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LINKING GIS WITH WATERSHED MODELING AND URBAN MANAGEMENT PLANNING

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Abstract: Geographic Information Systems (GIS) establish relationships between (1) spatial information, such as land use, stream networks, and their hydrologic and geometric characteristics; (2) point and time series data, such as industrial and municipal discharges, stream flow and water quality data; and (3) watershed and water quality simulation models to provide a technical platform to support resource management decisions. These linked systems can support inventories of ecological resources, prioritization of watersheds and identification of priority areas, and evaluation of watershed management alternatives. By using a GIS platform for watershed assessment and modeling, agencies can consider effects of anticipated changes in land use and implementation of watershed management in their routine planning and decision-making.

To support watershed management in Prince George's County, Maryland, USA, a Watershed Protection System (WPS) was developed to simulate pollutant transport, prioritize watersheds based on type and magnitude of environmental impairments, and evaluate watershed management plans. The WPS system has successfully been applied County-wide for assistance in decision-making on watershed management. A description of the conceptual design and preliminary results of the system applications is presented in this paper. This paper encompasses the development of a link between data coverages, watershed targeting, pollutant prioritization, watershed modeling analyses, data post-processing, and comprehensive watershed assessment and management.

INTRODUCTION

Watershed models can be used to simulate runoff/stream flow, erosion/ sedimentation, and pollutant loadings resulting from the interaction of stormwater runoff with land uses and land activities, topography, and other characteristics of watersheds. With adequate calibration and verification, watershed models can predict future runoff and pollutant loadings caused by new development of watershed area. Urban watershed planning techniques include statistical analysis of simulation results, potential pollution source ranking/prioritizing, and watershed impacts correlation due to various pollutant control alternatives.

Geographic Information Systems (GIS) are powerful tools for handling spatial data in sophisticated ways (Goodchild et al., 1993). In environmental modeling, GIS has been widely used to interpret and integrate spatial and temporal data. GIS systems that integrate point and nonpoint source (NPS) management are becoming a major tool for water quality managers. Several researchers have used GIS and environmental simulation models for NPS pollution assessment, especially for prioritizing potential pollution through displaying maps for visual interpretation (Chen et al., 1994). However, there is no GIS system which integrates watershed modeling and planning to evaluate urban watershed management.

As part of its comprehensive effort in stormwater and NPS pollution management, a Watershed Protection System (WPS) was developed for Prince George's County, Maryland, USA. The system is a tool for watershed management and planning in urban areas which integrates GIS, watershed modeling, and urban watershed planning. This integrated planning tool facilitates the evaluation of various urban management measures to control stormwater runoff and pollutant loads. This paper describes the development of a link between data coverages, watershed targeting, pollutant prioritization, watershed modeling, data post-processing, and comprehensive watershed management and planning. Examples of the application of this integrated WPS system to county, watershed, and site level analyses are also presented.

INTEGRATED SYSTEM DEVELOPMENT

The menu driven WPS system was developed under the standard SUN workstation X-view window platform. ARC/INFO software was selected for the GIS system. The interface between databases, data input/output, watershed model, and watershed management planning was developed by using Arc Macro Language (AML).

Based on various phases of the watershed and stormwater planning developed by the County, the integrated system considers water quality planning scenarios depending on the stage of watershed development, pollution prevention, and land use planning. Three levels of urban watershed assessment are available through the WPS system: (1) county-wide screening; (2) watershed-based evaluations; and (3) site-specific quick response analyses. As an urban watershed planning tool, the integrated system can be used to (1) prioritize watershed and identify the pollutants of concern; (2) set pollutant removal goals; (3) target land uses; (4) and pollution source; (5) evaluate pollution control practices; and (6) screen and develop watershed management plans. Figure 1 presents a schematic of the WPS components.

Watershed Model

There are numerous watershed and nonpoint source models applied by watershed planners ranging from simple and empirical models, to detailed and more mechanistic ones (U.S. EPA, 1992). A U.S. EPA supported watershed model - Storm Water Management Model (SWMM) was selected for this integrated system. The SWMM model (Huber and Dickinson, 1988) is a continuous simulation model and has been widely used for urban land uses. It simulates a wide range of processes affecting hydrology and water-quality including rainfall, snowmelt, surface runoff, subsurface contributions to runoff, flow routing, storage, and treatment of flows (Maidment, 1993). The model can predict up to ten pollutants (user-defined) in stormwater runoff, such as suspended solids, heavy metals, and nutrients.

In this study, daily continuous output data from SWMM simulation was generated for nine land use types provided by the County. The land use types are as follows: (1) low density residential; (2) medium density residential; (3) high density residential; (4) commercial; (5) open space; (6) industrial; (7) agricultural; (8) forest; and (9) barren land. Each land use category was first modeled and calibrated based on the local historical weather conditions and land use activities as a 100-acre generalized basin by running the RUNOFF block in the SWMM model. Daily runoff and pollutant concentrations over an 8-year simulation period were generated for each generalized basin, and then imported into ARC/INFO files for runoff and pollutant loadings.

This approach was used for preliminary watershed planning study. Thirteen parameters selected for this study are: (1) runoff; (2) total suspended solids; (3) dissolved solids; (4) total nitrogen; (5) ammonia; (6) total phosphorus; (7) dissolved phosphorus; (8) 5-day biochemical oxygen demand; (9) cadmium; (10) copper; (11) zinc; (12) manganese; and (13) lead. Two input files per basin were developed because the SWMM model can only simulate up to 10 parameters per run. The first input file includes the flow, solids, and nutrient parameters and the second file includes flow and metals parameters.

A more complex U.S. EPA supported watershed model, Hydrologic Simulation Program - FORTRAN (HSPF), was selected for comprehensive watershed analysis. HSPF can simulate major physical, chemical, and biological processes affecting water quantity and quality from complex watersheds to and within receiving water bodies (U.S. EPA, 1993). The integration of HSPF with GIS is under development to provide more detailed analyses, including assessment of sitting and sizing of stormwater treatment facilities.

Watershed Simulation and Management Program

The Watershed Simulation and Management Program (WSMP) is a part of the WPS system which incorporates urban watershed analysis, management and planning techniques with the SWMM model. The WSMP program, written in CLIPPER-based language, is user friendly and menu driven to allow users to simulate watershed land use runoff and pollutant loadings, to compare two watershed simulation results, to evaluate existing best management practices (BMPs) for pollution reduction, and to project future BMPs. The pollutants simulated in the WSMP program are the same as those simulated in the SWMM model. A FORTRAN program - PGFORNEW was developed to simulate watershed runoff and pollutant loadings using the daily data generated from the SWMM model in each generalized 100-acre basin.

The WSMP provides tabular and graphical simulation results for single watershed or two watersheds, including land use acreages and distribution (pie charts), monthly curves for runoff and pollutant loadings, bar charts of monthly summary of runoff and loadings for each year, and bar charts of annual, mean monthly, and mean annual simulation results. The program can also display simulation results for each 100-acre basin to identify the potential pollution sources.

Watershed Land Use Delineation

Prince George's County, MD, located within the fast growing Washington-Baltimore metropolitan area, encompasses over 485 square miles with high density urban and industrial land uses. The County has been delineated into forty one watersheds. The watershed boundaries were delineated from Maryland National Park and Planning topographic maps and digitized into AutoCAD for further analysis. The Maryland State Plane Coordinate System allows intersection of the digitized watershed boundaries with existing land use, soils, and other watershed boundaries. The area of each watershed was calculated and exported to a drawing exchange file (DXF) format for transfer to ARC/INFO. Once delineations were successfully completed, total acreage was estimated for each watershed.

It is important in urban watershed planning studies to delineate the boundaries of different land uses in order to target control efforts (Ventura and Kim, 1993). Land use distribution of each watershed was determined using the 1990 digitized land use data provided by the Maryland Office of Planning and verified by field observations. All land use data was categorized into nine land use types as defined above and stored in a spatial-data base for further analysis.

GIS Interface and Implementation

GIS has real power when it associates spatial data with modeling information (Shea et al., 1993). A GIS interface was developed to handle spatial and non-spatial data, support watershed modeling efforts, retrieve necessary data for watershed analysis, prioritize pollutants, and evaluate watershed management plans. In order to execute the WSMP program for estimating the surface runoff and associated pollutant loadings, land use type and its acreages within each watershed are required. Existing land use data stored in the spatial-data base can be used. The interface allows users to change the land use data based on proposed future land use development plans. The PGFORNEW program is then called and executed to generate runoff and pollutant loadings for an 8-year period. The daily simulation outputs for the watershed are then stored in another database for the application of WSMP program.

The WSMP program works under SunPC Window environment. In order to link the WSMP with the watershed model and the GIS user-interface platform, AML programs were developed to obtain the land use data, call and execute the PGFORNEW program, convert UNIX simulation outputs to DOS formats, re-login into SunPC Window environment, execute the WSMP program, and return to UNIX's X-Window environment. AML programs were also developed for other interfaces, including data retrieval of watershed characteristics and chemical/toxicological characteristics, existing and future BMP analysis, and watershed and pollutant prioritization.

EXAMPLES OF WPS APPLICATION

County-wide Screening

For county-wide screening and analysis of urban water quality problems, a watershed ranking method was developed based on simulated pollutant loadings. Pollutant loadings were simulated from the SWMM model and the WSMP program with considering the existing BMP's pollutant reduction. Mean annual pollutant loads were then calculated for the watershed pollutant rankings. The watershed rankings can be made based on one of thirteen parameters defined before. An example of the county-wide watershed rankings based on mean annual total phosphorus loadings is illustrated in Figure 2. Through the watershed ranking map, watershed planners can identify which watershed has potential pollution problems for the particular pollutant of interest to users.

Based on land use development plans, users can modify the existing land uses and re-run the WSMP program for each modified watershed. The WPS system can then be used to compare the existing and future land use conditions using the county-wide watershed ranking method. After comparison of simulation results of pre- and post- land use development, users can decide which watersheds need urban BMPs to reduce pollutant loadings.

The WPS system also allows the user to compare mean annual loadings of selected watersheds to mean annual loadings of a reference watershed to determine both the loadings and percent reduction required to equal that of the reference watershed (Prince George's County and Tetra Tech, Inc., 1994). The reference watershed can be an existing watershed or can be created by the GIS interface as a future watershed.

Watershed-based Evaluation

Watershed-based evaluation, the second level of the WPS application, allows users to analyze the stormwater impacts on the runoff and water quality within a watershed. Detailed analyses of watershed and pollutant characteristics can be performed through the integrated WPS system. Information about the existing BMPs in watersheds can be displayed graphically and tabularly. The pollutant reductions due to the application of the existing and future BMPs are calculated by applying watershed-wide pollutant removal efficiencies. Figure 3 presents evaluation steps for Low Beaverdam Creek watershed.

Once the WSMP program is executed, the user can view the monthly, annual, mean monthly, and mean annual runoff and pollutant loadings for a specified watershed. Comparison of simulation results from the existing watershed with proposed watershed can also be made to identify the needs for applying urban BMPs. Mean annual and pollutant loads for the watershed can be used to compare with local or State's water quality criteria for identifying non-compliance discharges.

Site-specific Quick Response Analysis

As a third level of the WPS application, site-specific quick response represents a special tool to analyze stormwater runoff and pollutant loads at a user-defined site. This tool is under development and will be able to simulate the reduction of runoff and pollutant loadings for each type of urban structural BMPs. A continuous simulation model - Structural BMPs Model (SBMPM) was developed to simulate hydrologic and water quality impacts of most common urban structural BMPs such as dry/wet ponds, wet detention ponds, wetlands, infiltration basins/trenches, and grassed swales. The FORTRAN-based SBMPM model is easily to incorporate into the WSMP program as a complete watershed planning tool. The SBMPM model was tested and applied to a 495-acre site, the Kettering subwatershed in the County.

Figure 4 presents the preliminary simulation results of the SBMPM application on a wet detention pond in the subwatershed. The simulation results indicate that mean annual removal efficiency is about 81 percent for total suspended solids (TSS) and 64 percent for total nitrogen (TN) in the detention pond. The mean monthly summary results may provide information about pollutant removal changes due to seasonal weather variation. The pollutant removal efficiencies calculated from the SBMPM model for the particular site can be used in the entire watershed for further watershed-wide and county-wide analysis.

The WPS system provides a comprehensive urban watershed management and planning tool at the county-wide, watershed-based, and site-specific levels. The system can simulate urban runoff and pollutant transport, prioritize watershed based on pollutant loadings, and evaluate watershed management plans.

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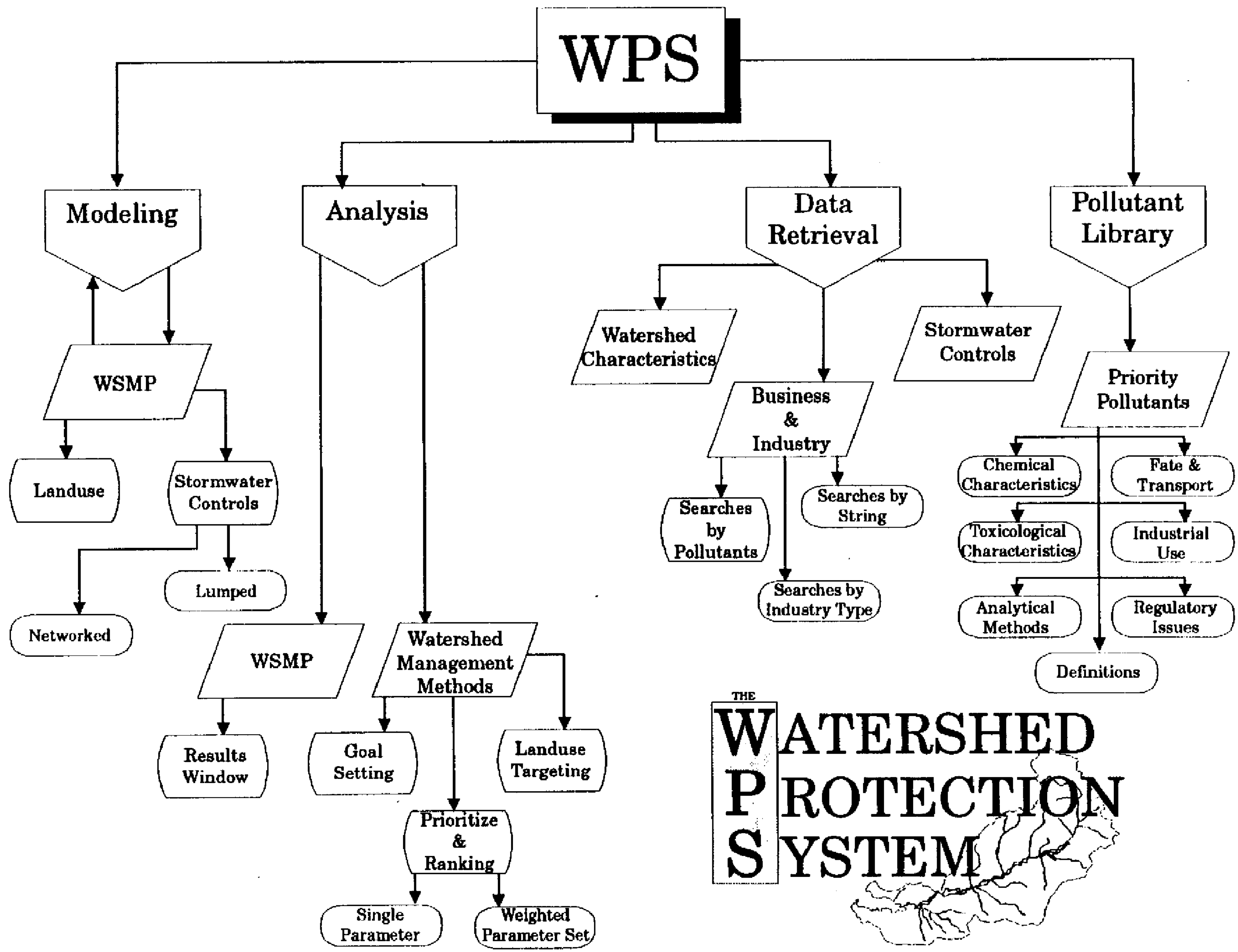


Figure 1. Schematics of the WPS Components and Operation

Mean Annual Total Phosphorous Loadings (lbs/Mcf)

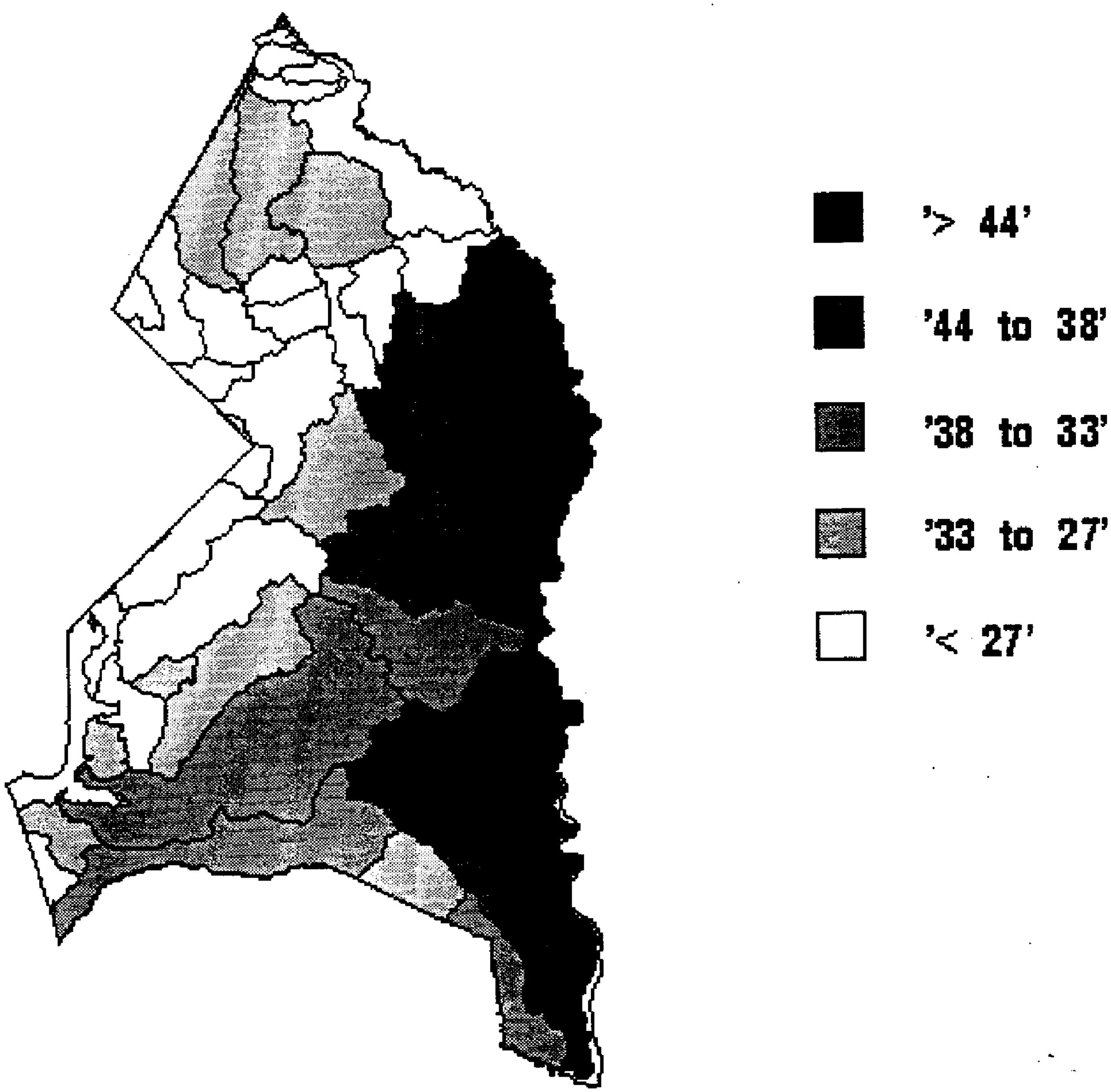
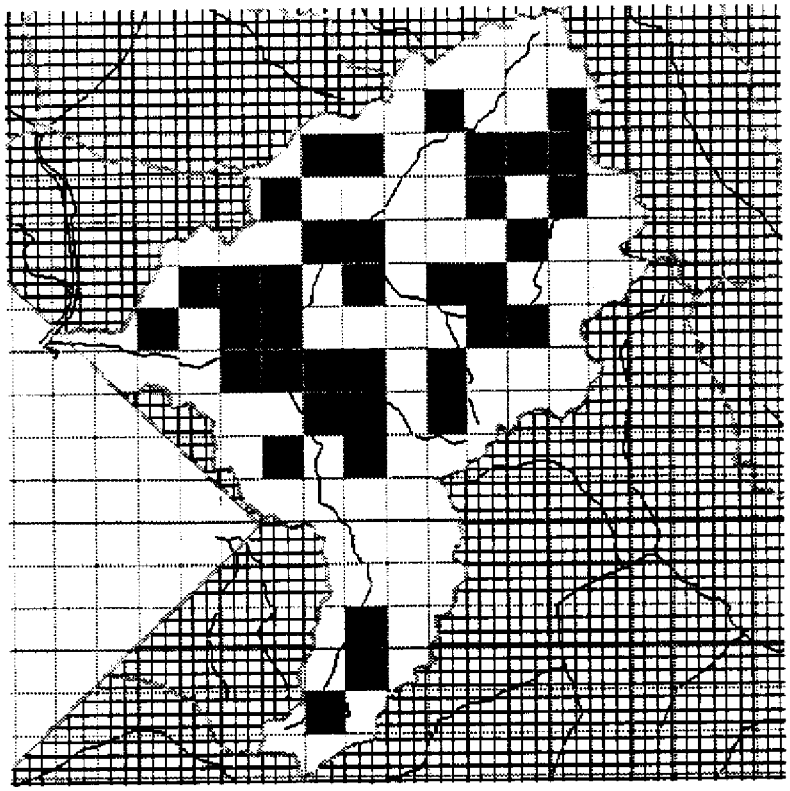


Figure 2. Example of County-wide Watershed Rankings Based on TP Loadings.



LANDUSE	EXISTING (acres)
FOREST	2342.81

Landuse Base Map

FOREST

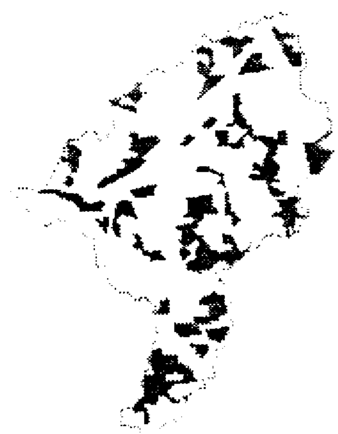


Figure 3. Steps and graphic output for Lower Beaverdam Creek evaluation.

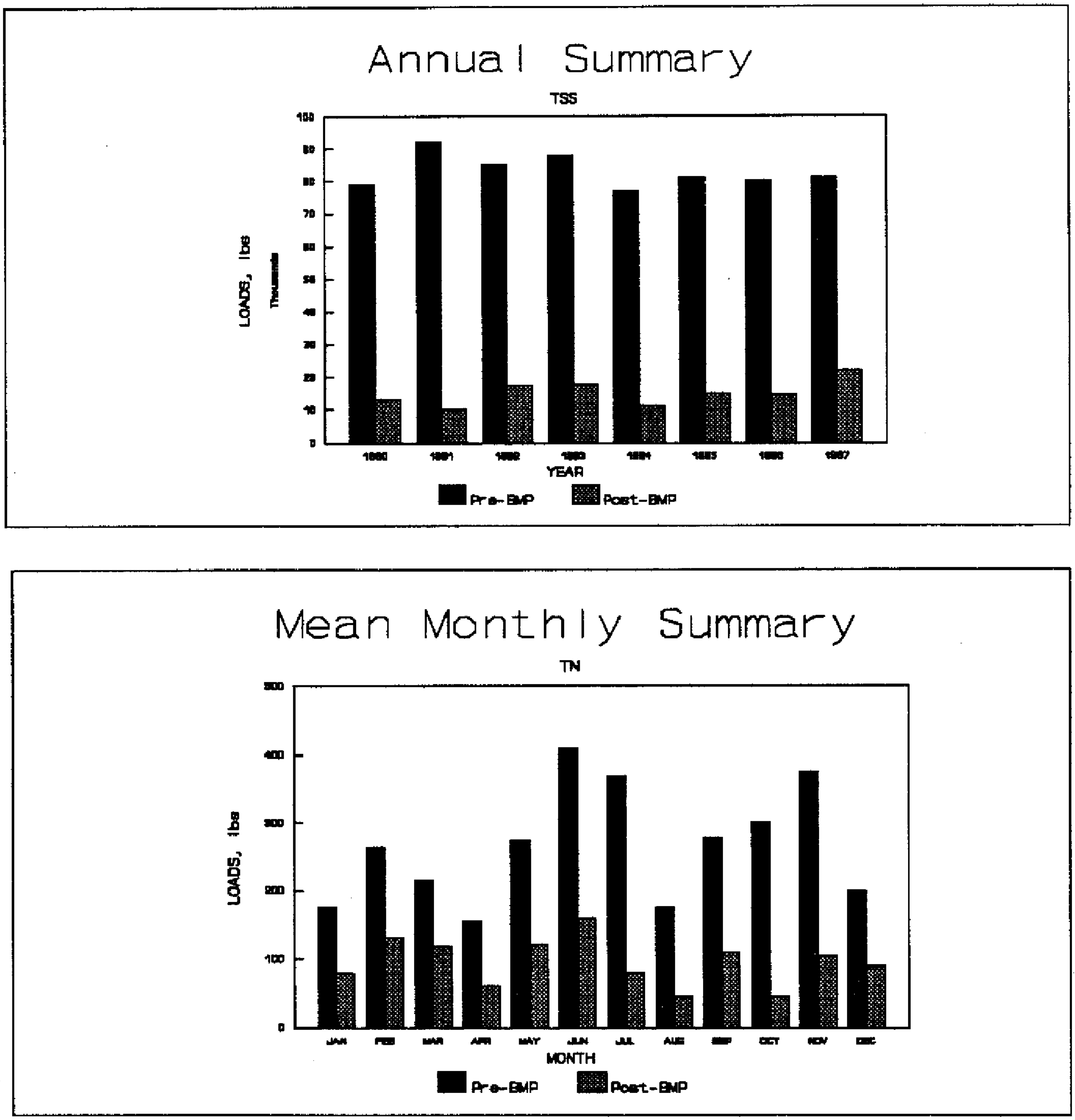


Figure 4. Preliminary Results of the SBMPM Model Application