On-Line Proceedings of the 19th
Annual ESRI User Conference
July 26-30, San Diego, CA 15 pp.
Available at: www.esri.com

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Teaching Spatial Analysis for Hydrology and Watershed Management

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ABSTRACT

The need for GIS courses that include advanced GIS concepts as well as address the special requirements of a discipline is rapidly growing. The goal of this paper is to describe a course developed at the University of Arizona for hydrologists and other earth scientists. A series of assignments has been developed on important topics such as interpolation of environmental data, creation and use of DEMs, linkage of GIS to hydrologic and erosion models, watershed assessment, and effects of database resolution. The paper reviews course content, philosophy, and direction. Examples of assignments using ARC/INFO are provided.

INTRODUCTION

Geographic information systems (GIS) are becoming ingrained in the hydrologic and watershed management communities for both research and application. With the rapid growth of this field over the last 10 years, there has been a commensurate increase in the development of curricula for GIS at the University level. The fact that many of these courses are taught at lower levels is a function of the technical requirements of the field; a large amount of introductory material is required in order for students to be able to apply advanced principles to research and management problems. However, it is precisely the ability to integrate technology with imaginative research objectives that will propel forward fields reliant on GIS. A graduate-level course has been developed in The University of ArizonaÆs School of Renewable Natural Resources in collaboration with the USDA-ARS Southwest Watershed Research Center (SWRC) that focuses on the application of GIS in hydrology and watershed management with an emphasis on the practical and theoretical roles of GIS as a research and management tool (Miller and Guertin, 1999; ESRI, 1998).

Watershed management and hydrology are both highly dependent on spatially distributed information. In past years, classes have been available at The University of Arizona that provide introductory material in GIS and introduce the topics of cartographic modeling and watershed assessment. Abundant classes are taught concerning the fields of hydrology and natural resources, including modeling and quantitative watershed analysis. The class described in this paper bridges these fields using advanced GIS and hydrology tools. Since the focus is on practical applications of narural resource science in a GIS environment, the objective of the course is to provide a rigorous introduction to techniques linking spatially distributed data to watershed analyses and modeling. Emphasis is placed on scaling issues and the impacts of uncertainty and error on research and management applications.

The topics investigated within a semester are fluid from year to year, subject to the skills and needs of the students. However, the primary goal remains the same; that the students become familiar with advanced topics and emerging scientific issues pertinent to hydrologic science. As such, this course moves from cartographic modeling through advanced spatial analysis and geostatistics to the application of distributed hydrologic modeling. Topics include watershed assessment for erosion potential and grazing capacity, appropriate interpolation techniques for rainfall and elevation data, kriging and the derivation of spatial statistics, impact of scale and error on watershed analyses, and integration of lumped and distributed rainfall-runoff models with GIS.

The majority of class work is performed on high quality GIS data layers provided by the SWRC covering the Walnut Gulch Experimental Watershed, a rangeland watershed located in southeast Arizona. Walnut Gulch is a unique facility that is heavily instrumented, with over 100 historical and current rain gauges and a nested subwatershed design. The watershed is subdivided into 31 primary subwatersheds ranging in size from several hectares to over 148 km^2 (Renard et al., 1993). The nested design and amount of instrumentation allow for investigations into effects of scale, interpolation, and GIS procedures on hydrologic research. Urban studies use theme layers covering Tucson, AZ. A variety of data are incorporated into the class, including high and low resolution digital elevation models (DEMs), both detailed and generalized soil and vegetation data, geologic maps, point sources of long-term climate records, SPOT and Landsat remote sensing imagery, and interferometric synthetic aperture radar data. Note that mutliple theme layers of differing resolutions and quality are available for vegetation, soils, and topography. These data allow for investigations into error and data quality on watershed classification, modeling, and management.

One of the truisms of GIS analysis is that there are numerous avenues available to arrive at a solution. It cannot be overstated, however, that the choice of technique can significantly alter the results. The choice of which method to use should therefore not be made in a vacuum, and the researcher should explore the relative merits and drawbacks to various GIS tools. The class focuses heavily on this issue since the ramifications are widespread, but often hidden or ignored, in the scientific literature. Weekly laboratory exercises focus on the impact of various techniques on model results and management decisions by requiring that the same topic be addressed from several directions and the results scrutinized for discrepancies.

It is presumed from course prerequisites that students understand the basics of the Arc/Info data model, specifically relating to the appropriate design of a GIS for a given research or management objective. A fundamental understanding of Arc/Info and ArcView commands and tools is assumed. Given these basic skills, students are free to pursue the pertinent issues of scale, error and uncertainty, cartographic modeling, geospatial analysis, and distributed hydrologic modeling.

COURSE FRAMEWORK

The course is taught with a standard lecture/lab format, and there are 5 principle means used to deliver information to the students. Lectures are used to provide introductory material and theory, labs are used to merge theory with practice and improve technical ability, a web site serves to disseminate information and proivide additional hints and GIS techniques, reading material provides information on the scientific history of the subjects and keeps the students aware of cutting-edge research, and each student is required to complete a class project of his/her own choosing. A textbook (Burrough and McDonnell,

1998) is used for supporting documentation, but primary sources are made available throughout the semester, and students are expected to maintain pace with the readings (see Appendix I for a list of these references). Students are advised to choose term projects that relate to their graduate studies and the seeds of several manuscripts have been germinated in this manner (Huth, 1997; Levick, 1998; Youberg, 1998; Heller, 1999; Levick et al., 1999; Miller et al., 1999a; Miller et al., 1999b).

In order to build on the studentsÆ GIS skills and understanding of the Arc/Info data model and fundamentals of hydrologic research, individual work is required throughout the semester. Weekly projects are assigned, and while students are expected to hand in their own results, group work is encouraged, and lab sessions are configured to promote collaboration. Homework assignments typically stretch beyond the bounds of the lab, and deadlines are treated loosely; they are used more to force students to keep pace than as a mechanism for assigning grades. Assignments are due in electronic form; most lab work takes the form of writing Arc Macro Language (AML) programs to solve hydrologic or management questions, and grades are based on the accuracy of results produced by running the AMLs. Proper documentation of the programs is mandatory. The class is designed for motivated students working with GIS in their research; as such the expectations and pace are high.

Taught in the Fall semester as a two-unit course, for the past two years the class has been limited to a weekly one-hour lecture and three-hour lab, which were taught sequentially. The instructors and students deemed this arrangement inadequate, and, starting in the Fall of 1999, the class will be expanded to three units with twice-weekly lectures and a three-hour lab. This expanded format will serve two purposes. First, lectures will not be limited strictly to lab-related information; second, the separation of lectures and labs should facilitate learning since each subject will be reinforced following brief intervals. In the past, students have reported feeling overwhelmed by the quantity of information presented in a four-hour block each week. While a commensurate increase in information will accompany the additional unit, the separation among lectures and labs should assuage concerns regarding the intensity of the class.

SCOPE AND SEQUENCE

It is increasingly clear that students in earth sciences are well served when they emerge with strong foundations in scientific techniques and GIS tools. Emerging research in hydrology relies on the combination of such disparate subjects as interpolation techniques, watershed characterization, spatial analysis, and physically-based modeling. To gain a comprehensive understanding, these topics should be explored individually, and universities are well equipped to provide such instruction. A need was identified at The University of Arizona for a class in which these and other topics were synthesized and applied to standard watershed modeling and assessment tools.

Topics chosen for this class are based on watershed research needs rather than on the improvement of GIS skills. That is not to imply that GIS skills are not taught and improved upon; rather, that the lectures and lab exercises are concerned primarily with forwarding hydrologic research using GIS as a tool to attain the various objectives. While several of the topics are traditional watershed management techniques, their implementation in a GIS is a relatively recent development, and several emerging research methods are introduced. As such, this class is designed to provide a foundation in emerging research issues and associated topics of concern, thereby providing future directions for study.

Individual topics and their associated laboratory exercises are presented in Table 1. Since this class is dynamic, this table is non-representative of the scope of work which will be covered as the class evolves through time. This year, for instance, will see the introduction of fuzzy classification for soil mapping and watershed fractal analysis. Please refer to the class web site (http://www.tucson.ars.ag.gov/wsm569) for up-to-date curricular information. Note that the subject matter grows increasingly complex through the semester. It has been the instructorsÆ experience that students grow increasingly more comfortable with the subject matter and the pace of the class increases as the semester progresses. This observation underscores the importance of regular exposure to GIS-based applications. The reliance on technical skill, i.e. understanding the data model and knowing the range of GIS commands, is a barrier to entry into the field of spatial analysis and has fostered a need for GIS specialists to provide support to staff scientists. Classes such as this are intended to meld science and technology and spur students into using these new-found skills in their research.

Issues of scale, uncertainty, and error are increasingly being recognized as critical to earth sciences. Hydrologic processes are largely scale-dependent, with different processes driving hydrological response at various scales. Various interpolation techniques are available to researchers, and the choice of technique may significantly alter research results. While GIS data are becoming widely available across the United States and the rest of the world, there is concern that the impacts of data quality and spatial error on watershed modeling and assessment are poorly understood. With its range of highly accurate data, the Walnut Gulch GIS data layers allow the class to probe these relevant issues. Scalar issues are addressed using the nested subwatershed design in concert with long-term historical rainfall and runoff data. Various interpolation techniques can be used to simulate rainfall from over 100 rain gauges to address hidden implications for runoff simulation and management. The impacts of error can be approached scientifically since several GIS layers exist at various resolutions and accuracy for vegetation, soils, and topography. The themes of error, spatial averaging, accuracy, and scale are fundamental to the class, and assignments are arranged to provide extended and repeated exposure to these subjects.

Table 1. Scope and sequence of topics for the Fall semester, 1998. This upcoming semester will introduce fuzzy sets and fractal analyses.

Topic	Lab Exercise	Weeks
The Arc/Info Data Model; Re-introduction of Basic Skills	Cartographic modeling of small town	1
Land classification	Application of the Universal Soil Loss Equation (USLE) for erosion tolerance and delineation of management regions	2 - 3

Capability assessment	Determine grazing capacity on Southwest rangeland using erosion tolerance, vegetation characteristics	4
Interpolation techniques; inverse distance weighting, spline, Thiessen	Derive rainfall surface from historical gauge data on a Southwest rangeland watershed	5
Advanced interpolation; kriging	Reproduce previous weekÆs exercise on rainfall using various kriging techniques	6-7
Hydrologically correct digital elevation models (DEMs)	Download, import, and smooth standard USGS data for rangeland watershed; run preliminary hyrdologic analyses	8
Improved DEMs; SAR, orthophotography	Use high quality survey data to reproduce topography for rangeland watershed used in previous week; assess differences among models.	9
Spatial statistics	Comparison of multiple interpolated surfaces using correlative statistics.	10
Lumped runoff modeling; impact of GIS resolution on results	Model runoff using SCS Curve Number technique on small urban watershed for multiple rainfall events with various surface models.	11
Influence of interpolated surfaces on research	Use previously created rainfall surfaces (weeks 6-9) as input to distributed Curve Number runoff modeling; determine which yields best results.	12
GIS and physically-based distributed modeling	Apply different GIS watershed characterization tools to provide input to KINEROS and assess influence on runoff simulation.	13
Class project	Students complete semester-long projects.	14-15

On the Conflict Between Creativity and Technical Ability

A significant hurdle to effective teaching at the level of application and theory is the high investment in technical ability required of the students. The course is not intended to be simply a forum for learning new GIS commands and tricks; rather, technical ability serves as a springboard for ideas and discussion surrounding the appropriate application of spatial modeling. However, by advancing into realms to which the students have not had prior exposure, it is inevitable that some breakdowns occur due to programming difficulties. This is unfortunate given that the commands and their sequences are secondary to the learning process, and progress can be impeded by a need to invest in learning new code, which is nonetheless recognized as a vital skill for any GIS analyst. To circumvent this issue, class notes relating to necessary commands are placed on a web site, some discussion is devoted to programming in class, and students are encouraged to work in collaboration with one another.

While these techniques have garnered successes, the hurdles of GIS jargon and heavy programming requirements for advanced applications remains high for some students. An inherent conflict is apparent in this problem. On the one hand, the class is designed to spur creative thinking and fresh approaches to problem solving, intellectual forays requiring a suite of tools that the students do not yet possess. To aid these forays, it would be advisable to simply give the students the tools in a "cookbook" fashion. On the other hand, reliance on "cookbook", or black-box approaches to GIS in research blinds the student to pratfalls and conflicts that are limitations on the research ideas. It is important, therefore, to find a balance between providing enough information to spur creative approaches and yet not shield the student from practical applications and limitations.

EXAMPLE APPLICATIONS

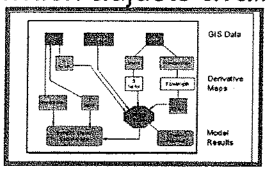
Three assignments that demonstrate the range of subject matter will be presented in the following section. For more detailed information on these or other assignments, including the algorithms employed in their solutions, please refer to the class web page (http://www.tucson.ars.ag.gov/wsm569).

Watershed Classification and Capability Assessment

Surface erosion, the detachment and removal of soil from the land surface, can be a significant contributor to land degradation. Soil loss through overland processes is a natural process, the rate of which is dependent on a series of interlocking factors, including rainfall erosivity, soil erodibility, the length and slope of the eroding surface, and vegetation cover. The annual erosion rate can be accentuated or reduced by anthropogenic influences, such as poor or improved land management, construction, or road building. GIS data layers for the Walnut Gulch Experimental Watershed are used in an exercise to determine appropriate stocking rates on a semi-arid rangeland watershed as a function of vegetative and soil characteristics with limitations on stocking rates a function of soil loss as predicted by the Universal Soil Loss Equation (Wischmeir and Smith, 1978).

One of the primary uses of Walnut Gulch is livestock grazing. GIS can be used to compute the allowable grazing capacity (number of animals/area) which will consider soil protection. Grazing capacity is an estimate of the number of animals that can be supported in an area on a sustainable basis and meeting other management goals. Grazing capacity can be computed as a function of the available forage, the forage demand per animal (species specific) and adjustments made for management practices. Forage production (lb/ac) can be obtained from National Resource Conservation Service (NRCS) soil or range site maps. NRCS maps usually provide production estimates for individual soil series or range sites for high, normal and poor precipitation years.

To successfully complete this assignment, students compose AMLs that must determine (1) available forage based on vegetation, (2) potential soil erosion based on the USLE, (3) allowable use, which is limited by the potential for soils erosion, (4) forage production, which adjusts available forage by allowable use, and finally (5) grazing capacity. Students

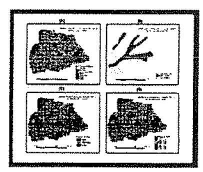


are provided with GIS layers of soils, rainfall erosivity (R factor), and topography (DEM); these are used to derive intermediate map products, and ultimately a grazing capacity map upon which management decisions can be made. Figure 1 outlines the steps used in the determination of grazing capacity.

Influences of Data Resolution on Urban Flood Prediction

Hydrologic models often require detailed spatial information for the area under investigation. GIS provides the researcher with tools to rapidly and extract relevant data to parameterize such models. There are, however, both limitations and benefits to this approach, with questions relating to resolution, spatial variability and model sensitivity foremost among them. In this lab the students become familiarized with some of these issues by using a simple runoff prediction tool in an urban watershed. The goal is to understand the ramifications of spatial resolution and attribution error on hydrologic model performance.

In this case, the SCS Curve Number method (USDA SCS, 1972), perhaps the most widely applied hydrologic model in the world, is used to model runoff for an urban Tucson watershed for multiple rainfall events with a variety of GIS data. Upon doing so, the performance of the model is assessed by comparing results to observed runoff values to determine the appropriateness of various source data. The High School Wash watershed is located directly to the East of the main portion of the University of Arizona campus, and actually incorporates some of the southeastern sections of the campus. GIS data sets of land cover and soils have been developed at a series of cell resolutions (25, 50, 100, 200, and 300 ft). Long term rainfall and runoff data have been collected within the watershed and a flume located at its outlet. Twenty-nine events were extracted from this historical database to provide a means to assess the impact of cell resolution on runoff accuracy.



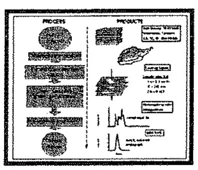
In this project, students model runoff for each cell resolution for each event. To do so, a combinatorial function must be created to derive Curve Numbers for the watershed based on land use and soils data (Figure 2). Map algebra statements are used to integrate the SCS Curve Number model with the various GIS layers and precipitation data. In this manner 135 maps of distributed runoff are produced (Figure 2D), and cumulative runoff predicted for the watershed for each event. Cumulative runoff estimates are then compared to the observed values by cell resolution. Table 2 presents the simulated runoff results using mean estimated values from the 29 events and the Nash-Sutcliffe coefficient (Martinec and Rango, 1989). Note the inverse trend in runoff prediction with increasing cell size, even though cell resolution was accounted for in the modeling process. Students are thereby introduced to the evaluation of runoff simulations since they are expected to interpret the results using a variety of parametric and non-parametric tests.

Table 2. Simulation results for 29 runoff events on High School Wash, Tucson, AZ. Prediction was made with the SCS Curve Number method using GIS techniques.

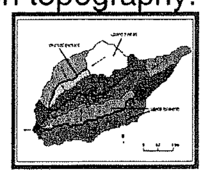
		Predicted runoff by grid cell size				
	Observed	*25*	*50*	*100*	*200*	*300*
Average runoff	0.264	0.273	0.263	0.253	0.229	0.218
Nash-Sutcliffe		0.802	0.807	0.804	0.766	0.733

Distributed Runoff Modeling

Distributed hydrologic models require both skilled application and wealth of spatially distributed data. Parameterizing these models can be onerous due to the amount and complexity of the input files. We investigate the use of GIS to circumvent some of these problems and apply the distributed physically-based runoff model KINEROS (Smith et al., 1995) to a rangeland watershed. The objectives of this exercise are to introduce emerging research in distributed modeling, become familiarized with model parameterization in GIS, and understand the limitations and influences of geographic data on model performance. The subwatershed characterization tool TOPAZ (Garbrecht and Martz, 1995) is used to delineate subwatershed elements and a separate program written by Syed (1999) takes output data from TOPAZ to generate input data files for KINEROS. KINEROS is run several times using a variety of input data sources to evaluate their influences on event-based runoff prediction.



Students are presented with theme layers of soils, vegetation, and topography for a portion of Walnut Gulch. TOPAZ is used to discretize the watershed into elements used in the modeling process based on topography. Primary GIS data are then manipulated to produce derivative map products representing distributed watershed characteristics necessary for hydrologic modeling such as canopy cover, soil texture, saturated hydraulic conductivity, and routing sequence (Figure 3). Historical rainfall data, measured at numerous rain gauges within the study area, is interpolated across the surface and input to the model on a per-element basis. KINEROS simulates excess rainfall for each element and routes the runoff to the outlet according to the scheme determined by TOPAZ (Figure 4).



This lab is used to introduce scale issues in hydrologic modeling. The effects of scale and the representation of hydrologic processes are important emerging topics in natural resource science. Figure 4 shows a small watershed subdivided into 18 elements (3 uplands, 10 laterals, and 5 channels). By lowering the estimated position at which channels begin on a hillslope, the size and number of elements changes. By increasing or reducing the complexity, the spatial variability of hydrologic processes in affected. Increasing the average element size decreases the complexity of watershed representation and reduces the spatial variability input to the model. Limiting the spatial variability can have an adverse effect on model efficiency, but creating an overly complex configuration introduces parameter estimation error and may not be necessary depending on the scale of application. In this lab, students vary the complexity of watershed representation and evaluate the impact of spatial averaging on model efficiency.

SUMMARY

A class has been developed at the University of Arizona that is designed for graduate students using GIS in their hydrologic and watershed management research. Students are exposed to emerging topics in spatial analysis and natural resource science through a series of lab exercises tailored to current topics and student need. Influences of scale, complexity, and the representation of spatially variable data on research and management decisions are stressed throughout the semester. Students are encouraged to probe the limitations imposed by various data sources to better understand the appropriate synthesis of spatial data, modeling, and interpretation.

APPENDIX I: READING LIST FOR WSM 569

General

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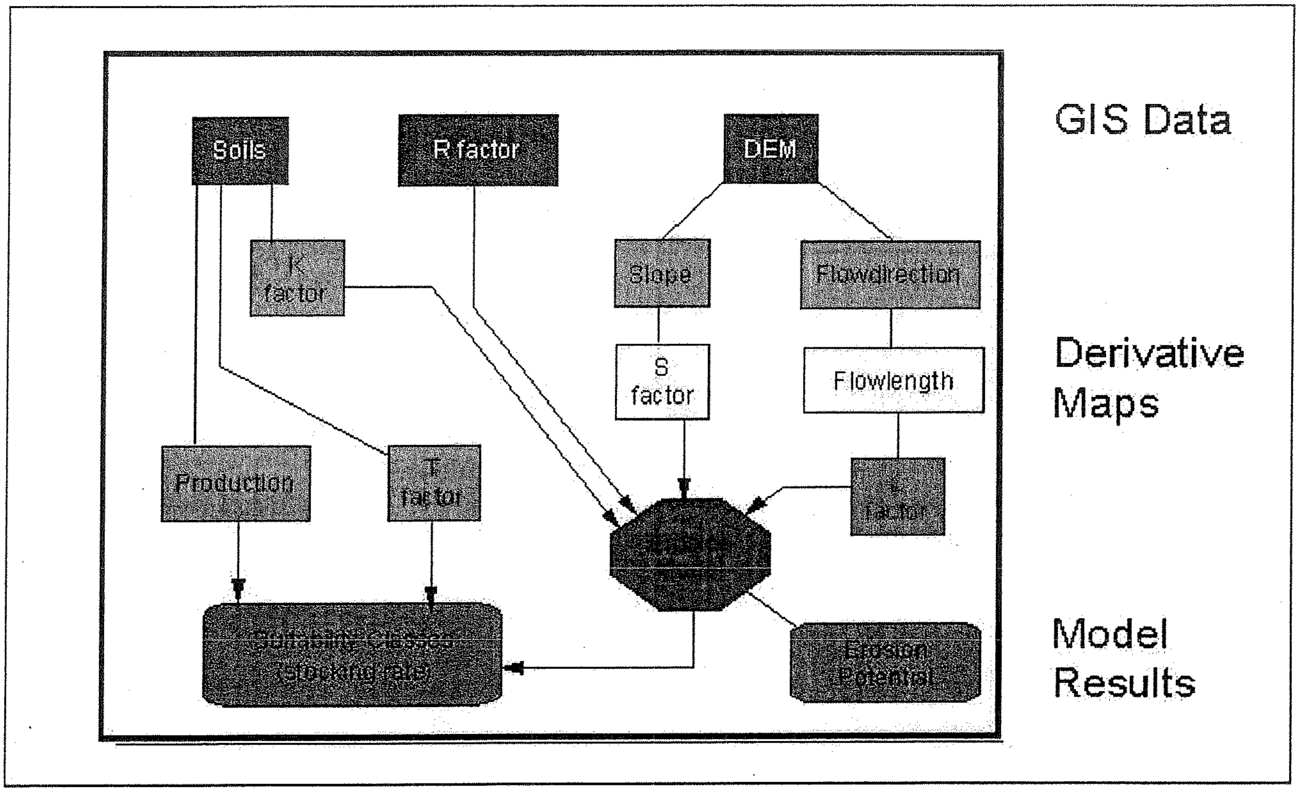

Figure 1. Flow chart illustrating methods used to derive grazing capacity using a GIS.

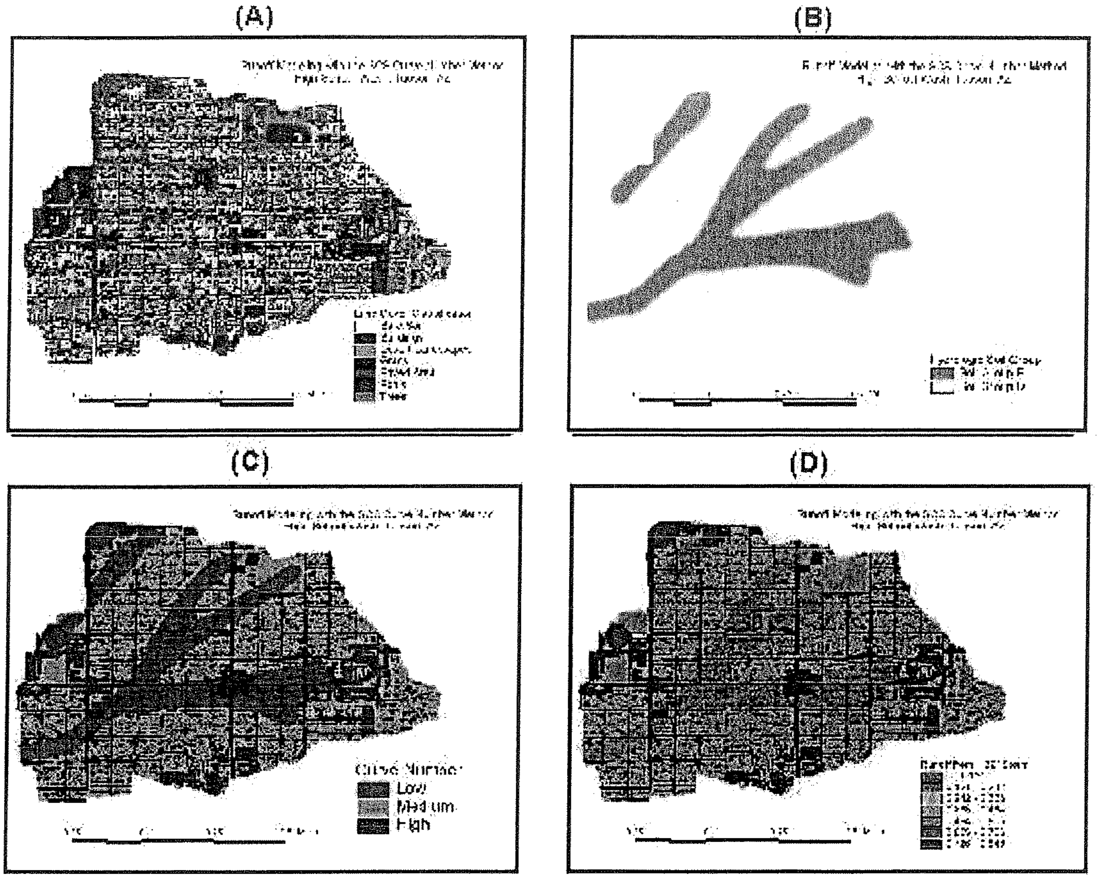

Figure 2. Series of maps showing the prediction of rainfall for an urban watershed using the SCS Curve Number Method. A land cover map (A) is combined with a soils map (b) to produce a distributed Curve Number map (C). Rainfall data is combined with the Curve Number coverage to simulate distributed rainfall, which is then area-reduced to predict total runoff depth for the watershed (D).

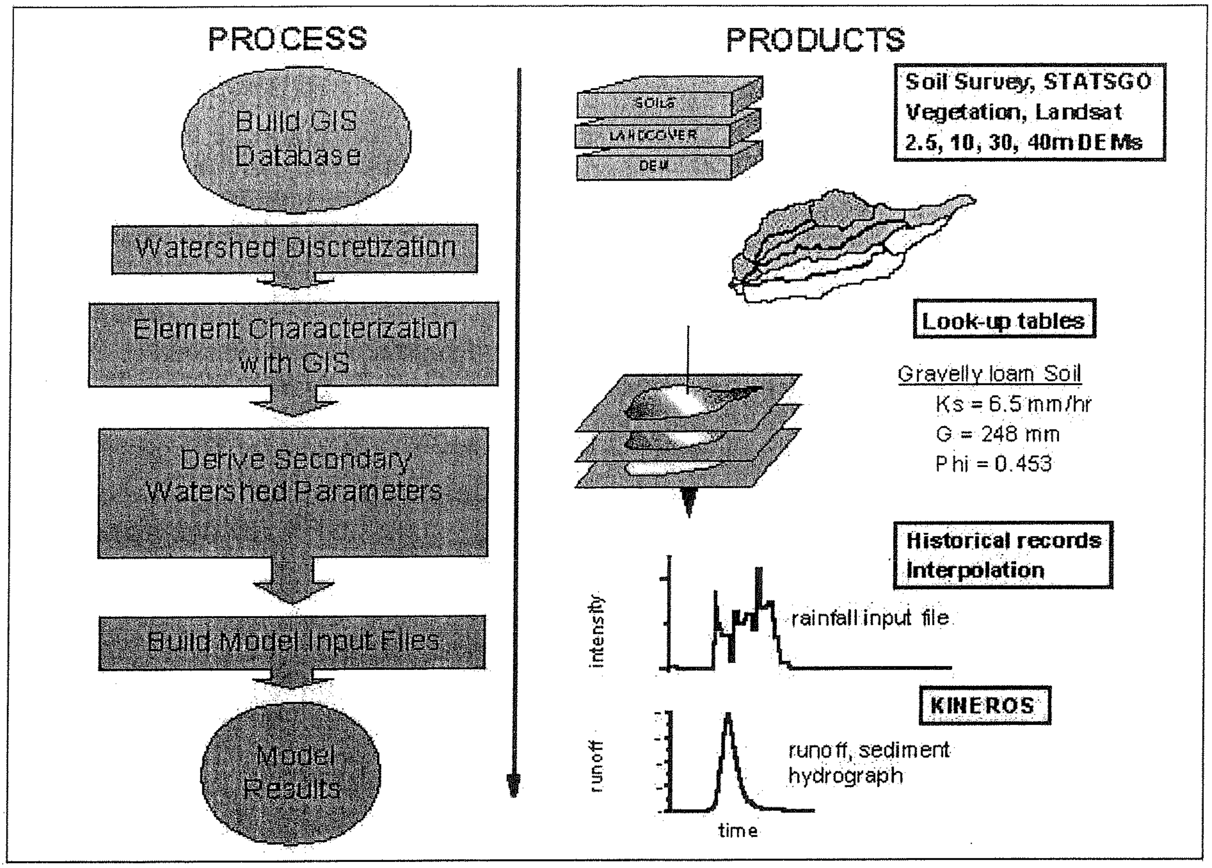

Figure 3. Schematic illustrating the use of GIS in the parameterization of distributed hydrologic models.

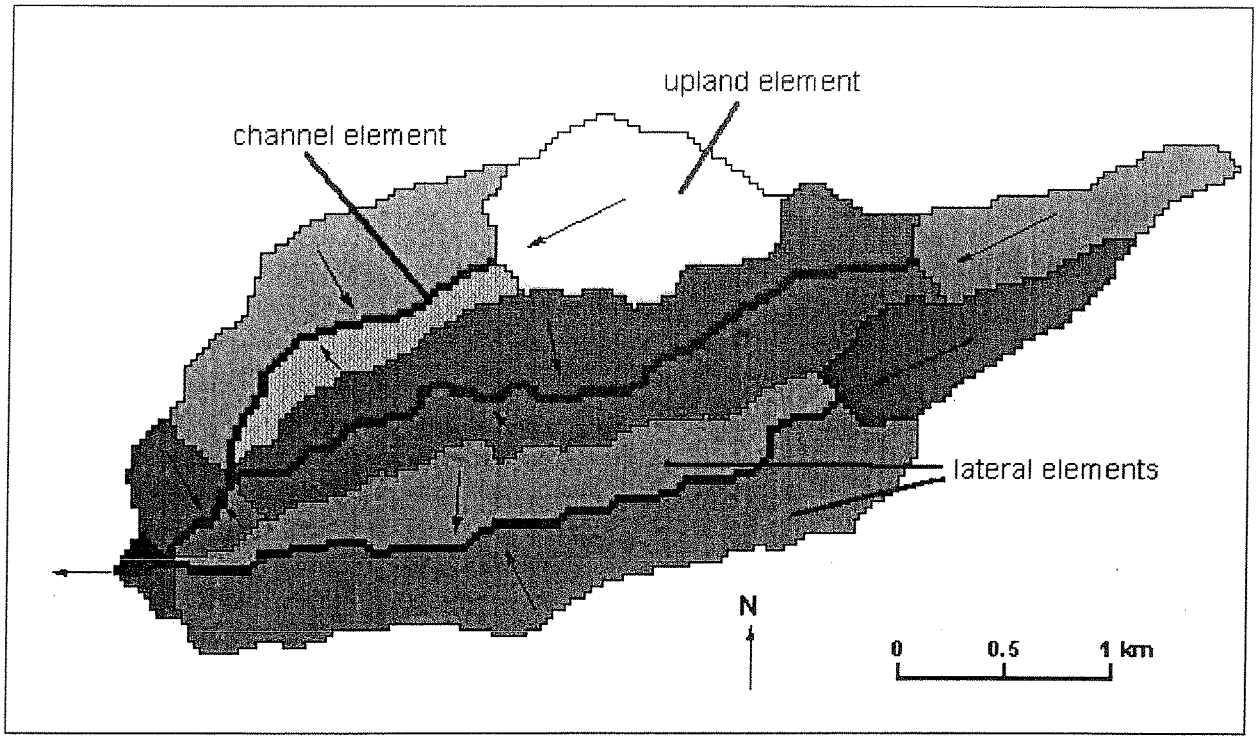

Figure 4. Subdivision of watershed 11, Walnut Gulch Experimental Watershed into upland, lateral, and channel elements for hydrologic modeling. Routing scheme is color-coded and illustrated by arrows indicating flow direction; channels are shown in blue.