Chapter 21

Application of GIS in Watershed Management

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This chapter presents a method to integrate a distributed watershed model with Geographic Information System (GIS) for management of soil erosion and fluvial sedimentation from nonpoint sources. Digitized data on soil, land use, topography and surface drainage pattern have been overlayed, using ArcInfo GIS, to generate input data file for the GAMES model. The GAMES output on erosion and sediment yield has been analyzed, using GIS, to prepare watershed maps to describe spatial distribution of soil erosion losses, sediment contributing areas and problem categories. This approach provides a powerful and faster technique for preparation of input file and interpretation of output of NPS and hydrologic models.

21.1 Introduction

In the Canadian Great lakes basin, pollution from nonpoint

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sources (NPS) has been recognised to be a serious environmental concern. The basic sources of nonpoint source pollution from agricultural land are sediment and associated pollutants transported in the solution or particulate form in the drained water. Soil erosion itself is of great concern to Canadian farmers. It affects soil productivity, capacity of stream and reservoirs and drainable water quality.

Control of soil erosion from agricultural land and transport of associated pollutants is essential to achieve sustainable agriculture and water quality goals. Selection of best management practice and implementation of remedial strategies requires careful consideration of financial constraints. The targeting of soil and water conservation practices and policies has been recognised to be cost effective and efficient for control of soil erosion and nonpoint source pollution. Targeting of sources of soil erosion and areas of nonpoint source pollution from agricultural land is very difficult by using simple indicators such as field slope and land use. Computer models have provided a very powerful tool to identify problem areas and quantify the magnitude of the problem.

Soil erosion and transport of pollutant are highly spatially temporally variable. Recent advances in modelling has given an avenue to describe these variations. The basic philosophy behind the application of modelling to manage nonpoint source pollution is to divide the watershed into square grids or irregular homogeneous response units (HRU), and soil loss and transport of pollutant from each grid or HRU is determined by application of appropriate algorithms describing erosion and pollutant transport processes. A GIS provides an effective tool for manipulation of spatial data such as soil, land use and topography, to generate input data suitable for NPS model. The output generated by an NPS model could be analyzed by GIS to create watershed maps describing spatial variations in soil erosion and delivery of pollutant from the watershed surface. This chapter describes an attempt to use GIS in conjunction with an NPS

model to describe spatial pattern of soil erosion and sediment transport, and to identify problem areas and possible locations for monitoring nonpoint source pollution.

21.2 Method

21.2.1 GAMES Model

The Guelph Model for Evaluating the Effects of Agricultural Management Systems on Erosion and Sedimentation, GAMES version 3.01, was used in this study. (Rudra et al., 1986). The model, developed at Guelph, has been used extensively in Ontario and elsewhere (Dickinson et al., 1990; and Seip and Botterweg, 1990). GAMES is a two component model: (i) soil loss component and (ii) sediment delivery component. The soil loss component is based on the Universal Soil Loss Equation (Wischmeier and Smith, 1978), and modified for seasonal time frame (Dickinson et al., 1982). The transport of sediment from land cell to downstream land cell and from land cell to stream is determined from the equation:

$$S_s = A_s \cdot DR_s \quad (21.1)$$

where:

S_s	=	seasonal sediment yield delivered from one land cell to another,
A_s	=	computed soil loss per unit area for the selected season,
DR_s	=	seasonal delivery ratio between two selected adjacent fields.

The seasonal delivery ratio is determined from the expression:

$$DR_s = \alpha [1/n_s \cdot S^{1/2} \cdot Hc_s / L_s]^\beta \quad (21.2)$$

In an event that runoff from one land cell travels across downstream land cells prior to entering the stream, the expression becomes:

$$DR_s = \alpha [1 / \sum (n_{sj} \cdot 1/S_{sj} \cdot 1/Hc_{sj} \cdot L_{sj})]^\beta \quad (21.3)$$

where:

- n_s = seasonal surface roughness (as indexed by Manning's n),
- S = land slope,
- Hc_s = seasonal hydrologic coefficient, an index of seasonal overland flow,
- L_s = seasonal length of the overland flow path, and
- α, β = calibrated parameters,
- j = refers to the j th cell.

GAMES uses a discretization concept in which the watershed is discretized into several homogeneous response units (HRU). For each HRU, data on input parameters are required. The parameters pertain to the land slope, channel slope, soil type, soil erodibility, cropping factors, SCS curve numbers, and location and efficiency of sediment detention structures. A complete description and a detailed procedure to estimate these parameters is given in the user's manual of the GAMES model (Dickinson and Rudra, 1990).

21.2.2 Watershed Selection

A representative agricultural upland rolling area, the Stratford Avon watershed in Southern Ontario was selected for this study. This watershed consists of 537 hectares of rolling agricultural land with an average slope of less than 9%. The dominant soil texture in this watershed is silt loam and loam. Approximately 10% of the watershed has organic soil. Excellent soils data base is available as this watershed was extensively studied for

pollution during the PLUARG period (Acton et al., 1979; Wall et al., 1989; and Coote et al., 1982).

During the study period, the Stratford Avon watershed was predominantly under corn cultivation with small percentage of area under pasture and hay. Fall ploughing has been practised throughout the watershed, with few if any conservation practices in place until quite recently. Since about 80% of the sediment loads in this basin have been observed to occur during the late winter and early spring period (February - May), GAMES was applied for conditions characteristic of that period.

21.3 Preparation and Manipulation of Input Data

21.3.1 Manual Procedure

Input data for the application of GAMES to selected watersheds with manual procedure could be developed in three stages:

1. Land use, soil, and land slope are independently determined from existing maps, aerial photographs, and field surveys. A map for each of these variables is prepared at a convenient base scale, usually 1:5000.
2. A comprehensive overlay of land use, soils and land slope are developed to divide the watershed areas into land cells (irregular fields), each of which are characterized by a single land use, a single soil type and a single class of slope.
3. The flow path pattern is developed from the layout of the stream pattern and field slope data.
4. Values of the various variables and factors in the GAMES are determined and assigned to each land cell. The procedure outlined by the GAMES manual (Dickinson et

al., 1990) is used to estimate these parameters.

21.3.2 GIS Databases

The main difference between GIS and manual procedure is that the overlays of soil type, land use and topography, and direction and length of overland flow is prepared by GIS software. ArcInfo (ESRI, 1989) GIS software was used in this study. Details on this procedure are given in the following section.

The watershed boundaries were defined using a shell. The boundaries were digitized as polygons and their characteristics were represented by attribute tables. Within the shell coverage on soil, land use, slope and topography were digitized. The polygon attribute table (PAT) files for soil type, land use, slope and topography, were created using the CLEAN and BUILD commands. Instead of assigning actual values to each polygon, an attribute coding procedure was used for each coverage. Each soil polygon was codified for erodibility (K-factor) and SCS drainage class. For the land use coverage, each polygon was coded for land use factor (C-factor) and SCS land use class. Slope was coded in terms of slope gradient, and topography was coded in terms of elevation class (topo rating). GAMES model can handle up to nine types of soils and nine types of land uses within a watershed. After assignment of attributes, the resultant coverage was prepared by the OVERLAY command. Small polygons were eliminated using a proper fuzzy tolerance. A preselected number was subtracted from the elevation of each water polygon to cause runoff to flow into the stream cells. The BUILD command was used to create the arc attribute table (AAT) file, and the DUMP command was then used to copy the PAT and AAT files into the comma delimited ASCII format for use as an input to the flow path program.

Determination of Flow Path Pattern

The flow pattern was determined using the DUMP files. The AAT and PAT files were divided into segments using the Q-EDIT

program. The size of the segment depended upon the capabilities of the spreadsheet program, such as QUATTROPRO in this case. The segmented file was imported into QUATTROPRO; after unnecessary columns were removed the AAT files were joined to create a "new" file. At this stage, the AAT file had arc length identification of polygon on the right (RPOLY) and polygon on the left (LPOLY).

A BASIC program was developed to determine the flow pattern using the data in the NEW file. In the BASIC program, all neighbouring cells around a source cell were identified through commonly served arcs. The topo rating of the source cell was compared with all the neighbouring cells to identify the downstream cell. In the case that two or more neighbouring cells had the same topo rating, and it was the lowest topo rating, then the neighbouring cell having largest boundary with the source cell was identified. Overland flow occurred when topo rating of the source cell exceeded or equalled the topo rating of the downstream cell. Before moving to next step, all backflow problems were checked and corrected manually. Backflow problems occurred when two neighbouring cells made each other their downstream cell. This procedure resulted in the identification of the downstream cell, which was downloaded as an ASCII file. The file with downstream cells was added to the resultant coverage PAT file.

Two options are available to determine flow path lengths, i.e. the ADS and ARCEDIT commands in the ArcInfo software. The ADS command is faster, but requires extra digitization of resultant coverage. Due to the unavailability at that time of a printer and digitizer, it was not possible to use this command. The flow path length was determined using the ARCEDIT command and resultant overlay image on the screen. At this stage, this file contained input data for all the cells in which soil erodibility, SCS drainage class, crop management factor and SCS land use class was in the coded form. Additional lines were added at the top of this file to describe soil and land use code and other inputs to complete the GAMES input file (Dickinson et al., 1990). Figures 21.1 and 21.2 illustrate soil and land use maps

prepared from digitized data.

Presentation of Outputs

The principle outputs of GAMES as applied to this study include soil loss and soil loss rate from individual fields within the watershed, total potential soil loss and average soil loss rate for the entire watershed, sediment yield from each field in the watershed to the stream and to the next downstream cell, total sediment yield and average sediment yield rate for the entire watershed.

In the present form, the model outputs are in tabular form. However, it has been well recognised that maps and graphs tends to show data set as a whole allowing the user to summarize the general behaviour and to study details. Therefore, they lead to much more thorough data analysis and more insightful interpretation.

In the manual method, soil loss and sediment yield outputs are classified into various categories in GAMESC, another version of GAMES. Outputs of GAMESC are used to prepare potential soil loss, delivery ratio and sediment yield maps manually. This is a very time-consuming procedure and the quality of maps is also not good.

In the GIS procedure, the GAMES outputs were processed by a spreadsheet program to classify soil loss and sediment yield into various class and to divide the entire watershed into four problem categories by selecting appropriate tolerance levels for soil loss and sediment yield. Problem category I includes area with soil loss greater than the chosen soil loss tolerance and sediment yield greater than the selected sediment yield tolerance. Areas in category II are those with estimated soil loss greater than the selected soil loss tolerance but are estimated to yield sediment less than is tolerable. Areas in category III exhibit estimated soil losses less than the tolerable soil loss but sediment yield greater than deemed tolerable. Areas in category IV are considered to have soil loss and sediment yield below the tolerance limits. The processed file in the ASCII form was merged with the resultant

Figure 21.1: Soil mapping of Stratford Avon watershed.

Figure 21.2: Land use mapping of Stratford Avon watershed.

PAT file, and the potential soil loss, sediment yield and problem classification maps were prepared using GIS commands.

Figure 21.3 illustrates the spatial pattern of potential soil loss for the spring period. It is evident that field erosion is quite spatially variable and that a major portion of the eroded soil moves within a small percentage of the basin, in localized areas. 83% of the sheet erosion volume is estimated to occur in 32% of the watershed area, 58% occurring in 15% of the area.

The spatial distribution of sediment yield is presented in Figure 21.4. Similar to the erosion picture presented above, but more pronounced, most of the spring sediment loads leaving the watershed is estimated to emanate from a small percentage of the watershed area: 79% of the sediment load is generated in 12% of the basin, and 57% in 5% of the area. Figure 21.4 clearly reveals that the watershed is characterized by very distinct sediment sources. Such information is vital to establish the sediment monitoring networks. Classifying the subwatersheds as shown in Figure 21.5, it is evident that the greatest expected impact of remedial soil and crop management measures will come from treating the subwatershed C followed by subwatershed A. Treatments in subwatershed B will give the least reduction in sediment yields.

21.4 Conclusions

The GIS procedure described in this study was used to process data on soil type, soil drainage class, land use and topography, and to prepare an input file for a NPS model (GAMES). The procedure also processed the GAMES outputs to produce watershed maps showing spatial distribution of soil loss, sediment yield and problem categories. This is a simple and flexible procedure. It has distinct advantages over the manual procedure. However, it requires soil and land use data in the digitized form and a compatible GIS software.

To facilitate automated estimation of topological parameters and an appropriate discretization scheme, the initial attempt to

Figure 21.3: Mapping of expected spring soil erosion rates in Stratford Avon watershed.

Figure 21.4: Mapping of expected spring sediment yield rates in Stratford Avon watershed.

Figure 21.5: Identification of subwatersheds A, B and C.

integrate the GIS with a NPS model is being extended to study digital elevation models (DEM) using Triangulated Irregular Networks of Elevation data (TIN).

21.5 References

Acton, C.J., G.T. Patterson, and C.G. Heath (1979). Final Report: Soil Survey of six agricultural watersheds in southwestern Ontario, Canada. 1975-1976 PLUARG, Task C, International Joint Commission, Windsor, Ontario.

Beasley, D.B., L.F. Huggins, and E.J. Monke (1980). ANSWERS: A model for watershed planning. Trans. ASAE 23:938-944.

Coote, D.R., E.M. Macdonald, W.T. Dickinson, R.C. Ostry, and R. Frank (1982). Agriculture and water quality in the Canadian Great Lakes Basin. I. representative watersheds. *J. Environ. Qual.* 11:473-481.

Dickinson, W.T., and R.P. Rudra (1990). GAMES-user's manual version 3.01. School of Engineering, University of Guelph, Guelph, Ontario. Tech Rep. No. 126-86.

Dickinson, W.T., R.P. Rudra, and G.J. Wall (1986). Identification of soil erosion and fluvial sediment problems. *Hydrologic Processes* 1:111-124.

Dickinson, W.T., R.P. Rudra, and G.J. Wall (1990). Targeting remedial measures to control nonpoint source pollution. *Water Resources Bulletin, American Water Resources Association.* 26(3):499-507.

Dickinson, W.T., and R. Pall (1982). Identification and control of soil erosion and fluvial sedimentation in Agricultural Areas of the Canadian Great Lakes Basin. Research Report to Supply and Services Canada, School of Engineering, University of Guelph, Guelph, Ontario.

Environmental System Research Institute (1989). ARCINFO User's Manual version 5.0, Redlands, California.

Henry, J.R. (1981). Agricultural Conservation Program: An Evaluation. *Water Resources Bulletin* 17(3):438-442.

Rousseau, A., W.T. Dickinson, R.P. Rudra, and G.J. Wall (1988). A phosphorous transport model for small agricultural watersheds. *Can. Agr. Eng.* 30:213-220.

Rudra, R.P., W.T. Dickinson, D.J. Clark, and G.J. Wall (1986). GAMES - A screening model of soil erosion and fluvial sedimentation on agricultural watershed. *Can Water Resour. J.* 11(40):58-71).

Seip, K.L. and P. Botterweg (1990). User's experience and the predictive power of sediment yield and surface runoff models. *Proc. Int. Symp. on Water Quality Modelling of Agricultural Nonpoint Sources: Part 1*, U.S.D.A. Rep. No. ARS 81:205-220.

Wall, G.J., T.J. Logan and J.L. Ballantine (1989). Pollution control in the Great Lakes Basin: An international effort. *Journal of Soil and Water Conservation*, 44:12-15.

Wischmeier W.H., and D.D. Smith (1978). Predicting rainfall erosion losses - a guide to conservation planning. USDA Agricultural Handbook No. 537, Washington, D.C.

Young, R.A., C.A. Onstand, D.D. Bosch, and W.P. Anderson (1987). AGNPS: Agricultural nonpoint source pollution model - a watershed analysis tool. *Conservation Research Report #35*, USDA-ARS, 77p.