

Nonpoint Source Pollution Management for RiverbasinL: Decision Support System Using Model-GIS-RDBMS Linkage

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Abstract - A Framework based on a direct linkage methodology among a distributed parameter nonpoint source pollution model with a Geographic Information System (GIS) and a relational database management system (RDBMS) was developed to investigate a watershed-scale nonpoint source pollution problem, management and planning for an area consist of a riverbasin and lakes. Distributed parameter nonpoint source pollution model used was an event-based model that simulates runoff and the transport of sediment and pollutants from mainly agricultural watersheds. Distributed parameter models are often applied to large problem domains. Linking such models to GIS and database management system can facilitate better data storage, manipulation and analysis than conventional methods. In this study, rather than manually implementing model, extracted data are integrated in an automatic fashion through a direct linking between the model engine and GIS. This direct linkage results in a powerful, up-to-date tool that would be capable of monitoring and instantaneously visualizing the transport of any pollutant that the model can simulate. Thereby, it reduces the time required to analyze the numerical output from the model, and enables users to identify critical areas of nonpoint source (NPS) pollution and furthermore, to perform various "what if" scenarios to support the decision making processes such as Best Management Practices (BMP) for the riverbasin. A case study was performed on a watershed of 98.1 km² (=24240 acres) in the upper segment of the Sand Hill River Subbasin in Minnesota by using this framework implementation. Simulated results showed that the optimal BMP scenario achieved an average reduction of about 26% from current nonpoint source pollutant levels on soluble and sediment-attached nitrogen and phosphorous. Especially, this optimal BMP scenario was most effective in controlling the erosion and sediment yield. As a result, a maximum 50% reduction of sediment yield was observed.

1 – INTRODUCTION

Nonpoint source pollution (NPS) is a type of the pollution generated from diffused sources in the public and private domain. The Environmental Protection Agency (EPA) defines the nonpoint source pollution as pollution originating from urban runoff, construction, hydrologic modification, silviculture, mining, agriculture, irrigation return flows, solid waste disposal, atmospheric deposition, stream bank erosion, and individual sewage disposal. More than fifty percent of the pollution entering the nation's waters comes from nonpoint sources (Tyler, 1992), and it is responsible for almost two-thirds of the pollution that prevents achievement of water quality standards (Alm, 1990).

Nonpoint Source Pollution management is highly dependent on hydrologic simulation models. Evaluating alternative management strategies through experiments and a limited amount of field measurements is not feasible, and a modeling study is often the only viable means of providing input to management decisions. The hydrologic system was commonly simplified in the past as a "lumped model." Under this simplification, the spatial distribution of parameters lost their real meaning in hydrologic modeling. In contrast to this simplification, a distributed parameter model maintains the spatial distribution of the parameters. Therefore, the application of distributed parameter models is of practical necessity especially in case of the nonpoint source pollution management. The major disadvantage of distributed parameter models are the large amounts of time required for assembling and manipulating the input data sets. The distributed nonpoint source pollution models used to study pollutant transport and erosion easily generate towering amounts of data for analysis in even a small watershed. On a large non-homogeneous watershed, a complete simulation and analysis can be very time consuming.

A logical step in improving the quality of the hydrologic modeling would be the integration of spatially distributed parameter models with practical data management scheme such as the geographic information system (GIS) and database management system (DBMS) (Arnold et. Al, 1998; Rothenthal et al., 1995). This integration of distributed hydrologic model-GIS-DBMS can be defined as a tool to collect, manage, analyze, simulate and display spatially varying information. This paper

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describes direct Model-GIS-DBMS linkage to: (1) effectively pinpoint critical areas where resources are threatened, (2) give the necessary information instantaneously based on BMP scenario simulations for further remediation and conservation efforts, (3) provide quality information to decision-makers cost effectively, and (4) help impartially distribute incentives and regulations used for water quality management.

2 - STUDY WATERSHED

The Sand Hill River Watershed District of the North Central Minnesota had proposed building a dam which will create a permanent pool of 5 km² (=1,217 acres) near the northwestern Minnesota town of Winger for flood protection on the main stem of the Red River of the North basin. The feasibility of the dam project has been controversial since it was first proposed more than 10 years ago due to concerns regarding low annual average flow rate and water quality problems. No definite solutions or alternatives for alleviating these problems have been investigated (Polk County Water Planning Task Force, 1990). This paper will investigate the application of a distributed parameter hydrologic model, AGNPS (Agricultural Nonpoint Source Pollution Model) and GIS-DBMS direct linkage to the upper segment area of 98.1 km² (=24,240 acres) which has an outlet at the proposed dam site.

The upper segment has a complex topographic pattern which consists of moraines, potholes, small lakes, wetlands and marshes that affects its hydrologic characteristics substantially (Figure 1). For the analysis of such complex topographic features, a spatially distributed model such as AGNPS is more suitable than a conventional lumped model. (Meals and Budd, 1998) Also nonpoint source pollution management on such complex topography is difficult to plan and highly dependent on simulation models because nonpoint source pollution is site specific. Evaluating alternative management plans through field experiments is usually not feasible, and thus simulation study is often the only practicable means of providing input to management decisions. In this sense, AGNPS is an ideal distributed parameter model for the study area to pinpoint "critical" areas of sediment and nutrient production in a watershed, and to estimate the potential benefits of implementing Best Management Practices (BMP) to alleviate current water quality problems.

3 - AGRICULTURAL NONPOINT SOURCE POLLUTION (AGNPS) MODEL

The AGNPS model was developed by the U.S. Department of Agriculture, Agricultural Research Service in cooperation with the Minnesota Pollution Control Agency (MPCA) and the Soil Conservation Service (Young et al., 1987, 1995) for the analysis of large agricultural watersheds ranging in size between 500 and 23,000 acres. The model was originally developed (1) to

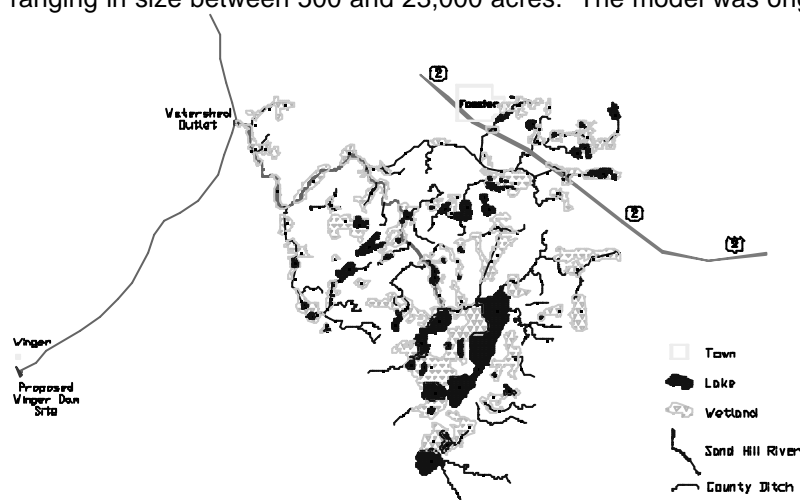


Figure 1 - Topographic Patterns of the Study Watershed

analyze and provide estimates of runoff with primary emphasis upon sediment and nutrients transport, from agricultural watersheds, and (2) to compare the effects of various conservation alternatives upon implementation on the management practices of the watershed.

AGNPS is a cell-based distributed parameter hydrologic model which requires 22 categories of information such as landuse, surface condition, channel data, fertilization, etc. for each cell, and is capable of generating both estimates of quantity and quality of runoff from the watershed for a given storm event (Young et al., 1987, 1995). Cell segmentation of 2.5-, 10-, and 40-acre parcels in the study watershed is shown in Figure 2. Analysis of pollutant loads from feedlots, investigations into the effects of implementing various conservation practices including impoundment terraces, and the ability to output water quality characteristics at intermediate points throughout the watershed network are all within the model's capabilities. The erosion component in the AGNPS model assumes overland erosion, channel erosion and deposition in impoundments. Field topography is the major factor in determining the type of flow, i.e. overland, overland-channel, overland-channel-impoundment, etc.

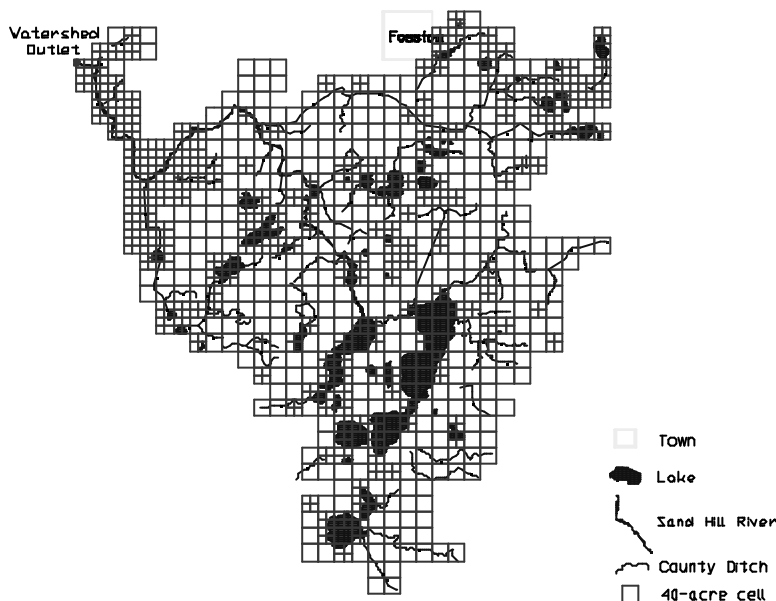


Figure 2 - Cell Segmentation of 2.5-, 10-, and 40-acre Parcels in the Study Watershed

4 - DIRECT LINKAGE BETWEEN MODELS AND GIS

There have been several attempts to integrate GIS with existing hydrologic models for the watershed modeling and simulation. Hydrologic modelings were performed with the extracted data from the GIS to execute available models. In most cases, either the data manipulations were done manually before running models, or all necessary data manipulation schemes such as transformation of data formats and extraction of usable data for existing models had to be provided by specially written software.

In summary, the main focus in the GIS usage with existing models has been one-directional data extraction to the model rather than direct data exchange to and from the model. It is imperative to develop data handling procedures to prepare inputs to the model, and to effect changes in watersheds, and procedures to analyze and display corresponding model results within the GIS environment. This bilateral linkage approach through effective use of DBMS will contribute to better hydrologic modeling and water resources management.

In this study, methods were developed for directly linking the distributed parameter model, AGNPS with the vector-based GIS, Geo/SQL (Generation 5 Technology, 1990) and the relational database management system (RDBMS), ORACLE in terms of pre and postprocessing of data, in applying the GIS to the ongoing water resources planning and decision making process in the study area. This direct linkage results in a powerful, up-to-date tool that would be capable of monitoring and instantaneously visualizing the transport of any pollutant that AGNPS can simulate. Thus, the linkage is truly bilateral rather than the conventional one-way data extraction setup for input preparation. The

advantage of linkage is that because the distributed parameter model such as AGNPS is often applied to large problem domains, a linkage to GIS and RDBMS may be a more appropriate tool for data storage, manipulation and analysis than a collection of many input and output files.

Visualization of the spatially varying data and time-dependent data such as runoff or sediment yield at the outlet will greatly enhance the ability of conservation managers to make further analyses and to make proper decisions. Furthermore, the graphical display may provide an indication of problems due to erosion and pollutant movement on a watershed and help pinpoint critical locations for further study and/or control action (Yoon and Disrud, 1994).

5 - METHODOLOGY

The basic data layers for the study area were developed by digitizing the relevant maps, including USGS-10 foot interval contour quadrangle maps of 1:24000 scale and SCS Soil maps. The spatial land cover/land use data were compiled from LANDSAT thematic maps. Prepared data were inserted into ORACLE database as separate characteristic data groups so that the maximum flexibility can be assured when various scenarios are applied later. Then data from the database and digital base layers were georeferenced to create a spatial database of study area. Sets of programmed SQL (structured query language) of the ORACLE database management system were implemented to extract necessary information in a usable data format whenever a specific area is selected in GIS for AGNPS.

After each AGNPS execution, an output file containing estimates of runoff volume, peak flowrate at the watershed outlet, area-weighted erosion for both upland and channel areas, sediment delivery ratio, sediment enrichment ratio, mean sediment concentration, and total sediment yield for different sediment particle size classes, and a nutrient analysis, which includes N, P and COD mass per unit area for both soluble and sediment absorbed nutrients, and N, P and COD concentrations in the runoff are created and loaded into temporary spatial database tables.

6 - CRITICAL AREA ASSESSMENT AND BMP SCENARIO SIMULATION

By using AGNPS-GIS-RDBMS linking methodology, assessment of nonpoint sources from the study watershed was performed using a 25-year, 24-hour storm event. The SCS synthetic rainfall type II distribution was applied to simulate rainfall distribution. Critical areas of high volume of flow, erosion and sediment, and nutrient yields were assessed within the watershed.

Sensitivity analysis of AGNPS model parameters was performed to construct "what if ," or alternative management scenarios to improve current water quality problems by using Model-GIS-RDBMS linkage. Results from the sensitivity analysis show that seven AGNPS parameters out of twenty-two were relatively effective in controlling nonpoint source pollutants from this particular watershed. They were SCS curve number, Manning's roughness coefficient, cover and management factor (C-factor), land slope, channel sideslope, practice factor (P-factor) and fertilization availability factor in descending order of significance.

Based on the sensitivity analysis, parameters were prioritized to minimize nonpoint source pollutants. After seven simulations by using AGNPS-GIS-RDBMS linkage, a best management practice (BMP) scenario was formulated and then simulated to evaluate potential improvements on current water quality problems. Simulated results showed that the BMP scenario achieved an average reduction of about 26% from current nonpoint source pollutant levels. Especially, the final BMP scenario No. 7 was most effective in controlling the erosion and sediment yield and a maximum 50% reduction of sediment yield was observed. Various rainfall frequencies including 1-, 2-, 5-, 10-, 25- and 100-year return periods were also investigated to determine the effect of various return periods on the current watershed response.

The direct AGNPS-GIS-RDBMS linkage developed in this study is a powerful tool that would be capable of monitoring the pollutant and sediment transports within the watershed. In addition, this system will be capable of effectively pinpointing areas of concern. The overall long range benefit will be easier information management for storing, retrieving, analyzing, updating and maintaining of various watershed related data, and more effective and flexible methods for water resources planning and management. Furthermore, the GIS would be advantageous when study areas are large,

analysis and modeling are performed repeatedly, or if alternative "what if" landuse/landcover scenarios are explored. Further diversified modeling and simulation activities can be done based on the established database.

7 - SUMMARY AND CONCLUSIONS

Methods were developed for directly linking the distributed parameter model, AGNPS with a GIS and a relational database management system (RDBMS) to investigate a nonpoint source pollution problem. AGNPS is an event-based model that simulates runoff and the transport of sediment and pollutants from mainly agricultural watersheds. Distributed parameter models such as AGNPS are often applied to large problem domains. Linking such models to GIS and relational database management system can facilitate better data storage, manipulation and analysis than conventional methods. Rather than manually implementing AGNPS, extracted data are integrated in an automatic fashion through a direct linking between the AGNPS model engine and GIS. Thus, the linkage is truly bilateral rather than the conventional one-way data extraction setup for input preparation. Thereby, it reduces the time required to analyze the numerical output from AGNPS, and enables users to assess critical areas of nonpoint source (NPS) pollution and furthermore, to perform various "what if" scenarios to develop best management practices (BMP) for the watershed.

A case study was performed on a watershed of 98.1 km² (=24,240 acres) in the upper segment of the Sand Hill River Subbasin in Minnesota by using this linkage implementation. Simulated results showed that the optimal BMP scenario achieved an average reduction of about 26% from current nonpoint source pollutant levels on soluble and sediment-attached nitrogen and phosphorous (Figure 4). Especially, this optimal BMP scenario was most effective in controlling the erosion and sediment yield. As a result, a maximum 50% reduction of sediment yield was observed.

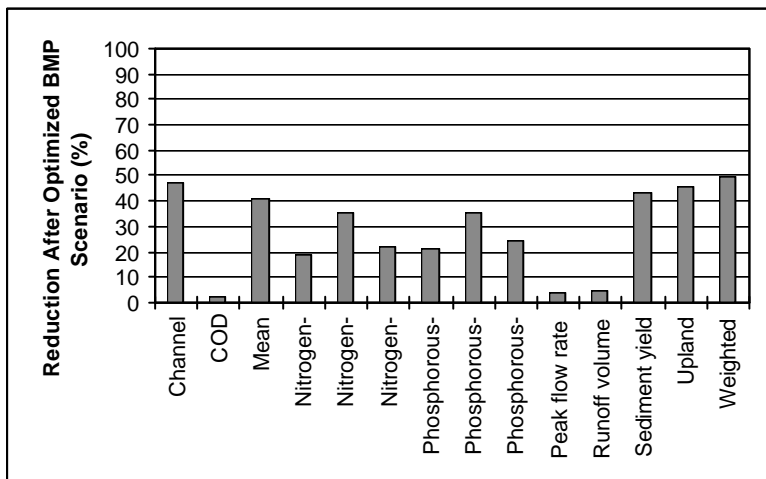


Figure 3 - Magnitude of Reductions (%) made by the Final BMP Scenario to Base Values at Watershed Outlet

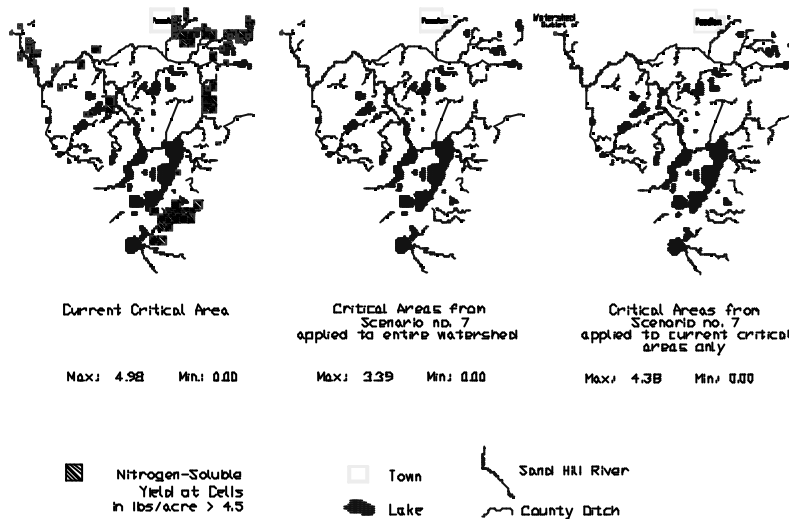


Figure 4 - Soluble Nitrogen Reduction Based on Optimal. BMP Scenario

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