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).

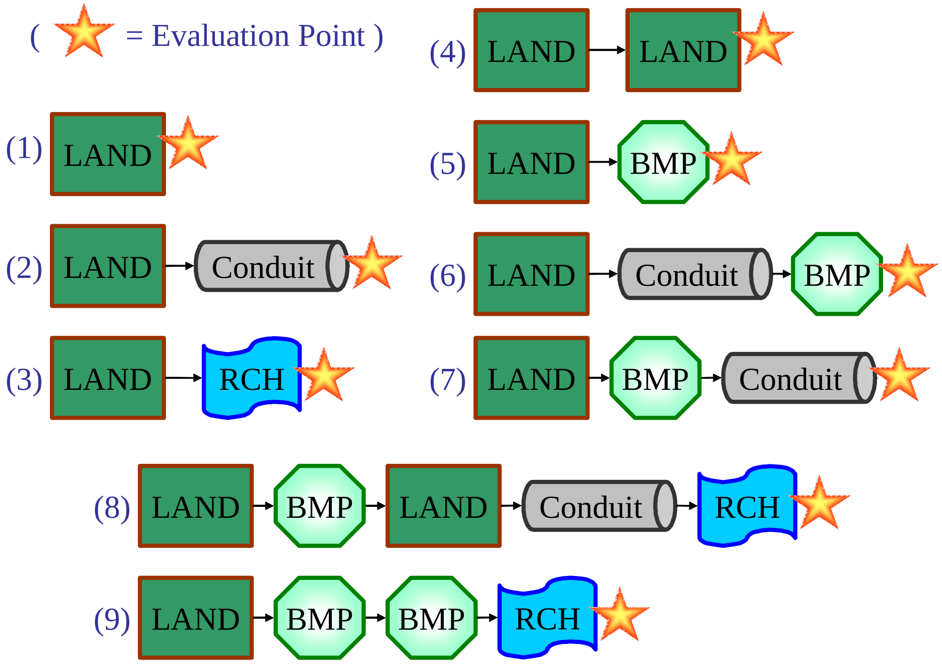


Figure A-1. Typical management configurations.

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.

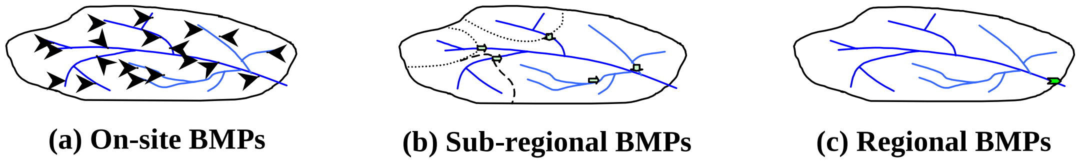
- Simulate hydrologic response and a level of detail sufficient for analysis of a hydrograph (peak flow and volume)
- Simulate multiple pollutant types, including nutrients (nitrogen and phosphorus), pathogens (fecal coliform bacteria, Escherichia coli [E. coli]) and metals (e.g., zinc, aluminum)
- Simulate 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.


(a) On-site BMPs

(b) Sub-regional BMPs

(c) Regional BMPs

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.

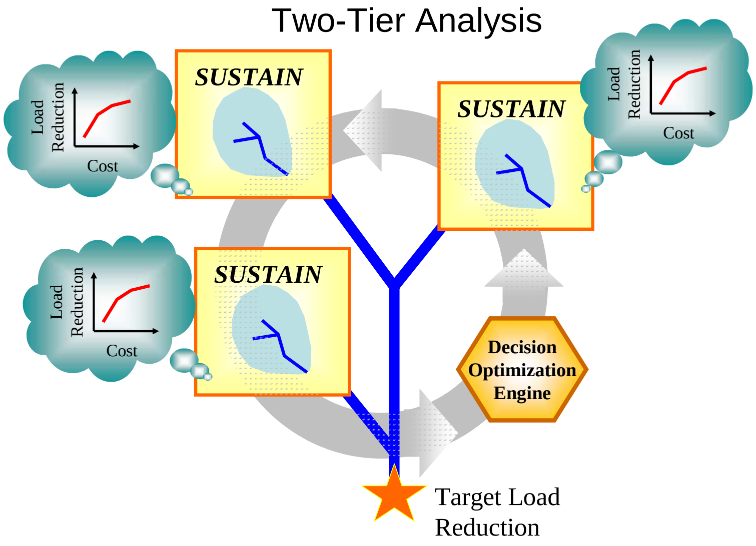


Figure A-3. Tiered watershed application.

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 Systems: BASINS, EPA TMDL Toolbox	Prince George's County BMP Module, P8 UCM, VFSMOD, MUSIC, DMSTA, SWMM, BMPAM 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	VB	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.

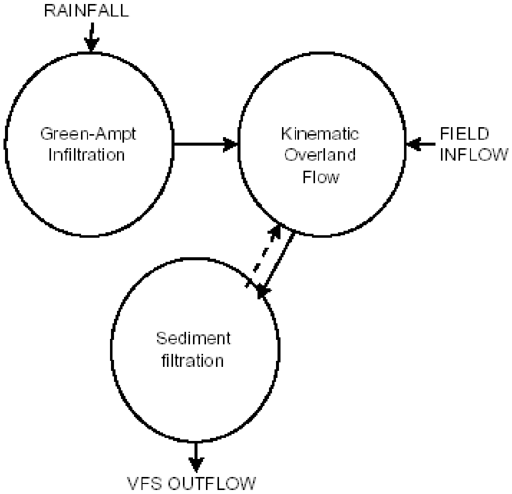


Figure B-1. Schematic representation of VFSMOD.

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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