DECISION SUPPORT FRAMEWORK FOR STORMWATER MANAGEMENT IN URBAN WATERSHEDS

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ABSTRACT: To assist stormwater management professionals in planning for best management practices (BMPs) implementation, the U.S. Environmental Protection Agency (USEPA) is developing a decision support system for placement of BMPs at strategic locations in urban watersheds. This tool will help develop, evaluate, select, and place BMP options based on cost and effectiveness and is based on a system called the Integrated Stormwater Management Decision Support Framework (ISMDSF). The ISMDSF, a generic public domain framework, 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 economic, environmental, and engineering factors.

The design of the ISMDSF is completed and programming work has begun. The ISMDSF has seven key components: framework manager, ArcGIS interface, watershed model, BMP model, optimization model, post-processor, and Microsoft Access database. They are integrated under a common ArcGIS platform. The ISMDSF will support evaluation of BMP placement at multiple scales from a few city blocks to large watersheds.

This paper provides an overview of this research effort and details of the framework design. It also includes modeling concepts and process formulations for the stand-alone BMP model in the ISMDSF. There is currently a confusing array of techniques typically used for analyzing hydrologic regimes and planning for BMPs. Integrating available BMP process simulation techniques into one model is highly desirable. The ISMDSF will provide a unified and consistent approach for evaluating the effects of BMP implementation.

KEY TERMS: stormwater, best management practices (BMPs), GIS, flow and water quality modeling, cost optimization.

INTRODUCTION

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 (USEPA) initiated a research project in 2003 to develop a decision support system for selection and placement of BMPs/LIDs 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) and 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).

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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 and 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 users are expected to have a fundamental understanding of watershed and BMP modeling processes.

WATERSHED-BASED PLACEMENT SCENARIO

The benefits of stormwater management are typically evaluated on a watershed basis. The ISMDSF provides a tool 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 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.

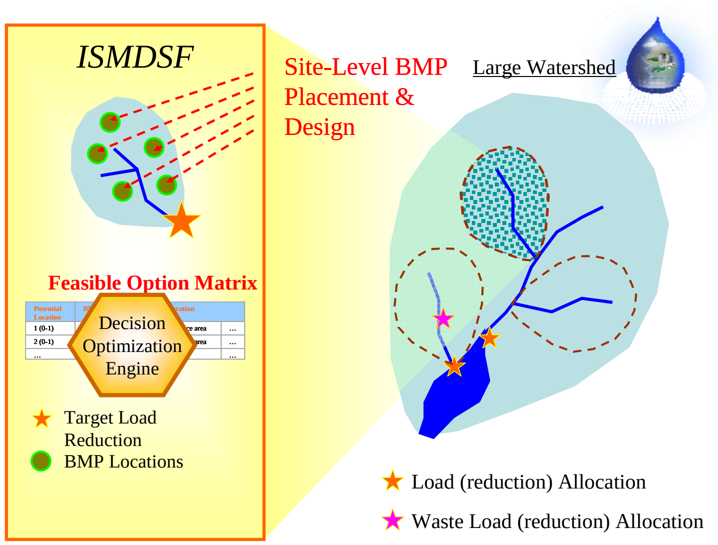

Figure 1. Application of ISMDSF for a Sub-watershed.

CONCEPTUAL DESIGN AND OPERATION 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.

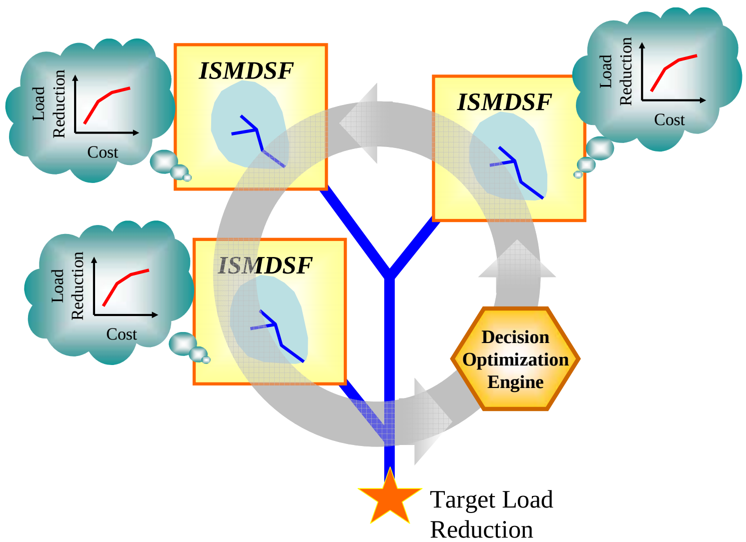

Figure 2. Two-tier Application of ISMDSF.

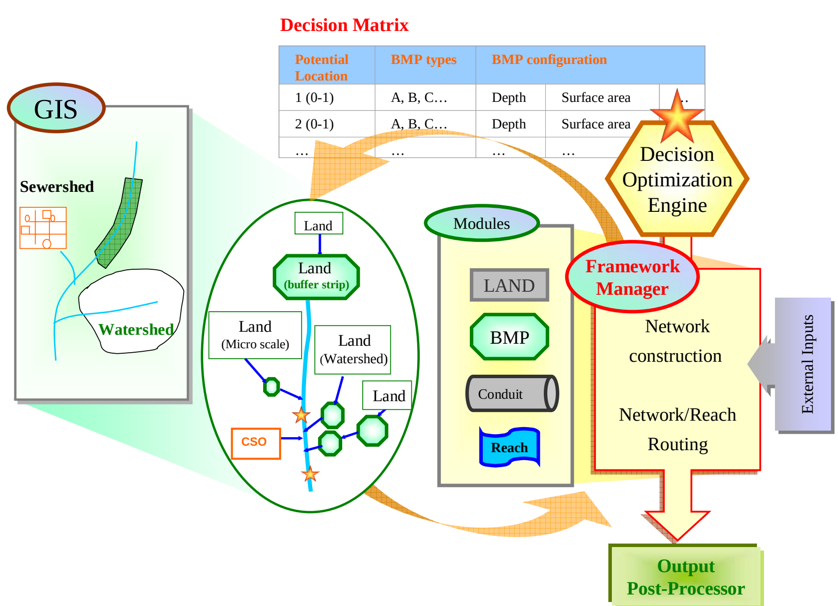

Figure 3. Conceptual Diagram of the ISMDSF System.

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.

The needed simulation codes for the LAND Module will initially be derived mostly from the existing runoff simulation routines in the Storm Water Management Model Version 5.0 (SWMM5) (USEPA 2004). Later, 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 (USEPA 2004). The BMP Module will build on the BMP Module previously developed for Prince George's County (Prince George's County 2001). The Conduit and Reach modules will use the SWMM5 algorithms, referred to as the Transport Block in previous SWMM versions (USEPA 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 are 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.

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.

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.

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.

The Stand-alone BMP Module

The BMP Module is a predictive tool for evaluating the effectiveness of BMP configurations for stormwater and runoff management from multiple sources under various event and/or continuous storm conditions, including critical conditions associated with TMDL development. The BMP Module will build on the one previously developed for the Prince George's County BMP Module, that addresses five major structural BMP types and four major processes shown in Table 1 (Prince George's County 2001). Table 1 also shows the relative dominance of each process for the five BMP types. 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 model uses continuous simulation of hydrographs and pollutant loads so that the effectiveness of LID approaches can be measured on a storm-by-storm basis to better characterize the mode and methods by which BMPs treat stormwater. It uses stormwater runoff time series from models such as SWMM, together with a series of process-based algorithms

Table 1. Representative BMPs and Major Processes Involved in ISMDSF BMP Module.

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.

for BMP simulation. Available processes include weir and orifice to define surface capacity and control, storm swale characteristics, hydraulic transport, infiltration and saturation, underdrain outflow, evapotranspiration, general pollutant removal, and stormwater filtration through a soil media. These processes are organized into two generic BMP classes based on their mode of operation shown in Figure 4: (a) storage/detention, and (b) channel-based. It offers the user the flexibility to design stormwater structural practices such as bioretention cells, rain barrels, roof gardens, vegetated swales, infiltration chambers, wetlands, and off-line regional stormwater retention and detention ponds. By configuring the site layout and routing, the user can also simulate BMPs such as reduced or disconnected imperviousness, as well as benchmark scenarios like pre-developed or developed condition without BMPs for comparison.

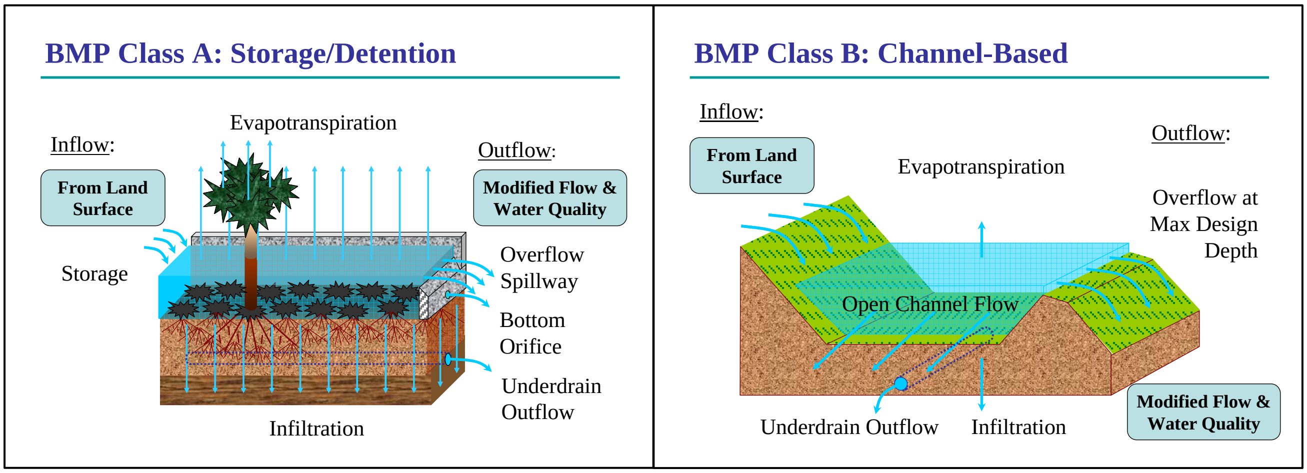

Figure 4. Process Schematics of Two BMP Classes.

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 of 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 AND NEXT STEPS

The ongoing Phase 1 effort to be completed in 2005 has developed a 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.

The Phase 2 effort to be completed in 2008 will expand the functionality and process simulation capability of the ISMDSF and 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.

CONCLUSIONS

This project represents an intensive effort by the USEPA to develop a decision support tool to 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

Any opinions expressed in this paper are those of the author(s) and do not, necessarily, reflect the official positions and policies of the USEPA. Any mention of products or trade names does not constitute recommendation for use by the USEPA.

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