TRAINING COURSE

ON

COMPUTER APPLICATIONS IN HYDROLOGY

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Module 16

Modelling

of

Soil Erosion

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MODELLING OF SOIL EROSION

Soil erosion is a process of land denudation involving both detachment and transportation of the surface soil materials. It is a complex dynamic process by which productive surface soils are detached, transported and accumulated in a distant place, resulting in exposure of subsurface soil and siltation of reservoirs and natural streams elsewhere. It leads to general reduction of raised land. The various important agents of soil erosion are running water, groundwater, wind, glacier, gravity etc. Excessive erosion from the area may be harmful in the following ways:

(i) It may lead to severe loss of valuable fertile soil which affects the agricultural productivity.

(ii) The loss of the soil cover reduces the water retention capacity of the land and may result in increased runoff.

(iii) The downstream surface water resources are polluted by both dissolved and undissolved substances captured by the eroding water.

(iv) Structures and agricultural fields lying downstream are damaged or otherwise devalued by the sediments deposited in or on them.

In India a total of 1750000 sq.km. out of the total area of 3280000 sq.km. is prone to soil erosion. Thus about 53% of the total land area of India is prone to erosion (Narayan & Rambabu, 1983). Most part of the Himalayas, particularly the Shiwaliks which represent the foothills of the Himalayas in the northern and eastern Indian states, are comprised of sandstone, grits and conglomerates with the characteristics of fluvial deposits and with deep soils. These formations are geologically weak, unstable, and hence highly prone to erosion. Accelerated erosion has occurred in this region due to intensive deforestation, large scale road construction, mining and cultivation on steep slopes. Approximately 30,000 sq. km. Have been severely eroded in the northeastern Himalayas due to shifting cultivation (Narayana & Rambabu, 1983).

SOIL EROSION BY WATER

Soil erosion has been classified according to the erosive agents (factors causing the occurrence and affecting the course of erosion processes): water, glacier, snow, wind, man, animals, etc.; by the forms which arise due to the effects of exogenous agents on the soil surface and by intensity the extent in which the soil particles are detached and transported. In the case of soil erosion by water, the following main forms are distinguished:

Sheet Erosion: Soil erosion resulting from raindrop splash and surface runoff is often called as sheet erosion. This is the uniform removal of soil in thin layers from sloping surface of soil between rills. Although important, sheet erosion is often unnoticed because it occurs gradually. The rain drops cause the soil particles to be detached and the following sedimentation reduces infiltration rate by sealing the soil pores.

Rill Erosion: When water takes the path of least resistance to flow over the soil surface it forms minute channels. Rill erosion is the removal of soil by water from small but well advanced channels in which the overland flow concentrates. Detachability and transportability of soil particles are both greater during rill erosion than during sheet erosion because of higher velocities. Rill erosion is most serious in regions where the storms are of high intensity and the top soils are loose and shallow.

Gully Erosion: If the channel formed in the land are so deepened and widened by erosion that their size is greater than those of common rills, then the land is no longer readily useable. The effect is then termed as gully erosion. These channels carry water during and immediately after rains. Gullies are usually formed by (i) water fall erosion at the gully head, (ii) channel erosion caused by water flowing through the gully (iii) alternate freezing and thawing of exposed soil banks and (iv) slides and mass movement of soil in the gully. Gullies are also referred to as ravines.

Mass Erosion : Mass erosion is the simultaneous slippage of large volumes of soil. It often occurs when clay layers below the surface are saturated. It is also associated with road construction in hilly terrain. Mass erosion may also be initiated by de-vegetation of steep slopes, where the network of roots may previously have helped retain the soil in position.

FACTORS AFFECTING SOIL EROSION

The main factors influencing soil erosion are climate, soil, vegetation, topography and man. Of these, the vegetation and to some extent the soil and the topography may be controlled. The climatic factors and largely also the topographic and soil factors are beyond the power of man to control.

Climate factors affecting erosion are precipitation, temperature, wind, humidity and solar radiation. Temperature and wind are the most evident through their effects on evaporation and transpiration. Wind also changes raindrop velocities and angle of impact while low temperatures, frost and snow accumulation can favour subsequent erosion during the soil thawing and snow melting. Humidity and solar radiation are involved less directly involved.

Physical properties of the soil affect its infiltration capacity and the extent to which the soil can be detached, dispersed and transported. The properties which most influence erosion include soil structure, texture, organic matter content, moisture content, density (compactness), shear strength as well as chemical and biological characteristics.

The vegetation effects are usually favourable in reducing erosion through interception of rainfall by absorbing energy of the raindrops and thus reducing the runoff, through retardation of erosion by decreased surface water velocity, through physical restraint of soil movement, through improvement of aggregation and porosity of the soil by action of roots and due to increased biological activity nourished by plant residues and through transpiration which decreases soil moisture, resulting in increased storage capacity of the soil.

Topographic features that influence erosion are degree of slope, length of slope and size and shape of the watershed. High water velocities occurring on steep slopes cause serious erosion by scour and sediment transportation.

Modelling Soil Erosion

Modelling soil erosion is the process of mathematically describing soil particle detachment, transport, and deposition on land surfaces. There are at least three reasons for modelling soil erosion : (a) Erosion models can be used as predictive tools for assessing soil loss for conservation planning, project planning, soil erosion inventories, and for regulation; (b) Physically-based mathematical models can predict where and when erosion is occurring, thus helping the conservation planner target effort to reduce the soil erosion; (c) models can be used as tools for understanding erosion processes and their interactions and for setting research priorities. There are three main categories of soil erosion models namely, empirical, physical and mixed. What follows is a brief review of some of the most widely used among them.

Empirical Models

Empirical models are generally cause-and-effect models in which a mathematical expression transforms a set of input variables into a description of the output without trying to describe the internal dynamics of the processes.

Universal Soil Loss Equation

The Universal Soil Equation (USLE) (Wischmeier et al., 1958; Wischmeir & Smith, 1978) is the best known and most used soil erosion model. USLE has been developed to estimate interril soil losses over extended time periods. A limitation of this model is that it does not estimate deposition, sediment yield, channel erosion, or gully erosion. In USLE, six major factors are used to describe the soil loss A: rainfall energy factor R, soil erodibility factor K, slope length factor L, slope steepness factor S, cropping and management factor C, and erosion control practices (e.g. contouring and terracing) factor P. The computed soil loss can be expressed as

$$A = RKLSCP$$

where L,S,C,P are all dimensionless. Thus the soil loss A has the dimension of R and soil loss dimension of K.

The rainfall factor R is dependent on the parameter EI, which is the product of kinetic energy of the storm times the maximum 30-minuts intensity. Maximum 30-minuts intensity is defined as twice the greatest amount of recorded rainfall in any 30 minutes. The soil erodibilty factor K is a function of percent of silt, and coarse sand, soil structure, permeability of soil and percent of organic matter. A nomograph has been developed to determine this factor. The slope length factor L is defined as the ratio of soil loss from a particular slope length to that from a unit plot length with all other conditions the same. The slope steepness factor S is a function of actual slope steepness. The cropping management factor C is defined as the ratio of soil loss from land cropped under specified conditions to the corresponding loss from tilted, continuous fallow. C ranges between near zero to one and depends on the type of vegetation cover, crop season and other management techniques. The erosion-control practice factor P takes into account the effect of conservation practises such as contouring, strip-cropping and terracing on erosion. It's value is the ratio of soil loss using one of these practices to the loss using straight row farming up and down slope.

Modified Universal Loss Equation

Williams (1975) modified USLE by replacing the rainfall energy factor with a runoff factor and named the model MUSLE (Modified Universal Soil Equation). Using MUSLE instead of USLE may increase the accuracy of sediment yield prediction, eliminating the need for delivery ratios (in small catchment), and is applicable to individual storms. It is easy to apply because it uses the USLE parameter dataset. The original MUSLE (in matric units) is expressed as

$$Y = 11.8\,(Qq_p)^{0.56}\,KCPLS$$

where Y is the total sediment yield from an individual storm, Q is the storm runoff volume, q is the peak runoff rate, K, L, S, C and P are the same as described in USLE.

Physical Models

WEPP (Water Erosion Prediction Project)

Water Erosion Prediction Project (WEPP) executed by USDA Soil Conservation Services and other US organisations. Its objective is to develop a new generation water erosion prediction technology. WEPP v. 97.3 is the newest available version of the resulting complex simulation computer program for continuous or single storm simulation of water erosion and accompanying processes. The WEPP model can be divided into six main conceptual components: climate generation, hydrology, plant growth, soils, management, and erosion.

KINEROS (KINematic EROsion Simulation model)

KINEROS (Smith, 1981) is an event-oriented, physically based model describing processes of interception, infiltration, surface runoff and erosion from small agricultural and urban catchments. It uses the Smith\Parlange infilteration model and the kinematics wave approximation to route overland flow. The catchment is represented by a cascade of planes and channels.

SEM/SHE (Soil Erosion Model)

SEM developed by Storm et al. (1987) is a physically based model which simulates the spatial and temporal variations of the soil erosion and sediment yield in a catchment. It has been developed based on a physical description of the involved processes. to improve model so as ANSWERS and MODANSW. The sheet erosion equations are to a large extent based on the ROSE model. Unique in erosion modelling are Sem's attempts to simulate rill erosion.

MEDALUS (MEDiterranean Desertification and Land Use)

MEDALUS is a physically based simulation model for vegetation growth. hydrology and soil degradation(Kirby et al.. 1992). The MEDALUS I model simulates a hillslope catena. consisting of successive slope segments. In each individual segment plant growth.

evapotranspiration, surface water and sediment transport, and soil water movement are simulated. The mode is focused on the Mediterranean, with special attention given to the influence of raindrop impact induced sealing on soil water infilteration and representative type of plants.

EUROSEM (European Soil Erosion Model)

EUROSEM developed by Morgan et al., 1991/92, is a single event process based model for predicting soil erosion by water from fields and small catchments. It can also be used to assess the risk of erosion and to evaluate the effect of soil protection measures. The equations used in the model to describe the processes of erosion are from many sources and are claimed to be representative of the current state of research in Europe. The equations are linked to the KINEROS model which provides the basis for generating runoff as infilteration excess and for routing runoff and sediment over the land. EUROSEM aims to simulate three situations: (i) A single plane or element for predicting erosion from small fields; (ii) Multiple planes and channels for predicting erosion along a slope; (iii) Multiple planes and channels for predicting erosion from a small catchment.

LISEM (Limburg Soil Erosion Model)

LISEM (DeRoo et al.) is a distributed physically based catchment mode of soil erosion developed by the Utrecht University and the Winand Wageningen. The model, integrated in a raster GIS, simulates single events in a small catchments. Both present land use and soil conservation scenarios can be evaluated using the model.

Mixed Models

Gupta and Solomon's model

Gupta and Solomon (1977) made an early effort to utilize spatial information in order to get information from hydrological processes in a river basin. The model was also designed for ungauged river sections. The sediment phase of the model is divided into sediment discharge generated within the grid element and the one generated by the channel flow. The land erosion is simulated by the following four processes : 1) Soil detachment by rainfall, 2) transport of detached sediment by rainfall, 3) sediment detachment by surface runoff, and 4) transport of detached sediment by overland flow.

ANSWERS (Areal Nonpoint Source Watershed Environment Response designed Simulation)

Beasley et al. 1980 developed a distributed-parameter, event-oriented model in order to supply information concerning effects that land use, management, and conservation practices or structures might have on the quality and quantity of water from agriculture watersheds. In this model, the watershed is first divided into series of small, independent cells. Within each cell, the runoff and erosion processes are treated as independent functions of the hydrologic and erosion related parameters. It is assumed that the parameters are uniform in each cell. The routing of runoff is based on developing a runoff and subsurface hydrograph for the cells so that the output of a cell is the input of the adjacent cell along the steepest slope downwards.

AGNPS (Agriculture Non Point Source)

Young et al. (1987) developed an event based distributed parameter model to analyse erosion and non-point source pollution in agricultural watersheds. The model was named Agricultural Non-Point-Source Pollution Model (AGNPS). It uses a distributed parameter approach to quantify watershed up to 20 000 ha by dividing the area into a grid of square cells of sizes of 0.4 ot 16 ha. Runoff characteristics and transport of nutrients are simulated for each cell and routed to its outlet, which permits the examination of the runoff, erosion, and chemical movement at any point in the watershed.

Erosion in AGNPS is modelled by a modified version of the USLE applied to each cell. The equation used is:

$$A = 2.24\ K\ L\ S\ C\ P\ EI\ SSF$$

where A, K, L, S, C, and P are factors explained in equation earlier. EI is the 30 minute energy intensity and SSF is a factor to adjust for the convex or concave nature of slopes within the cell.

EPIC (EROSION-PRODUCTIVITY IMPACT CALCULATOR)

EPIC (Sharpley et al. , 1990) was developed in 1980's by the USDA Agricultural Research Service and other US organisations as a complex semi-empirical model for continuous simulation if erosion and water pollution processes in small agricultural catchment. The model uses a daily time step to simulate weather, hydrology, soil temperature, erosion, nutrient cycling, tillage, crop management and growth, pesticide and nutrient movement with water and sediment and field-scale costs and returns.

SWRRB (Simulator for Water Resources in Rural basin)

This model was developed by Williams et al. (1985). It uses daily time step and it is based on EPIC and modifications of CREAMS for application to a large, complex, rural basin. The major differences compared to EPIC are that SWRRB does not have nutrient, economics, and crop growth components. The erosion component of SWRRB does not include erosion due to irrigation and wind. but has a sediment routing module for ponds and reservoirs. It also uses MUSLE relationship in predicting sediment yield. SWRRB does not have a formula for wind in the weather generation component but it estimates transmission losses and effects of ponds and reservoirs on water yield. The model was tested with data from two catchments (538 and 17.7 km^2).

HYDROLOGIC MODELLING USING GIS

In the early days GIS were mainly used as hydrological mapping tools. Nowadays they play a more important role in hydrological model studies. Their applications span a wide range from sophisticated analyses and modelling of spatial data to simple inventories and management tool, and can be found in many fields, such as land planning, natural resource management, environmental assessment and planning, ecological research etc. In the fields of hydrology GIS have been widely applied in water resources planning, development and management, in hydrological simulation and flow forecasting, in water quality modelling, in groundwater modelling and management etc. However, it is important to recognise that GIS is only a useful and powerful tool. The application of GIS has enhanced the capacity of models in data management, parameter estimation and presentation of model results, but GIS can not replace hydrological models in solving hydrological problems.

In general for complex watersheds, a model base alone made up of selected physical models or statistical model (e.g. erosion factor soil loss equations) will seldom yield a satisfactory erosion risk scenario for the entire catchment. Scale, sensitivity and working range of parameters values usually introduce severe limitations on the spatial applicability and therefore also on the accuracy of the model outputs. A combined approach using a model base reinforced with a relational decision rule-base will probably yield a more accurate overall assessment. Relational rules can be used to define and limit the physical boundaries of erosion model applications. The GIS can so be used as a controlling tool for application ranges of model parameters, especially the DEM related topographic variables used in erosion modelling.

There are four levels of linkage of hydrological model with GIS. These levels vary from essentially considering GIS and the model as separate systems to fully integrating the model and GIS. Currently the structure of soil erosion models and GIS systems are quite different preventing a complete integration of them. The lowest level of integration consists of using GIS as an aid in developing the input data file for the model. A user then takes the preliminary files and modifies them to produce a complete input file in the format required by the model. A similar procedure in the opposite direction can be applied to the outputs of the model in order to present and store them in GIS. This approach enables one to use an existing GIS and an existing model without modification to either but requires the most of user's effort. The next level of integration is to use an interfacing program specifically written to communicate between the GIS and the model. The interface program may serve as a control program issuing commands to the GIS and the model. Output from the GIS is converted into the proper input format for the model and then read by the model. Output from the model may likewise be converted to a GIS format and then displayed by the GIS. All these operations are carried out under the control of the interface program. A third level of integration occurs when the interface program is incorporated into the model. This requires modification to the input/output routines of existing models or developing special input/output routines for new models. Some programming may also have to be done within the GIS to alter its input/output structure to make it more compatible with that of the model. If one is making extensive changes to a model or developing a new model, this level of integration would be appropriate. The highest level of integration occurs when the model and GIS are essentially a single, integrated unit. One way of achieving this is by programming the model using the programming language appropriate to the GIS being employed. This makes GIS a master module which controls the model runs.

A number of studies have been carried out using the above models for soil erosion, nutrient transport etc. in the past. The main reason for using GIS in erosion and modelling is that runoff and soil erosion processes vary spatially. To account for this variability, the modelled catchment has to be broken down into many, relatively homogeneous cells. The extent of data required for the large number of cells is enormous and can not be presented and easily entered by hand, but can be obtained by using GIS.

Table 1 gives an overview of the data layers and procedures used in solving soil loss equation in GIS format. Various ways for including the effect of relief on erosion can however be incorporated in soil loss equations. Due to the usually strong geomorphic interdependence between slope steepness and slope length on most lithological faces, a combined LS factor evaluation is common in erosion studies. In GIS, the effect of two variables can be weighted conveniently by use of two dimensional table operations.

Table 1 :Data layers and procedures used in solving soil loss equations in GIS format

Erosion factors	**Databases, data layers**	**Description of GIS procedures**
Erosivity factor	Rainfall data	Spatial interpolation of station EI values; stored as R map
Erodibility	Soil data	Assignment of numerical K values to soil units by reclassification of the soil unit polygon map with the K value column from the soil attribute table; stored as K factor map
Combined LS slope length-gradient	Geomorphic	If regional geomorphologic relief classes xists,combined LS gradient or terrain factor values can be obtained using a 2-Dim table with row-wise, relief steepness classes and columnwise the slope length classes, resulting directly in a LS-value distribution for the area; stored as an LS map file.
Slope length	TMU	1. Using TMU: assign slope length values to terrain units as functions of steepness using a 2-Dim table, resulting in a length map; compute numerical L factor values by applying a slope function to length map.
	DEM	2. Using DEM: If field boundaries are available in digital format. assessment of field slope lengths is possible using DEM connectivity and neighbourhood operations.
Slope gradient	TMU	1. Using TMU: assign numerical slope radient values to TMU map using a TMU attribute table:compute S-factor values by applying a slope function to this reclassified map: stored as a S factor map

	DEM	2. Using DEM: Reclassification of the slope gradient surface in user defined slope class intervals; compute numerical S-factor values by applying a slope steepness function to map and store as an S factor file;
Land cover	Land cover	If necessary pre processing or spectral classification of remote sensing data; assignment of C factor values to land cover RS data classes using cover attribute table; stored as C factor map.
Conservation Practice	Land cover	For land use types with soil conservation practices, reclassify C factor map with P-factor values of land cover attribute table, using P=1 for non-conservation areas.

RELATIONAL RULE BASED MODELLING OF EROSION RISK

With expert knowledge of processes occurring in a watershed and survey information on the geomorphological terrain, soil and cover units in a relational data base structure, it is possible to formulate relational rules for classifying erosion risk. These heuristic rules may address several data layers simultaneously. Fig. 1 illustrates the modelling flow diagram commonly used in relational rule-based erosion hazard assessment. Examples of some rules addressing several data layers are:

- If terrain units equals denudational coral limestone, and the slope class >2 or soil unit equals (troporthent or dystropap), then classfiy erosion rank 4 (highly vulnerable to rill and interrill erosion);
- If terrain units equals denudational grantic ridge, slope class >=4, and landcover =cassava, then classify erosion rank 5 (very highly vulnerable to rilll and interrill erosion);

If more quantitative information and rule-based modelling is preferred, the soil unit dataplane could be entered in the modelling. Soil origins and topsoil horizon characteristics (lithic or mollic,...) could then be used, for example, to pinpoint available erodible or transportable soil materials.

SUMMARY

There are a number of models available for soil erosion modelling and various studies have been carried out using these models. The use of GIS offers a considerable potential in soil erosion modelling. The on site erosion prediction models clearly need GIS. Topography and land use can be simulated in great detail and data management and presentation is much easier than when a GIS is not used. Many powerful methods exist to derive useful products from a DEM such as slope gradient, flow direction, contributing area and slope length. From these basic variables, a wide range of erosion estimates can be derived. These variables can also be used in more complex physically based models either linked to, or integrated in, a GIS.

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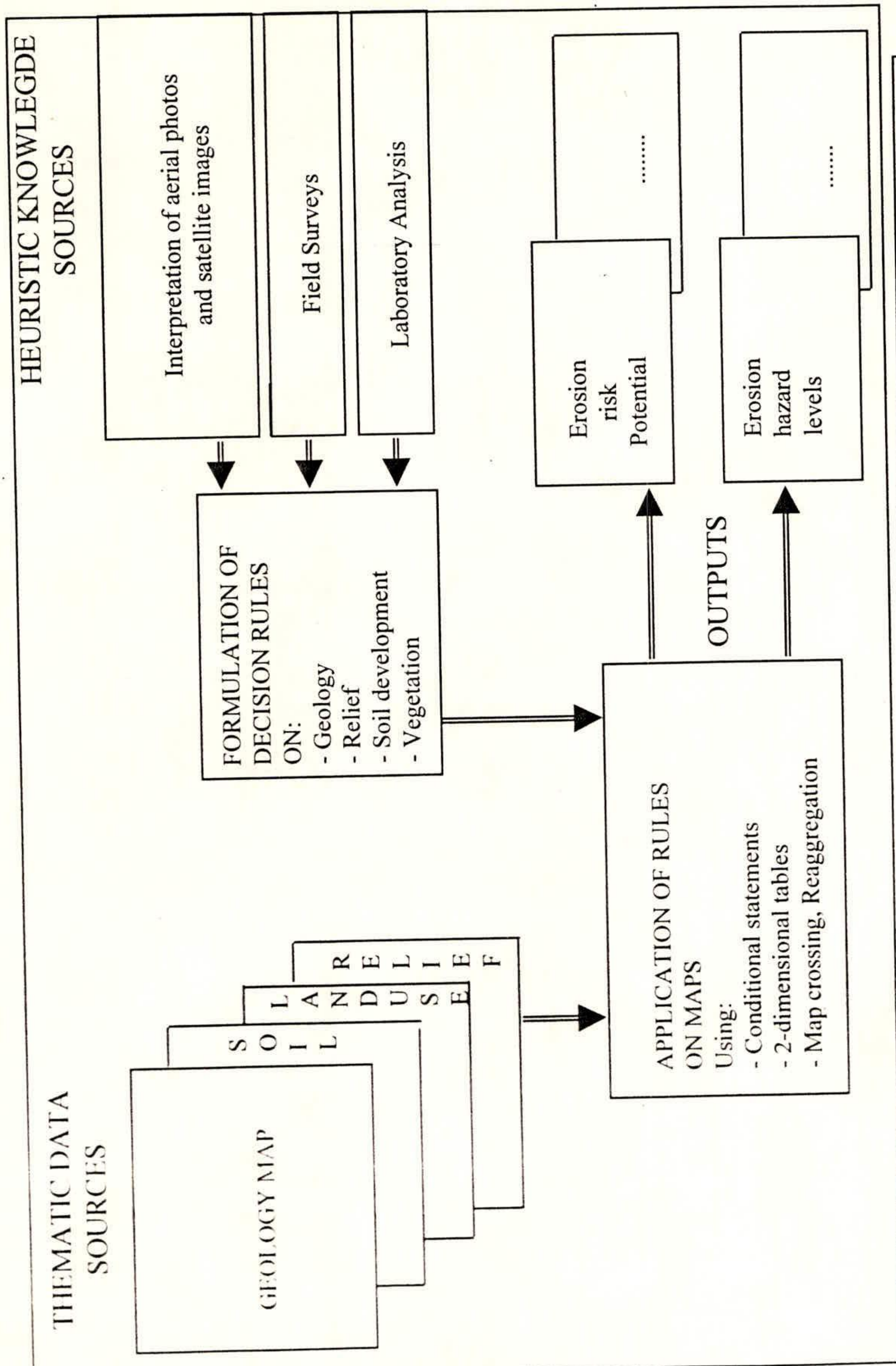

MODELLING FLOW DIAGRAM FOR RELATIONAL RULE-BASED EROSION ASSESSMENT USING GIS