FRAMEWORK DESIGN FOR BMP PLACEMENT IN URBAN WATERSHEDS

Fu-hsiung Lai[1], Leslie Shoemaker[2], and John Riverson[2]

[1]U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Water Supply and Water Resources Division, Urban Watershed Management Branch, 2890 Woodbridge Avenue (MS-104), Edison, NJ 08837; PH (732) 321-6632; email: lai.dennis@epa.gov
[2]Tetra Tech, Inc., 10306 Eaton Place, Suite 340, Fairfax, VA ; PH (703) 385-6000; email: leslie.shoemaker@tetratech-ffx.com, john.riverson@tetratech-ffx.com

Abstract

A number of stormwater control strategies, commonly known as best management practices (BMPs), are used to mitigate runoff volumes and associated nonpoint source pollution due to wet-weather flows (WWFs). BMP types include ponds, bioretention facilities, infiltration trenches, grass swales, filter strips, dry wells, and cisterns. Another control option is “low impact development” (LID) – or hydrologic source control – which strives to retain a site’s pre-development hydrologic regime by combining impervious area controls with small scale BMPs, reducing WWFs and the associated nonpoint source pollution and treatment needs.

To assist stormwater management professionals in planning for BMP/LID implementation, the U.S. Environmental Protection Agency (EPA) initiated a research project in 2003 to develop a decision support system for selection and placement of BMP/LID at strategic locations in urban watersheds. The BMP/LID assessment tools based on sound science and engineering will help develop, evaluate, select, and place BMP options based on cost and effectiveness. The system is called the Integrated Stormwater Management Decision Support Framework (ISMDSF). The ISMDSF will provide a means for objective analysis of management alternatives among multiple interacting and competing factors. The desired outcome from the system application is a thorough, practical, and informative assessment considering the significant factors in urban watersheds. The ISMDSF will be applied to several diverse urban watersheds to evaluate and demonstrate its capability (Lai et al. 2003, Lai et al. 2004, Riverson et al. 2004).

The initial phase of this research is expected to be completed in 2005 and will include a comprehensive design and a functional system with all pieces in place but not all functionalities. The subsequent phase will include enhanced geographical information system (GIS) capabilities for visualization of placement options, more powerful post-processors, expanded cost estimating functions, improved BMP simulation processes, and more importantly, a multiple objective optimization

component. The development of GIS-based tools and preparation of their documentation are expected to be completed by 2008.

Objective

The primary objective of this project is to develop methodologies and decision support tools for cost-effective placement of BMPs at strategic locations in mixed-land use urban watersheds based on integrated data collection and hydrologic, hydraulic, and water-quality modeling. The system will optimize the management needs based on achieving multiple user-defined criteria, including measurements of cost, water quantity, and water quality control. The ISMDSF will provide stormwater management professionals with a BMP assessment tool based on sound science and engineering that helps develop, evaluate, select, and place BMP options to achieve user defined criteria of cost, water quantity, and water quality management.

Intended Users

The system is intended to support local and county government engineers/planners, federal/state regulatory reviewers, private consulting engineers, concerned citizens, stakeholders, and academicians in the development of watershed-based management plans. The system is designed for knowledgeable practitioners who are familiar with the technical and scientific aspects of watershed modeling. The users are expected to have a fundamental understanding of watershed and BMP modeling processes.

Watershed-based Placement Scenario

The benefits of a stormwater management are typically evaluated on a watershed basis. The ISMDSF provides a framework for evaluating the benefit of placing a variety of BMPs throughout a watershed. Figure 1 shows that a relatively large watershed can usually be subdivided into several smaller sub-watersheds. For each sub-watershed, there is a predetermined suite of feasible BMP options (types, configurations, and costs) at strategic locations for placement of BMPs. This information is usually derived from an engineering investigation of local data including soil, land use, and development conditions. The ISMDSF generates time series rainfall-runoff data from BMP tributary areas and routes them through a BMP, or several BMPs in parallel or in series, and systematically compares their costs and pollutant removal effectiveness.

The ISMDSF produces data for deriving optimal production curves that relate pollutant load reductions with costs as shown in Figure 2. Each point on a curve in Figure 2 represents an optimal combination of BMPs at various locations in a given sub-watershed that will collectively remove the stated amount of pollutant load at the least cost.

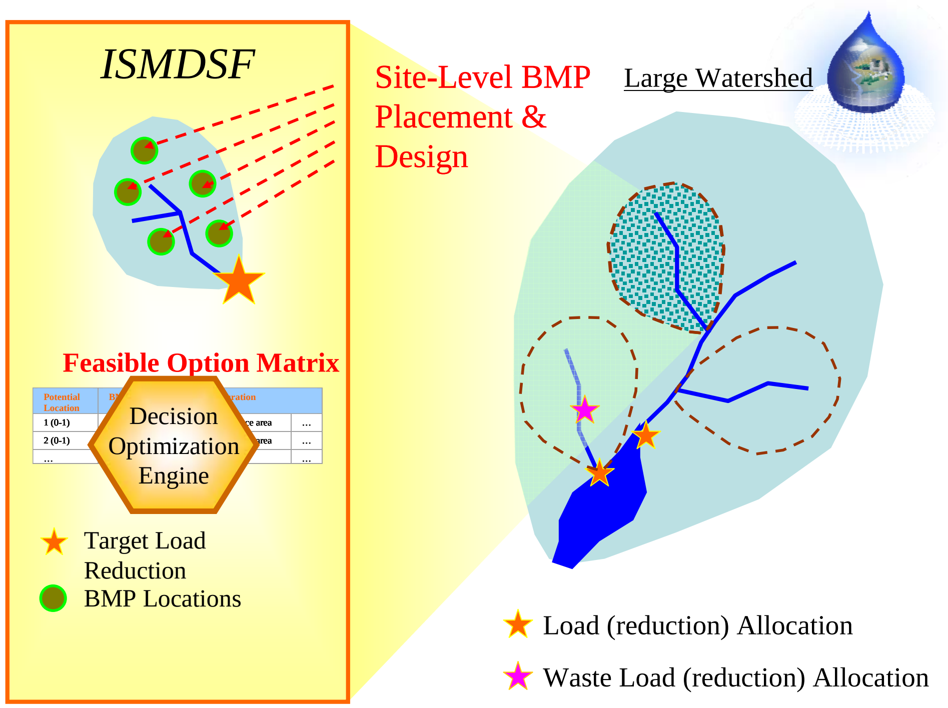

Figure 1. Application of ISMDSF for a sub-watershed.

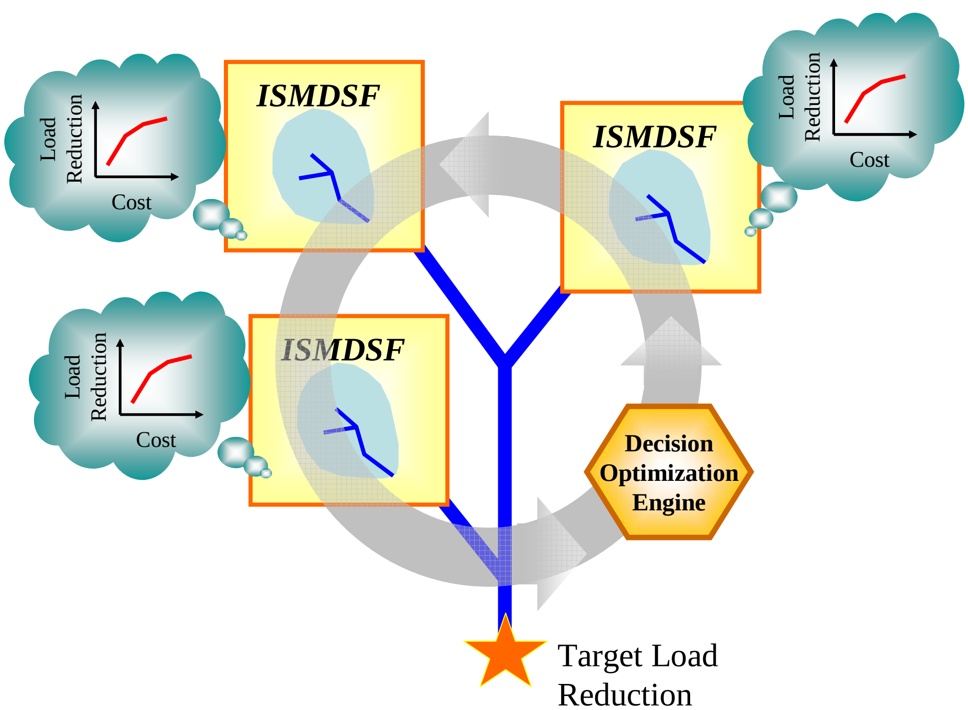

Figure 2. Two-tier application of ISMDSF.

Figure 2 also shows a conceptual diagram of a two-tier analysis that the ISMDSF is designed to perform in a watershed:

- First-tier application of the system is used to develop an optimal production curve for each sub-watershed.
- Second-tier evaluation combines optimal production curves in each sub-watershed to derive optimal combinations of BMP placement that meet the target load reduction for the watershed at the minimum cost.

The two-tier approach can be applied to a large watershed that contains several sub-watersheds or to a small watershed that requires the development of a detailed management plan, e.g., at a parcel or a street block level.

Conceptual Design of ISMDSF

The conceptual design and major system component relationships are shown in Figure 3. The use of distinct components developed as functional modules will provide flexibility in the development and maintenance of the modeling system. The key components that comprise the ISMDSF are described below:

- **Framework manager (FM)** - serves as the command center of the ISMDSF. The FM facilitates the linkages between GIS, external inputs, watershed and BMP simulations, post-processor, feasible options matrix, and the decision optimization engine.
- **Watershed module** - integrates locally derived data with watershed simulation models that predict flow and pollutant loading for input to BMPs.
- **BMP module** - performs process-based simulation to derive the performance (effectiveness) of a BMP.
- **Optimization module** - performs cost estimating and systematically compares performance and cost data of various BMP options and their placement scenarios.

In addition to linkage with external models for inputs of hydrology and pollutant time series, the ISMDSF will include four internal stand-alone simulation modules that can be used individually or in combination to represent various watershed systems:

- ***Land*** for performing watershed/landscape runoff simulation.
- ***BMP*** for process simulation of a BMP.
- ***Conduit*** for routing of flow and pollutant through a conduit network.
- ***Reach*** for stream conveyance and pollutant routing.

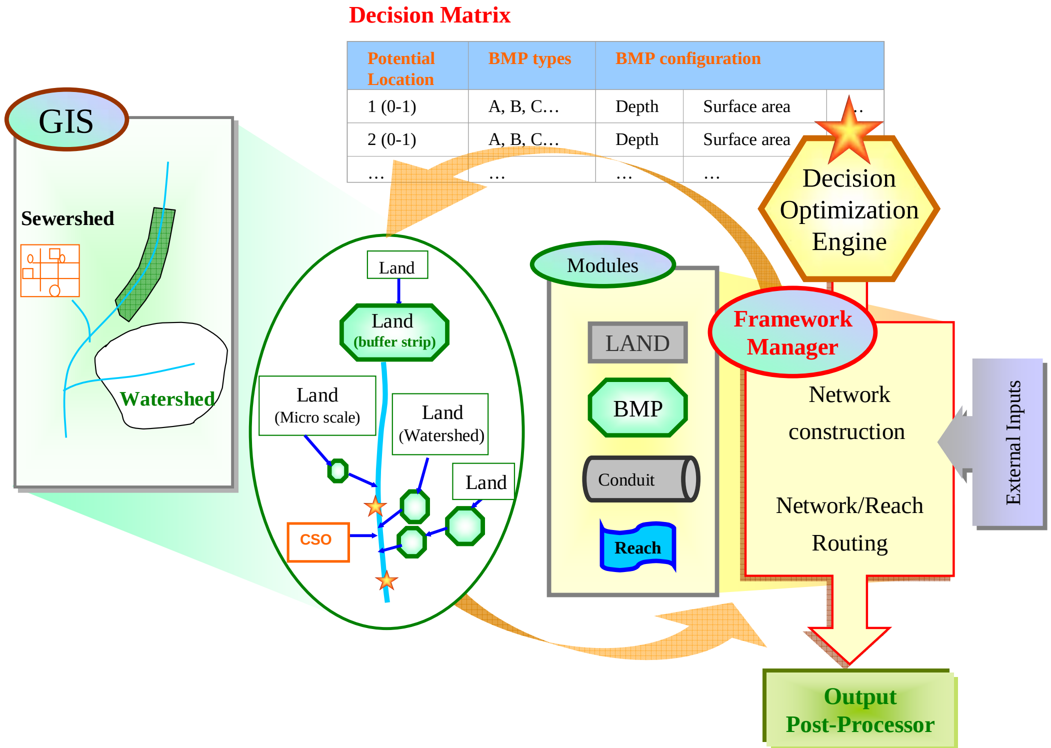

Figure 3. Conceptual diagram of the ISMDSF system.

During Phase 1, the needed simulation codes will be derived mostly from Storm Water Management Model Version 5.0 (SWMM5) (EPA 2004) and the Prince George's County BMP Module (Prince George's County 2001). The Land Module simulation will be performed by using SWMM5 watershed runoff techniques or by importing watershed modeling results from previously derived local studies. The BMP Module will build on a suite of simulation methods, previously developed for the Prince George's County BMP Module, that address five major structural BMP types and four major processes (Prince George's County 2001). The relative dominance of each process for general types of BMPs is shown in Table 1.

Table 1. Representative BMPs and Major Processes Involved

Structural BMP Types	**Storage Routing**	**Infiltration/ Filtration**	**Pollutant Routing/ Removal**	**Sheet Flow Routing/Pollutant Interception**
Detention Basin	+	(o)	o	-
Bioretention Basin	o	+	o	-
Wetland	+	(o)	+	-
Buffer Strip	-	+	(o)	+
Swale	o	+	+	-

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

The BMP Module will allow users to select from a library of BMP types, configure them based on physical features (i.e., size, weir type, media), and evaluate BMP performance by simulating the major processes that affect hydrology and pollutant behavior. The Conduit and Reach modules will use the SWMM5 algorithms, previously referred to as the Transport Block (EPA 2004, Huber et al. 1988).

The integration of the system components will provide a consistent approach for evaluating water and pollutant transport through a watershed. The system components were carefully selected to provide a robust approach with a manageable and relatively consistent level of complexity. More detailed formulations of specific BMP processes were likely to require significantly more detailed monitoring and data collection. More simplified approaches would place significant limitations on the time step and sensitivity for simulating flow and pollutant transport processes. A suite of modules in the framework that can simulate hydrology and pollutant processes allow performance evaluation of feasible management alternatives. A computationally efficient framework allows repeated application and evaluation of alternatives during optimization.

The ISMDSF includes an Optimization Module to identify the optimal or near optimal BMP placement and selection strategies for a pre-selected list of potential BMP sites and applicable types. The user can select the goals such as to minimize the total cost for the specified water quantity and/or water quality control targets. The Module will compare the control effectiveness and the total cost of a BMP implementation plan (including exact BMP locations and configurations) and can evaluate benefits at multiple assessment points in the watershed specified by the user. The Optimization Module can also be used to generate the optimal production (effectiveness vs. cost) curve shown in Figure 2 for the desired water quantity or water quality control effectiveness targets.

In Phase 2 work, the selected SWMM algorithms in the current framework will be replaced with the newer algorithms being developed for simulation of sediment loading and transport and pollutant load evaluation. The framework's modular design will facilitate the addition of new BMP types or alternate BMP process simulation techniques. The framework will also include additional optimization techniques, such as genetic algorithm, for deriving cost-effective BMP placement options.

The ISMDSF Framework Manager will use a system and interface architecture based on a GIS-based visualization and support for developing watershed simulation networks. The main user interface is based on the ArcGIS software system. This provides the flexibility to support spatial placement of BMPs and evaluation of drainage areas and flow networks. ArcGIS has two components. ArcView 8 and Spatial Analyst are used to read and edit the spatial and temporal datasets, and to interact with the Microsoft Access database components of the ISMDSF. The Access database consists of tables and queries that allow the ArcGIS interface and watershed and BMP simulation modules to interact and exchange data.

The user will be able to select and place a BMP at any location on land and stream (Figure 4) and to define assessment points for evaluation in a watershed. A control point button will be used to place BMPs/assessment points in the watershed and define the BMP types, including a "no BMP" option, for each control point (Figure 5).

Before defining BMPs in a watershed, the system must have a stream network and elevation base layers available for reference. These base layers can be derived from state or national sources or from more detailed spatial data available locally. BMPs can be classified as two distinct categories: in-stream BMPs or overland BMPs. In-stream BMPs are located within or along a stream channel, while overland BMPs are located off-line (i.e., not on the stream channel). Specific tools will allow the user to choose how a BMP is defined on the map. For overland BMPs, the user will draw a point, line, or polygon on the map, and the corresponding feature will be created and recorded in the BMP feature classes (BMP_Point, BMP_Line, BMP_Area). When defining an in-stream BMP, the user will zoom in to an appropriate scale and select points that are on or close to a stream on the map. The user's map-clicking point will automatically be snapped to the nearest point of the nearest stream to associate the BMP with the stream and the position along this stream. Once the user selects a position along the stream for a BMP, a point feature will be created for point-type BMP and a line feature will be created for linear BMP (e.g., buffer strip) after the length is given.

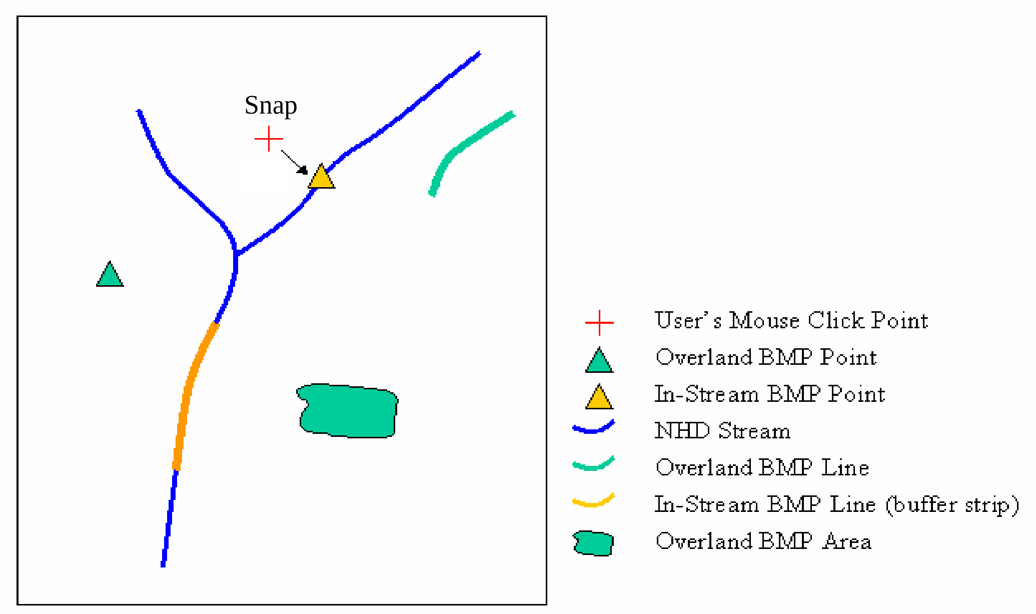

Figure 4. Placement of BMPs on land and stream.

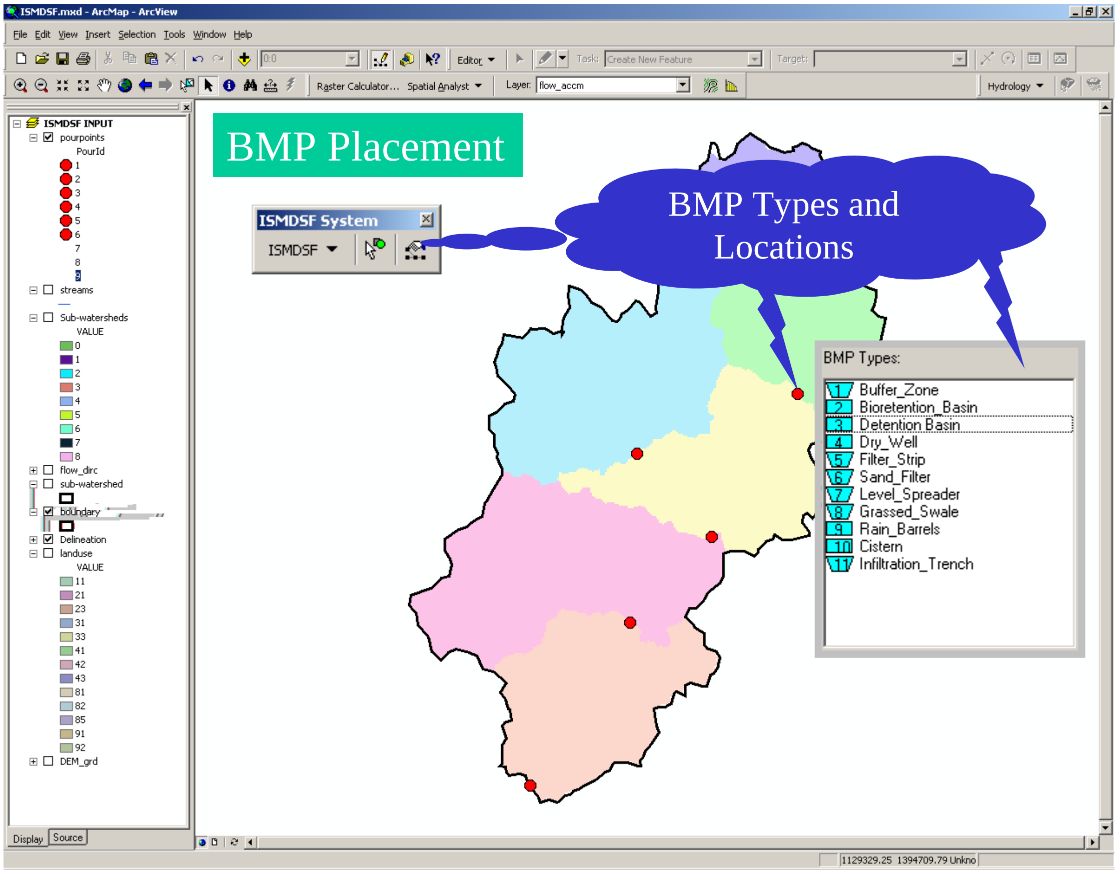

Figure 5. Defining types and locations of BMPs/assessment points.

Because of the complexity of BMP types and the relationship of BMPs with stream networks, an approach will be developed to organize BMP type and configurations, BMP linkage information, and flow routing through BMPs and stream networks. Since BMP drainage areas vary in terms of spatial boundaries and aerial coverage, there is a need for flexibility in how these areas are represented. The system will provide tools to delineate the drainage areas for BMPs by using auto-delineation, manual delineation, or simply importing pre-defined delineations.

Based on the delineated sub-watersheds within a watershed, BMP locations, and streams or pipes, a hydrologically connected network can be developed. A network is a set of schematic nodes and links that are topologically connected to each other. Water flows through the network according to the predefined flow directions. The network system will assume one-directional flow and does not currently support reversed flow conditions. The nodes in the network represent the control points, including assessment points and BMP locations. All control points are connected through streams or pipes that are defined as links. The user can further define each link as a stream, pipe, or flow-controlling device such as a weir, an orifice, or a flow divider.

A stream network is created by connecting control points based on flow direction derived from the topographic data or as designated by the user. The time series data of flow, sediment, and pollutants generated at the sub-watershed outlets will be routed through the BMP nodes, by calling the BMP simulation module, and then through the streams, by calling the Reach module shown in Figure 3.

All model output files containing relevant scenario information will be properly indexed for later analysis and plotting using Microsoft Excel. The spreadsheet post-processor will have a seamless integration with various ISMDSF components. Continued development of an integrated post-processor is planned for Phase 2.

Operation of ISMDSF

The ISMDSF is designed to perform the following sequence of analyses:

- Beginning with GIS view and database, a simulation network is developed that defines the relationships between land-area units, BMPs, and stream systems on a watershed.
- The user defines the assessment locations and decision criteria (e.g., flow frequency, phosphorus load) to be evaluated in assessing objectives.
- The FM identifies the modules (Land, BMP, Conduit, and Reach) to be used and prepares model input files.
- The FM routes the external inputs to appropriate modules and their outputs to the Output Post-Processor or other models.
- The FM sends outputs from Output Post-Processor to the Decision Optimization Engine.
- The Optimization Engine evaluates the current option and selects the next preferred option from that contained in the Feasible Option Matrix based on cost and defined decision criteria. The Feasible Option Matrix contains types, configurations, locations, and costs of feasible BMP options. The ranges and increments for alternative BMP designs are also specified.
- For a target output identified for management of the watershed, the location and type of BMPs are varied over a range of alternative options and numerous iterations of the ISMDSF are performed.
- The iterations end when the user defined convergence criteria are met.

The database associated with the selected optimal scenarios will be saved in the ISMDSF to allow users to perform additional assessment as needed. Users of the system are expected to use multiple applications ISMDSF under various assumptions to explore the management options in a specific watershed. Users must understand the watershed characteristics and localized constraints (e.g., poorly drained soils) in the selection of the potential BMP locations and types. The tool would not automatically select the best solution, but would be expected to be used as a tool to explore and test various approaches and eventually select optimal solutions based on user defined criteria and constraints.

Project Status

The ongoing Phase 1 effort has completed a draft conceptual design of the ISMDSF and will implement the following components:

- Programming and linkage of all internal watershed simulation modules (Land, BMP, Conduit, and Reach).
- Linkage with external watershed simulation models.
- Programming in Visual Basic for ArcGIS based watershed network development and ArcGIS linkage for placement of BMPs on the network.
- Capability to place BMPs and lateral features such as riparian zones.
- Ability to delineate contributing areas using automatic, manual, or import of pre-defined delineations.
- Preliminary post-processor.
- A cost routine for basic cost estimating and allowing users input of cost data.
- Manual creation of scenarios and cost comparison of various BMP types and placement options.

Initial testing of system components demonstrates that the design specifications of the system can be achieved. The system can be applied to complex configurations with multiple BMPs within a watershed.

Next Steps

The Phase 2 effort will continue to expand the functionality and process simulation capability of the ISMDSF. The effort will include:

- Improvement of GIS data layer linkage.
- Development of pre-processors to facilitate geographical data processing and preparation of model input data files.
- Enhancement of BMP modeling capabilities to include additional BMP options (e.g., wetlands and buffer strips) and processes to better handle infiltration, sedimentation, short-circuiting at a pond, and nutrient uptake and transformation.
- Improvement of post-processors for model output visualization and analysis.
- Enhancement of the cost-estimating module.
- Development of an optimization module using scatter search and genetic algorithm solution techniques and its interface with the framework manager for data management.
- Case study application to several sites showing diversity of BMP types, soil/climate, and watershed development conditions.

Since optimization analyses will require numerous runs of the watershed/BMP system, the runtime for the analysis is a consideration in the development of the system. The completed framework will be thoroughly tested to assure the coding accuracy and computational efficiency of individual components and linkages. Guidance documents will be prepared to assist users in applying the framework to complex watershed management planning studies. The application of the framework to real world case studies will demonstrate how it can be creditably applied. Continued research is needed to improve and validate the various BMP simulation algorithms. The modular framework of the system is designed to accommodate future updates of the individual framework component including BMP simulation routines.

Conclusions

This project represents an intensive effort by EPA to develop a decision support tool based on sound science and engineering that helps develop, evaluate, select, and place BMP options in an urban watershed based on user-defined cost and effectiveness criteria. There is currently no comprehensive watershed modeling system available in the public domain for evaluating the optimal location, type, and cost of WWF BMPs needed to meet water-quality goals. The successful development and demonstration of the ISMDSF will support federal, state, local, and watershed practitioners in developing sound stormwater management evaluations and cost optimizations.

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Disclaimer

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