Design of a Decision Support System for Selection and Placement of BMPs in Urban Watersheds

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Abstract

The U.S. Environmental Protection Agency (USEPA) has funded the development of a decision support system for selection and placement of best management practices (BMPs) at strategic locations in urban watersheds. The primary objective of the system is to provide stormwater management professionals with a BMP assessment tool based on sound science and engineering that helps 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 is being designed through a systematic review of modeling needs, technical requirements, current and emerging data management technology, and available watershed and BMP models. The ISMDSF will be applied to a real urban watershed to evaluate its ability.

There are four major design aspects for the ISMDSF development. First, the system provides a robust computer platform for BMP selection, sizing, and placement in the context of several integrated watershed factors and influences. Second, it is applicable to mixed land use urban watersheds, and can perform watershed simulation based on watershed size, scale, anthropogenic, and natural characteristics. Third, it incorporates hydrologic/hydraulic and water quality modeling, integrating surface runoff and direct discharges to surface water bodies, based on relevant data collection. Finally, it will have the capability to objectively evaluate multiple solution alternatives based on cost and the desired water-quality objectives.

Programs that would benefit from the application of the ISMDSF include Municipal Separate Storm Sewer System (MS4) permits under the NPDES Stormwater Program (Phase I and II), Total Maximum Daily Load (TMDL) evaluations, and source-water protection. The ISMDSF will provide a means for objective analysis of management alternatives among multiple interacting and competing factors. The desired outcome

from system application is a thorough, practical, and informative assessment considering the significant factors in urban watersheds. The systematic design process will ensure that the ISMDSF provides a platform with technical sophistication that is consistent with current and emerging technology.

Background

The purpose of this paper is to present the preliminary results of an ongoing research project funded by the USEPA under the Contract No. GS-10F-0076k. The design process was initiated with an evaluation of the modeling needs to meet the project objectives of developing a decision-support framework based on geographical information system (GIS) watershed/BMP database, cost, and hydrologic, hydraulic, and water quality modeling to cost-effectively achieve desired water quality goals (Lai et al. 2003). The needs were further refined to identify technical needs specific to modeling and associated interface capabilities. It was envisioned that the ISMDSF will include three key components: 1) a watershed module that integrates locally derived data with watershed simulation models that predict flow and pollutant loading, 2) a BMP module that performs process-based simulation and cost estimating, and 3) an optimization module that combines performance and cost data of various design alternatives. For hydrologic and water quality modeling, the following four major components are required: 1) watershed/landscape simulation, 2) stream conveyance and pollutant routing, 3) conduit routing, and 4) BMP process simulation. A conceptual design that describes the system components, relationships among components, and general flow of information was developed. The initial design recommendations included a stand-alone BMP simulation and evaluation module to complement both research and regulatory stormwater management needs, thereby

Key Technical Needs Identified

- 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 at a timestep suitable for evaluating short- and long-duration impacts consistent with evaluation of acute and chronic surface water criteria.
- 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 a full range of management practices at a similar level of spatial resolution and technical detail.
- Consideration of distributed or small-scale management practices, practices in series, and larger downstream facilities.
- 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 study area.

providing the essential missing piece in most of today's modeling systems. Initial recommendations also included a definition of the system and interface capabilities. System features emphasized the use of GIS-based visualization and support for developing networks that may include sequences of land parcels, management practices, and stream reaches. Preliminary recommendations included the selection of a system platform that employs ESRI ARC/GIS software and is compatible with current and future versions of comprehensive modeling systems such as BASINS and the EPA TMDL Modeling Toolbox (USEPA 2001, USEPA 2003). Currently available models that are best suited for supporting the four key components of the conceptual design were identified:

- ***Watershed/landscape simulation:*** SWWM (Huber and Dickenson 1988), HSPF (Bicknell et al. 1993), LSPC (Tetra Tech 2002).
- ***Stream conveyance and pollutant routing:*** HSPF/LSPC RCHRES, SWMM Routing (TRANSPORT Block in version 4.4).
- ***Conduit routing:*** SWMM EXTRAN/TRANSPORT.
- ***BMP process simulation:*** Prince George's County BMP Module; selected SWWM algorithms, including detention ponds and structural options; and selected buffer zone simulation techniques from VFSMOD (Muñoz-Carpena and Parsons 2003).

Review of Available Models

Models that have relevance to one or more areas of ISMDSF were selected for review, with emphasis on selection of models that are in the public domain or are available for distribution without charge. Proprietary models with limited information on model algorithms and documentation were excluded from the review. Watershed and BMP models selected for review are listed in Table 1.

Table 1. Available models reviewed

Watershed Models	BMP Models
SWMM, HSPF, LSPC, WAMview, WARMF, SLAMM, P8 UCM, ANSWERS, CASC2D/GSSHA, 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 Systems: LIFE

Table 2 summarizes key factors considered in BMP model evaluation and comparison. A majority of models simulate retention type facilities, and consider sediment deposition and first order decay of pollutants. Only a few models include the effects of vegetation, nutrient cycling, and resuspension of sediment and associated pollutants. VFSMOD considers the effects of buffer strips on hydrologic and pollutant removal explicitly.

The computer software technology and utilities used in the above models were also reviewed to identify the functionality and recent trends in software development. The following items were considered: 1) GIS features, 2) subwatershed/channel network representation, 3) data management utilities, 4) model code, and 5) interface code.

Table 2. 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 trench, dry well, porous pavement • 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 equation • 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 equation • Kinematic wave • University of Kentucky algorithm	• Sediment	Muñoz-Carpena and Parsons (2003)
DMSTA	• Wetland • Detention basin	• Storage • Seepage (in & out) • Evapotranspira-tion • 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 model • First order decay (k-C* model)	• User-defined pollutants	Wong (2002)
SWMM	• Detention basin • Infiltration practices	• Infiltration • Sedimentation • First-order decay • Universal removal equation	• Horton and Green-Ampt equations • Camp's theory for quiescent condition, Chen for turbulence	• User-defined pollutants	Huber and Dickenson (1988)

Many of the currently available models use ArcView as the data preparation/ visualization software, and use different programming platforms (like C or Visual Basic) for their pre- and post-processing interfaces. Most models include some visualization, as well as input and output processing support. However, none of the models reviewed used the latest trends in software systems. New interface development has the opportunity to employ the latest and most efficient software systems such as ArcGIS and ArcHydro structures (Maidment 2002).

The ISMDSF will selectively incorporate the algorithms and modeling systems in the existing models, while meeting the needs of the design and continuing innovation and growth of the framework. The following discussion contains a review of the currently available models with respect to the key components (hydrology, sediment, pollutant loadings, and reach routing) needed for the modeling system.

Land Simulation

Hydrology. Several watershed models, including SWMM, SLAMM (Pitt and Voorhees 2000), HSPF, and LSPC, can provide time series hydrology and pollutant loading at an hourly time step or less. This small temporal resolution is needed to generate time series flow and pollutant concentrations and loadings from small catchments for input to BMPs and eventually receiving waters. 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 either large time steps (i.e., one day or greater) or provide insufficient description of time-variable rainfall-runoff processes. Other models, such as CASC2D (Ogden 2001) and KINEROS (USDA 2003), use a cell- or grid-based framework for distributed modeling of the watershed landscape, allowing for more detailed simulation and sensitivity in evaluation of BMP placement. However, the greatest limitation of distributed models is the high computational needs for larger watersheds and the availability of spatially-detailed data. The spatial details 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 the ISMDSF. The initial recommendation is to use the pervious and impervious land simulation concept similar to that used in SWMM, HSPF, and 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 runoff volume determines the washoff and delivery of sediment to a stream segment. Because the erosion and transport processes are energy-driven, the model calibration will change with the time step and resolution of the rainfall data driving the model. For impervious land surface simulation, both HSPF/LSPC and SWMM use a similar sediment buildup and washoff formulation. HSPF and SWMM allow the user to apply preventive practices, such as street sweeping, to assess the effectiveness of sediment reduction from urban streets during a storm event. SWMM includes three methods for estimating sediment in urban runoff: (1) a rating curve, (2) a buildup and washoff approach, or (3) the Universal Soil Loss Equation (USLE) for pervious surfaces.

While USLE is a widely used empirical formula in models for prediction of soil erosion, some limitations of this approach are evident from the project requirements discussed above. The crop, soils, and precipitation intensity parameters supporting the USLE equation are based on long-term assessments of soil loss data for relatively large drainage areas (greater than five acres); the equation was not intended for making predictions based on specific rainfall events for relatively small drainage areas. The prediction results, though meaningful as a monthly or annualized loading estimate, are limited because they may not adequately represent the temporal variability of individual storms or storms in series for smaller catchments typically encountered in urban watershed application. In conclusion, shorter/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 the ISMDSF.

Runoff 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, the models will consider some of the pollutant mass as a fraction of the simulated sediment delivery. Base flow and interflow concentrations in HSPF and LSPC are specified as constant concentrations, but may be specified to vary monthly. SWMM does not allow for a variable buildup rate; however, it allows the user to specify the equation and method used (e.g., power-linear, exponential, or Michaelis Menton). As with its sediment simulation routines, SWMM allows for pollutants to be specified as either a function of the flow rating curve or as a buildup and washoff process. Pollutants can also be associated with sediment by expressing the pollutant mass as a fraction of sediment. Simpler models, such as GWLF (Haith et al 1992) and P8 (Walker 1990), use a fixed concentration of a pollutant in runoff and sediment, which makes them insensitive to changes in concentration or availability of pollutants over time. These models also use daily or monthly time steps; therefore, 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 ISMDSF design.

Flow and Pollutant Routing. Runoff, sediment and pollutants must be collected and routed through a flow network (e.g., conduits, channels, and streams) before entering a receiving water body. Many watershed models, e.g., SWMM and HSPF, include stream routing modules. SWMM has the additional pipe or conduit routing capability. 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 (i.e., less than one 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 have the most sediment and pollutant transport capabilities for sediment deposition, scour, decay, and temperature simulation. SWMM's routing includes first-order decay and settling, but does not include options for temperature, biological transformation, or algal growth. SWMM, however, can simulate complex hydraulics using a fully dynamic wave method.

For large river systems with longer retention times or waters that are tidally-influenced, an external linkage (outside the ISMDSF) with specialized receiving water models, such as EFDC (Hamrick, 1992) and WASP (Wool et al. 2003) will be needed to evaluate downstream receiving water impacts. Specialized receiving water models like WASP are also best suited for evaluating eutrophication processes and dissolved oxygen.

BMP/LID Models

Simulation of BMPs usually involves simplified representation of percent removal, partial or complete representation of the processes of hydraulic controls, settling, and transformation of pollutants. A number of available watershed models (e.g., SWMM, HSPF, LSPC, and SLAMM) can mimic BMP simulation by adjusting existing hydrologic and pollutant transport parameters. However, guidance for the application of watershed models such as SWMM and HSPF for BMP simulation is limited. Consistent application is difficult, and in the absence of standardized guidance and documented applications, intensive data collection and calibration is necessary. Some models, such as WAMView, can be adjusted to represent land practice BMPs based on the United States Department of Agriculture (USDA) Curve Number guidance (SWET 1999). Many of the currently available published BMP models are propriety (e.g., MUSIC). Specialized BMP simulation tools such as VFSMOD (Muñoz-Carpena and Parsons 2003) focus on specific BMPs, in this case vegetative filter strips.

Of the available systems, the Prince George's County BMP Module provides the capability to simulate a wide range of BMPs with particular emphasis on site-scale, distributed systems, using a process-based simulation approach to address hydrology and pollutant removal (Cheng 2002 and Prince George's County 2002). One specialized need for BMP simulation is the ability to handle highly distributed management techniques such as those employed in Low Impact Development (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. The Prince George's County has provided the system to users upon request and is willing to provide USEPA with the code for adaptation and incorporation into the ISMDSF.

For the process simulation of BMPs, it is recommended that the Prince George's County BMP Module is augmented by the selected BMP processes contained in models such as SWMM, SLAMM, and P8 for incorporation into the ISMDSF. In particular, BMP simulation techniques for stormwater ponds and detention structures can be provided by SWMM. The most recent developments for SWMM Version 5 will be evaluated for incorporation or linkage (USEPA 2002). For BMPs, such as riparian buffers, specialized simulation techniques are needed. Riparian buffers can be addressed by using the procedures in VFSMOD or by adapting the land-to-land transport routines used in SWMM or HSPF.

Conclusions and next Steps

The review of available models and BMP analysis systems confirms the initial selection of a short list of models best suited for integration into the ISMDSF 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. Furthermore, the ability to link the ISMDSF to other existing models provides analytical versatility for complex watershed and receiving-water-linked systems.

The ISMDSF project will continue with finalization of the detailed conceptual design, framework implementation, and prototype application. The short list of models and their individual components will be further evaluated for the simulation of desired processes. The detailed design will accomplish the following:

- Identify the specific components or algorithms of existing models that will be incorporated into the ISMDSF
- Articulate the structure and software systems needed for the ISMDSF
- Characterize the interfaces and linkages needed between the ISMDSF and other external entities (such as receiving water modeling systems)

The design will also outline a strategy for calculating costs and providing optimization of BMP selection and placement, but their actual integration into the ISMDSF will be the focus of the subsequent phase effort.

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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