Milwaukee River, and Oak Creek watershed models were linked to a model of the Lake Michigan estuary so that the impact of upstream water quantity and quality could be simulated. During the RWQMPU study, several year 2020-projected management scenarios to reduce nutrient, bacteria, and sediment loading were evaluated (SEWRPC 2007)

The history of environmental management, watershed planning, technical analyses, monitoring, and the availability of calibrated models made this location ideal for a case study application of *SUSTAIN*. A representative subwatershed, Oak Creek, was selected for examination for the case study, and TSS was selected as the pollutant for optimization and analysis. This case study examined the use of *SUSTAIN* for tiered analysis and BMP optimization for a single parameter.

4.1.1. Project Setting

The Oak Creek watershed covers parts of the cities of Milwaukee, South Milwaukee, Cudahy, Franklin, Greenfield, and Oak Creek and encompasses approximately 27 square miles. Table 4-1 provides a listing of the main characteristics of the watershed.

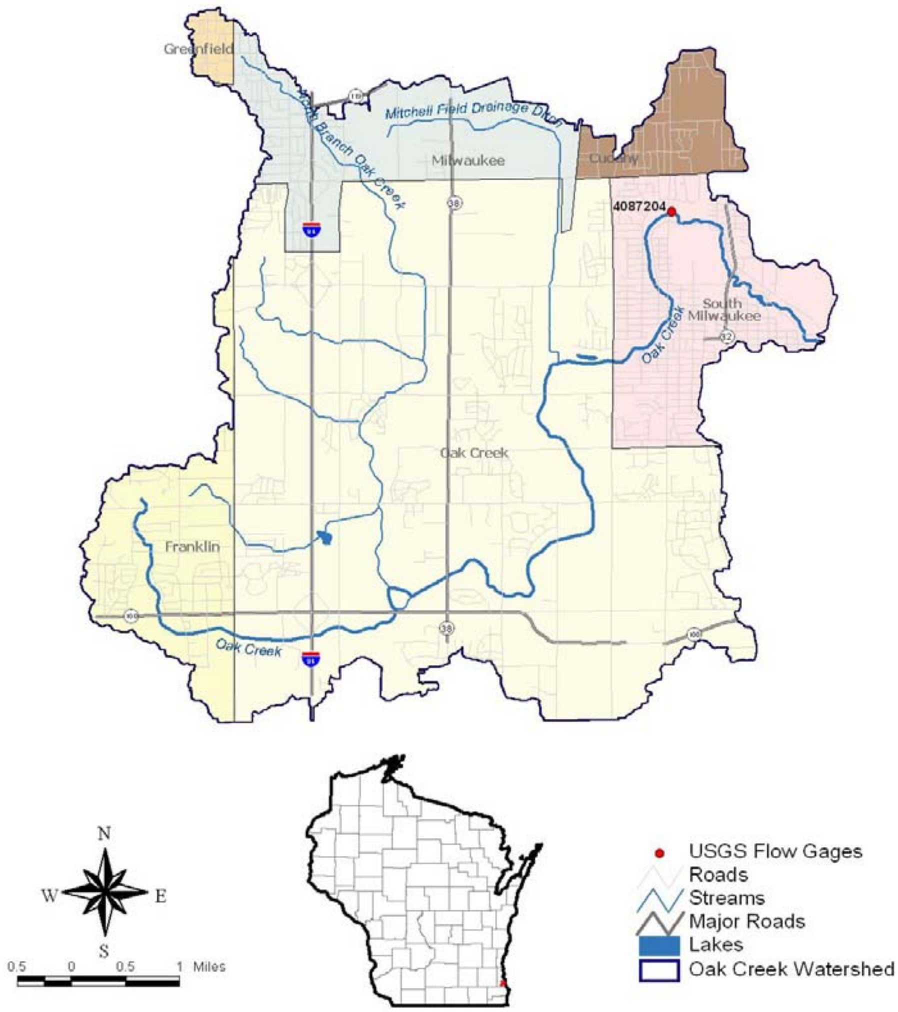


Figure 4-1. **Oak Creek Watershed and Upper North Branch Oak Creek.**

Table 4-1. **Watershed Characteristics**

Watershed drainage area (square miles)	26.2
Miles of streams	21.2
Miles of streams listed as outstanding or exceptional resource waters	0
Miles of streams on impaired waters list	13
General threats to stream water quality	Urban runoff Toxics Hydrological modification Stream bank erosion
Number of named lakes	1
Number of dams	1
Threats to lake water quality	Nutrient enrichment Sedimentation

The watershed has three major streams—Mitchell Field Drainage Ditch, North Branch of Oak Creek, and Oak Creek. The longest stream of the three, Oak Creek, has a perennial length of approximately 13.1 miles. North Branch of Oak Creek and Mitchell Field Drainage Ditch, which are tributaries to Oak Creek, have perennial lengths of approximately 5.8 and 2.4 miles, respectively. There is one reservoir in the watershed with a history of siltation and algal blooms.

Water quality in Oak Creek is degraded in part because of elevated sediment, sediment-associated total phosphorus, and fecal coliform loads. Because sediment data were closely correlated with nutrients specifically and peak discharges in general, TSS was selected as the pollutant on which to focus the case study analysis.

Pollution sources in the watershed include the following:

- Stormwater runoff from impervious urban land
- Runoff from agricultural lands
- Eroding streambanks and sedimentation
- Wildlife, pets, and residential lawns
- Erosion from construction sites
- Sanitary sewer overflows and industrial discharges
- Leaking underground storage tanks, landfills, runoff from salvage yards

The Upper North Branch Oak Creek (UNB) area, shown in the upper-left corner of Figure 4-1, was selected for further evaluation in the case study. The UNB is a headwater area of concern because of poor habitat, elevated sediment load, and sediment-associated total phosphorus and fecal coliform loads. The UNB has a drainage area of approximately 4.2 square miles with mixed land uses. The dominant residential and commercial land uses compose 68 percent of the total area. Table 4-2 lists the land use distribution of the study area. The Oak Creek watershed has discharges from 17 industrial facilities as well as sanitary sewer overflows.

Table 4-2. Upper North Branch Oak Creek Land Use Distribution

Land Use Type	Area (acre)	Area Percentage (%)
Water/wetland	41.0	2
Forest	323.7	12
Pasture/hay	88.5	3
Crop	168.4	6
Developed open space	263.4	10
Commercial	342.0	13
High density residential	684.6	26
Low density residential	766.3	29
Total	2,677.7	100

The UNB watershed provides an excellent setting for demonstrating how *SUSTAIN* can be applied in the implementation and tracking aspects of a watershed planning process. For this application, a single objective of TSS load reduction was selected. In terms of *SUSTAIN* functionality, this case study demonstrates the following:

- An external linkage to a previously modeled set of land use time series outputs
- The use of aggregated BMPs
- The tiered optimization approach

4.1.2. Data Collection and Analysis

The *SUSTAIN* case study application began with a review of watershed characteristics and compilation of related spatial and temporal model outputs. The next steps involved processing watershed model output data into the required input data format and conducting model setup. Model setup included land use reclassification and time series mapping, delineating potential BMP drainage areas, and selecting assessment points. The established model configuration was then used to evaluate different treatment scenarios to measure relative impacts, perform optimization analysis, and, finally, interpret and present results. Figure 4-2 is a roadmap of objectives and problem formulation for the case study.

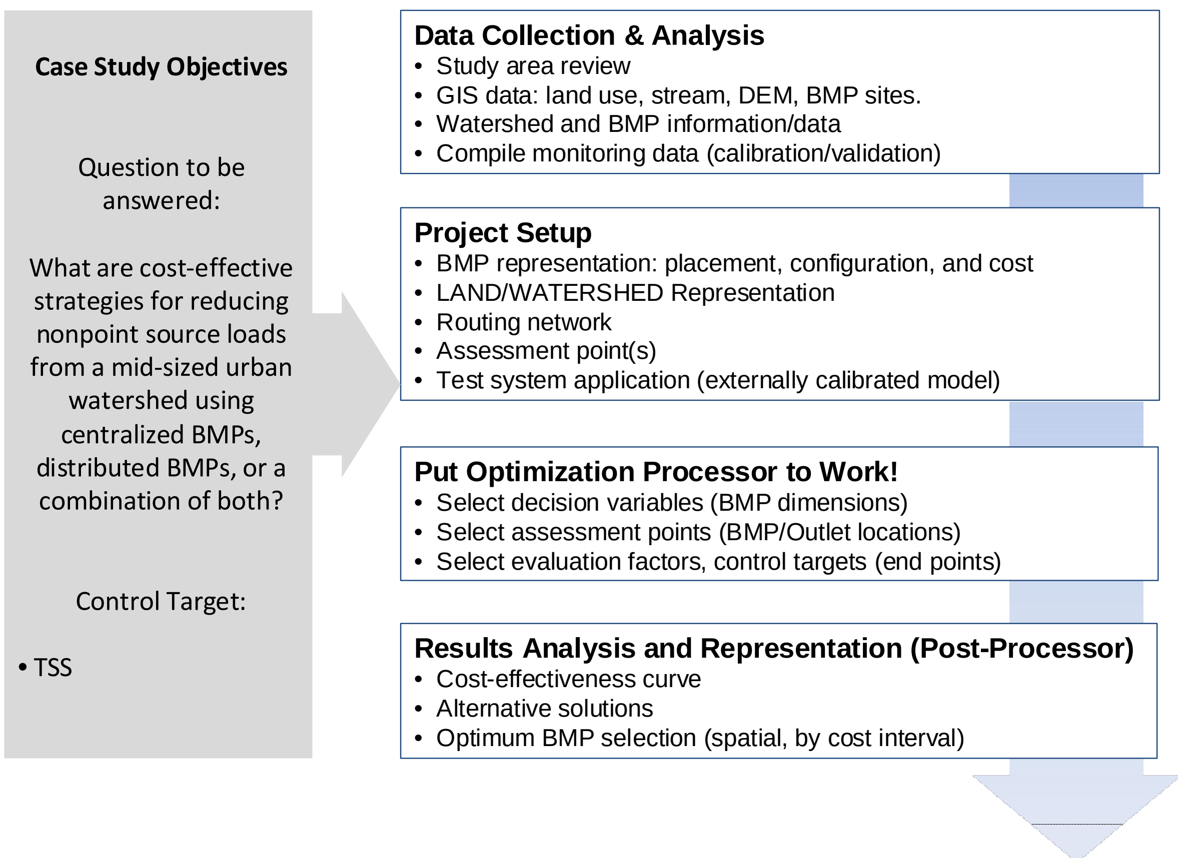


Figure 4-2. Upper North Branch Oak Creek Watershed case study road map.

4.1.3. Project Setup

Available sources of information including land use maps, local pollutant source characterization reports, and water quality assessment reports for the larger Oak Creek watershed, were used to set up the

SUSTAIN project and identify potential locations for management practices. The setup for management analysis also required the selection of a typical precipitation year for use in comparing alternatives and assessing downstream impacts. From the analysis of precipitation data, the hydrologic year 2001 (10/1/2000–9/30/2001) was determined to represent the average conditions in the watershed. Total rainfall depth for the year was close to the long-term average for the area. At the same time, both precipitation depth and intensity distribution during that year were relatively close to the long-term statistical average distribution. Figure 4-3 presents a graph of average annual precipitation at Milwaukee Airport for water years 1988–2002.

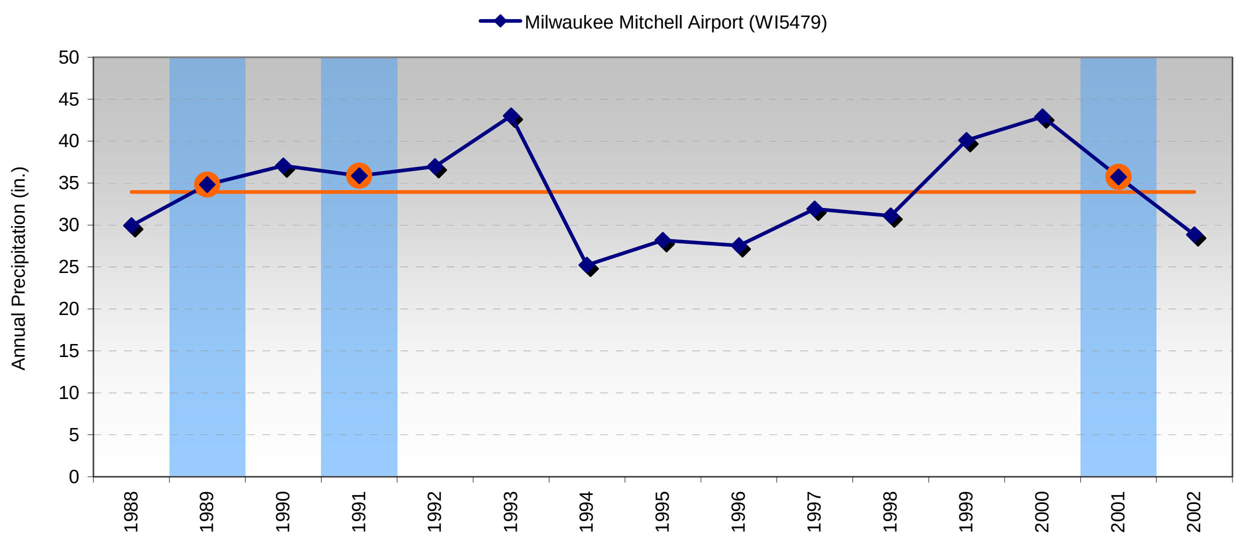
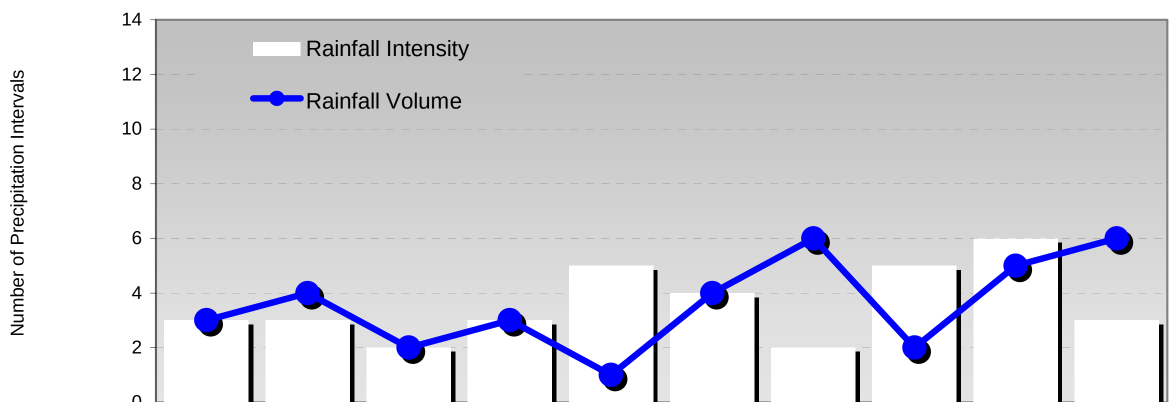


Figure 4-3. **Average annual precipitation volume at Milwaukee Airport for water years 1988–2002.**

Although the water year 2001 was not the closest year to the average annual value over the 15-yr evaluation period, it was the most recent average year among the set and had a typical rainfall magnitude and intensity distribution. Figure 4-4 shows rainfall volume and intensity distribution for wet intervals occurring in water year 2001. In the figure, the volume and intensity percentile ranges are based on the record of storms occurring over the 15-yr period. A year with a perfect typical distribution would have the same number of precipitation intervals in each bin.



	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
Rainfall Intensity	3	3	2	3	5	4	2	5	6	3
Rainfall Volume	3	4	2	3	1	4	6	2	5	6

Figure 4-4. **Rainfall volume and intensity wet-interval distribution for water year 2001.**

The previously developed model was successfully calibrated and validated for the Oak Creek watershed, inclusive of the land use types considered in this case study (SEWRPC 2007). Using *SUSTAIN*'s external modeling function, these previously developed land use time series were imported directly from the calibrated model. Figure 4-5 and Figure 4-6 show the modeled versus observed flow at the Oak Creek U.S. Geological Survey (USGS) gage for the selected water year 2001. Figure 4-7 and Figure 4-8 are examples of modeled versus observed TSS for water years 1995–2001 and water year 2001, respectively.

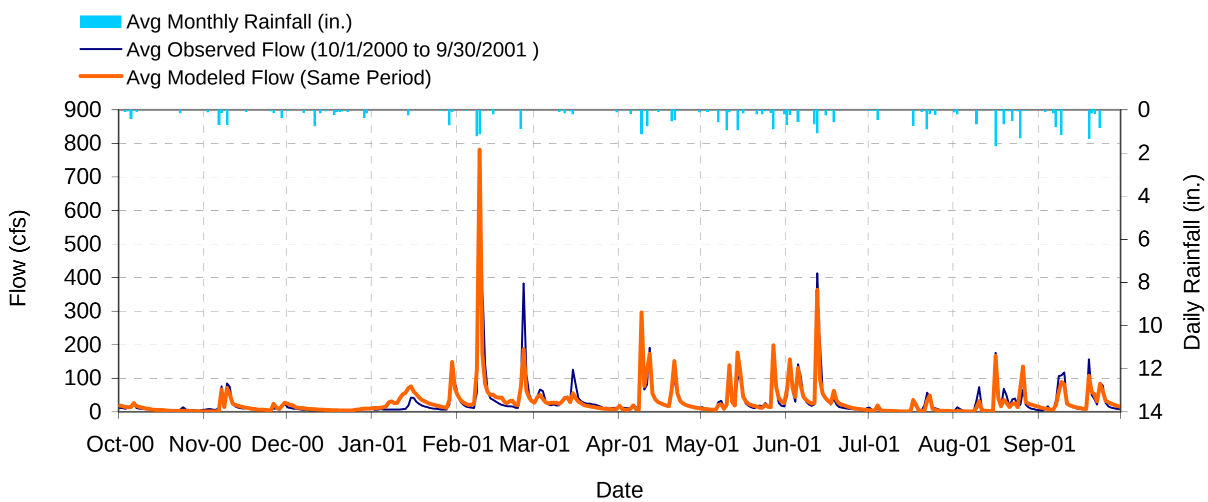


Figure 4-5. Comparison of daily flow at Model Outlet 58 with USGS 04087204 at South Milwaukee.

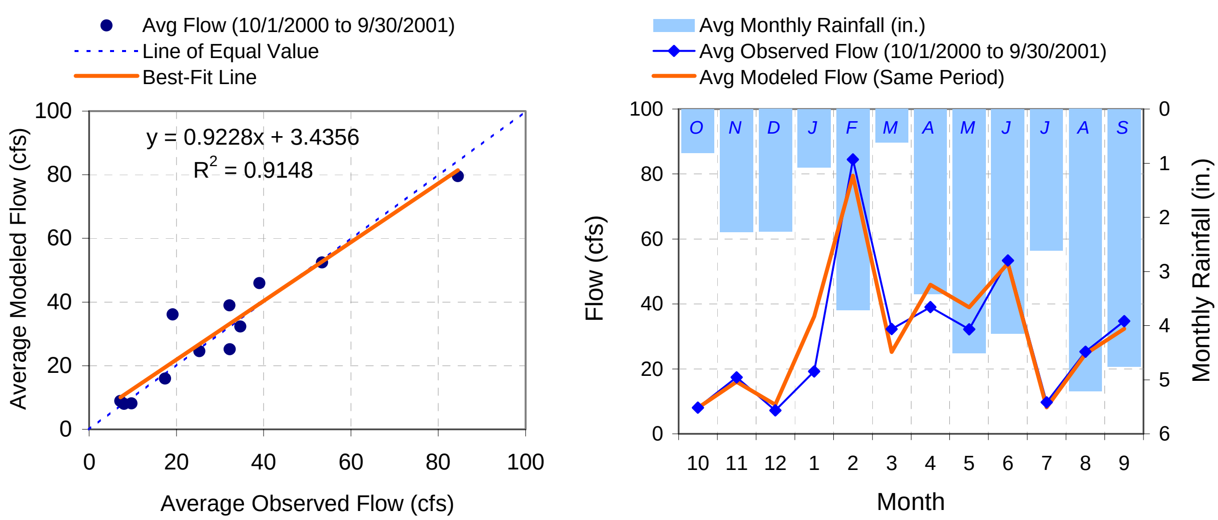


Figure 4-6. Comparison of monthly flow at Model outlet 58 with USGS 04087204 at South Milwaukee.

The land use time series from the calibrated watershed model were exported as unit-area hydrographs and pollutographs for each modeled land use type. Table 4-3 is a summary of annual average outflow and TSS load by modeled land use in Oak Creek on a unit-area basis.

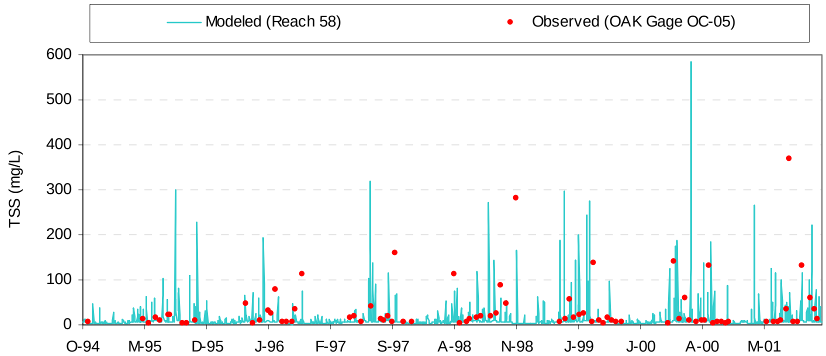


Figure 4-7. Modeled vs. observed TSS (mg/L) at Oak Creek gage OC-05, water years 1995–2001.

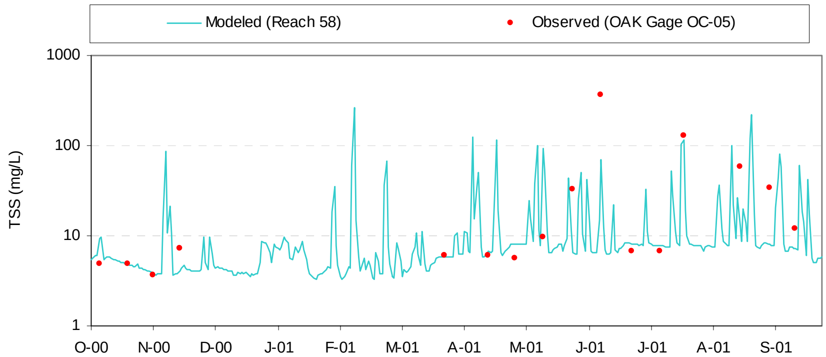


Figure 4-8. Modeled vs. observed TSS (mg/L) at Oak Creek gage OC-05, water year 2001.

Table 4-3. Summary of Modeled Annual Average Outflow and TSS Load in Oak Creek Watershed

Land Use ID	Land Use Name	Area (acres)	Flow (acre-in./yr)	TSS (lb/acre/yr)
1	GRASS_B	1,183	11.8	117
2	GRASS_C	7,782	11.2	120
3	GRASS_D	231	11.1	156
4	FOREST	1,087	11.4	105
5	CROP_B	380	12.5	460
6	CROP_C	1,395	11.7	1,253
7	CROP_D	127	11.5	2,278
8	PASTURE_B	156	13.7	30
9	PASTURE_C	693	12.6	118
10	PASTURE_D	110	12.3	263
11	WETLAND	1,270	9.2	303
12	ULTRA_LOW	58	22.3	527
13	RESIDENTIAL	608	22.3	511
14	COMMERCIAL	2,095	22.3	784
15	INDUSTRIAL	403	22.3	913
16	GOVT_INSTIT	106	22.3	529
17	TRANS_FREE	229	22.3	949

4.1.4. Optimization and Results Analysis

For the purposes of optimization, the study area was divided into 11 subwatersheds. Figure 4-9 shows the land use distribution in the study area, overlain with the modeled subwatersheds.

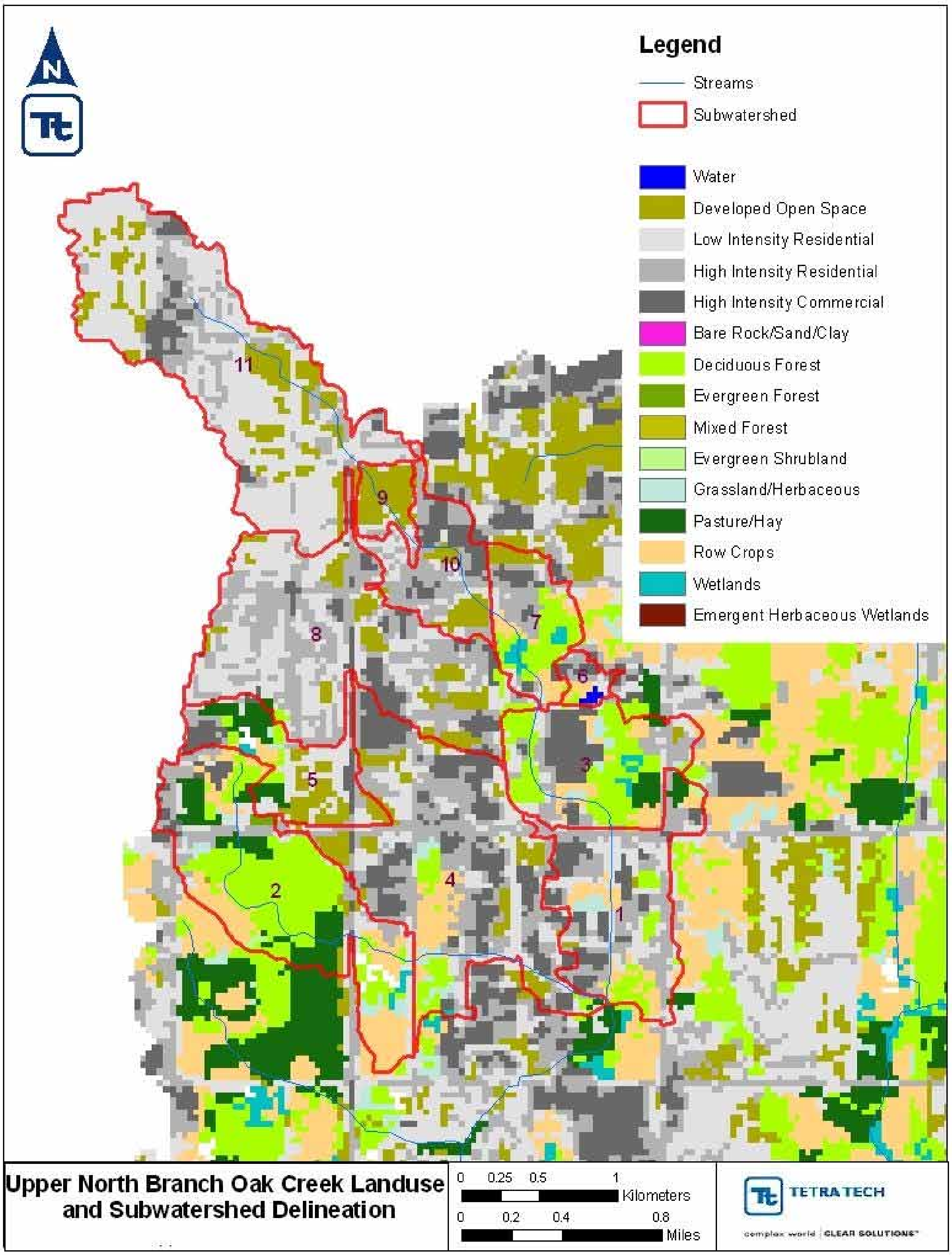


Figure 4-9. Land use distribution in the modeled subwatersheds.

Figure 4-10 shows how the subwatersheds were classified into six groups on the basis of prevailing land uses, suitable management practices, and location in the watershed. Groups 1 through 4 are labeled in the map as A, B, C, and D. For those areas, BMP placement was applied to urban land uses. Subwatershed 6 was singled out for special consideration as the fifth group because it is not part of the drainage area of the other larger subwatersheds. Because of its small size, BMPs in subwatershed 6 were optimized directly during the tier-2 optimization. The remaining subwatersheds (2, 3, 5, 7, and 9) were mostly non-urban and were assumed to need no additional management and were not evaluated for BMP placement because the objective of this analysis was to target TSS loads from urban areas.

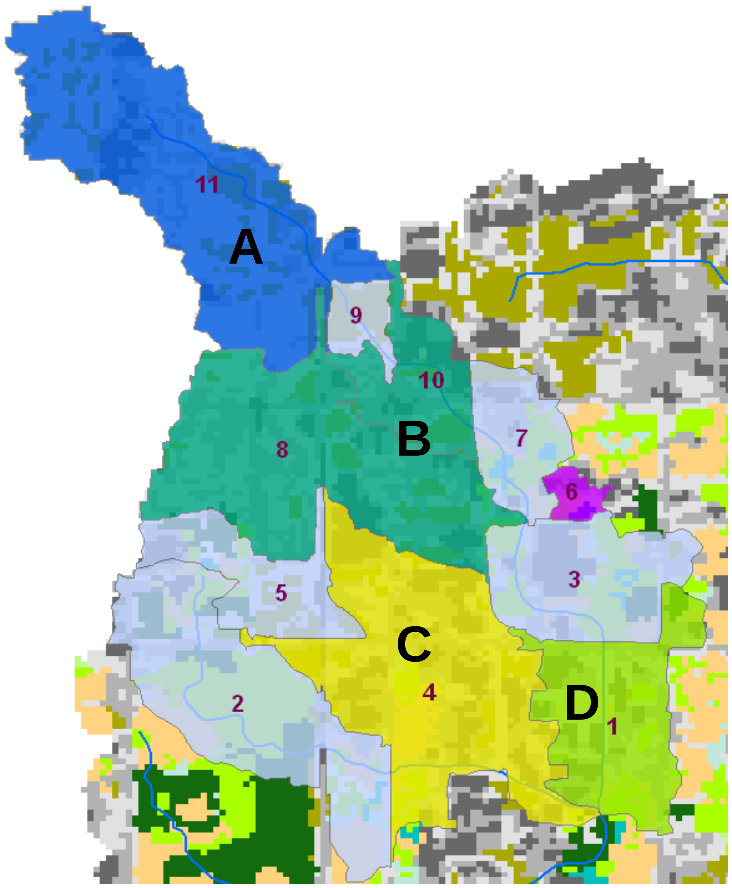


Figure 4-10. Subwatershed grouping for two-tiered optimization.

BMP Representation

For this case study, both distributed and centralized BMP options were evaluated. Distributed BMP options include rain barrels, bioretention, and porous pavement. The centralized BMP option is an infiltration basin.

To improve computational efficiency, the aggregate BMP option (as described in Section 3.3.3), was used. An aggregate BMP consists of a series of process-based optional components, including on-site interception, on-site treatment, routing attenuation, and regional storage/treatment. The aggregate BMP component evaluates storage and infiltration characteristics from multiple BMPs simultaneously without explicit recognition of their spatial distribution and routing characteristics within the selected watershed. For this case study example, the aggregate BMP had four component BMPs—rain barrels (on-site interception), bioretention (on-site treatment), porous pavement (on-site treatment), and dry infiltration basin (regional treatment). Figure 4-11 is a schematic diagram of aggregate BMP components, drainage areas to BMPs, and BMP-to-BMP routing networks. Figure 4-12 lists the area percentage of each land use that contributes to each of the aggregate BMP components.

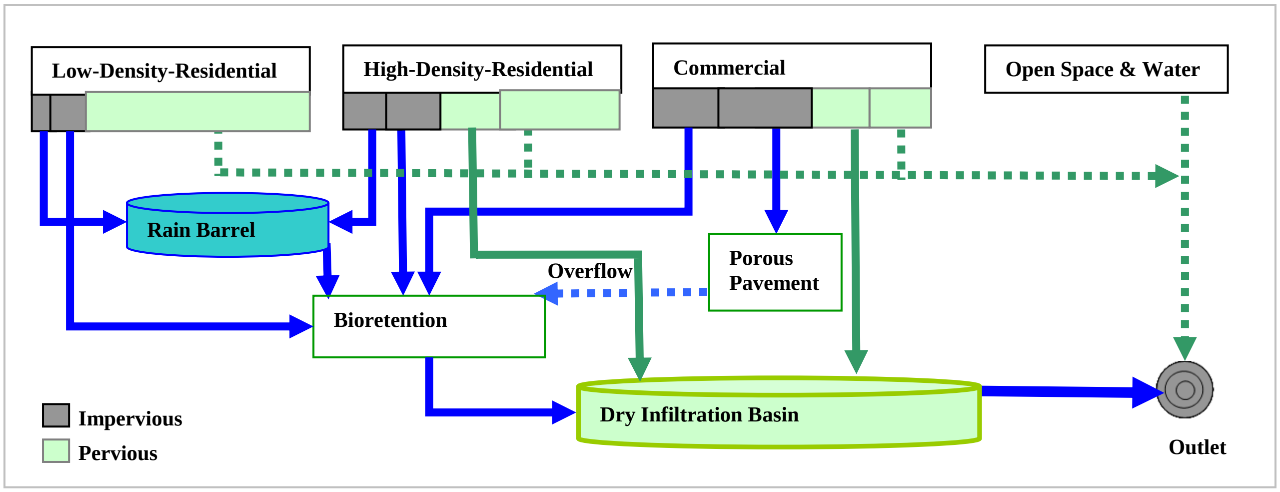
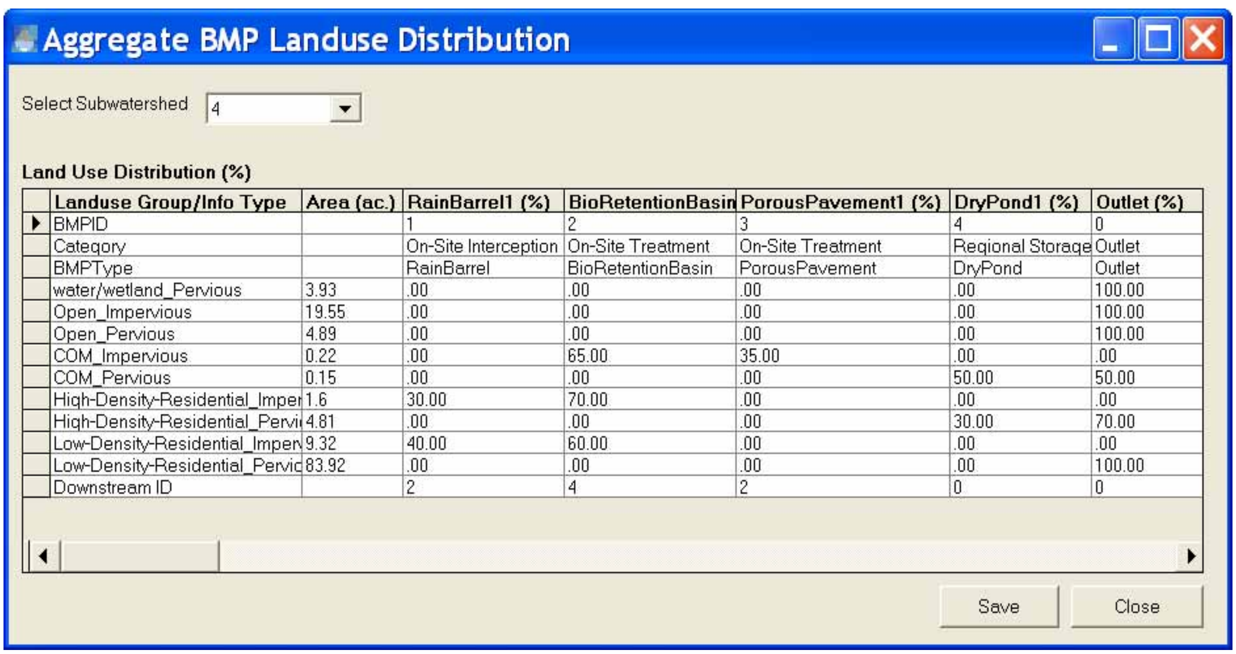


Figure 4-11. **Aggregate BMP schematic.**



Aggregate BMP Landuse Distribution

Select Subwatershed 4

Land Use Distribution (%)

Landuse Group/Info Type	Area (ac.)	RainBarrel1 (%)	BioRetentionBasin	PorousPavement1 (%)	DryPond1 (%)	Outlet (%)
BMPID		1	2	3	4	0
Category		On-Site Interception	On-Site Treatment	On-Site Treatment	Regional Storage	Outlet
BMPType		RainBarrel	BioRetentionBasin	PorousPavement	DryPond	Outlet
water/wetland_Pervious	3.93	.00	.00	.00	.00	100.00
Open_Impervious	19.55	.00	.00	.00	.00	100.00
Open_Pervious	4.89	.00	.00	.00	.00	100.00
COM_Impervious	0.22	.00	65.00	35.00	.00	.00
COM_Pervious	0.15	.00	.00	.00	50.00	50.00
High-Density-Residential_Imper	1.6	30.00	70.00	.00	.00	.00
High-Density-Residential_Pervi	4.81	.00	.00	.00	30.00	70.00
Low-Density-Residential_Imperv	9.32	40.00	60.00	.00	.00	.00
Low-Density-Residential_Pervic	83.92	.00	.00	.00	.00	100.00
Downstream ID		2	4	2	0	0

Save Close

Figure 4-12. **Aggregate BMP land use distribution.**

As shown in Figure 4-11, the rain barrel component collects runoff from rooftops (as part of the impervious surfaces) in low- and high-density residential areas. Bypass from the rain barrel is routed to bioretention, together with runoff from the non-rooftop impervious surfaces in low- and high-density residential areas and impervious areas that could be subjected to the porous pavement option in commercial areas. It was assumed that the parking lot portions of the commercial impervious area could be converted to porous pavement as a treatment option. In addition to the distributed BMPs (i.e., rain barrel, bioretention, and porous pavement), a centralized facility—dry infiltration basin—was also a candidate for consideration. In addition to outflow from the bioretention component, the centralized facility receives outflow from part of the pervious areas in high-density residential and commercial land uses. Outflow from the centralized facility is routed to the watershed outlet. The other areas that are not routed to any aggregate BMP components are assigned to drain directly to the watershed outlet.

To run the optimization analysis, the user must define decision variables that will be used to explore the various possible BMP configurations. For this analysis, the decision variables are the number of fixed-size units of the distributed BMP types and surface area for the centralized BMP type (dry infiltration basin). Because the decision variable values range from zero to a maximum number depending on the drainage area, it is possible for one component in the treatment train to never be selected. During the optimization scenario, if the BMP number or size value of zero is selected, that point will act as a transfer node in the network (i.e., inflow = outflow), and the associated cost that is a function of the number of BMPs or BMP surface area will not set to zero.

The physical configuration parameters, infiltration, and water quality simulation parameters of each BMP components are listed in Table 4-4.

Table 4-4. BMP Parameters

Parameter	Rain Barrel	Bioretention	Porous Pavement	Dry Infiltration Basin
Physical Configuration				
Unit size	28 ft^3	60 ft^2	0.1 acre	Max: 3,000 ft^2
Design drainage area (acre)	0.02	0.1	0.1	N/A
Substrate depth (ft)	N/A	2.5	2	1
Underdrain depth (ft)	N/A	1	1	1
Ponding depth (ft)	4	0.5	0.2	Orifice height: 0.5 Weir height: 4
Infiltration*				
Substrate layer porosity	N/A	0.5	0.5	0.4
Substrate layer field capacity	N/A	0.3	0.2	0.3
Substrate layer wilting point	N/A	0.15	0.05	0.15
Underdrain gravel layer porosity	N/A	0.5	0.5	0.5
Vegetative parameter, *A*	N/A	0.6	1	0.6
Underdrain background infiltration rate** (in./hr), f_c	N/A	0.5	0.5	0.5
Media final constant infiltration rate (in./hr), f_c	N/A	3	3	1
Water Quality* **				
TSS 1st order decay rate (1/day), *k*	0.2	0.2	0.2	0.2
TSS filtration removal rate, P_{rem} (%)	N/A	85	60	85

* Source: Tetra Tech 2001.
** Soil map shows the majority background soil has hydrologic soil group of C; therefore, 0.5 in./hr background infiltration rate is assumed.
*** Based on calibration using University of Maryland monitoring data (Tetra Tech 2003).

BMP Cost

Cost estimation is a critical component because the optimization process needs the data to evaluate and compare cost-effectiveness of one scenario relative to the others. Table 4-5 presents the cost functions for the BMP types used in this case study (rain barrels, bioretention, porous pavement, and a dry infiltration basin).

Table 4-5. BMP Cost Functions for the Case Study

BMP Type	Cost Function	Reference
Rain Barrel	$15/ft^3	BMP Cost database
Bioretention	$6/ ft^3	BMP Cost database
Porous Pavement	$12/ft^2	BMP Cost database
Dry Infiltration Basin	Cost = 12.4 × $V^{0\ 760}$ V is the volume of the basin in ft^3	CASQA Stormwater BMP Handbook (CASQA 2003)

Optimization

A two-tiered optimization approach was applied to this case study. As previously described, the same set of management actions (aggregate BMP) was applied to subwatersheds A, B, C, and D. Tier-1 optimization analyses for these areas result in a unique, cost-effectiveness curve for each. A second round of optimization (tier-2) is then performed and assessed at the most downstream outlet of the watershed. Tier-2 decision variables include discrete points (representing a combined management options) along the tier-1 cost-effectiveness curves and BMP options for subwatershed 6. For subwatershed 6, the optimization is allowed to select distributed or centralized BMPs, or a combination of both. The optimization objective is to maximize TSS load reduction at the watershed outlet and minimize the cost of implementation.

Tier -1 Optimization for Subwatershed A

This section describes the process for developing tier-1 cost-effectiveness curves using subwatershed A as an example. Figure 4-13 shows the BMP placement and routing network for tier-1 subwatershed A. The total area of subwatershed A is 515 acres. The subwatershed is further subdivided into six subareas, with sizes ranging from 36 to 138 acres. This subwatershed was intentionally subdivided into subwatersheds of about 100 acres in size because preliminary testing has shown that given an hourly time step, the aggregate BMP approach closely resembles a fully articulated network in areas of around 100 acres (see Section 3.3.6). The aggregate BMP treatment train previously described in the BMP Representation section is applied to each of the six subareas. The watershed outlet (J4 in Figure 4-13) is designated as the assessment point, and TSS annual load is used as the evaluation factor.

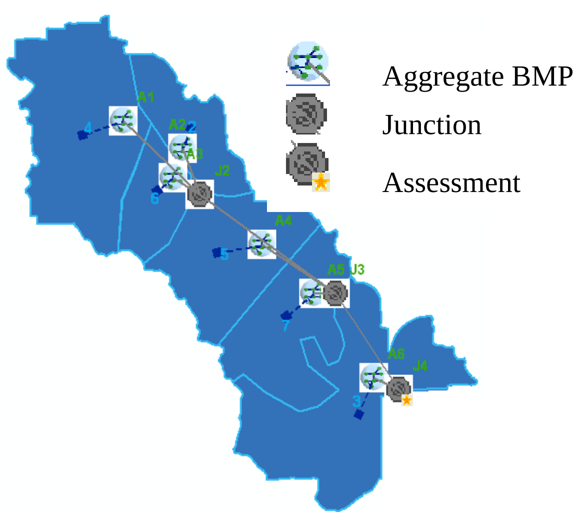


Figure 4-13. Aggregate BMP arrangement in tier-1 subwatershed A.

Tier-1 Optimization Results

The full set of results of all tier-1 optimization runs are summarized in Figure 4-14 as small gray circles with near-optimal solutions in larger orange circles along the upper-left frontier. Each near-optimal solution represents one combination of decision variables, including the number of rain barrels, bioretention units, area of porous pavement, and size of infiltration basin for each subarea of subwatershed A. Figure 4-14 also highlights five solutions as green circles (numbered 1 to 5) selected to be the tier-2 search domain and their associated costs and TSS load reductions are summarized in Table 4-6. These specific solutions were selected to account for the full range of achievable TSS reduction.

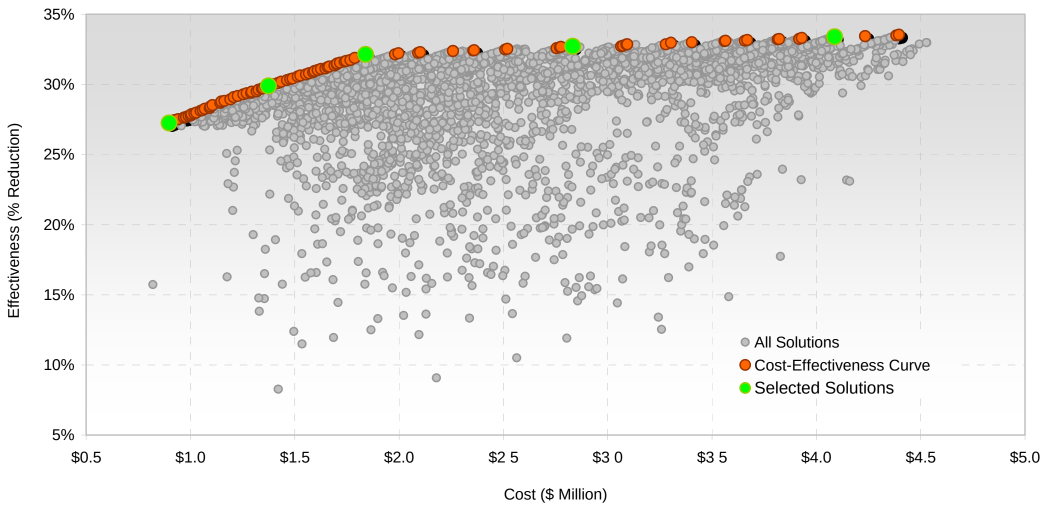


Figure 4-14. Tier-1 cost-effectiveness curve for subwatershed A with the selected solutions.

Table 4-6. Selected Tier-1 Solutions on the Cost-Effectiveness Curve

Solution ID	Cost ($ million)	TSS Load Reduction (%)
1	0.90	27.3
2	1.37	29.9
3	1.84	32.1
4	2.83	32.7
5	4.09	33.4

Figure 4-15 shows the BMP cost distribution for all the near-optimal solutions on the cost-effectiveness curve with respect to the cost of four BMP options (rain barrel, bioretention, porous pavement, and dry infiltration basin). The graph also reveals the BMP selection preference with increase in total cost. The figure shows that the dry pond is the most cost-effective choice and, thus, is the first option to be fully used throughout the range. The next choices are bioretention and rain barrel. Porous pavement was the last to be considered suggesting that it is the least cost-effective BMP type among the four types considered in this case study for TSS load reduction.

The same procedure was applied to develop the tier-1 cost-effectiveness curves for Subwatersheds B, C, and D. The four curves, together with that for subwatershed 6 and the remaining untreated areas, become the input decision variables for the tier-2 optimization analysis.

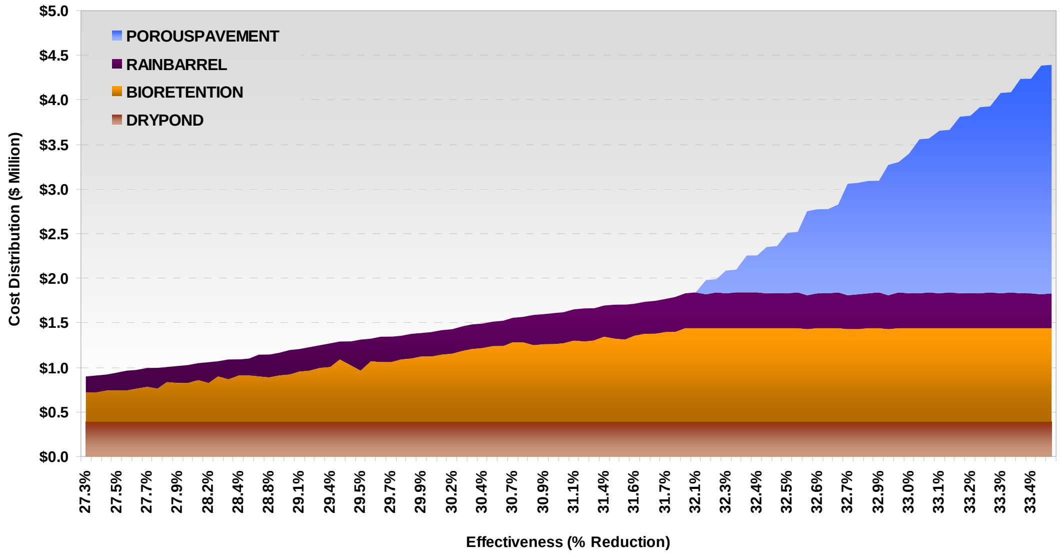


Figure 4-15. **Composition of best solutions on tier-1 cost-effectiveness curve for subwatershed A.**

Tier-2 Optimization

The tier-2 optimation analysis is assessed at the outlet of the Oak Creek watershed. The decision variables include the selected points along the four tier-1 cost-effectiveness curves and BMP selection for subwatershed 6. The untreated areas are included as a fixed boundary condition of TSS load and not involved in the optimization runs. Since runoff from the untreated areas is expected to be relatively clean, the water would boost the assimilative capacity of streams in and downstream of the watershed. The inclusion of this relatively clean water will influence the optimization results.

Figure 4-16 shows a schematic of the tier-2 analysis network with the objective to develop the cost-effectiveness curve that meents TSS reduction load goals at the outlet. The analysis involves stream routing. The four most downstream segments (J3–J4, J4–J10, J10–J13, and J6–J12) are simulated as trapezoidal channels, while shorter segments are assumed dummy conduits considering the travel time of those segments are likely less than an hour. This provides the benefit of reducing computation time.

Tier-2 Optimization Results

The optimization analysis resulted in the tier-2 cost-effectiveness curve shown in Figure 4-17. The cost-effectiveness curve suggests that the maximum achievable TSS load reduction, given the objectives and constraints associated with the study, is approximately 30 percent. To further examine the cost-effective solutions, three selected solutions are highlighted in Table 4-7.

Table 4-7 shows that for the lowest tier-2 reduction target of 16 percent, only the most downstream subwatersheds C and D were treated. In addition, rain gardens were preferred in subwatershed 6. The most cost-effective solution that achieves a 16 percent load reduction at the outlet costs $1.85 million. At the next selected tier-2 target of 23 percent, the cost would increase to $2.75 million because subwatershed B is added to the list. Finally, for a 30 percent load reduction, all four tier-1 subwatersheds were selected for treatment.

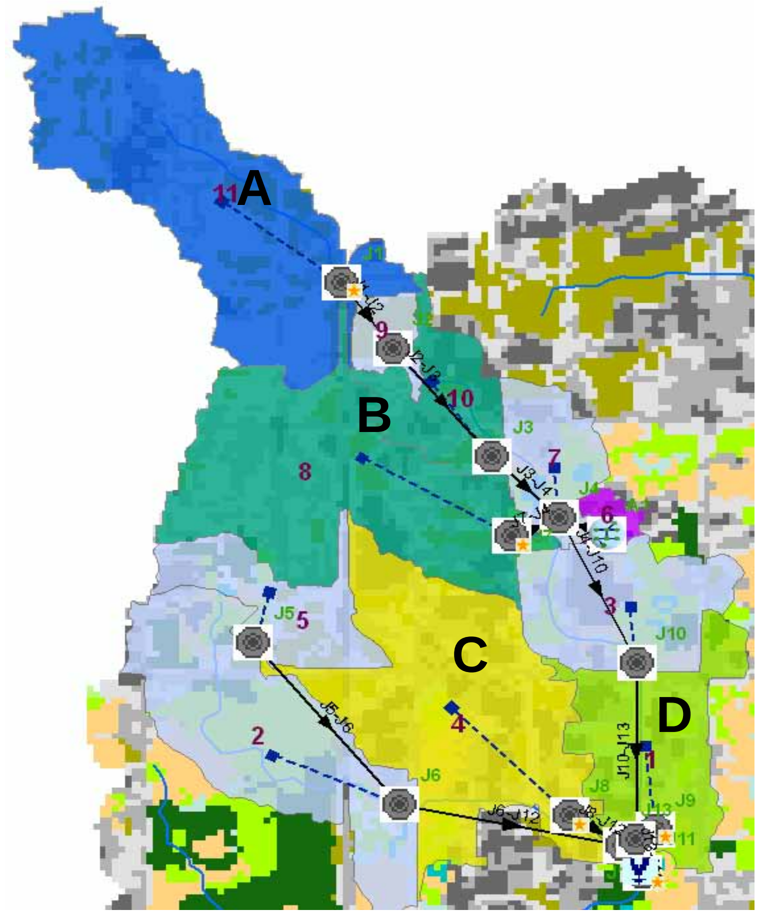


Figure 4-16. Schematic of tier-2 analysis network.

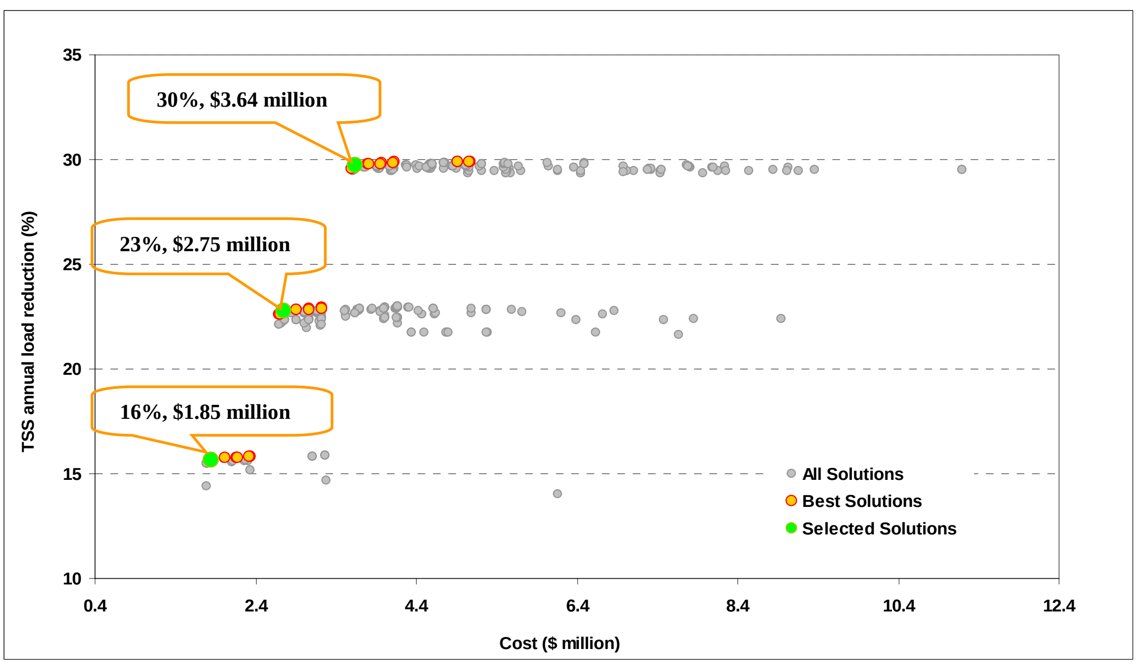


Figure 4-17. Tier-2 cost-effectiveness curve.

Table 4-7. **Selected Tier-2 Best Solutions**

			16	23	30
Tier-2 TSS Load % Reduction Target			16	23	30
Total Cost ($million)			1.85	2.75	3.64
Tier-1 Subwatersheds TSS Load % Reduction Allocation		A	0	0	27.3
		B	0	27.3	27.3
		C	27.3	27.3	27.3
		D	27.3	27.3	27.3
Subwatershed 6	Distributed Rain Barrels (#)		0	0	0
	Distributed Rain Gardens (ft^2)		2,100	2,100	2,100
	Distributed Porous Pavement (acre)		0	0	0
	Dry Infiltration basin (acre)		0	0	0

A closer examination of the three tier-2 cost-effective solutions suggests that it is more cost-effective to provide load reductions at lower subwatersheds than at upper subwatersheds. This is because stream segments through natural processes will inherently provide some load reduction benefit from settling or transport routing. Hence, placing BMPs at upper reaches to reduce loads is not as cost-effective as at downstream reaches since the same investment in urban areas close to the assessment point at the watershed outlet would yield a greater reduction. In other words, why spend money to reduce a load when it can be reduced for free in stream transport? It is assumed that the streambanks are stable and erosion does not take place. Had streambank erosion been factored in as a problem, the types of BMPs selected upstream to control peak discharge or pollutant load might have resulted in a completely different set of solutions. Note that *SUSTAIN* does not include a streambank erosion simulation mechanism. This case study example further highlights the importance of careful formulation of the problem and understanding of the associated implications and findings of the results.

It is also interesting to observe that although higher levels of treatment options were available from among tier-1 subwatersheds (as shown in options 2 to 5 in Table 4-6), none of them were included in the the tier-2 optimal solutions due to unfavorably higher marginal costs. Furthermore, the load reduction in stream segments mitigated the need for additional treatment.

It is important that readers examine the specific conclusions drawn from this exercise in the context of this specific problem formulation and the imposed assumptions and constraints. Had the same problem been formulated slightly differently, it might have resulted in a completely different set of solutions. When working with a relatively large watershed, hydrological and water quality responses to various BMP treatment options can be complex and result in several competing effects that could cloud intuitive interpretation. *SUSTAIN* provides a framework for quickly exploring the response to multiple problem formulations and examining the impact of the inherent cost and BMP performance assumptions. Using the framework to examine the responses at several intermediate nodes in a complex network would help in selecting the best solutions.

4.1.5. Summary

This case study has demonstrated: (1) how *SUSTAIN* can be linked to an existing watershed model, (2) using aggregate BMPs, and (3) using a tiered watershed optimization approach for identifying the cost effectiveness of BMP solutions. In summary, the aggregate BMP approach is a simplified approach for preserving the physically based response of distributed BMP types that, preliminary tests have shown can reduce computational effort without compromising accuracy when used appropriately. Also, the tiered approach is an efficient way of disaggregating an optimization problem for large watersheds into manageable units for decision making BMP placement. Finally, the results-interpretation process further highlights the fact that *SUSTAIN* is a tool, not an advisor. Users must interpret model results and weigh them in light of user-specified assumptions, problem formulation, and optimization goals. Its application must be preceded by an intimate understanding of the study area and the influential factors affecting decision making for stormwater management.

4.2. Little Rocky Run Watershed

Fairfax County is in Northern Virginia and is part of the Greater Washington, DC, metro area. The county has undergone significant growth over the years and is considered to be almost completely built-out according to the county's comprehensive development plan (Fairfax County 2007). In many areas, stormwater management involves retrofitting existing facilities and incorporating new stormwater treatment for older areas in which treatment has not previously existed. To assist with planning efforts, the county is developing watershed management plans to assess watershed conditions, identify stormwater management needs, and prioritize future stormwater/BMP implementation efforts. The Fairfax County Department of Public Works and Environmental Services (DPWES) previously developed watershed management plans for 11 of the 30 watersheds in the county and began developing watershed management plans for the remaining 19 watersheds in 2006. The detailed plans incorporate an assessment of current and future watershed conditions and problem areas, identify the county's structural and nonstructural needs, analyze stormwater management and BMP options, and prioritize recommended stormwater projects on the basis of measurable goals. County staff are using watershed plans and technical tools to address stormwater planning needs, MS4 and TMDL requirements, Chesapeake Bay nutrient- and sediment- reduction goals, and local stakeholder concerns. Hydrologic, hydraulic, and water quality models (SWMM, HEC-RAS, and other systems) were developed to assess watershed conditions and quantify the benefits of various stormwater management practices. The models provide the foundation for the watershed planning process. Little Rocky Run is included in the group of watershed management plans being developed by Fairfax County.

SUSTAIN was used to evaluate the influence of various BMP scenarios for both a flood control target (10-yr design storm peak flow rate) and a water quality target [total phosphorus (TP) reduction of 40 percent]. In terms of *SUSTAIN* functionality, this case study demonstrates the following:

- The use of the internal SWMM land use time series generation option
- Multiobjective optimization formulation for flood control and water quality objectives

4.2.1. Project Setting

In the western portion of the county (Figure 4-18), the Little Rocky Run watershed is approximately 7 square miles in area, with an average imperviousness of 30 percent. Land use is primarily residential (61 percent), followed by open space (19 percent), and areas occupied by institutional and public facilities (18 percent). The watershed includes approximately 20 miles of stream channel and 13 regional ponds. The watershed was selected for development of a *SUSTAIN* case study because of several factors, including the availability of detailed watershed planning data and a recently completed and calibrated SWMM design storm model. Flood control in peak flow reduction and improvements in sediment and nutrient levels are two primary stormwater management goals for this recently developed watershed.

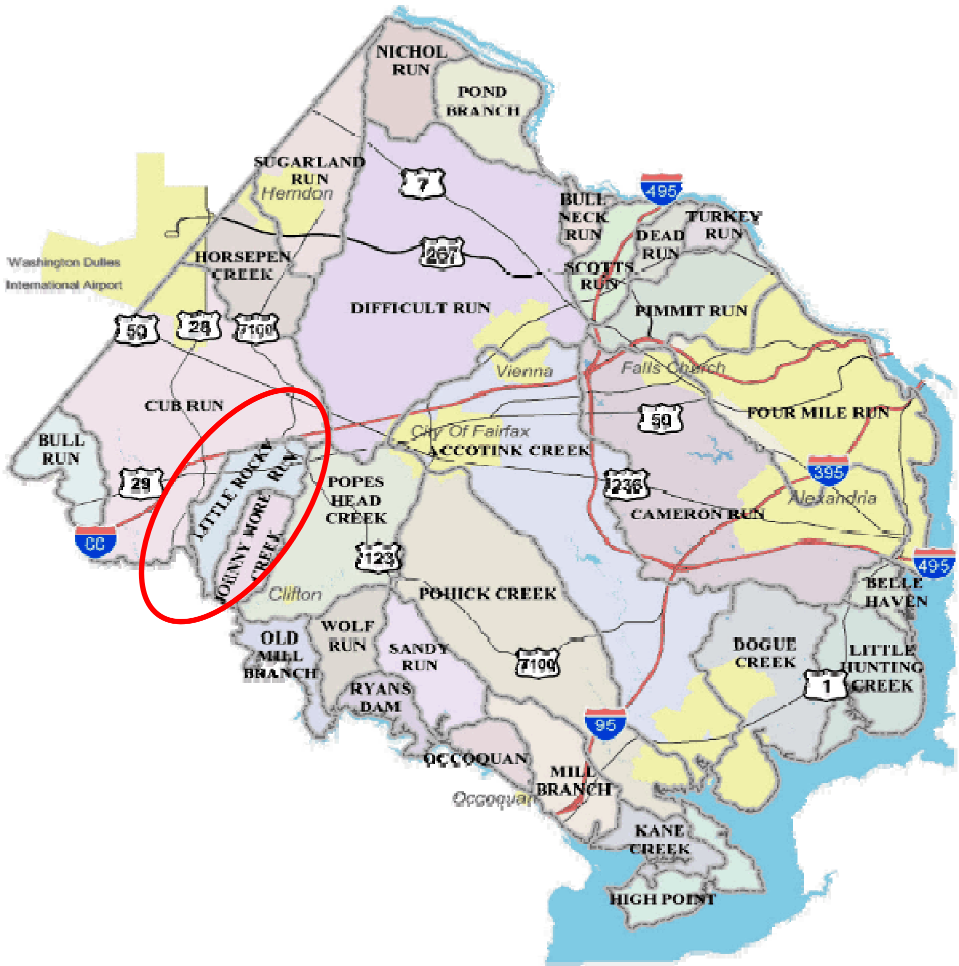


Figure 4-18. **Little Rocky Run watershed in Fairfax County, Virginia.**

4.2.2. Data Collection and Analysis

This *SUSTAIN* case study application began with a review of watershed characteristics followed by assembling information related to the existing watershed modeling activities for the area, including the simulated time series outputs and model parameters used in the existing watershed models. Available sources of information included land use maps, pollutant source information, existing BMP information, local BMP cost data, and the existing Little Rocky Run SWMM model. Figure 4-19 shows the selected watershed for the case study application—a mixed land use area in the headwaters of the Little Rocky Run watershed.

4.2.3. Project Setup

The next step was to transfer the compiled model parameters into the LAND module (based on SWMM5) in *SUSTAIN* for model setup. Model setup also involved land use reclassification, assigning flow and water quality time series to corresponding land use types, delineation of BMP tributary areas, and selection of assessment points. The established model configuration was then used to evaluate different treatment scenarios to measure relative impacts, perform optimization analysis, and finally, interpret and present results. Figure 4-20 shows a roadmap of this case study and its objectives.

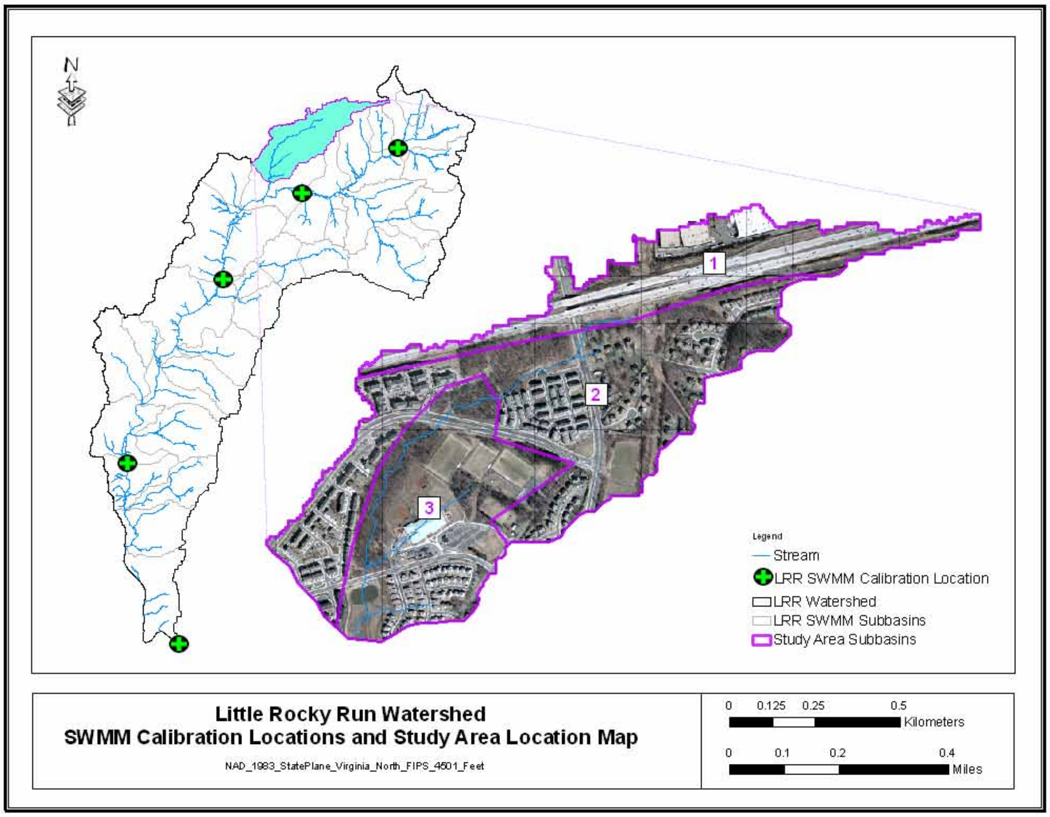


Figure 4-19. **Selected study area in Little Rocky Run watershed.**

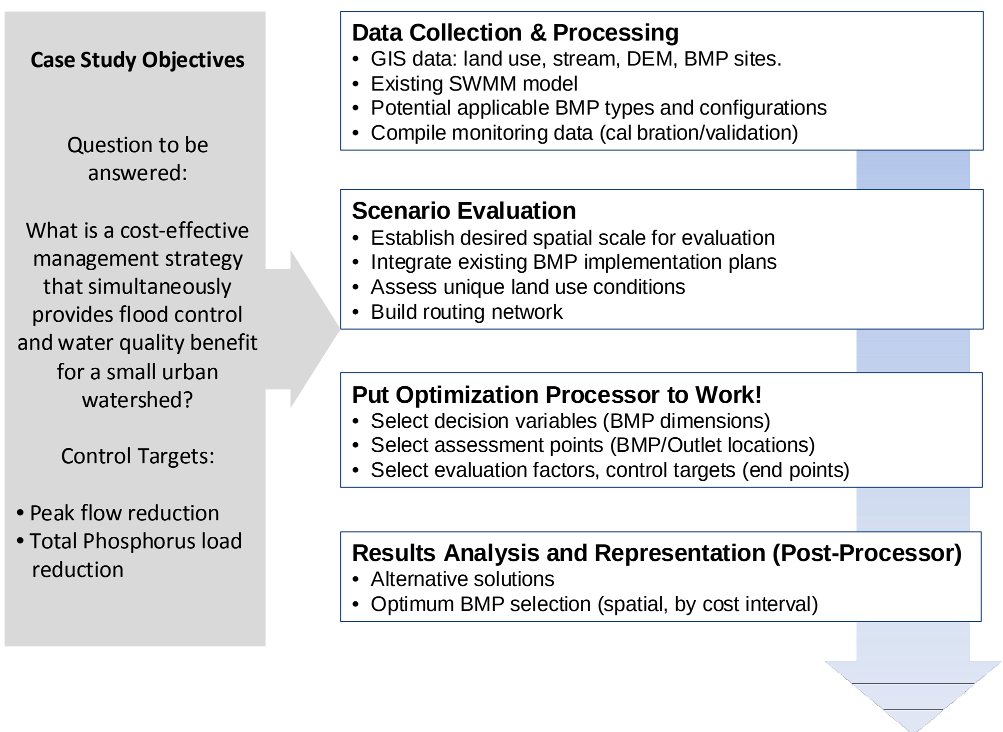


Figure 4-20. **Little Rocky Run case study road map.**

Existing SWMM Modeling

A comprehensive SWMM (version 5) 2-, 10-, and 100-yr design storm model for the Little Rocky Run watershed was developed for watershed planning purposes (Tetra Tech 2009). The model calibration was performed at five locations following the county's approved methodology (Tetra Tech 2008). These locations were selected from a consideration of land use, soils, slope, and major confluences along the mainstem. Calibration was performed beginning with the most upstream location and proceeding downstream to the watershed outlet. At each calibration location, SWMM model predictions were compared to the peak flows estimated by the Anderson and USGS methods (Anderson 1970; USGS 2001), which are documented in the county's SWMM calibration methods (Tetra Tech 2008).

The Anderson approach was developed for estimating peak runoff rates from watersheds with varying degrees of development and design storms with recurrence intervals of 2.33 years to 100 years. The regression relationship in the approach was derived from analysis of flood data at eighty-one watersheds in and around Washington, DC with sizes ranging from 0.00034 mi^2 to 570 mi^2. The imperviousness of these watersheds varies from less than 1 percent to 100 percent, and the watershed conditions from natural to fully developed (Anderson 1970).

In the Anderson approach, the peak flow rate from a watershed is expressed as a function of five independent variables, including the watershed area, length, slope, percentage of imperviousness, and the type of drainage collector system.

Alternatively, the USGS (2001) has developed regression equations, using urban runoff data from 199 basins in 56 cities and 31 states, to relate urban peak flow rates with basin characteristics for various recurrence intervals at different regions. The regression equations were built into a computer program called National Flood Frequency (NFF, Version 3.2) for peak flow predictions from recurrence interval storms ranging from 2 to 500 years, along with the corresponding confidence interval of the estimations.

The SWMM calibration was performed using the 2-, 10-, and 100-yr 24-hour design storms. The watershed GIS data were used to generate the input data parameters, summarized in Table 4-8, for the Anderson approach and the USGS method. Model calibration locations are shown in Figure 4-19.

Table 4-8. List of Input Parameters for Both the Anderson and the USGS Methods

SWMM Junction	Area (A) (mi^2)	Index of Slope (S) (ft/mi)	Longest Flow Path (L) (mile)	Lag Time (T) (hr)	% Impervious (I)	Impervious Co-efficient (K)	Flood-Frequency Ratio (R)			Development Factor (USGS Method)
							2-yr	10-yr	100-yr	
3	0.56	53.93	0.98	0.33	26.96	1.40	1.00	1.84	3.92	11.00
13	2.19	49.72	2.35	0.52	22.40	1.34	1.00	1.89	4.12	10.00
18	3.54	39.48	3.94	0.71	25.57	1.38	1.00	1.85	3.98	10.00
28	6.19	42.71	6.47	0.90	28.89	1.43	1.00	1.82	3.84	11.00
32	7.18	32.67	8.89	1.12	25.00	1.38	1.00	1.86	4.00	9.00

Previous SWMM calibration studies of the Little Rocky Run watershed (Tsihrintzis and Hamid 1998; Zaghloul 1983) focused on the parameters of depression storage, infiltration parameters, and slope at each calibration location. The calibration target was based on the relationship between the Anderson approach peak flow estimation and the USGS method peak flow estimation range, as follows:

- When the computed peak flows from the Anderson approach fall within the range USGS estimation range, the target flow for calibration is the USGS estimated range

- When the estimated flows from the Anderson approach is outside the flow range from the USGS method, the target flow for calibration is ±20 percent of the Anderson approach estimates

The calibration process ends when a good match is reached between the SWMM predicted peak flow rate and the estimates from the Anderson/USGS methods. Table 4-9 compares the peak flows from the USGS method, the Anderson approach, and the calibrated SWMM.

Table 4-9. Comparison of Predicted Peak Flows (ft^3/s) in the Little Rocky Run Watershed

SWMM Junction	The USGS Method			The Anderson Method			SWMM		
	2-yr	10-yr	100-yr	2-yr	10-yr	100-yr	2-yr	10-yr	100-yr
3	124–510	271–1,113	400–2,300	341.9	629.0	1,338.8	289.7	580.1	1,021.4
13	278–1,138	600–2,460	897–5,163	801.4	1,511.1	3,299.1	488.5	1,133.4	2,157.4
18	387–1,585	819–3,361	1,222–7,038	1,056.0	1,957.2	4,197.9	612.5	1,457.3	2,839.7
28	678–2,782	1,388–5,692	2,051–11,809	1,549.3	2,823.0	5,944.9	933.7	2,260.5	4,346.2
32	564–2,316	1,188–4,872	1,785–10,275	1,506.7	2,801.2	6,027.0	945.3	2,308.0	4,498.2

An example calibration plot is shown in Figure 4-21. It shows the predicted peak flows by three methods on the same graph. The figure shows that the calibrated SWMM model peak flow rates are within the USGS peak flow estimation range for 2-, 10-, and 100-yr 24-hour design storms.

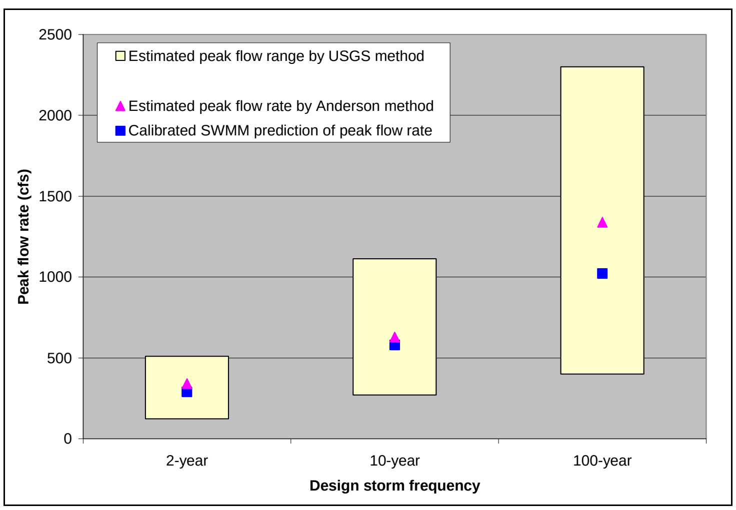


Figure 4-21. SWMM calibration results at junction 3 of the Little Rocky Run watershed.

Validation of Land Module in *SUSTAIN*

Figure 4-19 shows the selected study area for the case study application—a mixed land use area in the headwaters of the Little Rocky Run watershed. The study area is approximately 240 acres, and the land use distribution of the area size and imperviousness are presented in Table 4-10.

To ensure that *SUSTAIN's* internal land simulation module would reproduce the results of the calibrated SWMM model, *SUSTAIN* was set up for the same area using the SWMM input parameters from the calibrated Little Rocky Run model (Table 4-11). A 10-yr, 24-hour design storm was used to compare the simulated surface runoffs using the internal land simulation option in *SUSTAIN* and standalone SWMM model.

Table 4-10. Land Uses of the Case Study Area in the Little Rocky Run Watershed

Land Use Groups	Area (acres)	Percent of Total Area (%)	Imperviousness (%)
Transportation	65.4	27	52
Residential and Other Urban	95.9	40	21
Open Space	79.5	33	10
Total	240.8	100	25

The study area was subdivided into three subareas on the basis of the type of treatment received (Figure 4-22). The areas that received quantity control onlt were grouped into subarea B1. The areas that use BMPs to provide water quality treatment were grouped into subarea C. Lastly, the areas not served by stormwater management facilities or received waivers because of the construction of downstream stormwater facilities were grouped into subarea D. Fairfax County (2007a and 2007b) include additional information on the subarea delineation and SWMM modeling approach.

Table 4-11. Major Input Parameters for Modeling of Three Subareas

Subarea	C	B1	D
Area (acre)	4.82	36.63	167.64
Width (ft)	21.37	162.43	743.38
Slope (%)	1.31	1.31	1.31
Imperviousness (%)	24.95	26.05	22.41
Impervious Manning's *n*	0.015	0.015	0.011
Impervious Depression Storage (in.)	0.1	0.1	0.04
Pervious Manning's *n*	0.266	0.269	0.282
Pervious Depression Storage (in.)	0.2	0.2	0.1

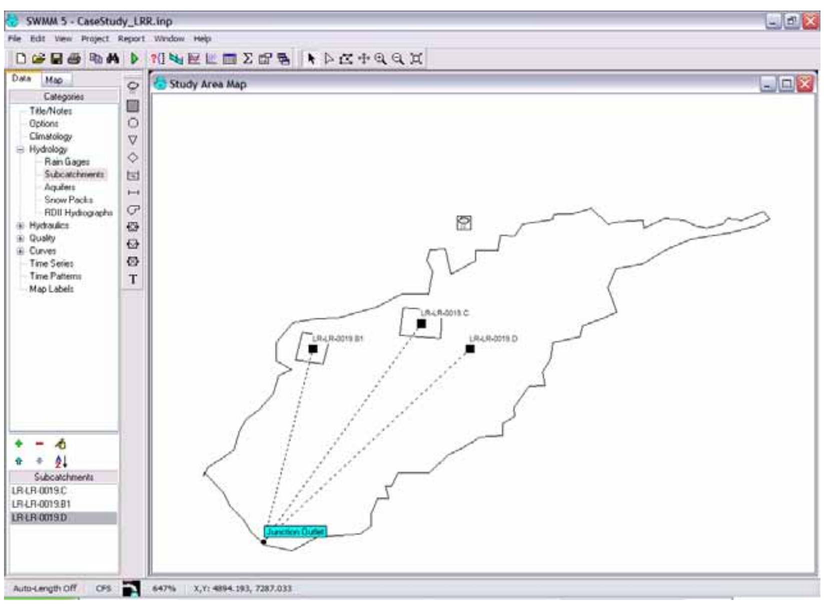


Figure 4-22. Representation of three subareas.

Figure 4-23 shows the hydrograph generated at the outlet of the study area by the standalone SWMM model. The same model configuration was replicated in *SUSTAIN* using the internal land simulation module. Figure 4-24 shows a one-to-one comparison of the computed flows on the two separated hydrographs generated. The perfect duplication of peak flow computations is a good confirmation that the SWMM model codes were correctly incorporated into the Land Module of *SUSTAIN*.

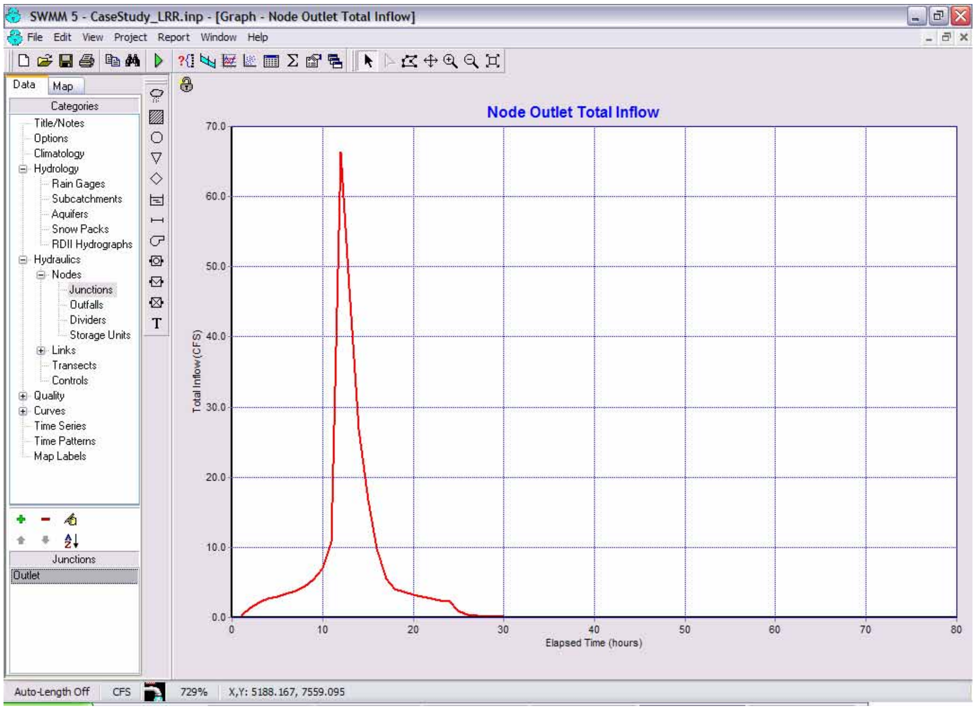


Figure 4-23. **SWMM-generated hydrograph at the outlet of the study area.**

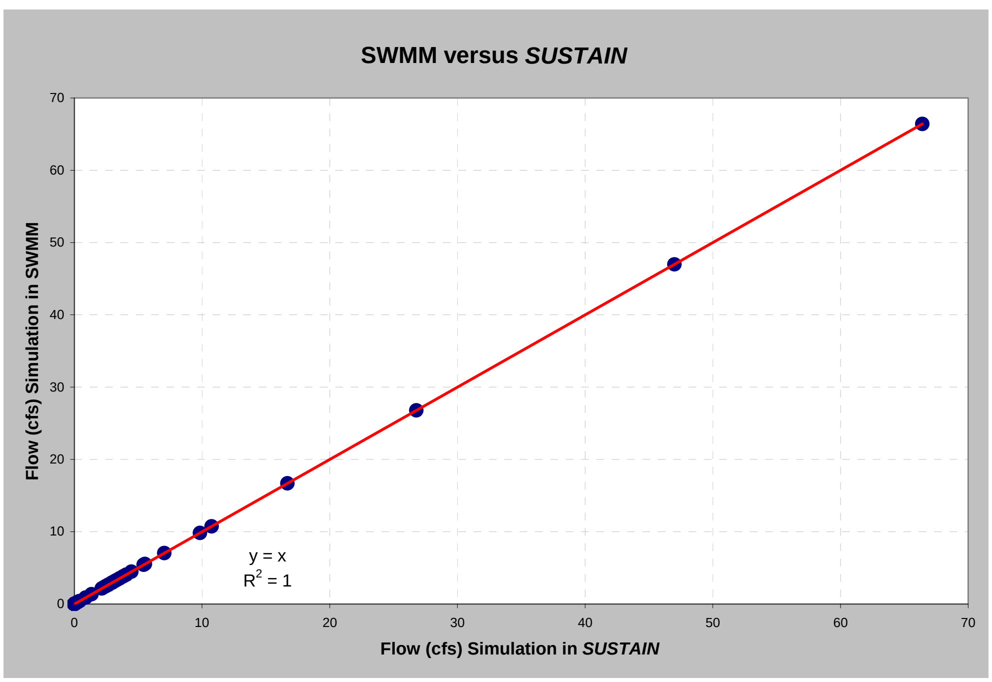


Figure 4-24. **SWMM versus *SUSTAIN*-generated hydrograph comparison.**

4.2.4. Optimization and Results Analysis

The optimization problem can be mathematically expressed as:

Objective:

$$\text{Minimize} \quad \sum_{i=1}^{n} Cost(BMP_i)$$

Subject to:

$$Q \leq Q_{target}$$

$$L_{TP} \geq 40\%$$

where

BMP_i = BMP (i.e., bioswales, bioretention, and wet pond) configuration decision variables associated with location *i*,
Q = the computed 10-yr design storm peak flow at the pond outlet,
Q_{target} = the target value of the 10-yr peak flow rate at the pond outlet, and
L_{TP} = the computed amount of TP load reduction percentage at the study area outlet.

To facilitate the BMP evaluation, the study area was grouped into three subbasins, one for each of the three major land use types: transportation (27 percent), residential and other urban (40 percent), and open space (33 percent). The land use distribution of the area size and imperviousness are presented in Table 4-10. This configuration was used to optimize the placement of BMPs to reduce peak flow rate and nutrient load.

SWMM input parameters used to represent the physical characteristics of a subbasin for runoff computations include area, width, slope, percent imperviousness, Manning's *n* for both pervious and impervious surfaces, depression storage for both impervious and pervious surfaces, percentage of impervious surfaces with zero depression storage, subarea internal routing method and percentage, and the Horton infiltration parameters. Below is a summary of how each of the input parameters was generated. Table 4-12 summarizes the numerical values of the SWMM input parameters for the three subbasins.

Area—the surface area of a subbasin, calculated in a GIS environment using area summary functions.

Width—the width of a subbasin, which, according to the SWMM User's Manual, is calculated by dividing the subbasin area by the longest flow path. The longest flow path is automatically generated using ArcHydro.

Slope—slope for a subbasin is calculated as *rise over run*, in which the *run* represents the longest flow path, and *rise* represents the elevation difference between the starting and ending points of the longest flow path.

Percent imperviousness—the percent imperviousness of a subbasin is calculated by dividing the total planimetric impervious area (i.e., building, roadway, parking lot, and sidewalk) by the total area of the subbasin.

Manning's *n*—the Manning's *n* values for both impervious and pervious surfaces are estimated on the basis of land surface characteristics. The area of each land use type in a subarea is used to calculate the area-weighted Manning's *n* for the whole subarea.

Depression storage—the depression storage is a volume that must be filled prior to the occurrence of runoff on both pervious and impervious areas. In the absence of users' defined values, default values of 0.2 in. for pervious surface and 0.1 in. for impervious surface are suggested.

Percentage of impervious surface with zero depression storage—a default value of 25 percent is used in the initial model setup as suggested in the SWMM manual.

Table 4-12. **Subbasin SWMM Parameters**

Subbasin	**1**	**2**	**3**
Land Use Groups	**Transportation**	**Residential and Other Urban**	**Open Space**
Area (acre)	65.4	95.9	79.5
Width (ft)	145.22	404.77	237.19
Slope (%)	1.31	1.31	1.31
Imperviousness (%)	51.6	20.5	9.5
Impervious Manning's *n*	0.015	0.015	0.015
Impervious Depression Storage (in.)	0.11	0.11	0.11
Pervious Manning's *n*	0.266	0.266	0.266
Pervious Depression Storage	0.23	0.23	0.23

Table 4-13 is a summary of the hydrologic soil group distribution in the case study area from county-provided SSURGO data. Note that a major portion (90.6 percent) of subbasin 3 (open space) has D soils, while subbasins 1 (transportation) and 2 (residential and other urban) have a mixture of B and D soils.

Table 4-13. **Hydrologic Soil Group Distribution in Study Area Subbasins**

	Soil Group B (%)	**Soil Group C (%)**	**Soil Group D (%)**
Subbasin 1	56.35	6.14	37.51
Subbasin 2	40.09	5.47	54.44
Subbasin 3	8.64	0.81	90.55

The Green-Ampt infiltration equation was used to simulate the infiltration loss. The equation requires that three parameters be specified. As a conservative assumption, the parameters for D soils are assumed for all three subbasins:

- The average capillary suction (*Su*) = 3 in.
- Hydraulic conductivity (*Ks*) = 0.5 in./hr
- The initial moisture deficit (*IMD*) = 0.25 (fraction)

As described in Section 3.2.3, *SUSTAIN* uses the buildup and washoff processes for water quality simulation. The calibrated SWMM model for the Little Rock Run watershed focused only on flows and did not include water quality components. Pollutant loads from the watershed were estimated using a simplified spreadsheet tool, STEPL (provide a reference). Nevertheless, there are several SWMM modeling studies in Fairfax County in which the buildup and washoff parameters were determined (Behera et al. 2006). These studies were reviewd and representative buildup and washoff coefficients were derived as shown in Table 4-14 and used in *SUSTAIN* for estimating TP concentrations.

Table 4-14. TP Buildup and Washoff Parameter Values

	Buildup $B = Min(C_1, C_2t^{C3})$			**Washoff** $W = C_1q^{C2}B$	
Name	C_1	C_2	C_3	C_1	C_2
Residential Impervious	8.0	0.045	0.523	0.83	1.38
Residential Pervious	6.3	0.031	0.42	0.70	1.49
Transportation Impervious	7.4	0.04	0.429	0.76	1.403
Transportation Pervious	6.3	0.031	0.42	0.70	1.49
Open Space Impervious	7.3	0.032	0.388	0.70	1.42
Open Space Pervious	6.0	0.030	0.394	0.692	1.465

BMP Representation

Three BMP types considered in the analysis included bioswale, bioretention, and a regional wet pond. Bioswales and bioretention facilities are distributed BMPs to treat runoff from local impervious areas with bioswales for highways and roads and bioretentions for residential and other urban areas. Regional wet ponds are centralized BMPs and typically are large facilities designed to treat large drainage areas. An existing regional wet pond was located at the study area outlet and, therefore, receives runoff from the entire study area. Figure 4-25 shows a flow chart diagram of the BMP simulation network. Table 4-15 lists the BMP parameters that were used in the model.

Bioswales

Bioswales are modified vegetated swales that use bioretention media beneath the swale to improve water quality, reduce the runoff volume, and reduce the peak runoff rate. In addition to provide drainage conveyance function as traditional drainage swales, bioswales use vegetation, compost, and/or riprap to enhance infiltration, water retention, and removal of silt, nutrient and pollutants through a variety of physical, chemical, and biological processes.

Bioretention

Bioretention cells, also known as rain gardens, are small-scale, shallow vegetated depressions that provide water quality benefits by rapid filtering through soil media, biological and chemical reactions in the soil matrix and root zone, and infiltration into the underlying subsoil. Bioretentions can be designed as on-line or off-line facilities with respect to the stormwater conveyance.

Regional Wet Pond

As a traditional practice that is mainly used for flood control, regional ponds were constructed in rapidly urbanizing areas in Fairfax County. There is a regional pond at the outlet of the case study area. The pond was designed to attenuate the peak discharge for 2-, 10-, and 100-yr 24-hour design storms.

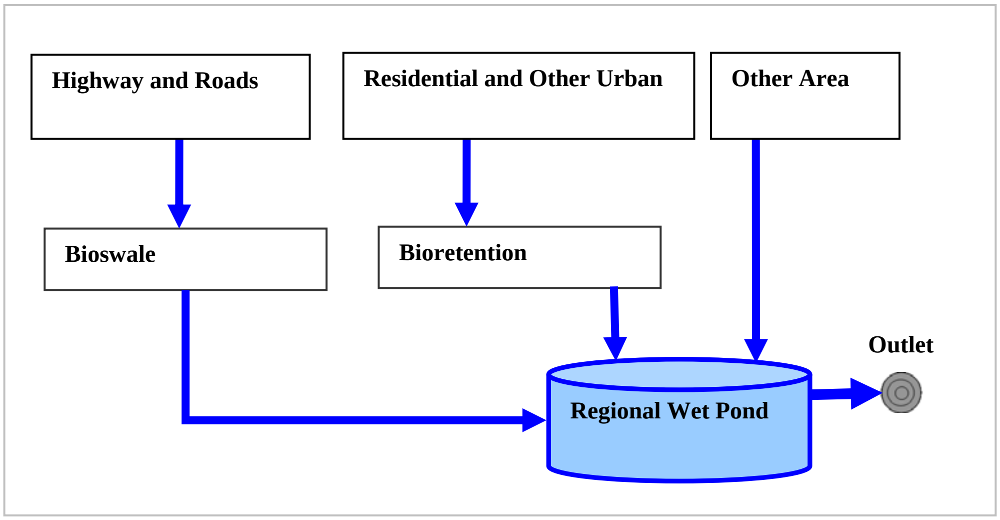


Figure 4-25. BMP placement schematic in the Little Rocky Run case study area.

Table 4-15. BMP Parameters

Parameter	Bioswale	Bioretention	Regional Wet Pond
Physical Configuration			
Maximum size (acre)	0.36	0.33	2.24
Drainage area (acre)	25.5	33.6	241
Substrate depth (ft)	2	2.5	N/A
Underdrain depth (ft)	N/A	1	N/A
Ponding depth (ft)	0.5	0.5	Orifice height: 1 Weir height: 4.75
Infiltration*			
Substrate layer porosity	0.5	0.5	N/A
Substrate layer field capacity	0.3	0.3	N/A
Substrate layer wilting point	0.15	0.15	N/A
Underdrain gravel layer porosity	0.5	0.5	N/A
Vegetative parameter, A	0.6	0.6	N/A
Underdrain background infiltration rate (in./hr), fc	0.5	0.5	N/A
Media final constant infiltration rate (in./hr), fc	3	3	N/A
Water Quality**			
TP 1st order decay rate (1/day), k	0.2	0.2	0.2
TP filtration removal rate, Prem (%)	65	65	N/A

* Source: Tetra Tech 2001
** Based on calibration using University of Maryland monitoring data (Tetra Tech 2003)

BMP Cost

For the case study, annualized life cycle cost functions summarized in Table 4-16 were used to estimate costs of BMPs considered. Annualized life cycle costs include the initial installation cost, as well as maintenance and replacement costs.

Table 4-16. Annualized BMP Cost Function

BMP Type	Annualized Cost Function	Reference
Bioretention	$1.03/ft^2 per year	Fairfax County BMP Factsheets (Fairfax County 2005)
Bioswale	$0.67/ft^2 per year	Fairfax County BMP Factsheets (Fairfax County 2005)
Wet pond	Cost = $0.12 \times 24.5 \times V^{0.705}$ ($ per year) V is the volume of the wet pond in ft^3	CASQA Stormwater BMP Handbook (CASQA 2003).

Bioretention Cost

Table 4-17 shows the breakdown of installation and annualized costs for a typical bioretention cell with a surface area of 900 ft^2. A bioretention cell is assumed to have a life span of 25 years, at which point it will be removed and replaced.

Table 4-17. Annualized Life Cycle Cost for a Bioretention Cell with a Surface Area of 900 ft^2

	Required Cost per Year (2005 Dollars)											
Item	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**…**	**25**
Installation*	10,000												
Mulching and Debris Removal		350	350	350	350	350	350	350	350	350	350		
Replace Vegetation		200	200	200	200	200	200	200	200	200	200		
Remove & Replace													10,000
Total Cost	10,000	550	550	550	550	550	550	550	550	550	550		10,000
Annualized Cost	$925/year (includes replacement in year 25)												

Source: Fairfax County BMP Factsheets
* The developer cost, which is not included in the annualized cost.

Bioswale Cost

Table 4-18 shows the installation cost and annualized costs for a bioswale with a surface area of 900 ft^2. A bioswale is also assumed to have a life span of 25 years, at which point it will be removed and replaced.

Table 4-18. Annualized Life Cycle Cost for a Bioswale with a Surface Area of 900 ft^2

	Required Cost per Year (2005 Dollars)												
Item	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**…**	**25**
Installation*	10,000												
Mowing		100	100	100	100	100	100	100	100	100	100		
Reseeding/Replanting		100	100	100	100	100	100	100	100	100	100		
Remove & Replace													10,000
Total Cost	10,000	200	200	200	200	200	200	200	200	200	200		10,000
Annualized Cost	$600/year (includes replacement in year 25)												

Source: Fairfax County BMP Factsheets
* The developer cost, which is not included in the annualized cost.

Wet Pond Cost

Wet Pond costs were estimated as described below.

Construction Cost

$$\text{Cost} = 24.5 \times V^{0.705} \text{ (see Table 4-16)} \quad (4\text{-}1)$$

where

Cost ($) = the cost for construction, design, and permitting, and
V = volume of the wet pond in ft^3.

Converting the capital cost to annualized capital cost by assuming a 20-yr life span and 0.05 annual interest rate gives

$$\text{Annualized Capital Cost (\$/yr)} = 0.08 \times 24.5 \times V^{0.705} \quad (4\text{-}2)$$

Maintenance Cost

The mid-range of maintenance cost is approximated to be four percent of capital cost per year.

$$\text{Annualized Maintenance Cost (\$/yr)} = 0.04 \times 24.5 \times V^{0.705} \quad (4\text{-}3)$$

Annualized Life Cycle Cost (including capital and maintenance cost)

$$\text{Annualized Cost} = 0.12 \times 24.5 \times V^{0.705} \text{ (see Table 4-16)} \quad (4\text{-}4)$$

where

Annualized Cost ($) = the cost of construction, design, permitting, maintenance, and replacement, and
V = the volume of the wet pond in ft^3.

Simulation Period and Evaluation Factors

As previously described, the objectives of this optimization case study are to provide flood control up to the 10-yr design storm and achieve a minimum of 40 percent reduction of TP load. Because of local water quality improvement needs and the ultimate downstream effect on the Chesapeake Bay, reduction in nutrient loading is an important objective for the stormwater management in Fairfax County. BMP effectiveness was measured at the designated assessment point at the study area outlet.

The use of continuous simulation provides modelers with an opportunity to capture the dynamic responses of BMPs under various storm conditions. However, among the large potential sets of data, it is often possible to identify one set of data that can reasonably represent either the long-term average treatment performance of BMPs or a critical condition that is most closely associated with the nature of the problem being studied. From the analysis of precipitation data, the calendar year 1994 (January 1, 1994–December 31, 1994) was determined to be representative of average hydrologic conditions in the watershed. The total rainfall depth for the year was close to the 17-yr average of 43.3 in. In addition, both precipitation depth and intensity distribution were relatively close to the long-term statistical average distribution. Figure 4-26 shows the average annual precipitation at the Washington Dulles International Airport for calendar years 1990–2006.

As mentioned previously, calendar year 1994 had the most typical rainfall magnitude and intensity distribution from among the four highlighted years that were close to the 17-yr average. Figure 4-27 shows the rainfall volume and intensity distribution for wet intervals occurring in calendar year 1994 at

Washington Dulles International Airport. In the figure, the volume and intensity percentile ranges correspond to storms occurring over the 17-yr period. A year with a perfect typical distribution would have the same number of precipitation intervals in each bin.

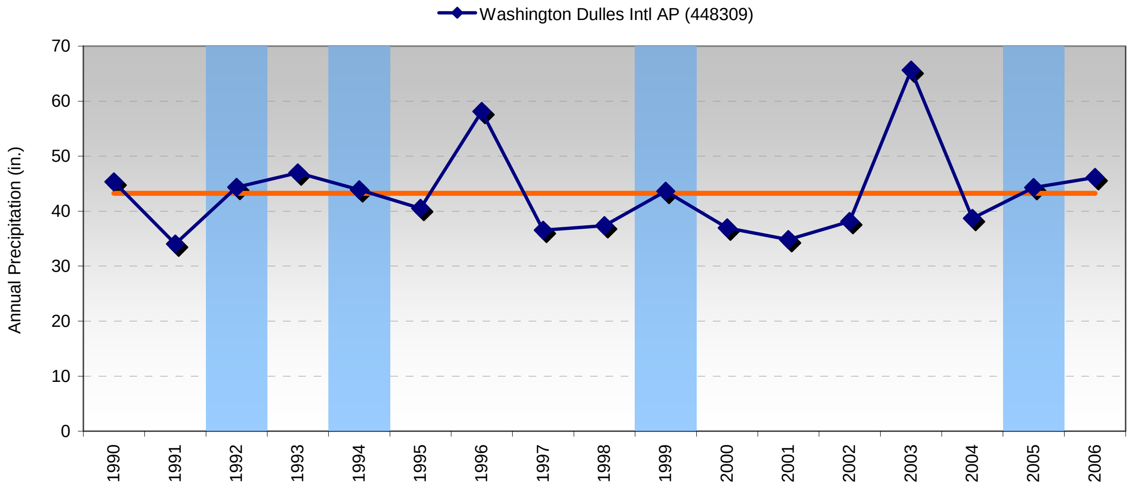


Figure 4-26. Annual precipitation at the Washington Dulles International Airport.

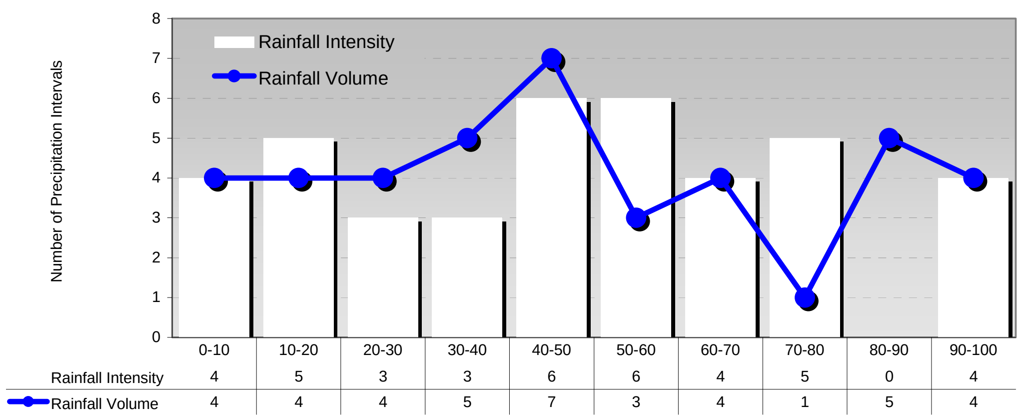


Figure 4-27. Volume and intensity distribution of storm events in 1994.

Existing Condition with Regional Wet Pond

The study area includes an existing regional wet pond that was designed to attenuate the peak discharge from 2-, 10-, and 100-yr storm events. Using *SUSTAIN*, the simulated 10-yr, 24-hour design storm peak flows and TP annual loads are summarized in Table 4-19. Note that peak flows values are reasonably compared to the original SWMM model results assessed at the outlet of the case study area.

Table 4-19. 10-Yr Design Storm Peak Flows and TP Annual Load under Existing Conditions

	10-yr, 24-hr Design Storm Peak Flow (cfs)		**TP Annual Load (lb/yr)**	
Model	**Pond inflow**	**Pond outflow**	**Pond inflow**	**Pond outflow**
SUSTAIN	108.3	53.4	78.2	59.8
Fairfax County SWMM	107.7	50.4	N/A	N/A

Optimization Setup

Bioswales and bioretention cells were recognized as feasible BMPs for the case study area to attenuate peak flow and reduce pollutant load. The decision variables used in the study included the size of surface area of bioswales and bioretention cells, and the storage capacity of the wet pond. Although the size of an existing regional pond was treated as a decision variable, it is not to suggest that the existing pond size can be reduced. Instead, the benefit of adding supplemental storage capacity in the form of bioswales and bioretentions could demonstrate a net increase to the overall on-site storage capacity, thereby yielding additional flood control capacity for the wet pond. The difference between the required versus the optimized size equals the net gain in flood control capacity for the wet pond. Two optimization objectives were defined in this exercise: (1) to maintain the 10-yr design storm peak flow at the pond outlet, and (2) to reduce the TP load by 40 percent.

Optimization Results

Using Scatter Search techniques, a near-optimal solution was identified after approximately 300 model runs. Figure 4-28 shows the near-optimal solution that meets both the 10-yr peak flow (top portion) and TP load reduction (bottom portion) targets. This solution is presented alongside a scenario without any BMPs (PostDev) and the existing condition with only the existing wet pond (Existing). This best solution carries an annualized life cycle cost of $64,400 per year.

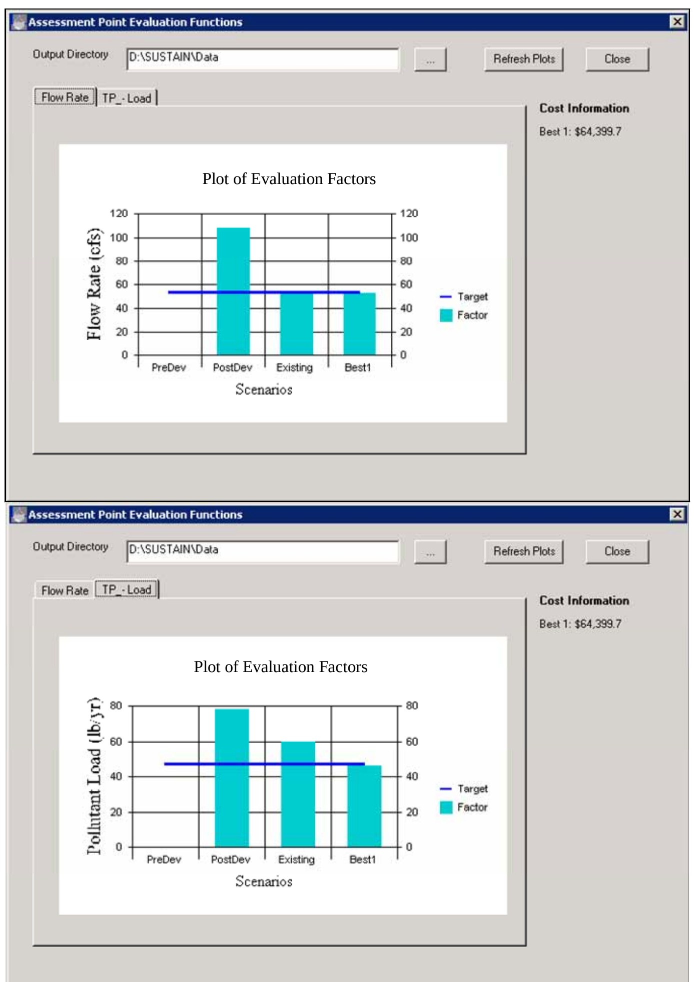


Figure 4-28. **Results showing the benefits of BMPs.**

Figure 4-29 presents all the solutions examined during the search process and the near-optimal solutions are highlighted in orange. The blue points indicate the cost and peak flow rate of all the solutions evaluated. The small number of blue points located to the left of the optimal solutions and below the flow rate target line are the solutions that meet the peak flow target, but not the water quality target. Table 4-20 compares the best solution with the existing scenario and lists the selected BMP decision variable values for the best solution. It shows that, relative to existing condition life cycle cost (related to the existing wet pond), to achieve the 10-yr peak flow *and* the TP load reduction targets, an additional $35,000 per year would be needed. This additional investment for water quality improvement would require 0.36 acre (15,700 ft^2) of bioswales to treat runoff from roads and highways and 0.04 acre (1,740 ft^2) of bioretention area to treat residential and other urban areas. The best solution also indicates that the new BMPs for water quality improvement yield a 17 percent net savings in terms of flood mitigation storage volume at the regional wet pond.

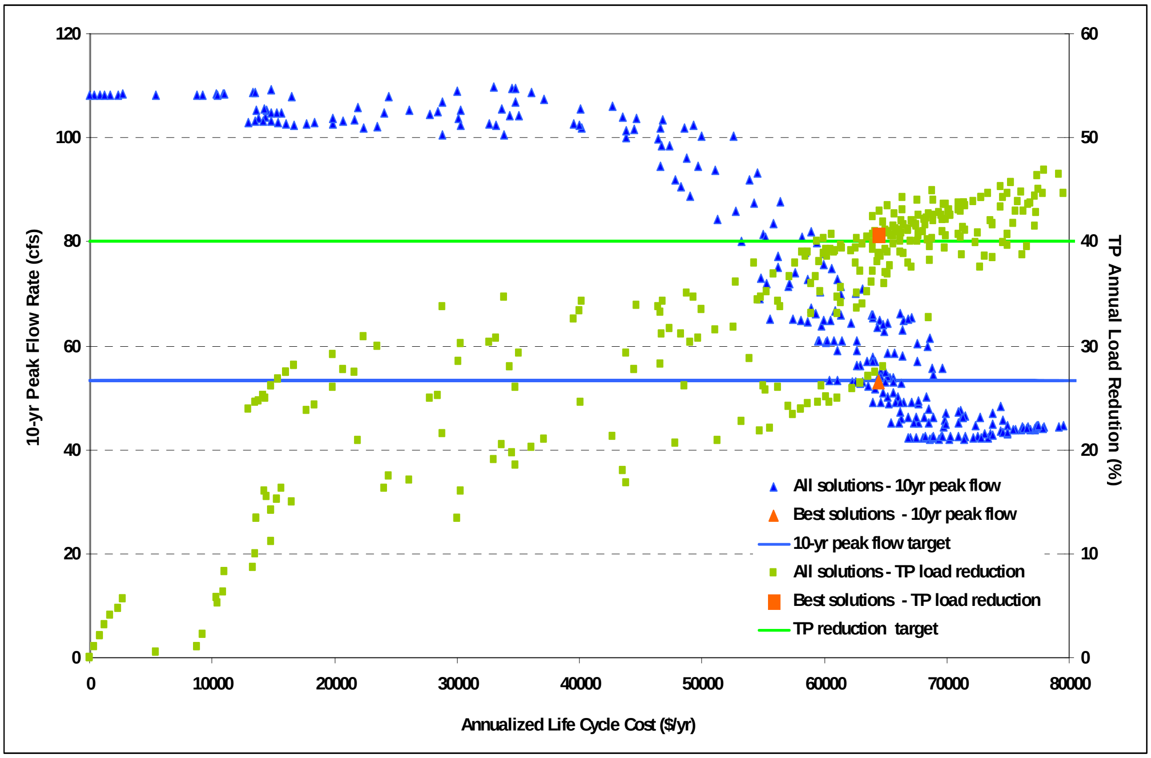


Figure 4-29. **Domain of optimization searches and identified best solutions.**

Table 4-20. **Cost-Effective Solution Details**

	Existing Scenario	**Best Solution**
Annualized cost ($/yr)	29,017	64,400
10-yr peak flow (cfs)	53.4	53.0
TP annual load reduction (%)	23.5	40.7
BMP		
Regional pond area (acre)	2.24	1.86
Bioswale area (acre)	0	0.36
Bioretention area (acre)	0	0.04

4.2.5. Summary

This case study has demonstrated: (1) a verification of the internal SWMM land module against the standalone SWMM 5 model and the use of the internal model to generate flow and pollutant loads from land, and (2) use of the Scatter Search optimization technique to find a near-optimal solution, given multiple control targets of peak flow and TP load reduction. Using optimization to guide decision making has been demonstrated to provide meaningful insights into the hydrologic response and benefits of BMPs for stormwater management. *SUSTAIN* is a powerful tool for decision-making. However, the outcomes from a *SUSTAIN* application would very much depend on the user-defined goals and assumptions. Hence, the results must be interpreted considering the user-specified assumptions, problem formulation, and defined optimization constraints. As stated before, the *SUSTAIN* application must be accompanied by an intimate understanding of the study area and the identification of influential factors that affect the decision making to achieve stormwater management goals.

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Appendix A. Needs Analysis and Technical Requirements

This appendix presents an evaluation of technical needs for developing a computer framework to assist stormwater management professionals in planning for BMP implementation in urban watersheds that achieves the desired source water and water quality protection cost effectively. The objective is to define the need for a system that can address both placement and selection of management practices in urban areas. The major programs targeted for *SUSTAIN* applications include urban watershed planning, stormwater management, and TMDL implementation. *SUSTAIN* must also be applicable to additional programs such as MS4s, the stormwater Phase II NPDES permit program, and source water protection. Each program requires the evaluation of key management questions and consideration of related indicators. Source water protection studies will need to address water supply protection; typically including eutrophication related indicators (i.e., phosphorus) and sediment. For TMDLs, the key indicators will be dictated by the waterbody's designated use (e.g., primary contact, warm water fishery) and the type of pollutants causing the impairment (i.e., metals, nutrients, fecal coliforms). The needs analysis addresses the various watershed protection programs by identifying three general categories of questions typically asked in urban management projects:

- What are the parameters for measuring the benefit or impact of management to protect source waters?
- What is the difference in performance between management options/scenarios including one or more practices?
- Which management alternatives will achieve environmental targets at the lowest cost?

These three questions are discussed in the Needs Analysis section below. It is followed by a discussion of specific technical requirements for building *SUSTAIN*.

A.1. Needs Analysis

SUSTAIN was designed to answer three needs analysis questions. For each question, specific capabilities required are included to show how individual elements work to meet overall project objectives.

1. *What are the parameters for measuring the benefit or impact of management? What is the target value to achieve?*

To select an optimal condition and compare the benefits of various management practices or combinations of practices, a performance measure or **indicator** must be selected to use for evaluation. In examining environmental conditions in urban areas, multiple performance measures or indicators of condition are recommended. The specific performance measures vary depending on the designated use of the water body (warm water fishery, cold water fishery, recreation) and the condition of the water body. For example, multiple factors or *stressors* might influence a warm-water fishery. Some potential stressors are changes in hydrology measured as peak flow and frequency of 1-yr stream flow events, elevated nutrient concentrations, elevated sediment concentrations, and higher summer temperatures. Each of these stressors can be measured using performance measures such as peak flow, flow volume, temperature, and nutrient concentration. Predictive models can use these performance measures as output values for optimization and selection of alternatives. A specific value or **target** can be set as a goal. For example, the temperature target might be set as a maximum of 85°F. Targets can be set on the basis of water quality standards or using expert examination of water quality conditions. Multiple stressors typically affect urban streams. Table A-1 provides a summary of the most commonly used performance measures and the specific parameters used. The selection of one or more performance measures suitable for the local conditions is appropriate for evaluating the benefits of management.

Table A-1. Summary of Recommended Indicators and Measurement Units

General Performance Measure	**Specific Performance Measure**	**Measurement (units)**
Hydrology	Flow	Volume (ft^3)
		Frequency (x/yr of selected peak, volume)
		Duration (hr)
Sediment	Total sediment	
	Total suspended sediment	Concentration (mg/L)
	Total solids	Load (tons/year, tons/month)
Water Quality	Pollutant	
	Nitrogen (NO_3, NH_3, TKN)	Concentration (mg/L)
	Phosphorus (TP, PO_4)	4-day average concentration (mg/L)
	Metals (typically zinc, lead, arsenic, manganese, aluminum)	Load (loads per day, month, or year)
	Pathogens	Pathogens—geometric mean (cfu/mL)
	Dissolved oxygen	Dissolved oxygen—daily minimum, daily average
Ecological measures	Temperature	Summer mean, 7-day average
	Others—typically not modeled, habitat condition, species diversity, stream condition, fish quantity and diversity	

2. *What is the difference in performance between management options/scenarios including one or more practices?*

To determine optimal solutions for a complex watershed, *SUSTAIN* needs to address multiple locations and practices in various combinations throughout the watershed. It must be sensitive to conditions like the following:

a. For each practice, *SUSTAIN* needs to be able to simulate the selected suite of performance measures. The framework must be capable of evaluating changes in performance measures on the basis of an unbiased evaluation of individual practice performance for a range of structural and nonstructural practices. Typical structural and nonstructural practices that the framework would evaluate can be classified into three general categories of BMPs using the mode of application. These categories are Point BMPs, Linear BMPs, and Area-Based BMPs. Examples of each type are shown in Table A-2.

Table A-2. Typical Structural and Nonstructural Practices by Mode of Application

Point BMPs		**Linear BMPs**	**Area-Based BMPs**
Dry extended detention pond	Infiltration trench	Vegetated Buffer Strips	Fertilizer management
Wet retention pond	Porous pavement	Riparian Zone Restoration	Impervious area minimization
Shallow marsh	Dry swale		Disconnected impervious areas
Extended detention wetland	Wet swale		Site level water management
Submerged gravel wetland	Inlet devices		Soil management
Organic filter	Baffle box		Street Sweeping
Sand filter	Oil-grit separator		
Bioretention			

b. Multiple practices in various combinations need to be considered. Figure A-1 provides a schematic of some of the potential combinations that *SUSTAIN* needs to evaluate. The options include various combinations of land areas, BMPs, conduits (pipes), or stream reaches (RCH). Some swales or buffers are illustrated by land-to-land series (number 4). Series of two or more BMPs might need to be considered (number 9).

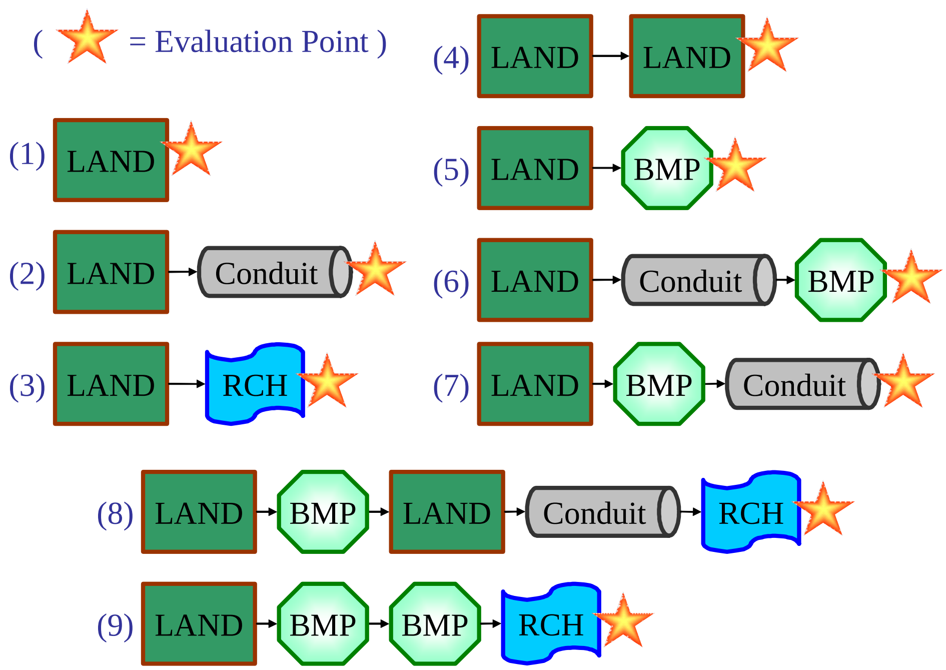

Figure A-1. Typical management configurations.

c. The location of individual or multiple practices relative to a water body or receiving water might vary as well. Some BMPs are located on-site, with very small drainage areas; other BMPs, such as stormwater ponds, are located closer to stream systems and have larger drainage areas.

3. *Which management alternatives will achieve environmental targets at the lowest cost?*

The effectiveness of BMP options (sizes, locations) in achieving the desired water quality goal must be compared based on costs. The scenarios can also be evaluated based on the cost required to achieve the desired environmental condition. For each individual practice or combination of practices, the system will include a method for estimating the costs of construction and O&M (Heaney et al. 2002).

A.2. Technical Requirements

Specific technical requirements were defined for the identified needs. For example, consideration of the full set of indicators (hydrology, sediment, pollutants, and ecological impact) requires simulation of dynamic hydrology and time-varying loads of sediment and pollutants, and potentially other ecological indicators such as temperature or relationships to biological indicators. Evaluating the implications of various configurations of management practices requires the ability to consider the performance of individual and multiple practices and the sensitivity of each of those practices to their relative location in the network. It is usually necessary to simulate longer time periods and storm sequences to demonstrate response to a wide set of forcing conditions. The technical requirements for *SUSTAIN* are listed below.

- Simulate hydrologic response and a level of detail sufficient for analysis of a hydrograph (peak flow and volume)
- Simulate multiple pollutant types, including nutrients (nitrogen and phosphorus), pathogens (fecal coliform bacteria, Escherichia coli [E. coli]) and metals (e.g., zinc, aluminum)
- Simulate fate and transport of pollutants at a time step suitable for evaluating short-duration and long-duration impacts consistent with evaluation of acute and chronic surface water criteria
- Simulate multiple size classes of sediment for input to management structures
- Simulate other habitat stressors, such as temperature
- Simulate in-stream dissolved oxygen based on inputs of biological oxygen demand, sediment oxygen demand, nutrient loads, and other environmental factors
- Evaluate urban and mixed land uses, including pervious and impervious areas
- Consider a full range of management practices at a similar level of spatial resolution and technical detail
- Consider distributed or small-scale upstream management practices, practices in series, and larger downstream facilities
- Link watershed management to downstream measures of environmental conditions (e.g., dissolved oxygen in a river, nutrient concentration in a lake or estuary) outside the immediate vicinity of a study area

Consequently, specific modeling procedures and algorithms were determined to fulfill the objectives of *SUSTAIN*. For example, simulation of hydrologic response requires that the model support the examination of rainfall/runoff processes at a level of detail sufficient to plot a time variable hydrograph and/or a pollutograph. Supporting model applications at multiple scales is essential for the *SUSTAIN* application. Scale may vary widely depending on the location and size of a watershed. The need to provide a modular modeling system and multiple scale applications govern the software and system designs.

A.2.1. Spatial Scale

One dominant technical requirement of *SUSTAIN* is the ability to site management practices at multiple scales. The way that BMPs are placed at different spatial levels, i.e. on-site, sub-regional, and regional (Figure A-2), influences the overall cost-effectiveness of the stormwater controls system (Zhen 2002). In an urban setting, examples of the on-site scale are building lots and neighborhoods with a drainage area of less than 10 to 100 acres. The recently promoted LID technologies are normally applied on a micro or on-site scale because the major design consideration is to retain and treat runoff near its source. Typical BMPs used for LID include bioretention/rain gardens, rain barrels, filter strips, grass swales, infiltration trenches, and detention or retention ponds. They operate at one point within a landscape, and treat runoff from a certain drainage area. Other types of BMPs that are not necessarily associated with LID, such as riparian buffers are linear by nature, and function by intersecting the landscape immediately adjacent to streams. Area-based BMPs, such as reduced/disconnected imperviousness and street sweeping, represent changes in human behavior and activity which may occur at many different scales.

Conventional BMPs collect runoff at hydrologic junctions farther downstream, at a level typically associated with the sub-regional scale. The sub-regional scale or township-level drainage areas are on the order of 100 to 5,000 acres. At this scale the benefits of management are often measured by the impact on receiving streams, lakes, or other larger waterbodies. The regional scale, which is the largest evaluation level, represents a county-level drainage area that is typically greater than 5,000 acres.

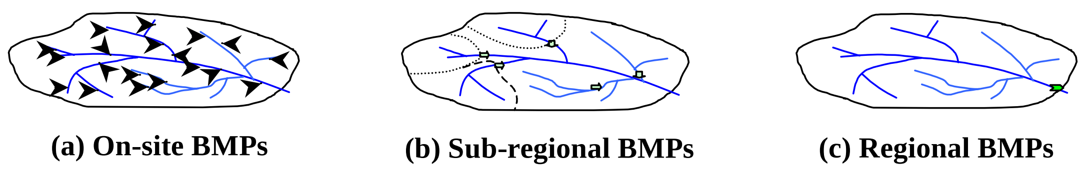

Figure A-2. BMP placement at various spatial levels: (a) on-site; (b) sub-regional; and (c) regional.

The system may ultimately be applied in a tiered or nested application (Figure A-3). More detailed small scale applications could be combined and evaluated on a larger scale to develop optimal solutions. Various combinations of watersheds might be used to provide a manageable level of detail and maintain computational efficiency. To address the technical requirement for multi-scale simulation, the landscape modeling, which provides the hydrologic and water quality time series data for simulation of BMPs, should be able to represent various spatial resolutions. The spatial and temporal resolution of *SUSTAIN* also needs to vary according to the type, location, and spatial density of the BMPs evaluated. The model needs to provide an unbiased evaluation of on-site, sub-regional, and regional BMPs to provide input appropriate for optimization and comparative analysis of management plans.

A.2.2. System and Modeling Requirements

From the defined technical requirements, modeling procedures or algorithms and system requirements were identified. System requirements are organized into four areas: (1) operational system features, (2) watershed/landscape simulation, (3) BMP simulation, and (4) stream conveyance simulation. While evaluating the candidate modeling algorithms, some of the practical constraints, limitations, and capabilities of each alternative were considered. Also considered were the simulation options and flexibility of the application. Each system requirement category is described in more detail below.

Operational Requirements

SUSTAIN must provide a framework for long-term simulation of the landscape, management practices, and hydrological system. The overall system provides the linkages between the land activities, the management practices, and the stream or hydrologic network. The system must also provide the utilities to support the placement and sizing of BMPs, developing watershed simulation networks that may include sequences of land parcels, management practices, and stream reaches. Several operational requirements are placed on this system. For example, the system should operate at a short or variable time step sufficient to represent hydrologic and pollutant loading pollutographs, typically 1 hour or less. The system should support placement of BMPs of various types (i.e., linear stream buffers, impoundments), calculation of the associated drainage area, and construction of networks of land uses, BMPs, and streams or pipe conveyances. *SUSTAIN* should be configured to simulate small subwatersheds or cells to a minimum size of approximately 1 acre. The system should be able to represent larger complex watersheds by subdivided smaller subwatershed units. To provide computational flexibility, the ability to define a mixture of larger and smaller units should be considered. *SUSTAIN* should also have the ability link to other external models, either watershed models for inputs of flow and pollutant time series or receiving water models. External linkage to receiving water models will facilitate examination of downstream environmental condition. For example, an evaluation of management scenarios to control nutrients in a watershed could be linked to a lake model for the purposes of evaluating in-lake chlorophyll-a.

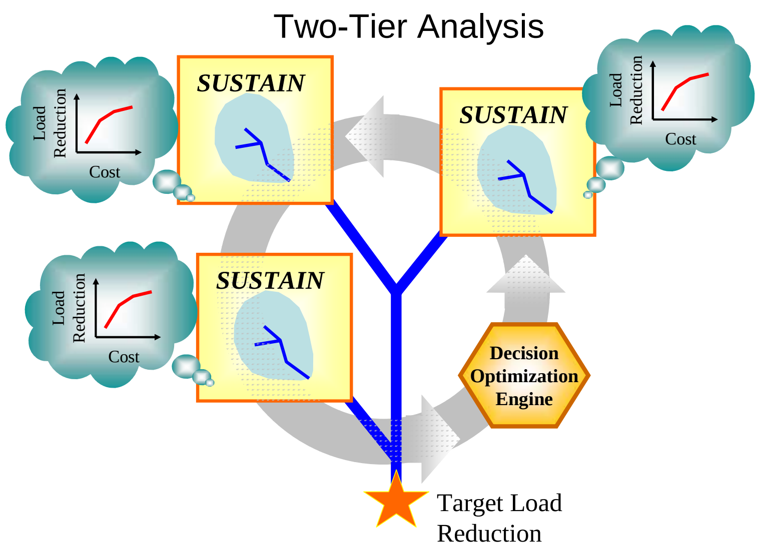

Figure A-3. Tiered watershed application.

Watershed/Landscape Simulation

The watershed/land simulation includes the algorithms to process water, sediment, and pollutant routing on the landscape. The technical requirements include a continuous simulation and small simulations time steps. The algorithms to represent these processes must also be of sufficient detail to evaluate changes in surface management and physical site characteristics that can be used as management variables. The algorithms for the following simulations are needed to meet the technical requirements:

- Physically based infiltration simulation (e.g., Green-Ampt)
- Overland flow routing/hydrograph generation
- Pollutant accumulation and washoff
- Sediment detachment and transport
- Land-to-land flow routing
- Groundwater interaction

BMP Simulation

A wide range of BMPs, both structural and nonstructural, needs to be evaluated by *SUSTAIN*. The simulation methods must provide an unbiased evaluation of the effectiveness of BMPs. Nonstructural management practices can include minimizing impervious areas, augmenting soil infiltration capacity through lawn management, recycling of roof runoff (e.g., using rain barrels), and disconnecting impervious surfaces (e.g., rain gutter outlets). Nonstructural management practices may also include source controls such as minimizing or reducing fertilizer and pesticide applications. Nonstructural practices can be evaluated by adjusting impervious areas, changing pollutant accumulation rates (e.g., changes in fertilizer application rates), or changing surface roughness characteristics (e.g., vegetative management). Nonstructural practices are area-based since the dominant management is spatially distributed.

Structural practices involve the placement and construction of a facility that captures and manages runoff from a site. Structural practices are typically *point-based*, since they are in a specific location and manage runoff captured from a defined drainage area. The typical practices use various combinations of storage, infiltration, filtration, biological processes, and hydrologic separation to provide control of hydrology and remove or reduce sediment and pollutants. Table A-3 provides a summary of the dominant and secondary functional processes employed in various structural management practices. Some management practices employ additional processes, identified as optional on the table, depending on the specific design features and the site conditions. For example, a stormwater detention facility might use infiltration as well as deposition/settling if the site has permeable soils with sufficient infiltration capacity. Table A-3 shows that many practices use similar processes to achieve flow, sediment, and water quality control. The table also identified the need for a management practice modeling system that can simulate these key processes, including storage/detention, infiltration, filtration, biological uptake/conversion, and hydrodynamic separation. The technical requirement to simulate these processes supports the selection of the algorithms for simulation of BMPs.

The following specific capabilities are recommended:

- Process-based simulation of retention and detention types of management with, at a minimum, first order decay and settling
- Time series simulation of point-based structural management practices that considers runoff routing and hydrodynamic separation
- Area-based practices, including surface cover management, through the use of watershed/ landscape analysis
- Linear practices such as riparian buffers by routing surface and sub-surface runoff/pollutants from one land unit to the next

Stream Conveyance Simulation

The stream routing and conveyance network component provides a linkage between subwatershed/landscape units, management practices, and other direct discharges within an urban watershed. The stream conveyance module is used to route runoff, sediment, and pollutants through a stream network, which is often present in an urban watershed. The rigor of simulation for the stream portion is related to the dominant processes present in urban streams. Key features include settling, resuspension, and decay (i.e., fecal coliform) and changes in the stream channel (i.e., stream bank erosion or degradation). Therefore, during conveyance in a stream, the module should consider settling, resuspension, and decay processes. Accounting for stream bank erosion should be considered as an option as well. Larger waterbodies, including rivers, lakes, and tidal waters might require more detailed simulation of chemical and biological processes. These systems can best be simulated through external linkage to several comprehensive receiving water models such as Environmental Fluid Dynamics Code (EFDC; Hamrick 1992) and WASP (Wool et al. 2003).

Table A-3. Types of Structural BMPs and Major Processes

Structural BMP Types	Storage Detention	Infiltration	Filtration	Biological Uptake and Conversion	Structure-Facilitated Hydrodynamic Separation
Dry Extended Detention Pond	+	(o)	-	-	-
Wet Retention Pond	+	(o)	-	o	(o)
Shallow Marsh	+	(o)	-	+	(o)
Extended Detention Wetland	+	(o)	-	o	(o)
Submerged Gravel Wetland	+	(o)	+	+	-
Organic Filter	o	(+)	+	o	-
Sand Filter	o	(+)	+	o	-
Bioretention	o	(+)	+	+	-
Infiltration Trench	o	+	(o)	o	-
Porous Pavement	-	+	(o)	-	-
Dry Swale	o	(o)	-	-	-
Wet Swale	o	(o)	-	o	-
Buffer Strip	-	+	(o)	o	-
Baffle Box	+	-	-	-	+
Inlet Devices	-	-	+	(o)	(+)
Oil-Grit Separator	+	-	-	-	+

Note: ( ) optional function; + major function; o secondary function; – insignificant function
Definitions of the process groupings:

- Storage detention: detaining water
- Infiltration: infiltrating water to the ground
- Filtration: passing water through a porous medium
- Biological uptake and conversion: reducing nutrients and other pollutant as aquatic plants and microorganisms use them for growth
- Structure-facilitated hydrodynamic separation that considers physical design features: separating insoluble pollutants (solids, oil, and floatables) by introducing physical or hydrodynamic forces, e.g. baffles, whirlpool effect

Appendix B. Model Evaluation and Selection

B.1. Introduction

This appendix provides a summary of the targeted evaluation and selection of public-domain software in accordance with the design requirements of *SUSTAIN*. Currently available models and modeling frameworks were identified and evaluated according to their technical capabilities and software systems. The review effort focused on identifying key models that addressed one or more of the needed algorithms or analysis methods. The purpose of the review was to identify candidate models or portions of models for integration or adaptation into *SUSTAIN*.

B.2. Overview of Available Models

The review of available models followed a structured process based on the results of the technical needs analysis. Generally the review focused on publicly available models and modeling systems, although proprietary models that have been published and have relevant capabilities were included for comparative purposes. The following are some example considerations in the selection of available models for review:

- Is the model in the public domain, and how easily adaptable, current, and available is the source code for the model?
- Is the model well established with an extensive application history and record?
- Is the model appropriate for small to mid-size urban watersheds?
- How rigorous are its algorithms in simulating watershed processes?
- Is the model relevant for pollutants present in urban areas?
- Does the system include interface capabilities or linkages that could be relevant to the *SUSTAIN* design?

The selection of models for review focused on identifying models that could have relevance to one or more areas of *SUSTAIN*. For this reason some models with specialized features that are not typically used in urban environments (e.g., WAMView [SWET 2002]) were included. The emphasis was on selection of models that are in the public domain or are available for distribution without charge. Other proprietary models with limited information on model algorithms and documentation were excluded from the analysis (i.e., Mike-SHE, MOUSE [DHI Inc. Web site]). The set of models selected for review is listed in Table B-1 and profiles for each model are provided in Section B.3. A distinct set of evaluation factors was developed for watershed models, BMP systems, and interface and software platforms.

Table B-1. Available Models Reviewed

Watershed Models	BMP Models
SWMM, HSPF, LSPC, WAMview, WARMF, SLAMM, P8 UCM, ANSWERS, CASC2D, KINEROS, WEPP, DR3M-QUAL, SWAT, AnnAGNPS, AGNPS, GWLF	Prince George's County BMP Module, P8 UCM, VFSMOD, MUSIC, DMSTA, SWMM, BMPAM
Systems: BASINS, EPA TMDL Toolbox	Systems: LIFE

B.2.1. Watershed Model Evaluation Factors

The following factors were identified for evaluation of available watershed models. The evaluation results are summarized in Table B-2. These factors are closely aligned with general modeling considerations and the four major categories of simulation needs (i.e., land, reach, conduit, and BMP).

- At what spatial scale (cell, field, catchment, subwatershed, or watershed) is the modeling application most suitable?
- At what time scale (continuous or event-based) is the simulation performed, and what is the minimum applicable computation time step?
- What land uses (urban and nonurban) can be simulated? Are point sources addressed?
- How rigorous are its algorithms for hydrology simulation, how is the rainfall-runoff simulation performed, and is groundwater interaction included?
- How rigorous are its algorithms at water quality (pollutant loading) simulation? How does it address sediment, nutrients, and other pollutant loading generation, transport, and transformation, if included?

In landscape or watershed models, an essential feature is how the area is segmented. For evaluation purposes segmentation was defined as four distinct options:

- Catchment (CM): Capable of simulating multiple watersheds and subwatersheds
- Cell: Watershed area represented as a network of cells. Flow is routed from cell to cell
- Field: Limited to a small single simulation unit, typically a field or monitoring plot
- Watershed (Wsh): Limited to single watershed for each model simulation

B.2.2. BMP Technical Evaluation Factors

The following factors were considered in BMP model evaluation as summarized in Table B-3.

- What types of BMPs can be addressed?
- What pollutant removal processes and mechanisms are simulated?
- What algorithms are applied for flow routing and pollutant removal process simulation?
- What water quality constituents can be simulated?

B.2.3. Model Interface Evaluation Factors

The model interface features of the models were evaluated, using the following factors:

- What GIS features, if any, are incorporated?

- How is the subwatershed/channel network represented?
- Data management utilities
- Model code
- Interface code

Table B-4 and Table B-5 contain model interface evaluations for watershed models.

B.3. Evaluation and Review of Available Models

This section provides an evaluation and review of available models. The models reviewed are organized into three groups—landscape models, BMP models, and comprehensive modeling systems. Within each group, the models are sequenced based on their expected relevance to urban management analysis. Regardless of their position in the sequence, all models reviewed might have specific features that could prove useful for the development of *SUSTAIN*. A narrative discussion is provided below for each model, including key features, capabilities, special techniques, and software capabilities. The narrative description supports earlier summary tables (Table B-2 to Table B-5). Section B.4 provides further discussion of the strengths and weaknesses of the reviewed models and identifies the models for integration into the *SUSTAIN* design.

B.3.1. Landscape Model Reviews

Landscape models are models that simulate land-based hydrology and water quality, and provide sediment and pollutant loading estimates. Many of these models also incorporate some of the features of BMP models (i.e., simulation of various management practices) and stream conveyance systems. The following landscape models were reviewed for potential integration of components and interface with *SUSTAIN*.

SWMM

The Stormwater Management Model (SWMM) is a dynamic rainfall-runoff simulation model developed by EPA and primarily applied to urban areas, for single-event or long-term (continuous) simulation using various time steps (Huber and Dickinson 1988). It was developed for the analysis of surface runoff and flow routing through complex urban sewer systems. The last official version was 4.4h. SWMM5 is a completely revised and updated release of SWMM. However, SWMM5 will continue to be expanded with new functions, particularly a quality routine.

In SWMM, flow routing is performed for surface and subsurface conveyance and groundwater systems, including the options of nonlinear reservoir channel routing and fully dynamic hydraulic flow routing. By choosing the fully dynamic hydraulic flow routing option, SWMM can simulate backwater, surcharging, pressure flow, and looped connections. SWMM has a variety of options for quality simulation, including the traditional buildup and washoff formulation, as well as rating curves and regression techniques. The Universal Soil Loss Equation (USLE) is included to simulate soil erosion. SWMM incorporates first-order decay and particle-settling mechanisms in pollutant transport simulations, including the option of a simple scour-deposition routine in conduits. Storage, treatment, and other BMPs can also be simulated. A more detailed description of its BMP simulation capabilities is provided in the next section.

Table B-2. Watershed Model Evaluation Summary

Criteria		SWMM	HSPF	LSPC	WAMview	WARMF	SLAMM	P8 UCM	ANSWERS	CASC2D	KINEROS	WEPP	DR3M-QUAL	SWAT	AnnAGNPS	AGNPS	GWLF
Land Uses	*Urban*	●	●	●	◖	●	●	●	--	--	--	--	●	○	--	--	●
	Rural	◖	●	●	●	●	-	-	●	●	●	●	-	●	●	●	●
	Point Sources	●	●	●	◖	●	●	●	-	-	-	-	●	●	●	●	◖
Time Scale	*Continuous*	●	●	●	●	●	●	●	●	●	-	●	●	●	●	-	●
	Single Event	●	●	●	●	●	-	●	●	●	●	●	-		-	●	-
	Time Step	V	V	V	V	V	V	Hour	V	V	V	V	V -	Day	Day	Event	Day
Hydrology	*Runoff*	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Flow Routing	●	◖	◖	◖	◖	○	○	◖	●	◖	◖	◖	◖	○	○	--
	Baseflow	●	●	●	●	●	○	○	--	●	--	--	○	●	--	--	○
Pollutant Loading	*Sediment*	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Nutrients	●	●	●	●	●	●	●	●	-	-	-	●	●	●	●	●
	Others	●	●	●	●	●	●	●	-	-	-	-	-	●	●	-	-
Pollutant Routing	*Transport*	◖	●	●	◖ [1]	●	◖	○	◖	●	●	◖	●	●	●	●	○
	Transformation	○	●	●	◖ [1]	●	-	-	-	-	-	-	-	◖	-	-	-
Operation Unit		CM/Cell	CM	CM	CM/Cell	CM	CM	CM	Cell	Cell	Field	Field	CM	HRU	CM	Cell	Wsh
Public Domain		Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Sources: LSPC (Tetra Tech 2002), WAMview (SWET 2002), WARMF (Chen et al. 1999; Chen et al. 2001;Weintraub et al. 2001), P8 UCM (Walker 1990), ANSWERS (Bouraoui et al. 1993), CASC2D (Ogden 2001), KINEROS (USDA 2003; Woolhiser et al. 1990), WEPP (Flanagan and Nearing 1995), DR3M-QUAL (Alley et al. 1982a; Alley et al. 1982b), SWAT (Neitsch et al. 2001), AnnAGNPS (AnnAGNPS 2000), AGNPS (Young et al. 1986), GWLF (Haith et al. 1992).

●High ◖Medium ○Low - Not Incorporated

1 Ongoing work links WASP with the model

V Variable simulation time step

CM = Catchment: Capable of simulating multiple watersheds and subwatersheds.

Cell = Watershed area is represented as a network of cells. Flow is routed from cell to cell.

Field = Limited to small, single simulation unit, typically a field or monitoring plot.

Wsh = Watershed: Limited to single watershed simulation.

Table B-3. Summary of BMP Models and Capabilities

Model	Types of BMP	Processes/ Mechanisms	Algorithms	Water Quality Constituents	Reference
Prince George's County BMP Module	Detention basin Infiltration practices (e.g., infiltration trench, dry well, porous pavement) Vegetative practices (e.g., wetland, swale, filter strip, bioretention)	Storage Infiltration Overflow/outlet flow Decay process Soil media pollutant removal	Storage routing Holtan's equation Weir/orifice flow First-order decay	User-defined pollutants	Prince George's County (2001)
P8 UCM	Detention basin Infiltration practices Swale/buffer strip Manhole/splitter	Storage Infiltration Overflow/outlet flow Settling/decay	Linear reservoir Green-Ampt method Second-order decay Particle removal scale factor	Sediment User-defined pollutants	Walker (1990)
VFSMOD	Vegetative filter strip	Infiltration Overland flow routing Sediment transport	Green-Ampt method Kinematic wave University of Kentucky algorithm	Sediment	Muñoz-Carpena and Parsons (2003)
DMSTA	Wetland Detention basin	Storage Seepage (in & out) Evapotranspiration Phosphorus cycle	Storage-stage CSTR in series Dynamic phosphorus cycling	Phosphorus	Kadlec and Walker (2003)
MUSIC	Detention basin Infiltration practices Vegetative practices	Storage Infiltration Decay	CSTR in series First order decay (k'-C* model)	User-defined pollutants	Wong (2002)
SWMM	Detention basin Infiltration practices	Infiltration Sedimentation First-order decay	Horton and Green-Ampt methods Camp's theory for quiescent condition and Chen for turbulence	User-defined pollutants	Huber and Dickenson (1988)
WETLAND	Detention basin Wetland	Storage Infiltration Nutrients cycling (C, N, P) Sediment deposition, resuspension, decomposition. Dissolved oxygen influx Microbial and vegetative activities (growth and death)	Water budget ET: Pan data or Thornthwaite's method Monod kinetics Constant vegetative growth rate Freundlich isotherms for P sorption/desorption First-order mineralization	Nitrogen Phosphorous Carbon DO Sediment Bacteria	Lee (1999) Lee et al. (2002)

Table B-3. (Continued)

Model	Types of BMP	Processes/ Mechanisms	Algorithms	Water Quality Constituents	Reference
VAFSWM	Detention basin Wetland	Storage Infiltration Particle settling Adsorption to plant and substrate Vegetative uptake	Water budget ET: user specified rate CSTR in series First-order kinetics (adsorption, plant uptake)	User-defined pollutants Sediment	Yu, Fitch and Earles (1998)
REMM	Vegetative buffer strip	Infiltration Evaportransporation Surface and subsurface flow routing Nutrients cycling (C, N, P) Erosion Sediment transport	Green-Ampt equation ET: modified Penman Monteith equation, and Darcy Buckingham equation Storage routing Darcy's equation Nutrient cycling: Century Model Nitrification: First-order Weir/orifice flow Erosion: USLE Sediment transport: Einstein and Bagnold equations	Sediment Nutrients (C, N, P)	SEWRL, USDA-ARS (1999)

SWMM has been applied to address various urban water quantity and quality problems in many locations in the United States and other countries (Donigian and Huber 1991; Huber 1992). In addition to its use in developing comprehensive watershed-scale planning, typical uses of SWMM include predicting CSOs, assessing the effectiveness of BMPs, and providing time series input to dynamic receiving water quality models (Donigian and Huber 1991.)

HSPF

Hydrological Simulation Program–FORTRAN (HSPF) is a comprehensive package developed by EPA for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants (Bicknell et al. 1997). This model can simulate the hydrologic and associated water quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. HSPF incorporates the Agricultural Runoff Management (ARM) model and Nonpoint Source Runoff (NPS) model into a watershed analysis framework that includes fate and transport in one-dimensional stream channels. It allows the integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions. The result of this simulation is a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a watershed.

HSPF simulates three sediment types (sand, silt, and clay) in addition to a single organic chemical and transformation products of that chemical. Further, the in-stream model assumes that the receiving waterbody is well mixed with width and depth and is thus limited to well-mixed rivers and reservoirs. The transformation and reaction processes include hydrolysis, oxidation, photolysis, biodegradation, volatilization, and sorption. Sorption is modeled as a first-order kinetic process in which the user must specify an adsorption and desorption rate and an equilibrium partition coefficient for each of the three solids types. Resuspension and settling of silts and clays (cohesive solids) are defined in terms of shear stress at the sediment water interface. The model computes the capacity of the system to transport sand at a particular flow. Settling and/or scouring are defined by the difference between the sediment load in suspension and the transport capacity.

Table B-4. Watershed Model Interface Evaluation Summary

Features	SWMM	HSPF	LSPC	WAMview	WARMF	SLAMM	P8 UCM	ANSWERS
GIS for Setup	N/A	ArcView (BASINS)	ArcView	ArcView	ArcView	N/A	N/A	GRASS
Data Management	v4: Text files v5: Database Text files	WDM	Access Text files	Database Text files	Database Text files	Text files	Text files	Database Text files
Network	v4: Table v5: Graphical	Graphical (BASINS)	Graphical	Graphical	Graphical	N/A	Table	Graphical
Interface Code	C	Avenue	VB/Avenue	Avenue	VB	VB	FORTRAN	AML
Model Code	v4: FORTRAN v5: C	FORTRAN	C++	FORTRAN, VB	FORTRAN V	B	FORTRAN	FORTRAN

Table B-5. Watershed Model Interface Evaluation Summary

Features	CASC2D	KINEROS	WEPP	DR3M-QUAL	SWAT	AnnAGNPS	AGNPS	GWLF
GIS for Setup	N/A	N/A	N/A	N/A	ArcView	ArcView	N/A	AVGWLF Tt Extension
Data Management	Text files	Text files	Access Text files	WDM Text files	dBASE Text files	Access Text files	Text files	Text files
Network	GIS Text files	Text file	N/A	Text file	GIS	GIS	Graphical	Graphical
Interface Code	N/A	N/A	VB	N/A	Avenue	VB Avenue	FORTRAN	VB Avenue
Model Code	C	FORTRAN	FORTRAN	FORTRAN	FORTRAN	FORTRAN	FORTRAN	VB

Sources: LSPC (Tetra Tech 2002), WAMview (SWET,2002), WARMF (Chen et al. 1999; Chen et al. 2001;Weintraub et al. 2001), P8 UCM (Walker 1990), ANSWERS (Bouraoui et al. 1993), CASC2D (Ogden 2001), KINEROS (USDA 2003; Woolhiser et al. 1990), WEPP (Flanagan and Nearing 1995), DR3M-QUAL (Alley et al. 1982a; Alley et al. 1982b), SWAT (Neitsch et al. 2001), AnnAGNPS (AnnAGNPS 2000), AGNPS (Young et al. 1986), GWLF (Haith et al. 1992).
BASINS–Better Assessment Science Integrating Point and Nonpoint Sources, WDM–Watershed Data Management, VB–Visual Basic, AML–ARC Macro Language, SWMM v4–Version 4.0, SWMM v5–SWMM Version 5.0.

The model has been extensively used for both screening-level and detailed analysis. The Chesapeake Bay Program used HSPF to model total watershed contributions of flow, sediment, nutrients, and associated constituents to the tidal region of the bay (Donigian et al. 1990, Donigian and Patwardhan 1992). Moore et al. (1992) describe an application to model BMP effects on a Tennessee watershed. Scheckenberger and Kennedy (1994) discuss how HSPF can be used in subwatershed planning. Donigian et al. (1996) describe the use of HSPF to identify and quantify the relative pollutant contributions from both point and nonpoint sources and to evaluate agricultural BMPs for the LeSueur Basin of southern Minnesota.

LSPC

The Loading Simulation Program in C++ (LSPC) is a watershed modeling system that includes streamlined HSPF algorithms for simulating hydrology, sediment, and general water quality on land, as well as a simplified stream transport model (Tetra Tech. and USEPA 2002). The model, based on the Mining and Data Analysis System (MDAS) methodology, was specifically developed to handle large, complex watersheds (with 1,000 or more subwatersheds) and to support TMDL development for such cases. The key advantage of LSPC is that it has no inherent limitations in terms of modeling size or model operations. In addition, the Microsoft Visual C++ programming architecture allows for seamless integration with modern-day, widely available software such as Microsoft Access and Excel.

This dynamic watershed model provides the linkage between source contributions and in-stream response. It is used to simulate watershed hydrology and pollutant generation and transport, as well as stream hydraulics and in-stream water quality. LSPC is capable of simulating flow, sediment, metals, nutrients, pesticides, and other conventional pollutants, as well as temperature for both pervious and impervious lands. The reach routing module also simulates fate and transport of these pollutants through a stream network. Table B-6 lists the HSPF modules that are currently supported in the LSPC watershed model.

In addition to LSPC's data management and programming platform features, the model was also designed with specific tools to support and assist in the development of TMDLs for areas affected by nonpoint and/or point sources. The TMDL tools allows for evaluation of land use-level and point source-level loads, evaluation of load reduction options, and comparison of baseline versus alternative scenario results.

Table B-6. HSPF Modules Supported in the LSPC Watershed Model

Simulation Type	HSPF Module	HSPF Module Description
Land-based processes	PWATER	Water budget for pervious land
	IWATER	Water budget for impervious land
	SNOW	Incorporates snowfall and snowmelt into water budget
	SEDMNT	Production and removal of sediment
	PWTGAS	Est. water temperature, dissolved gas concentrations
	IQUAL	Simple relationships with solids and water yield
	PQUAL	Simple relationships with sediment and water yield
In-stream processes	HYDR ADCALC	Hydraulic behavior, pollutant transport
	CONS	Conservative constituents
	HTRCH	Heat exchange, water temperature
	SEDTRN	Behavior of inorganic sediment
	GQUAL	Generalized quality constituent

WAMView

Watershed Assessment Model (WAM) is a GIS-based model that allows engineers and land use planners to interactively simulate and assess the environmental effects of various land use changes and associated land use practices (SWET 2002). WAM was originally developed with an Arc/Info interface for the entire Suwannee River Water Management District (SRWMD; 19,400 km^2 of northern Florida) and has since been customized for St. Johns River Water Management District (SJRWMD) in northeast Florida to accommodate its special regional and geological characteristics. The SJRWMD version includes an ArcView interface, and thus it is called WAMView. WAMView provides hourly time series of flow, TSS, and nutrients for all the contributing watersheds. The simulated hydrologic parameters include source cell surface and groundwater flow, and stream reach daily flow; simulated water quality parameters are suspended solids, sediment N, sediment P, soluble N, soluble P, BOD, bacteria, and toxics. The model provides water quality daily outputs at source cells, subbasins, and stream reaches. An effort is under way to link WAMView to the WASP model.

The water quality assessments are accomplished using two methods. The first method provides spatial assessment using impact indices, and the second uses detailed hydrologic and water quality transport modeling. The method used depends on the watershed assessment parameter of interest. The indexing approach is used for parameters that are hard to quantify and that are also directly associated with pollutant transport, while the modeling approach addresses the major pollutants of sediment and nutrients. Both approaches provide outputs at the source cell, sub-basin, and basin outlet levels. Both approaches use the watershed characteristic data from existing GIS coverage to determine the appropriate input data (indices for index approach and model parameter sets for the modeling approach). These data are used to calculate the combined impact of all watershed characteristics for a given grid cell. Once the combined impact at each unique cell within a watershed is determined, the cumulative impact for the entire watershed is determined by first attenuating the constituent to the subbasin outlets and then calculating an area-weighted ranking/index at the attenuated load generated at each cell. Constituents are attenuated based on the flow distances (overland flow route to nearest waterbody, through wetlands or depressions, and within streams to the subbasin outlet), flow rates in each related flow path, and types of wetlands or depression encountered. The contaminant transport modeling is accomplished by first simulating all the unique grid cell combinations of land use, soils, and rain zone by using a unique cell model that contains several source cell models, including GLEAMS (Knisel 1993), EAAMOD (SWET 1999), a wetland module, and an urban module. The unique cell model, also called the BUCSHELL (Basin Unique Cell Shell Program) model, operates on square grid cells with a typical size of 1 hectare (100 m x 100 m). The cell model simulates the daily flow and constituents from each unique cell within the watershed using one of the four submodels unique to WAMView, e.g., GLEAMS, EAAMOD, URBAN, and WETLAND, depending on land uses and soil. The time series outputs for each grid cell are routed and attenuated to the nearest stream and then routed through the stream using WAMView's BLASROUTE (Basin Land and Stream Routing) module. The BLASROUTE module predicts flow, stage, and water quality. It routes through a stream network with attenuation, also routes through depression and wetlands. The model uses linear reservoir flow routing, and applies attenuation based on flow rate, characteristics of flow path, and flow distance. It also allows outlet stage and concentration definition with backflow.

WAMView is limited for *SUSTAIN* because of its development and application emphasis on rural areas. However, the cell-based representation and model configuration process provide potential benefits for assessing the localized loading and spatial implications in the placement of BMPs.

WARMF

WARMF (Watershed Analysis Risk Management Framework) was developed by Systech Engineering, Inc., as a decision support system for calculating TMDLs (Chen 1999). The GIS map-based tool contains five interconnected modules: Engineering, Data, Knowledge, TMDL, and Consensus. In WARMF, a watershed is divided into a network of land catchments, stream segments, and stratified lakes. The engineering module is a dynamic watershed simulation model that calculates daily runoff, nonpoint source loads, groundwater flow, and hydrology and water quality of river segments and stratified reservoirs. The data module contains meteorological, air quality, point source, reservoir release, and flow diversion data. The nonpoint source loads are routed together with point source loads to predict water quality in rivers and lakes. The simulation models embedded in the WARMF engineering module were adapted from well-established simulation codes. The main computing engine was taken from the Integrated Lake-Watershed Acidification Study (ILWAS) model. The ILWAS model divides a watershed into land catchments, stream segments, and lake layers. Land catchments are further divided into canopy and soil layers. These watershed compartments are connected to form a network for hydrologic and water quality simulations.

The hydrologic model simulates the processes of canopy interception, snowpack accumulation and snowmelt, infiltration through soil layers, evapotranspiration from soil, exfiltration of groundwater to stream segments, kinematic wave routing of stream flows, and flow routing of reservoirs. Such detailed simulations track the flow paths of precipitation from canopy through soil layers and streams to lakes. Along each flow path, the chemistry module performs mass balance and chemical equilibrium calculations to account for the processes of dry deposition to the canopy, nitrification of ammonia on the canopy, ion leaching from sap to the canopy surface, washoff by through-fall, ion leaching by snowmelt, and the soil processes, e.g., litter fall, litter breakdown, litter decay, nitrification, denitrification, cation exchange, anion adsorption, weathering, and nutrient uptake.

The algorithms of WARMF were derived from many available codes. Algorithms for snow hydrology, groundwater hydrology, river hydrology, lake dynamics, and mass balance for acid base chemistry were based on the ILWAS model. Algorithms for erosion, deposition, resuspension, and transport of sediment were adapted and modified from ANSWERS. The pollutant accumulation on land surface was modified from SWMM. Instead of using export coefficients, an algorithm for mixing and washoff was used to simulate the processes that generate nonpoint source loading. The first-order decay of coliforms and BOD and its impact on dissolved oxygen follow the techniques used in traditional water quality models. The sediment adsorption-desorption of pesticides and phosphorus and the kinetics of nutrients and algal dynamics were adapted from WASP5.

WARMF provides step-by-step roadmaps for calculating TMDLs and for building consensus. WARMF also offers GIS-generated maps, tables, and graphing capabilities. In addition, the costs/benefits of pollutant trading, stakeholders, alternative ranking, and the nominal scores of rankings are calculated at the watershed scale. These tools can be used for management analysis at the watershed scale. Support for site-scale, land-use-specific, and subwatershed-level analyses is limited.

The major limitation of WARMF is that it is not a public domain model. WARMF is also oriented to rural land areas. The management and alternatives analysis is limited to watersheds, and simulation of multiple levels of controls by subwatershed/land use requires repeated simulation. The strength of WARMF is detailed representation of chemical processes, especially with respect to metals and pH.

SLAMM

The Source Loading and Management Model (SLAMM) was originally developed to better understand the relationships between sources of urban pollutants and runoff quality (Pitt 1993). SLAMM is strongly based on actual field observations, with minimal reliance on pure theoretical processes that have not been adequately documented or confirmed in the field. It has been continually expanded since the late 1970s and now includes a wide variety of source area and outfall control practices (infiltration practices, wet detention ponds, porous pavement, street cleaning, catch basin cleaning, and grass swales). Beginning with version 5, SLAMM is Windows-based and thus is called WinSLAMM.

The model performs continuous mass balances for particulates and dissolved pollutants and for runoff volumes. Runoff is calculated by a method developed by Pitt (1987) for small-storm hydrology. Runoff is based on rainfall minus initial abstraction, and infiltration is calculated for both impervious and pervious areas. Triangular hydrographs, parameterized by a statistical approach, are used to simulate flow. Exponential buildup and rain washoff, as well as wind removal functions, are used in computing runoff pollutant loadings. Water and sediment from various source areas are tracked as they are routed through treatment devices. SLAMM is mostly used as a planning tool to better understand sources of urban runoff pollutants and the effectiveness of their control.

SLAMM is capable of considering many stormwater controls that affect source areas, drainage systems, and outfalls, for a long series of rainfall events. The program considers how particulates filter or settle out in control devices. Particulate removal is calculated based on the structural design characteristics. Storage and overflow of devices are also considered. At the outfall locations, the characteristics of the source areas are used to determine pollutant loads in solid and dissolved phases. Another ability of SLAMM is to accurately describe a drainage area in sufficient detail for water quality investigations, but without requiring a great deal of superfluous information that field studies have shown to be of little value in accurately predicting discharge results. SLAMM also applies stochastic analysis procedures to more accurately represent actual uncertainty in model input parameters to better predict the actual range of outfall conditions (especially pollutant concentrations). Like all stormwater models, SLAMM needs to be accurately calibrated and then tested (verified) as part of any local stormwater management effort.
The major limitation of SLAMM is that it is strongly based on a statistical approach that uses the current available field observations; therefore, it is not a process-based model. Some of the key features of the model have potential for incorporation into *SUSTAIN*. For instance, the algorithms and data used for addressing source control could be applied to *SUSTAIN*.

ANSWERS

The Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) model is a comprehensive model developed to evaluate the effects of land use, management schemes, and conservation practices or structures on the quantity and quality of water from agricultural or rural watersheds (Beasley 1986). It was among the first generation of distributed watershed models, which allow for a better analysis of spatial as well as temporal variabilities of pollutant sources and loads. It was initially developed on a storm event basis to enhance the physical description of erosion and sediment transport processes in agricultural watersheds. Data preparation for ANSWERS is rather complex, especially when watersheds are large. The output routines, however, are quite flexible and results are available in several tabular and graphical forms. The program has been used to evaluate management practices for agricultural watersheds and construction sites primarily in Indiana. It has been combined with extensive monitoring programs to evaluate the relative importance of point and nonpoint source contributions to Saginaw Bay in Michigan. This application involved the computation of unit area loadings under different land use scenarios for evaluation of the tradeoffs between load allocations (LAs) and wasteload allocations (WLAs). Recent model revisions include improvements to the nutrient transport and transformation subroutines (Dillaha et al. 1988). Bouraoui et al. (1993) describe the development of a continuous simulation version of the model.

The main limitation of ANSWERS is its emphasis on erosion and sediment transport in rural areas, which are not tested for primarily urban areas.

CASC2D

The Cascade 2 Dimensional (CASC2D) sediment model is a fully unsteady, physically based, distributed-parameter, square-grid, two-dimensional, infiltration-excess (Hortonian) hydrologic model for simulating the response of a watershed subject to rainfall (Ogden 2001). Major processes simulated include continuous soil-moisture accounting, rainfall interception, infiltration, surface and channel runoff routing, soil erosion, and sediment transport. Raster (square grid) is the computational unit. CAS2D allows the user to select a grid size (typically 30–200 m) that appropriately describes the spatial variability in all watershed characteristics. CASC2D is physically based and solves the equations of conservation of mass and energy to determine the timing and path of runoff in the watershed. CAS2D applies Green and Ampt with or without a redistribution method for infiltration simulation; an explicit finite-difference, two-dimensional, diffusive-wave method for overland flow routing; and options of explicit one-dimensional, diffusive-wave or implicit dynamic-wave channel routing. The empirical Kilinc and Richardson (1973) soil erosion model as modified by Julien (1995) is applied in CASC2D to determine the sediment transport from one overland flow grid cell to the next. CASC2D employs Yangs' (1973) method to routing sand-size sediment in stream channels. Silt and clay size sediment are assumed to be transported with flow; deposition or erosion of silt and clay within the channels is neglected (Ogden 1998). The physically based distributed model is superior in simulation of runoff process at small scales within the watershed. As a spatially distributed model, CASC2D offers the capability of determining the value of any hydrologic variable at any grid point in the watershed at the expense of requiring significantly more input than traditional approaches. CASC2D can accept spatially varied hydrologic parameter input or rainfall input; however, because of the extensive data amounts required, data uncertainty may result in a non-unique calibration.

CASC2D development was initiated in 1989 at the Center for Excellence in Geosciences at Colorado State University funded by the United States Army Research Office (ARO). The original version of CASC2D has been significantly enhanced under funding from ARO and the U.S. Army Corps of Engineers Waterways Experiment Station (USACEWES). USACEWES has selected CASC2D as its premier two-dimensional surface water hydrologic model. CASC2D is also one of the surface-water hydrologic models supported by the Watershed Modeling System (WMS), developed at Brigham Young University. The GRASS GIS developed by the U.S. Army Construction Engineering Research Laboratories can be used in the preparation of CASC2D data sets.

The limitations of CASC2D are as follows:

- CASC2D is a fully distributed, physically based, state-of-the-art hydrologic model, but with the exception of sediment, it does not have an integrated water quality component
- Because the program uses a distributed scheme and physically based algorithms, application requires extensive input data preparation and calibration

KINEROS

The Kinematic Runoff and Erosion (KINEROS) model is an event-oriented, physically based model that describes the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds (USDA 2003). The model represents a watershed by a sequence of planes and channels and solves the partial differential equations describing overland flow, channel flow, erosion, and sediment transport by using finite-difference techniques. The spatial variations of rainfall, infiltration, runoff, and erosion parameters can be accommodated. KINEROS can be used to determine the effects of various artificial features, such as urban developments, small detention reservoirs, or lined channels on flood hydrographs and sediment yield. This model is suitable for small agricultural and disturbed urban watersheds.

The following are the limitations of KINEROS:

- It is an event-based model
- It is primarily designed for small agricultural and disturbed urban areas

- It simulates only sediment

WEPP

Developed by the U.S. Department of Agriculture's (USDA) Agricultural Research Service (ARS), the Water Erosion Prediction Project (WEPP) model is a distributed-parameter, continuous-simulation model developed to provide a new generation of soil erosion prediction technology (USDA NSERL 1995). The model requires inputs for rainfall amounts and intensity; soil textural qualities; plant growth parameters; residue decomposition parameters; effects of tillage implements on soil properties and residue amounts; slope shape, steepness, and orientation; and soil erodibility parameters. Parameters used for predicting erosion, including soil roughness, surface residue cover, canopy height, canopy cover, and soil moisture, are updated daily. The basic output from WEPP consists of runoff and erosion summary information, which can be produced on a storm-by-storm, monthly, annual, or average annual basis. The model output files contain time-integrated estimates of runoff, erosion, sediment delivery, and sediment enrichment, as well as the spatial distribution of erosion.

The limitations of WEPP are as follows:

- The emphasis of this model is on erosion and sediment simulation from pervious land areas; therefore, it has limited applicability for evaluation of urban areas with significant impervious areas
- The model simulates only sediment

SWAT

SWAT is a continuous-time, physically based river basin or watershed-scale model developed by the USDA's ARS (USDA ARS, SWAT Web site) for agricultural watersheds. SWAT was developed to predict the impact of agricultural land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soil, land use, and management conditions over long periods of time using readily available inputs. The major components of SWAT are hydrology, weather, erosion, soil temperature, crop growth, nutrients, pesticides, and agriculture management. A flow routing component transports flow and loading from each subwatershed across subsequent watersheds and allows for accumulation of subwatershed contributions. Model inputs are based on geographic units comprising unique land use and soil characteristics. The SWAT inputs include land use, land use practice, soil, climate, elevation and slope, stream network and morphology, water uses, and point sources. The SWAT outputs include total nitrogen, phosphorus, and sediment loads from each subwatershed and stream segment. SWAT accounts for sediment contributions from overland runoff through the Modified Universal Soil Loss Equation (MUSLE), which provides increased accuracy, compared with the original USLE method, when predicting sediment transport and yield. The model is capable of simulating long time periods (over 100 years) while retaining its computational efficiency, and it can link sediment contributions to specific source areas (i.e. subwatershed and/or land use areas). Importantly, SWAT allows for the application of specific agricultural management measures to geographic units. Management measures that can be applied to model units include varying planting and harvest patterns, fertilization practices, and quality of manure nutrient content (via livestock feed).

The following are limitations of SWAT:

- The model is not suitable for urban land uses
- The model runs at a daily time step, and is not suitable for fast-responding urban drainage

AnnAGNPS

The Annualized Agricultural Nonpoint Source Pollution (AnnAGNPS) model is a batch-process, continuous-simulation, pollutant loading computer model written in standard FORTRAN 95 (AnnAGNPS 2000). The model is capable of simulating (1) water; (2) sediment by particle size class and source of erosion; and (3) chemicals (nitrogen, phosphorus, organic carbon, and pesticides). Pollutant loadings are generated from land areas (cells) and routed through stream systems on a daily basis. The rainfall-runoff process is simulated using the Curve Number method, and sediment erosion is simulated using the USLE method. The model simulates and tracks nutrients in both particulate form (combined with sediment) and dissolved form. Special land use components such as feedlots, gullies, field ponds, and point sources are included.

The following are limitations of AnnAGNPS:

- It is not suitable for urban watersheds
- It uses a daily time step
- The model applies empirical methods for rainfall-runoff and water quality simulations that are not robust enough to handle shorter response processes

Single-Event AGNPS

Developed by the USDA's ARS, the Agricultural Nonpoint Source Pollution (AGNPS) model addresses concerns related to the potential impacts of point and nonpoint source pollution on water quality (Young et al. 1986). It was designed to quantitatively estimate pollution loads from agricultural watersheds and to assess the relative effects of alternative management programs. The model simulates surface water runoff along with nutrient and sediment constituents associated with agricultural nonpoint sources, as well as point sources such as feedlots, wastewater treatment plants, and stream bank or gully erosion. The rainfall-runoff process is simulated using the Curve Number method, and sediment erosion is simulated using the USLE method. Single-event AGNPS simulates and tracks nutrients in both particulate form (combined with sediment) and dissolved form. The available version of the model is event-based. The structure of the model consists of a square-grid-cell system to represent the spatial distribution of watershed properties. This grid system allows the model to be connected to other software such as GIS and DEMs. This connectivity can facilitate the development of a number of the model's input parameters.

The Single-Event AGNPS has the following limitations:

- It is not suitable for urban land uses
- The version currently available is event-based
- The model applies empirical methods for rainfall-runoff and water quality simulations that are not robust enough to handle shorter response processes

GWLF

The Generalized Watershed Loading Function (GWLF) model was developed at Cornell University to assess the point and nonpoint source loading of nitrogen and phosphorus from urban and agricultural watersheds, including septic systems, and to evaluate the effectiveness of certain land use management practices (Haith et al. 1992). One advantage of this model is that it was written with the express purpose of requiring no calibration, making extensive use of default parameters. The GWLF model includes rainfall/runoff and erosion and sediment generation components, as well as total and dissolved nitrogen and phosphorus loadings. The rainfall-runoff process is simulated using the Curve Number method, and sediment erosion is simulated using the USLE method. It simulates and tracks nutrients in both particulate form (combined with sediment) and dissolved form. The model uses daily time steps and allows analysis of annual and seasonal time series. The model also uses simple transport routing, based on the delivery ratio concept. In addition, the simulation results can be used to identify and rank pollution sources and evaluate basin-wide management programs and land use changes.

The limitations for application of GWLF to urban areas are as follows:

- It uses a daily time step
- The algorithms applied for hydrologic and water quality simulations are empirical, not process-based, approaches
- It is a lumped single-watershed model that cannot represent a stream network

B.3.2. BMP Model Reviews

The following BMP models were evaluated as the candidate models to be incorporated into *SUSTAIN*.

Prince George's County BMP Module

The Prince George's County Department of Environmental Resources, Programs and Planning Division, working with Tetra Tech, Inc., has developed a BMP evaluation module to assist in assessing the effectiveness of BMP/Low Impact Development (LID) technology (Cheng 2002). This module uses simplified process-based algorithms to simulate BMP control of either observed time series or modeled flow and water-quality time series generated from runoff models such as HSPF. The design and evaluation methodology for the BMP Module has five basic aspects: (1) the incorporation of input runoff data, (2) design and representation of a site plan, (3) configuration of BMPs of various sizes and functions, (4) schematic representation of flow routing through a network of BMPs, and (5) evaluation of the impact of the site design and BMP configurations on hydrology and water quality. The module platform provides interactive linkages between the first four design aspects. The BMP module's assessment post-processor offers a series of evaluation methods for measuring the impact of the design and BMP configurations on hydrology and water quality.

Under this methodology, two generalized conceptual models were developed to characterize the function of a wide range of BMPs. These models have been categorized in the module as Class A and Class B BMPs. Class A BMPs are those that retain water for some duration of time and have some means for controlling outflow. Examples of Class A BMPs are stormwater detention and retention ponds or reservoirs, catch basins, and bioretention cells. Class B BMPs are open channels whose stormwater control is a function of the shape and channel characteristics. Examples of Class B BMPs are grass swales and stream buffers zones. The physical processes represented in the BMP Module include evapotranspiration and infiltration (using the Holtan-Lopez empirical infiltration equation), orifice outflow (standard orifice equation), underdrain outflow, weir-controlled overflow or spillway (using weir equations for sharp-crested rectangular and v-notch triangular options), BMP bottom slope and bottom roughness (Manning's equation for open channel flow), underdrain filtration of pollutant, and general loss or decay of pollutant (first-order loss equation). In addition to the physical design and placement of BMP structures, the module offers the user the flexibility to define flow routing through a BMP or BMP network; simulate Improved Management Practices (IMPs), such as reduced or discontinued imperviousness through flow networking; and compare BMP controls against some defined benchmark, such as a simulated predevelopment condition. Because the underlying algorithms are based on physical processes, BMP effectiveness can be evaluated and estimated over a wide range of storm conditions, BMP designs, and flow routing configurations.

SWMM BMP Simulation Capabilities

The SWMM (version 4.4h and previous versions) is divided into four primary computational *blocks* or *modules*. They include:

- Runoff (converting rainfall to runoff and generate nonpoint source runoff water quality time series)
- Transport (kinematic wave flow routing and water quality routing through conveyance and storage, applying first-order decay)
- EXTRAN (performing dynamic wave flow routing)
- Storage/treatment (simulating treatment and storage devices, applying storage routing, first-order decay, and Camp's (1946) sedimentation theory to up to five settling velocity ranges)

The SWMM simulation of major BMP processes (storage, infiltration, first-order decay, and sediment settling) is achieved by using one or a combination of the four blocks. The Storage/Treatment Block offers the most flexibility in terms of simulating conventional stormwater treatment devices (e.g., ponds and swales). The overland flow rerouting (land-to-land routing) options in the Runoff Block can be used to mimic the parcel (individual lot)-level LID sites.

P8 UCM

The Program for Predicting Polluting Particles Passage through Pits, Puddles, and Ponds, Urban Catchment Model (P8 UCM), is used to model generation and transport of stormwater runoff pollutants in an urban setting (Walker 1990). Calculations are performed on continuous water balances and mass balances using hourly rainfall and daily air temperature time series. Primary applications of this model are the evaluation of BMP site plans for compliance with treatment objectives expressed in terms of removal efficiency for TSS. Secondary (and less accurate) predictions from this model are runoff quality, loads, violation frequencies, water quality impacts due to proposed development, and loads generated for driving receiving water quality models (Walker 1990). The model can simulate a variety of treatment devices (BMPs), including swales, buffer strips, detention ponds (dry, wet, extended), flow splitters, and infiltration basins. Methods applied in P8 include quasi-linear reservoir storage routing, Green-Ampt infiltration equation, second-order reactions, and particle removal by use of a scale factor. Compared with other models, second-order reaction simulation is a unique feature of P8; however, the lack of parameter estimates for the second-order decay coefficient in the model and literature limits the usefulness of such a method.

VFSMOD (Vegetative Filter Strip Model)

Vegetative Filter Strip Model (VFSMOD) is a field-scale, mechanistic, storm-based model designed to route the incoming hydrograph and sedimentograph from an adjacent field through a vegetative filter strip (VFS) and to calculate the outflow, infiltration, and sediment trapping efficiency (MuℑOz-Carpena and Parsons 2003). The model handles time-dependent hyetographs, space-distributed filter parameters (vegetation roughness or density, slope, infiltration characteristics), and different particle sizes in the incoming sediment. VFSMOD consists of a series of modules simulating the behavior of water and sediment in the surface of the VFS. The current modules available are shown in Table B-1 and summarized below:

- Green-Ampt infiltration module: A module for calculating the water balance in the soil surface
- Kinematic wave overland flow module: A one-dimensional module for calculating flow depth and rates on the infiltrating soil surface

- Sediment filtration module: A module for simulating transport and deposition of the incoming sediment along the VFS

VFSMOD is essentially a one-dimensional model for the description of water transport and sediment deposition along the VFS. The model can also be used to describe transport at the field scale (or field edge) if flow and transport are mainly in the form of sheet flow (Hortonian) and the one-dimensional path represents average conditions (field effective values) across the VFS.

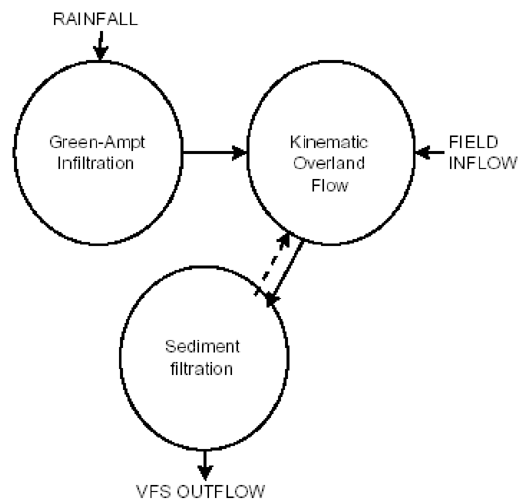

Figure B-1. Schematic representation of VFSMOD.

VFSMOD uses a variable time step, chosen to limit mass-balance errors induced by solving the overland water flow equation. The kinematic wave model selects the time step for the simulation, to satisfy convergence and computational criteria for the finite element method, (Muñoz-Carpena et al. 1993a, 1993b). The model inputs are specified on a storm basis. The model integrates the state variables after each event to generate storm outputs.

MUSIC

The Model for Urban Stormwater Improvement Conceptualization (MUSIC) was developed by the Cooperative Research Center (CRC) for Catchment Hydrology in Australia (Wong 2002). MUSIC is designed to simulate urban stormwater systems operating at a range of temporal and spatial scales: catchments from 0.01 km^2 to 100 km^2 and modeling time steps ranging from 6 minutes to 24 hours to match the catchment's scale. MUSIC provides a user-friendly interface to allow complex stormwater management scenarios to be quickly and efficiently created and the results to be viewed using a range of graphical and tabular formats. The stormwater control devices that can be simulated in MUSIC include ponds, bioretention, infiltration buffer strips, sedimentation basins, pollutant traps, wetlands, and swales. Major algorithms applied in BMP simulation are a continually stirred reactors (CSTRs) in series model and a first-order decay (k-C*) model (see Section 3.3 of main report).

LIFE

The Low Impact Feasibility Evaluation (LIFE) model is a continuous-simulation, physically based model that simulates the hydrologic and hydraulic processes that take place in bioretention facilities, vegetated swales, green roofs, and infiltration devices, as well as the effects of site fingerprinting and soil compaction (Medina et al. 2003). The model also simulates runoff generation from all categories of land cover, including roadways, landscaping, and buildings, over a variety of land uses and soil types. The

LIFE model is a visually oriented, interactive tool developed on an Extend^{TM} dynamic simulation platform. The LIFE model is a proprietary model and its modeling details are not available for review.

IDEAL

The Integrated Design and Evaluation Assessment of Loadings (IDEAL) model is a spreadsheet model for assessing the impact of BMPs in urban areas on discharge of water, sediment, nutrients, and bacteria into streams (Barfield 2002). The model predicts effluent loads and concentrations of the above elements coming from the watershed as impacted by vegetative filter strips, dry detention ponds, and wet detention ponds. The IDEAL model is capable of estimating the runoff and pollutant loadings from urban areas, categorized into pervious, impervious connected, and impervious unconnected areas. Flows and loadings are summed and then directed to a pond that can be dry (no permanent pool) or wet (permanent pool). The model routes these loadings through BMPs to determine pollutants removal efficiencies using empirical technologies that have been experimentally validated. The model predicts single storm values and converts them to average annual storm values using stochastic procedures. The IDEAL model is designed to estimate BMP long-term pollutant removal efficiencies and is not intended to be used to give accurate estimation on a storm event basis.

DMSTA (Dynamic Model for Stormwater Treatment Area) Model

DMSTA simulates daily water and mass balances in a user-defined series of wetland treatment cells, each with specified morphometry, hydraulics, and phosphorus cycling parameters (Kadlec and Walker 2003). Up to six treatment cells can be linked in series and/or parallel to reflect compartmentalization and management to promote specific vegetation types. Each cell is further divided into a series of CSTRs to reflect residence time distribution. Water-balance terms for each cell include inflow, bypass, rainfall, evapotransportation, outflow, seepage in, and seepage out. Parameter estimates for the phosphorus cycling model have been developed for various vegetation types. Water column storage, solid (biomass, sorption) storage, uptake, recycle, and permanent burial processes are considered in dynamic phosphorus cycling simulation. The model is coded in Visual Basic for Applications and the user interface is a Microsoft Excel workbook.

WETLAND

The WETLAND model is a dynamic compartmental model to simulate hydrologic, water quality and biological processes, and to assist the design and evaluation of wetland. The WETLAND model adopted the continuous stirred-tank reactor (CSTR) prototype, and it is assumed that all incoming nutrients are completely mixed throughout the entire volume. The model can simulate both free-water surface (FWS) and subsurface flow (SSF) wetlands. The WETLAND model is constructed in a modular manner, and it includes hydrologic, nitrogen, carbon, dissolved oxygen, bacteria, sediment, vegetation, and phosphorous submodels. The hydrologic submodel uses a vertical dynamic water budget approach to calculate surface storage, and carries out the computation at hourly time step. The factors considered in the hydrologic model include inflow, precipitation, infiltration, and evapotranspiration. The Nitrogen submodel simulates ammonification, immobilization, nitrification, denitrification, and peat accumulation, and inclusion of NH_3 volatilization, atmospheric deposition and N fixation in the modeling of overall N cycle is optional. Sorption of NH_4^+ to the soil and organic matter is not modeled because it is assumed that sorbed NH_4^+ is still available to the attached microbes. The carbon model includes five variables: biomass C, standing dead C, particulate organic C, dissolved organic C, and refractory C; The standing dead C and biomass C is connected to the vegetation submodel. The dissolved oxygen submodel track the oxygen influx from incoming stream flow, precipitation, reaeration from atmosphere, point sources, and biomass flux. In addition, oxygen is assumed to be passed from vegetation stand to wetland bottom at a constant rate during the growing season. The bacteria submodel accounts for all the microbial growth and activity in the model. Both autotrophic and heterotrophic bacteria are modeled. Sedimentation is modeled in the sediment sub-model. The processes simulated include inflow, outflow, deposition, resuspension, and decomposition. Up to five different sediment classifications can be modeled. A simple vegetation submodel is included to simulate the biomass growth and death. The phosphorous submodel considers four pools for the P cycle: particulate and dissolved for both the surface and bottom layer of the wetland. Processes modeled in the phosphorous model include mineralization and additions from biomass decomposition. Besides the hydrologic submodel, all the other submodels compute using daily time step.

The strength of the WETLAND model lies on the linked Monod kinetics for the water quality variables, also the model accounts for the seasonal variation by allowing users to change parameter values for different season/time period. The weaknesses of this model include the completely mixed assumption, which overlook the effect of the system shape, and the needs for extensive kinetic parameters.

VAFSWM

The Virginia Field Scale Wetland Model (VAFSWM) is a field scale model for quantifying the pollutant removal in a wetland system. It includes a hydrologic subroutine to route flow through the treatment system; Precipitation, evapotranspiration, and exchange with subsurface groundwater are considered in the hydrologic balance. The model adopted a continuous stir tank system in series schema. VAFSWM models mechanisms of settling, diffusion, adsorption to plants and substrate, and vegetative uptake for a pollutant in dissolved and particulate forms in a two segment (water column and substrate), two state (completely mixed and quiescent) reactor system by employing first-order kinetics. The governing equations for quiescent condition are identical to that of turbulent condition, however far lower settling velocities are assumed to account for the greater percentage of finer particles during the quiescent state.

The VAFSWM is a relatively simple model that includes the most dominant processes within the wetland system. However, the users need to provide and calibrate the requisite kinetics parameters.

REMM

Riparian Ecosystem Management Model (REMM) has been developed as a tool that can help quantify the water quality benefits of riparian buffers. REMM simulates the movement of surface and subsurface water movement, sediment transport and deposition, nutrients transport, sequestration, and cycling, as well as vegetative growth in riparian forest systems on a daily time step. In REMM, the riparian system is considered to consist of three zones between the field and the water body. Each zone includes litter and three soil layers, and a plant community that can have six plant types in two canopy levels. REMM can be used to quantify nitrogen and phosphorous trapping in riparian buffer zone, determine buffer effectiveness, investigate long-term fate of nutrients in buffer zones and, evaluate influence of vegetation type on buffer effectiveness, and determine impacts of harvesting on buffer effectiveness.

The strength of REMM is its capability of simulating subsurface compartment, and the comprehensive nutrients cycling. Comes with the complexity, one disadvantage of the model is the extensive data requirement. REMM is still under development and has been continuously updated. Currently, a user interface is being built to assist input and output data management.

B.3.3. Modeling System Reviews

Several systems have been developed that include multiple models and software systems to facilitate data storage, data preparation, model input file development, model application and linkages, and output post-processing. These comprehensive systems have the potential for integration or communication with *SUSTAIN*. As these systems continue to evolve, *SUSTAIN* will consider options to preserve compatibility with these systems.

BASINS

Better Assessment Science Integrating point and Nonpoint Sources (BASINS), developed by EPA, is a multipurpose environmental analysis system for use by regional, state, and local agencies in performing watershed and water quality based studies (USEPA 2001). BASINS has three major objectives: (1) to facilitate examination of environmental information, (2) to support analysis of environmental systems, and (3) to provide a framework for examining management alternatives.

BASINS integrates a GIS, national watershed and meteorological data, and state-of-the-art environmental assessment and modeling tools into one convenient package. Originally released in 1996, with a second release in 1998, a third in 2001, and a fourth in 2004, BASINS comprises a suite of interrelated components. The current version is BASINS 4.0.

In a departure from previous versions, BASINS 4.0 databases and assessment tools run on a non-proprietary, open source GIS system architecture (MapWindow). Its components work together to support the user in performing various aspects of environmental analysis. The components include (1) nationally derived databases with Data Extraction and Project Builder tools; (2) assessment tools (TARGET, ASSESS, and Data Mining) that address large- and small-scale characterization needs; (3) utilities to facilitate importing local data and to organize and evaluate data; (4) Watershed Delineation tools; (5) utilities for classifying elevation (DEM), land use, soils, and water quality data; (6)Watershed Characterization Reports that facilitate compilation and output of information on selected watersheds; (7) an in-stream water quality model; (8) two watershed loading and transport models; and (9) a simplified GIS-based, nonpoint annual loading model. Installed on a personal computer, BASINS allows the user to assess water quality at selected stream sites or throughout an entire watershed. The software makes it possible to quickly assess large amounts of point source and nonpoint source data in a format that is easy to use and understand, as well as to prepare and set up watershed and in-stream transport models to facilitate the TMDL analysis for waterbodies of concern.

A limitation of the current BASINS configuration is that data currently housed in the BASINS system is typically too general to support detailed urban analysis. The system data would need be updated with local data to facilitate application and provide higher resolution analysis necessary for *SUSTAIN*. For more information, see the BASINS Web site (see http://www.epa.gov/waterscience/basins/).

EPA TMDL Modeling Toolbox

The TMDL Modeling Toolbox is a collection of models, modeling tools, and databases that have been widely applied over the past decade in the development of TMDLs. The Toolbox takes those proven technologies and provides the capability to more readily apply the models, analyze the results, and integrate watershed loading models with receiving water applications (USEPA 2003). The design of the Toolbox is such that each of the models is a standalone application. The Toolbox provides an exchange of information between the models through common linkages. The modular design of the Toolbox allows for additional models to be easily incorporated and integrated with the other tools. In addition, the Toolbox provides the capability to visualize model results, a linkage to GIS and nongeographic databases (including monitoring data for calibration), and the functionality to perform data assessments.

The Toolbox allows for the steady-state/dynamic simulation of mass transport and water quality processes in all types of surface water environments, including overland flow, small creeks, rivers, lakes, estuaries, coastal embayments, and offshore areas. The Toolbox contains assessment tools, watershed models, and receiving water models, including the following:

Assessment Tools

- Water Resources Database (WRDB)

- Watershed Characterization System (WCS)
- WCS Sediment Tool
- WCS Mercury Tool
- WCS LSPC Tool

Watershed Models

- Loading Simulation Program in C++ (LSPC)
- Watershed Assessment Model (WAMView)
- Stormwater Management Model (SWMM)

Receiving Water Models

- A Dynamic, One-Dimensional Model of Hydrodynamics and Water Quality (EPDRiv1)
- Stream Water Quality Model (QUAL2K)
- CONservational Channel Evolution and Pollutant Transport System (CONCEPTS)
- Environmental Fluid Dynamics Code (EFDC)
- Water Quality Analysis Simulation Program (WASP)

The Toolbox has a wide variety of included models and open architecture that facilitates linkages and flexibility in application. A limitation of the system is the lack of specific models and tools for simulating BMPs. Although LSPC and WAMView can be used to simulate BMPs, the systems do not include detailed, process-based simulation capabilities or convenient tools to quickly set up and evaluate alternative BMP management alternatives.

B.4. Discussion and Results of Model Review

A review was conducted of available models such as SWMM (Huber and Dickinson 1988; Huber 2001), HSPF (Bicknell et al. 1993), and SLAMM (Pitt and Voorhees 2000), as well as publicly available modeling systems, such as BASINS (USEPA 2001) and the TMDL Modeling Toolbox (Tetra Tech and USEPA 2002). Based on this review, there is no single system or model with the flexibility and capability to incorporate all the technical needs listed below for the *SUSTAIN* development.

- Ability to simulate hydrologic response and a level of detail sufficient for analysis of a hydrograph (peak flow and volume)
- Ability to simulate multiple pollutant types, including nutrients (nitrogen and phosphorus), pathogens [fecal coliform bacteria, *Escherichia coli (E.Coli*)] and metals (zinc, aluminum, etc.)
- Ability to simulate fate and transport of pollutants and evaluate both acute and chronic impacts
- Ability to generate sediment loading to streams
- Ability to simulate sediment transport in streams
- Ability to simulate multiple size classes of sediment for input to management structures
- Ability to simulate other habitat stressors, such as temperature
- Ability to simulate in-stream dissolved oxygen based on inputs of biological oxygen demand, sediment oxygen demand, nutrient loads, and other environmental factors
- Ability to evaluate urban and mixed land uses, including pervious and impervious areas

- Consideration of short and long time periods (single- and multiple-event simulation)
- Consideration of a full range of management practices at a similar level of spatial resolution
- Consideration of distributed or small-scale management practices and larger downstream facilities
- Consideration of a series of management practices at various locations in the watershed
- Modeling of management practices on a time-variable basis consistent with the need to evaluate hydrology and pollutant measures
- Ability to consider placement of management practices at any location in the watershed (e.g., at various distances from waterbodies, at various stream orders)
- Ability to link watershed management to downstream measures of environmental condition (e.g., dissolved oxygen in a river, nutrient concentration in a lake or estuary) outside the immediate vicinity of a selected study area

However, many models can provide portions of the needed features and algorithms. Comparison of the available models and the technical needs supports selection of a subset of models for further consideration, and their potential incorporation in *SUSTAIN* is organized according to the key components identified in the preliminary design discussion. Table B-7 summarizes the strengths and weaknesses of the selected watershed models in light of the *SUSTAIN* design requirements. Presented below is a process-focused summary discussion of the models that supports the landscape and BMP model selection.

B.4.1. Watershed Models

The selection of watershed models for integration into *SUSTAIN* are discussed separately for hydrology, sediment, pollutant loadings, and reach routing.

Hydrology

Several watershed models, including SWMM, SLAMM, HSPF, and LSPC, can provide time series hydrology and pollutant loading at an hourly time step or less. This short temporal resolution is needed to address small catchments and to provide concentration and load predictions and time series inputs to management practices. This temporal resolution is necessary for the flexibility to predict the range of hydrologic and water quality measures identified in the needs analysis. Some models, such as SWAT (Neitsch et al. 2001), AnnAGNPS (AnnAGNPS 2000), AGNPS (Young et al. 1986), and GWLF (Haith et al. 1992), are inappropriate because they use large time steps (1 day or greater) or insufficient description of time-variable rainfall-runoff processes. Other models, such as CASC2D and KINEROS, use a grid-based framework for distributed modeling of the watershed landscape. The grid-based formulation has benefits for detailed simulation and sensitivity to the placement of management within the landscape. However, its greatest limitations are high computational needs for larger watersheds and the availability of spatially detailed data. The spatial detail can significantly increase the data preparation and setup time for the model. Currently, CASC2D and KINEROS do not include water quality simulation capabilities. Further evaluation is needed to determine whether cell- or grid-based modeling components can be incorporated into *SUSTAIN*. The initial recommendation is to use pervious and impervious land simulation routines from SWMM, HSPF, and/or LSPC.

Sediment

The HSPF and LSPC watershed models use a sophisticated process-based system to describe sediment simulation for pervious areas and buildup/washoff for impervious areas. For pervious segments, sediment is represented as a direct function of the rainfall intensity. The rainfall intensity determines the rate and volume of material detached from an infinite soil matrix, while the scouring process determines the washoff and delivery of sediment to a stream segment. Scour can be used to represent gully erosion. Because this process is energy-driven, the calibration changes with the time step and resolution of the rainfall data driving the system. For impervious land surfaces, both HSPF/LSPC and SWMM use similar approaches to simulate buildup and washoff of solids on the land surface. HSPF and SWMM allow the user to apply special actions, such as street sweeping during the simulation, to assess the impact of such a management activity on the overall delivery of solids from urban streets. SWMM allows three ways for estimating sediment in runoff: (1) a rating curve, (2) a buildup and washoff approach, or (3) the USLE for pervious surfaces.

If the methods described above are compared with another popular sediment estimation method such as USLE (which is used by many of the models described in Section A.3), some limitations, in light of the project requirements, are evident. The parameters feeding the USLE equation are based on long-term assessments, and the results, though meaningful as a monthly or annualized loading estimate, fail to adequately represent the detailed variability of individual storms or storms in series. In conclusion, short/variable time step methods, such as those available in HSPF and LSPC for pervious areas and in SWMM, HSPF, and LSPC for impervious areas, are better suited to satisfy the assessment objectives outlined for *SUSTAIN*.

Pollutant Loading

Among the shorter/variable-time-step simulation models like SWMM, HSPF, and LSPC, buildup and washoff of pollutants on a land surface is often used as the primary process for generating pollutant loadings. In HSPF and LSPC, pollutants can also be represented as sediment-associated; therefore, some of the pollutant mass will be considered as a fraction of the simulated sediment delivery. Base flow and interflow concentrations in HSPF and LSPC are specified as constants, or they can be expressed as monthly variable concentrations. SWMM does not allow for a variable buildup rate; however, it allows the user to specify the equation and method used (power-linear, exponential, or Michaelis-Menton). As with sediment, SWMM allows for pollutants to be specified as a function of the flow rating curve or by using buildup and washoff. Pollutants can also be associated with sediment by expressing the mass as a fraction of sediment. Simpler models, such as GWLF and P8, use a fixed concentration of a pollutant in runoff and sediment, making them insensitive to changes in concentration or availability of pollutants over time. These models also use daily or monthly time steps, and they cannot support the evaluation of short-duration loading and impacts on stream systems. For pollutant loading, HSPF, LSPC, and SWMM include the preferred techniques for integration into the *SUSTAIN* design.

Reach Routing

Landscape output must also be collected and routed via flow networks (channels and streams). Many watershed models, including SWMM and HSPF, include stream routing modules. These routing techniques, which involve some simulation of in-stream transport and pollutant transformation processes, are sufficient for smaller streams with relatively short conveyance times (less than 1 day). Urban streams typically have short retention times and limited opportunity for biological and chemical processes to result in significant transformation of pollutants. Of the reviewed models, HSPF and LSPC reach routing have the most detailed simulation capabilities for sediment and pollutant transport including sediment deposition, scour, decay, and dynamic temperature simulation. SWMM’s transport functions include first-order decay and settling but do not include an option for temperature, biological transformation, or algal growth. SWMM can simulate complex hydraulics using a fully dynamic wave method. For areas with large, longer-retention-time river systems or tidally influenced systems, an external linkage (outside *SUSTAIN*) can provide the ability to evaluate downstream impacts. Linkage with specialized receiving water models, such as EFDC (Hamrick 1992) and WASP 6.0 (Wool et al. 2003), ultimately can be used to consider the impacts of urban stormwater runoff on larger, more complex waterbodies. Specialized receiving water models like WASP (Wool et al. 2003) are also best suited for evaluating eutrophication processes and dissolved oxygen.

Table B-7. Strengths and Weaknesses of Major Watershed Models

Model	Strengths	Weaknesses
SWMM	The best available public domain model for simulation of sewer systems hydraulics: Fully dynamic hydraulic routing Hydraulic structure (manhole, weir, orifice, etc.) simulation Overland flow routing between pervious and impervious areas within a subcatchment Various options for quality simulation: buildup and washoff, rating curves, and regression techniques Offers base flow simulation Performs continuous simulation using variable time step	Considers only settling and first-order decay in in-stream pollutant routing and transformation
HSPF	Comprehensive simulation of watershed hydrology and associated water quality processes on pervious and impervious land surfaces Capable of simulating the in-stream transfer and reaction processes, including hydrolysis, oxidation, photolysis, biodegradation, volatilization, sorption, and resuspension and settling of cohesive and noncohesive solids Performs land-to-land routing Offers base flow and interflow simulation Performs continuous simulation using variable time step	Does not perform fully dynamic hydraulic flow routing
LSPC	Includes a streamlined set of HSPF subroutines and algorithms Simulation of watershed hydrology, and associated water quality, processes on pervious and impervious land surfaces No inherent limit to the size and scale of watershed modeling Generalized in-stream water quality simulation, as well as sediment associated land and in-stream processes Performs continuous simulation using variable time step	Does not perform fully dynamic hydraulic flow routing
WAMView	Grid based model with cell size down to 0.1 ha Offers dynamic channel routing and allows outlet stage and concentration definition with backflow. Simulates wetland and depressions in the channel Output overland, wetland, and stream load attenuation mapped back to source cells	Source code and detailed documentation is not available Does not perform land to land routing
CASC2D	Fully unsteady physically based distributed watershed model at a user-specified resolution Offers fully dynamic hydraulic channel routing Uses diffusive wave method to route overland flow Performs continuous simulation using variable time step	Only simulate sediment, not other water quality constituents Does not simulate subsurface flow Fully physically based distributed model; therefore, its application requires extensive input data preparation and calibration Not suitable for urban watersheds

B.4.2. BMP/LID Models

Simulation of BMPs varies between simplified representation of percent removal and partial or complete representation of the processes of hydraulic controls, settling, and transformation of pollutants. A number of available watershed models have the potential for use in BMP simulation (e.g., SWMM, HSPF, LSPC, and SLAMM), but representation is achieved by custom adjustment of hydrologic and pollutant transport parameters. Guidance for the application of watershed models such as SWMM and HSPF for simulation of BMPs is limited. Consistent application is difficult, and in the absence of default data and documented applications, intensive data collection and calibration are necessary. Some models, such as WAMView, can be adjusted to represent land practice BMPs based on the USDA Curve Number guidance. Many of the currently available, published BMP models are propriety (e.g., MUSIC) or have had limited release in the public domain (e.g., BMPAM). Specialized BMP simulation tools such as VFSMOD (Muñoz-Carpena and Parsons 2003) focus on specific BMPs, in this case vegetative filter strips.

Most of the currently available systems have limited process simulation or lack guidance for the selection and evaluation of management practices. Of the available systems, the Prince George's County BMP Module provides capabilities to simulate a wide range of BMPs with particular emphasis on scale-scale, distributed systems, using a process-based approach to address hydrology and pollutant removal. One specialized need for BMP simulation is the ability to handle highly distributed management techniques such as those employed in LID procedures. The Prince George's County BMP Module was designed specifically to address LID simulation and networks with multiple management practices. The structure of the BMP Module can facilitate the incorporation of additional BMP types and is suitable for linkage with a variety of watershed and receiving water models. Prince George's County has provided the system to users upon request and is willing to provide EPA with the code for adaptation and incorporation into *SUSTAIN*.

For the process simulation of BMPs, the Prince George's County BMP Module, augmented by portions of selected BMP processes provided by models such as SWMM, SLAMM, and P8, is recommended for incorporation into *SUSTAIN*. In particular, BMP simulation techniques for stormwater ponds and detention structures can be provided by SWMM. For BMPs such as riparian buffers, specialized simulation techniques are also needed. Riparian buffers can be addressed by using the procedures in VFSMOD (Muñoz-Carpena and Parsons 2003) or by adapting the land-to-land transport routines used in SWMM or HSPF.

B.5. Conclusions

The review of available models and BMP analysis systems confirms the initial selection in Task 1 of a short list of models best suited to be included in the *SUSTAIN* system. The final recommended list of models was based on an evaluation of the needs, the level of analysis included, the software capabilities, and the availability of the code supporting the models. Each of these models provides essential software tools; algorithms describing watersheds, receiving waters, or BMP processes; and a history of application and testing. In addition, existing models can be linked with *SUSTAIN* for combined simulation of large, complex watersheds and receiving waters. The selected models are the following:

- Watershed/landscape models: SWWM, HSPF, LSPC
- Stream conveyance and pollutant routing models: HSPF/LSPC stream routing and pollutant transport functions, or SWMM routing and transport (SWMM5)
- Stream conduit (combined sewer overflow, or CSO) models: SWMM

- BMP simulation models: Prince George's County BMP Module, including new algorithms for detention ponds and structural options, and selected buffer zone simulation techniques from VFSMOD

Development of the system will also require a framework manager, and supporting GIS tools, optimization, cost estimation, and post-processing techniques. The relevant components of the selected models, supporting algorithms, and tools will be integrated into a seamless framework that can provide the required functionality.

Appendix C. Summary of the Optimization Technical Panel Meeting

C.1. Background

Watershed and stormwater managers need modeling tools to evaluate how best to address environmental quality restoration and protection needs in urban and developing areas. A place-based analysis system, based on cost optimization, is essential to support government and local watershed planning agencies as they coordinate efforts across the watershed to achieve desired improvements in water quality at a minimum cost.

A two-day workshop was convened September 15-16, 2006, at the Fairfax, Virginia, office of Tetra Tech, Inc., to bring together experts to discuss the current state-of-the-art in optimization concepts and methods to support development of the optimization component in *SUSTAIN*. The invited experts included the following:

- Dr. James P. Heaney (University of Florida)
- Dr. Manuel Laguna (University of Colorado)
- Dr. Arthur E. McGarity (Swarthmore College)
- Dr. S. Ranji Ranjithan (North Carolina State University)
- Dr. Christine A. Shoemaker (Cornell University)
- Dr. Richard M. Vogel (Tufts University)
- Dr. Laura J. Harrell (Old Dominion University)

Optimization decision variables include BMP locations, types and design configurations. Because there can be an extremely large number of possible combinations of BMP choices that can meet desired water quality and quantity constraints, strategies are needed to identify specific BMP options for implementation from a vast output database. The primary objective of the workshop was to identify the best strategies available for implementation in *SUSTAIN*. A secondary objective of the workshop was to discuss and report issues related to cost estimating and in defining and quantifying the effectiveness of individual BMPs or several BMPs in parallel or in series. This appendix is a summary of the workshop discussion and recommendations.

C.2. Key Discussion Issues

The workshop focused on discussing and acquiring experts' knowledge on issues listed below in four categories:

C.2.1. General Issues

- ***Trend and focus*** - What are the current trends and focus in optimization research for watershed planning?

- ***Algorithm selection and evaluation*** – It was proposed to program two search algorithms in *SUSTAIN*: 1) Scatter Search and 2) genetic algorithm. Which one is more robust in providing placement decisions? Should other solution techniques be considered? How can it be confirmed that global or near global solutions have been found?

C.2.2. Optimization Approach

- ***Two-tier approach*** – Presumably a tiered optimization approach will facilitate placement of BMPs in different spatial scales. Can a two-tier or cascading optimization approach work to develop large scale solutions? BMPs may be placed at the site scale or subwatershed scale, but overall control performances are evaluated at the watershed scale
- ***Top down vs. bottom up*** **-** Should a watershed optimization process be top-down (from the watershed to subwatershed to site scales) or bottom-up?

C.2.3. Computational Efficiency

- ***Aggregation of distributed BMPs*** **-** BMPs include distributed types such as green roofs, bioretention basins, porous pavements and rain barrels. What are the most efficient solution strategies and computational approaches to simulate and optimize hundreds of distributed BMPs? How should the distributed BMPs be lumped (usually at parcel scales)? How should the BMP clusters be represented by lumped hydrologic parameters (e.g., depression storages and infiltration rates)?
- ***Simplified approach to derive effectiveness from multiple BMPs*** **-** BMPs can be in series or in parallel in a given subwatershed. It will be computationally demanding if process simulations are performed for each combination of treatment trains. Can experiments be performed to establish a database for deriving a regression formula that can be used to estimate the pollutant load reduction from all possible combinations of BMPs?
- ***Development of cost-effectiveness curves*** – What is the most efficient way to generate cost-effectiveness curves (cost vs. effectiveness) when using meta-heuristic algorithms? The curve can be derived from multiple *costs vs. load reduction* points by simulating multiple runs under a range of load reduction targets. This option will be computationally time-consuming because a large number of simulation runs may be required to derive multiple optimal solutions

C.2.4. Problem Formulation - Objectives, Constraints and Variables

- ***Pollution vs. flood control objectives*** **-** How to reconcile the potential conflicts between meeting pollution control and flood control objectives? The pollution control effectiveness is usually assessed by a continuous simulation, while flood control effectiveness is assessed by an event simulation
- ***Multiobjective optimization*** **-** How should the objective equation be formulated?
- ***Future land use management*** **-** Is the future land use management a decision variable in the BMP placement decision? In other words, should the land use planning and water quality management be integrated? *SUSTAIN* is designed for placing BMPs in watersheds with known existing or future land uses
- ***Cost estimating*** **-** For estimating the cost of BMPs, what will be the level of detail required to maintain the consistency of decision parameters used in optimization analyses?
- ***Financial resources and implementation schedule*** – How to include constraints on financial resources and schedules of BMP implementation in the optimization framework?

C.3. Discussion Summary

This section summarizes the discussion and input from the invited experts, organized by the discussion issues.

C.3.1. General Issues

Trend and focus - *What are the current trends and focus in optimization research for watershed planning?*

An emerging trend is to apply optimization techniques, especially meta-heuristic algorithms, to solve stormwater management issues. Although a number of research projects have been completed in recent years, most of them are conducted in academia and most of them were developed on a case-by-case basis. There has not been any generic decision support system developed that can be used by a general public practitioner to optimize size, type and locations of BMPs.

During the discussion, the application of neural networks and parallel computing for the purpose of reducing search time was brought up. Although there are uncertainties that neural networks can accurately represent the real simulation module with limited training process, it was suggested that they can be used as a filter during the search process to avoid spending CPU time to evaluate *bad* solutions. Parallel computing can be employed where a network of computers is available to use all possible resources to obtain the search results in a shorter time.

A hybrid approach of combining traditional and meta-heuristic algorithms can be promising as traditional algorithms are more efficient for reaching local optima and meta-heuristic algorithms have the advantage of not being trapped at the local optima.

Algorithm selection and evaluation - *It was proposed to program two search algorithms in SUSTAIN: 1) Scatter Search and 2) genetic algorithm. Which one is more robust in providing placement decisions? Should other solution techniques be considered? How can it be confirmed that global or near global solutions have been found?*

There is no quick answer for the question of which algorithm is better than the other. In terms of solution techniques, it was mentioned that Evolution Strategies are claimed to be faster at numerical optimization than traditional Genetic Algorithms. A participant presented a *stochastic RFB-Cornell radial basis function approach* and showed it converged significantly faster than a few other techniques for a particular case study she conducted. The participant also suggested that the alternatives for optimization algorithms need to be evaluated carefully since the simulation time can be substantial. It was also noted that using commercial software *Solver* associated with spreadsheet analysis could be an efficient alternative. Other participants also found commercial software useful for testing new search algorithms.

To address the question of how to confirm that global optima has been found, the experts agreed that, theoretically, global optima cannot be proved when using meta-heuristic techniques. That is why the term *near optimal* should always be used instead of *optimal*. However there are a few ways to help gain confidence:

- Use a benchmark test case with known optima
- Compare and try different solution techniques
- Use commercial software to compare results

Another way of looking at the *near optima* is that although it is not guaranteed to be the *optima*, they are better than the other solutions that have been checked during the search process. This leads to the suggestion that starting the search with a good solution might result in the near optimal solution faster. It was pointed out that local optima can be proved by checking the derivative if the problem is continuous.

Other than one member, the invited experts appeared unfamiliar with the Scatter Search method. Two experts both talked at several times about the potential utility of traditional dynamic programming techniques.

The workshop experts demonstrated the following optimization applications that can be further explored:

One expert talked about the experience of using Genetic Algorithm (GA) to optimize the locations of infiltration practices for reducing peak flow. A curve number (CN)-based distribution model was used to simulate the hydrological responses and infiltration BMPs are represented as change of CN. A series statistical analysis was performed to check if there is another way to identify the optimal BMP locations without using optimization. The results were negative; this confirmed the need for applying optimization techniques to get the cost-effective solutions for stormwater management issues. It was also commented that a decision support system does not necessarily provide BMP design details as part of the solution; instead it is only necessary to suggest the general categories of BMPs and the expected treatment (i.e., infiltration and/or storage) capacity. In addition, sometimes simplified optimization such as Linear Programming (LP) may give results that are comparable to GA solutions. The following web site was suggested to download papers and manuscripts for more detail: (http://ase.tufts.edu/cee/faculty/vogel/bio.asp).

Another expert presented a spreadsheet optimization tool that used the Excel add-on optimization engine Solver to find cost-effective BMPs. The BMPs were represented as a combination of on-site depression storage (DS) and/or centralized storage/release systems.

A third expert showed Storm Water Investment Strategy Evaluator (StormWISE), which is a screening level stormwater management optimization tool. This tool employs a top-down approach to prioritize investment in subwatersheds for pollution control. The essential component of this tool is the generalized pollutant-removal/cost functions for each land use in each subwatershed (first-stage). The functions are then used for the second-stage optimization. As the pollutant-removal/cost functions are well-behaved, a classical optimization technique, mixed integer/linear programming, is used to solve the second-stage optimization problem. The following Web site (http://watershed.swarthmore.edu) has more details.

Two panelists pointed out the importance of providing diverse alternative solutions. One presented a case study where an evolutionary algorithm was applied to obtain diversified alternative solutions that have comparable objective values. It was emphasized that the approach was efficient because it was performed along the search process for the main optimization problem so that it did not require to rerun the model. Another expert also commented that there might often be multiple feasible solutions within a very small percentage of benefit or cost range. In that case the system needs to identify the most diversified alternatives that the user can choose from (using their own judgment).

C.3.2. Optimization Approach

Two-tier approach - *It is believed that a tiered optimization approach will facilitate placement of BMPs in different spatial scales. Can a two-tier or cascading optimization approach work to develop large scale solutions? BMPs may be placed at the site scale or subwatershed scale, but overall control performances are evaluated at the watershed scale.*

Overall, the experts agreed that the tiered approach is promising; however, they foresee the obstacle of daunting computation time if the meta-heuristic optimization algorithm is employed. A few ideas came up during the discussion. The first group of ideas focused on reducing the complexity of the simulation system by either employing a simpler and faster simulation approach or by using a generic cost-pollutant-removal function to eliminate the needs of detailed BMP simulations. The second group of suggestions focused on improving optimization efficiency. One expert mentioned the use of dynamic programming (DP) for the second tier analysis. If applicable, DP can be more efficient than meta-heuristic algorithms. However, it is recognized that implementing DP in a decision support system such as *SUSTAIN*, which is intended to be applicable to many different cases, would be difficult because DP requires a case-by-case problem formulation. Another suggested using neural networks as a filter during the optimization process to avoid spending time in evaluating *bad* solutions.

Top down vs. bottom up - *Should a watershed optimization process be top-down (from the watershed to subwatershed to site scales) or bottom-up?*

The top-down approach involves applying generalized cost-benefit functions (such as the pollutant-removal/cost functions in StormWISE) to prioritize the distribution of load reduction requirements at the subwatersheds, given a target at the watershed level. The advantage of this approach is that an efficient classical optimization algorithm can be used because the generalized cost-benefit functions are smooth and convex. The challenge of this approach is to obtain reasonably accurate cost-benefit functions. If the cost-benefit function is not accurate, the solutions can be skewed. Also, this approach does not explicitly address BMP implementation details.

For the bottom-up approach, the search starts with the potential locations identified; therefore it explicitly addresses the BMP implementation details. The downside of this approach, as commented on by one expert, is that the amount of site-specific information and data required for specifying sites and potential BMPs could be prohibitive. Also, the approach is simulation intensive and when it is applied for a large watershed the computation time required can be extensive.

From discussions, a strategy that combines bottom-up and top-down procedures appears promising. The overall optimization process can start with the top-down approach as applied in StormWISE using generic cost-benefit functions to identify the high priority subwatersheds, then perform a detailed bottom-up optimization search for each priority subwatershed to derive a more accurate and site-specific cost-benefit curve. By doing so, the computation time is expected to be reduced because detailed simulation/optimization is conducted only for the priority subwatersheds. The search process is then completed with another round of top-down optimization using the cost-benefit functions derived from the previous step.

C.3.3. Computational Efficiency

Aggregation of distributed BMPs - *BMPs include distributed types such as green roofs, bioretention basins, porous pavements and rain barrels. What are the most efficient solution strategies and computational approaches to simulate and optimize hundreds of distributed BMPs? How should the distributed BMPs be lumped (usually at parcel scales)? How should the BMP clusters be represented by lumped hydrologic parameters (e.g., depression storages and infiltration rates)?*

One participant presented the approach of using aggregated depression storage to represent the site-scale or distributed BMPs (such as green roofs, porous pavement, rain-gardens, etc.) at the catchment level. Another suggested using response functions to represent distributed BMPs at the scale of a neighborhood or region of an urban area. The response functions need to be in the form of simplified formulations derived from regressions or theoretical means. It was suggested that a highly detailed simulation model driven by an optimizer can be used to generate data for curve fitting.

Simplified approach to derive effectiveness from multiple BMPs - *BMPs can be in series or in parallel in a given subwatershed. It will be computationally demanding if process simulations are performed for each combination of treatment trains. Can experiments be performed to establish a database for deriving a regression formula that can be used to estimate the pollutant load reduction from all possible combinations of BMPs?*

This topic was discussed under aggregation of distributed BMPs.

Development of cost vs. effectiveness curves - *What's the most efficient way to generate cost-effectiveness curves (cost vs. effectiveness) when using meta-heuristic algorithms? The curve can be derived from multiple cost vs. load reduction points by simulating multiple runs under a range of load reduction targets. This option will be computationally time-consuming because a large number of simulation runs may be required to derive multiple optimal solutions.*

One participant suggested that the cost-effectiveness curve can be developed in a continuous search at various target values without stopping the search. The process can start with solving the optimization problem with the highest target value. After getting the near-optimal solutions, relax the target and resume the search. The previous solutions are kept and can be selectively used to construct the reference set for the subsequent searches.

Simplification of the Channel/Pipe Routing Simulation

Channel/pipe routing is computationally extensive because it employs the kinematic wave flow routing method. To reduce the computation burden, it is desirable to simplify the routing simulation during optimization runs and only use the kinematic wave approach for evaluation runs. The possible simplified routing options include, but are not limited to:

- Adopt the simple approach of steady flow routing (from the SWMM) for the optimization runs
- Pre-run the routing module with kinematic wave approach to build a stage-discharge relationship and then use that relationship during the optimization runs

C.3.4. Problem Formulation - Objectives, Constraints and Variables

Pollution vs. flood control objectives - *How should the potential conflicts between meeting pollution control and flood control objectives be reconciled? The pollution control effectiveness is usually assessed by a continuous simulation, while flood control effectiveness is assessed by an event simulation.*

One participant suggested to address flood control objectives by penalizing corresponding solutions if flooding occurs during the long-term simulation.

Another expressed the idea of using goal programming. The approach should be to solve the event-based flood control problem first and then, in most cases, the solution for the pollutant control will be automatically included in it. Otherwise it is necessary to add extra dimensions in the optimization problem formulation. Someone also mentioned that in urban land uses first-flush may be the main cause of pollution, but in rural areas the larger storm events may be the major factor because of erosion. It was commented that in suburban situations there will be a combination of both, therefore, both situations should be addressed. It was suggested that one approach could be to include flood control considerations as part of the screening stage of the analysis (i.e., narrow the search for water quality BMP's to the subwatershed drainage areas where flood frequency is high). Another participant commented that although extreme events may be a major source of pollution or erosion, no BMPs are designed to handle catastrophic events.

Multiobjective Optimization – *How should the objective function be formulated?*

The need for multiobjective optimization was recognized. Formulation was discussed in the context of sequential analysis or various supplementation analyses of the near optimal solutions. No specific recommendations were made on the solution of multiple objectives, although time and complexity constraints were recognized.

Future land use management - *Is the future land use management a decision variable in the BMP placement decision? In other words, should the land use planning and water quality management be integrated? SUSTAIN is currently designed for placing BMPs in watersheds with known existing or future land uses.*

It was noted that land use planning can have an implicit impact on the stormwater management solutions. For example, aggregating the development areas, which have a larger percentage of imperviousness, can increase the cost-effectiveness of stormwater control practices.

Cost estimating - *For estimating the cost of BMPs, what will be the level of detail required to maintain the consistency of decision parameters used in optimization analyses?*

One participant commented that the cost function is very important in decision-making and mostly overlooked. LIDs make the cost estimation difficult because many LIDs have multiple purposes. *CAPITA*, a wastewater treatment database, was mentioned for cost estimation. This database contains realistic cost data for mostly conventional treatment units. It was also pointed out that it is difficult to estimate the land cost. Another suggested that if the actual cost data were not available, then as long as the *relative costs* were correct, the solutions would still be valid. It was suggested that the *SUSTAIN* system allows the flexibility for users to use default data or enter locally derived cost information.

Another participant mentioned that it might be useful to use *resources consumed* as the surrogate for cost.

Financial resources and implementation schedule - *Should constraints on financial resources and schedules of BMP implementation be included in the optimization framework?*

It was recognized that the system does not need to include schedules of BMP implementation because the BMP options are discrete and solutions for the next target may not be inclusive of the solutions derived under the current goal. An example was goven where there is a choice between large structures versus small distributed systems. The funding limitation can drive the solution to either implementing the distributed or the centralized systems, then the solutions are mutually exclusive. When there is a need for next phase planning a separate optimization should be performed based on the future conditions.

It was commented that it is desirable to formulate the optimization problem as minimizing the cost because if the constraint is the actual budget then the cost function needs to be accurate. Otherwise the solution could be skewed.

C.4. Conclusions

The workshop included a thorough discussion of the tiered optimization approach, comparing top-down and bottom-up search strategies. Expert opinions were gathered on how to prove if the optimization solutions are *good*, if not the best, and how to evaluate and improve the search efficiency.

In summary, the following items were identified as the major items worth considering in *SUSTAIN* development and future improvement:

- Combine top-down and bottom-up search strategies for the tiered optimization
- Explore the use of classic optimization techniques, such as LP, Nonlinear Programming (NLP) and DP, for the second tier top-down optimization
- Evaluate the employed optimization techniques by:
    - using a benchmark test case with known optima
    - comparing different solution techniques
    - using commercial software to compare results (below are a few Web sites the experts have mentioned):
        - www.palisade.com Evolver
        - www.solver.com Frontline Systems, Inc.
        - www.mgc.ac.cn/genomecomp GenomeComp
        - www.inria.fr/recherche/equipes/dolphin.en.html Dolphin
        - csmr.ca.sandia.gov/projects/opt.html Sandia
- Provide diverse near-optimal solutions
- Represent the distributed or site-scale BMPs using the hydrologic simulation parameters (i.e., depression storage and infiltration parameters)
- Explore the feasibility and options of applying the simplified channel/pipe routing approach for optimization runs
- Explore the concept of relative cost

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