Integration of GIS and Simulation Model for Watershed Management

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Abstract: Simulation models are powerful tools in support of watershed analysis and assessment of management scenarios at the watershed scale. This paper integrates GIS and AGNPS (Agricultural Nonpoint Source Pollution Model) to analyze the effect of land use change on nonpoint source pollution in a study watershed. ArcView Nonpoint Source Pollution Modeling (AVNPSM), an interface between ArcView GIS and AGNPS is developed to facilitate agricultural watershed modeling. The interface consists of five modules: a parameter generator, input file processor, model executor, output visualizer, and statistical analyzer. Basic input data to the interface include: soil, digital elevation model, land use/cover, water features, and management practices. The interface was applied to the study watershed to simulate the impact of land use change on runoff, sediment, and nutrient yields based on a 25-year, 24-hour period of single storm event of 4.5 inches. The simulation results show that expansion of urban land will probably lead to an increase in surface runoff, peak flow, and soil erosion. The magnitude of the effect is related to the extent and proximity of proposed land use change to water bodies in the watershed.

Keywords: AGNPS; GIS-interface; Simulation; Nonpoint source pollution

1. INTRODUCTION

Simulation models are useful tools for analysis of watershed processes and their interactions, and for development and assessment of management scenarios at the watershed scale. Implementation of those models often requires integration of GIS, remote sensing, and multiple databases for development of the model input parameters and for analysis and visualization of the simulation results [He et al. 2001]. A number of interfaces between GIS and simulation models have been developed to facilitate such endeavor, e.g. GRASS and WEPP (Water Erosion Prediction Project) [Engel et al. 1993], and Arc/Info and HEC-HMS (Hydrologic Modeling System) [Hellweger and Maidment 1999]. This paper describes ArcView Nopoint Source Modeling (AVNPSM), an interface between ArcView GIS and AGNPS (Agricultural Nonpoint Source Pollution Model [Young et al. 1989] for watershed analysis and nonpoint source modeling at the watershed scale and discusses its application through a case study [He et al. 2001].

2. THE ARCVIEW NONPOINT SOURCE MODELING INTERFACE

2.1 Model Description

AGNPS (Version 5.0) is a single storm-event based simulation model for evaluating sediment and nutrient transport from agricultural watersheds [Young et al. 1989; USDA Agricultural Research Service 1995]. The model includes three basic components: hydrology, erosion and sediment, and nutrients (N, P, and Chemical Oxygen Demand). The hydrologic component calculates overland runoff (in inches) and peak flow rate (in cubic feet per second) based on the SCS (Soil Conservation Service) curve number equation (Eq. 1).

$$Runoff = \frac{(ra\inf all - 0.2 * retention)}{(ra\inf all + 0.8 * retention)} \qquad (1)$$

Where storm rainfall represents total rainfall from a storm in inches, and retention factor is calculated by Eq. 2:

$$Retention\ Factor = \frac{1000}{Curve\ No.} - 10 \qquad (2)$$

Where the curve number is the SCS Curve Number, which is related to soil and land use factors.

Upland erosion is computed based on the Universal Soil Loss Equation (USLE):

A=R*K*LS*C*P*Slope Shape Factor (3)

Where, A is the computed average soil loss per unit area, expressed in tons/acre; R is the rainfall and runoff factor and is the number of rainfall erosion index (EI) plus a factor for runoff from snowmelt or applied water; K is the inherent erodibility of a particular soil; L is the slope-length factor, S is the slope-steepness factor; C is the cover and management factor; P is the support practice factor; and slope shape factor represents the effect of slope shape on soil erosion [Young et al. 1989].

In the nutrient component, AGNPS divides nutrient transport into the soluble nutrients, which are transported in the runoff, and the sediment nutrients, which are transported in the sediment. The soluble nutrients (N and P) are the amount of initial soluble N and P in the top 1 cm of soil prior to the rainfall event in lbs/acre (or kg/ha). Sediment attached nutrient is the amount of nutrient (N or P) contained in the sediment.

AGNPS works on a cell basis and requires 22 input parameters (Figure 1). Through a routing function, it links the upland erosion, sediment, and nutrients (N, P, and COD) with the downstream water quality. This feature allows the examination of amount of sediments and nutrients either for the entire watershed (measured at the watershed outlet) or on a cell by cell basis. By comparing runoff estimates from individual cells, problem areas within the watershed can be identified for targeting the best management practices [He et al. 1993].

Output of AGNPS includes estimates of surface runoff volume (inches), peak flow rate (in cfs), sediment yield (tons), mass of sediment attached and soluble N in runoff (lbs/acre), mass of sediment attached and soluble P in runoff (lbs/acre), and soluble chemical oxygen demand (lbs/acre). These results can be viewed in either tabular or map format for examination of critical runoff, sediment, and nutrient loading areas.

2.2 ArcView-AGNPS Interface

Analysis of nonpoint source pollution in an agricultural watershed by AGNPS involves providing 22 input parameters for each of the cells that represent the entire watershed, which is often a tedious and time-consuming task. To facilitate the implementation of watershed analysis by AGNPS, ArcView Nonpoint Source Modeling (AVNPSM), a WINDOWS-based interface was developed to integrate the AGNPS with ArcView (Version 3.0a or later versions) Spatial Analyst using Avenue (a programming language for ArcView) scripts [He et al. 2001].

The basic databases required for the AVNPSM include: soil database, digital elevation, land use/cover, water features such as watershed boundary and course of streamflow, climate, and crop management information. A soil database such as STATSGO (State Soil Geographic Data Base) is used to extract information on soil texture, hydrologic group, and soil erodibility factor (K). A digital elevation model (DEM) is used to derive slope, slope length, aspect, and other related parameters. Land use/cover file is used to determine SCS curve number and management factors such as crop management (C), fertilization , and support practice (P), etc. The water feature database is used to help create the watershed coverage and process and edit the flow direction file. Climate data (storm events) are used to calculate surface runoff and soil erosion in the AGNPS model. Management information includes crop types and rotation, fertilization level, and tillage practices. These files need to be processed to either an Arc/Info coverage or ArcView shape format to be compatible with the format requirement of the AVNPSM interface.

Once the input files are ready, the interface can generate the required AGNPS parameters (Parameter Generator), create an AGNPS input file (Input Processor), display the simulated AGNPS output (Output Visualizer), and conduct statistical analysis such as central tendency and analysis of variance (Statistical Analyzer). These components of the interface are discussed separately below:

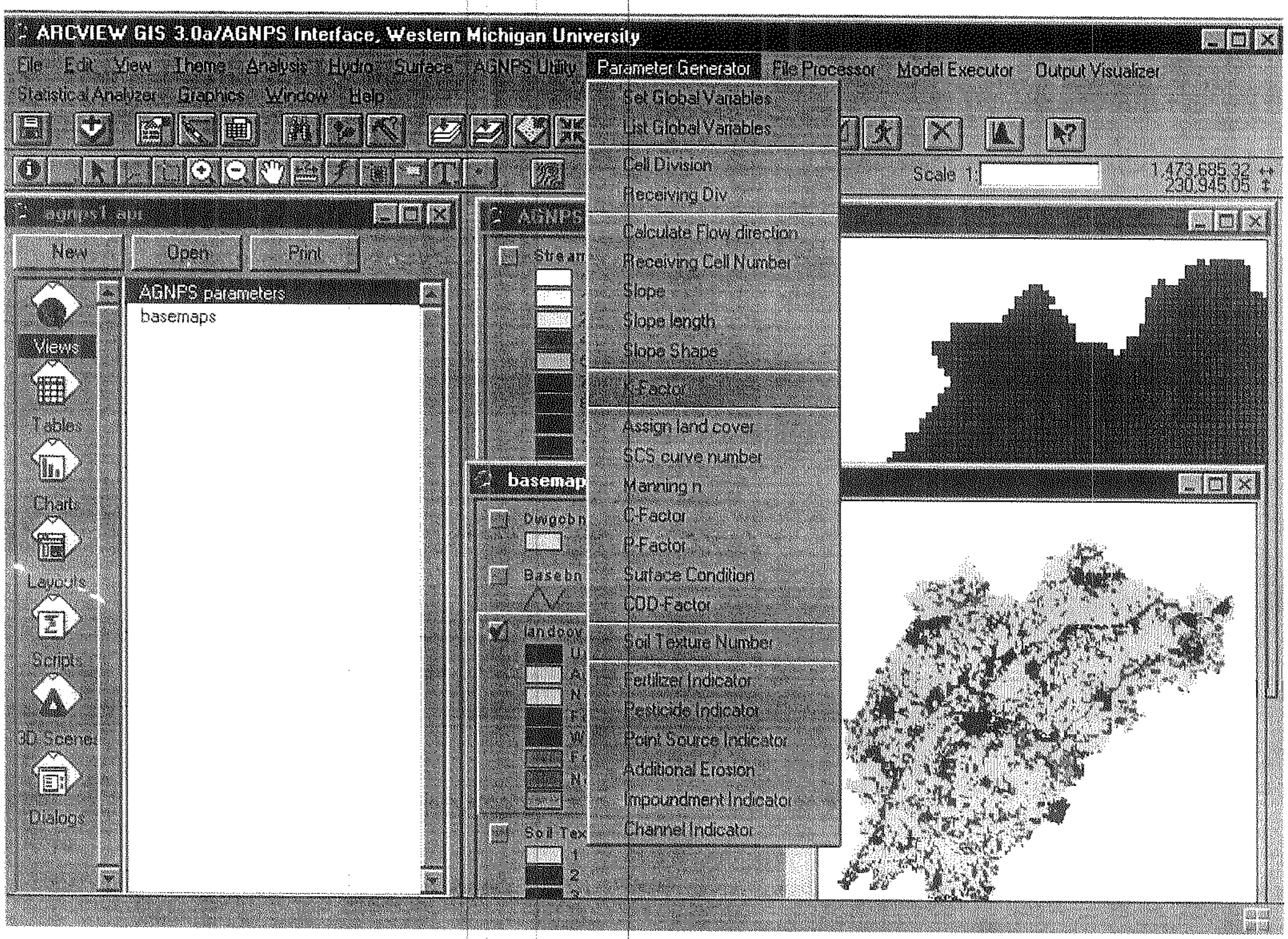

Figure 1. The ArcView nonpoint source modeling (AVNPSM) interface.

Parameter Generator. The AVNPSM, developed using ArcView Avenue scripts, provides a pull-down menu to generate the required parameters. As shown in Fig. 1, a user first needs to set global variables, that is, giving the name and location of the basic GIS layers: soil, DEM, land use/cover, and water features (watershed boundary). The user can then list these global files to ensure they are set correctly. Once this is done, the user can follow the pull-down menu to generate each parameter sequentially. During the FISHNET (file name for dividing the study watershed into grids based on the watershed boundary database) creation (in the AGNPS Utility module), the user can determine the number of grids (cells) in a watershed either by grid size or by number of cells. The interface will create a grid file covering the entire watershed

Input File Processor. Once all the 22 parameters are generated, the user can go to the File Processor module to develop an input file for AGNPS model. The file is in ASCII format and compatible with AGNPS input format requirement.

Model Executor. AGNPS model execution is done either within Windows or separately in the simulated DOS mode. Depending on the number of grids in the input file, model execution takes no more than a couple minutes.

Output Visualizer. The simulated AGNPS results of hydrology, sediment, and nutrients can be viewed either in tabular or in map format. Users can select any variable from the output file and display it in ArcView for analysis of spatial pattern using the Output Visualizer.

Statistical Analyzer. Although able to perform central tendency analysis such as mean and standard deviation, the ArcView GIS (Version 3.1) lacks other statistical functions. The AVNPSM interface adds the ANOVA (analysis of variance) function to the ArcView and enables a user to examine the relationships of land use/cover and simulated results of hydrology, sediment, and nutrients.

Land Use Change Simulator. A land use change icon (P icon) in the AVNPSM interface allows a user to specify land use change scenario in a sub-basin or specific area based on the land use/cover file and evaluate the hydrologic impact of this change to the downstream area.

3. SIMULATION OF LAND USE CHANGE SCENARIO AND ITS IMPACT ON WATER QUALITY

The AVNPSM interface was applied to the Dowagiac River, a major tributary of the St. Joseph River in southwestern Michigan that flows into Lake Michigan, U.S.A. for simulating the impact of land use scenario on water quality. The total drainage area of the watershed is approximately 181,400 acres (73,435 ha). Agriculture is the major land use in the watershed, accounting for 61 percent of the total land. A recent study by the local communities indicates a potential population growth of more than 10 percent in several townships of the Dowagiac Watershed during the first decade of the 21^{st} century. Such growth is likely to lead to conversion of some agricultural, grassland and forest land to residential and commercial areas to meet the increasing service and housing demands [Cass County Conservation District 1998]. To help resource planners and managers understand the potential impacts of these developments on water quality in the Dowagiac River, a land use change scenario is simulated and its water quality effect is analyzed by using the AGNPS model.

The entire Dowagiac River Watershed is divided into 4803 cells, with the size of each cell equal to 16 ha (40 acres). Digital elevation data at a scale of 1:250,000 were acquired from the U.S. Geological Survey. State Soil Geographic Data Base (STATSGO) was obtained from the U.S. Department of Agriculture Natural Resource Conservation Service. The watershed boundary was acquired from the Michigan Department of Environmental Quality Hydrologic Studies Unit. Land use/cover data of 1978-1981, the only data available for the study area, were obtained from the Michigan Resource Information System (MIRIS) for the entire Dowagiac River Watershed.

The single storm event chosen in the model was a 24-hour rainfall of 4.5 inches (11 cm) with an exceedance probability of 4 percent (recurrence interval of 25 years) from the Dowagiac Weather Station. In the Dowagiac River Watershed, this type of storm usually occurs in the summer months (June through August).

The AVNPSM was used to derive all the 22 input parameters and generate an input file for the AGNPS model. AGNPS Version 5.0 was run to produce estimates of surface runoff, soil erosion and sediment, and nutrient loadings.

The simulated land use change scenario is to convert the northwest corner of the La Grange Township to residential and commercial developments because it is adjacent to the City of Dowagiac and very likely to face residential and commercial expansion issues in the next decade. The selected area is about 1,400 acres (560 ha) and includes urban, agricultural, nonforest vegetation, forest, and forested wetland. Conversion of this area to urban land represents an expansion of the current urban land by about 1240 acres (500 ha). Assuming all other factors remaining same, the AGNPS model was run to simulate the effect of the changed land use on water quality and the result is summarized in Table 1.

As shown in Table 1, conversion of about 1,240 acres of non-urban land to urban land is simulated to cause little increase in the peak flow rate and sediment yield at the mouth of the river but has almost no impact on runoff volume and nutrient yields. This is probably due to the fact hat the size of the proposed land use change was too small to have any impact at the watershed level. If more land in the watershed is converted to urban uses, it might lead to greater changes in discharge and sediment yield at the outlet of the watershed. In addition, the hydrologic effects are related to the types of land use change and the locations of the changes. The simulated land use change is in the northwest corner of the La Grange Township, adjacent to the City of Dowagiac. If the land use changes were to occur in areas adjacent to a waterbody such as a lake or river, a greater impact on water quality would have produced. In simulating the effect of urban land expansion on water quality, this study assumed the land cover is the only variable to be changed and all other factors such as soil, topography, and management practices are to remain unchanged. In reality, urban development often causes changes in some related factors such as topography and landscape irrigation. The simulated magnitude of the land use change impact on water quality should be evaluated using the field data in order to support the informed land use decision making process. Resource planners and decision makers should also realize that the location of the land use change such as proximity to a waterbody has significant impact on water quality and need to consider this factor in dealing with the land use issues in the Dowagiac River Watershed.

Table 1. Summary of the impact of the simulated land use change in La Grange Township on runoff, sediment, and nutrients at the outlet of the Dowagiac River Watershed from a single storm event of 4.5 in.

Variable	Simulated Result Using the Baseline Data	Simulated Result Using the Proposed Land Use Scenario
25-Year Recurrence, 24-hour Storm (inches)	4.50	4.50
Surface Runoff (inches)	1.82	1.82
Peak Flow Rate (cfs)	3,231	3,235
Total Sediment Yield (tons)	9,985	9,992
Total N in Sediment (lbs/acre)	0.85	0.85
Total P in Sediment (lbs/acre)	0.43	0.43

4. SUMMARY AND CONCLUSIONS

This study integrates AGNPS and digital databases of soil, land cover/use, topography, water resource features and management practices to simulate the impact of land use change scenario on runoff, sediment, and nutrient yields based on a 25-year, 24-hour period of single storm event of 4.5 inches in the entire Dowagiac River Watershed. The simulation results show that expansion of urban land will probably lead to an increase in surface runoff, peak flow, and soil erosion. The magnitude of the effect is related to the extent and proximity of proposed land use change to water bodies in the watershed.

AGNPS requires 22 input parameters. Manual input of these input parameters for each of the 4,803 cells in the Dowagiac River Watershed would be time consuming, tedious, and problematic. This study develops AVNPSM, an interface between ArcView and AGNPS to derive, analyze, and visualize the required model parameters and simulated results from the databases of soil, topography, land cover, and water resource features. The interface consists of parameter generator, input file processor, model executor, output visualizer, statistical analyzer, and land use change simulator. Application of the interface to the study watershed indicates that it is user friendly, and robust, and significantly improves the efficiency of the nonpoint source pollution modeling process. With the interface, land use change scenarios can be readily explored in the model to help resource planners and decision makers develop watershed management plan to minimize sedimentation and nutrient loading to the receiving waters.

5. REFERENCES

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