TRAINING COURSE

ON

COMPUTER APPLICATIONS IN HYDROLOGY

(UNDER WORLD BANK AIDED HYDROLOGY PROJECT)

Module 12

GIS Application

in

Rainfall Runoff Modelling

BY

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GIS APPLICATION IN RAINFALL RUNOFF MODELLING

INTRODUCTION

12 The use of computers in hydrologic analysis has become so widespread that it provides the primary source of data for decision making for many hydrologic engineers. Geographic information systems (GIS) provide a digital representation of watershed characteristics used in hydrologic modeling. This lecture summarizes past efforts and current trends in using digital terrain models and GIS to perform hydrologic analyses. Three methods of geographic information storage are discussed: raster or grid, triangulated irregular network, and contour-based line networks. The computational, geographic, and hydrologic aspects of each data storage method are described. The use of remotely sensed data in GIS and hydrologic modeling is reviewed. Lumped parameter, physics-based approaches to hydrologic modeling are discussed with respect to their geographic data inputs.

Geographic information systems link land cover data to topographic data and to other information concerning processes and properties related to geographic location. When applied to hydrologic systems, nontopographic information can include description of soils, land use, ground cover, ground water conditions, as well as man-made systems and their characteristics on or below the land surface. Description of topography is called terrain modeling, and because of the tendency of surface water to flow downhill, the hydrologic importance of terrain modeling is clear. While maps have been the most common historical form of representing topography, the advent of digital maps in GIS provides an alternate method of storing and retrieving this information. The amount of digital data required to accurately describe the topography of even small geographic regions make GIS a memory intensive and computationally intensive system. Even so, there is adequate GIS software available for mainframe, mini, and microcomputers. The characteristic that differentiates a GIS from general computer mapping or drawing systems is the link to the information database. Once the database is constructed, correlation between different pieces of information can be examined easily through computer-generated overlay maps. For hydrologic modeling purposes, there is generally an extra step of generating hydrologic parameters that are dependent on database information. This hydrology-GIS link is a significant complicating factor, because it involves complex empirical or physics-based relations.

Hydrologic applications of GIS's have ranged from synthesis and characterization of hydrologic tendencies to prediction of response to hydrologic events. While the underlying assumption of any GIS application is that the database of information is available, the acquisition and compilation of the information is hardly a trivial exercise. Often, appropriate data is only available in map form, so that even with modern digitizing hardware and software the process is labor intensive. The payoff comes from the multiple ways in which the data can be used once it is made digitally accessible in a GIS. Thus, it is clear that the potential value of application of GIS to hydrologic modeling and assessment justifies the continued study of this technology. It is less clear however to what degree a GIS can replace current activities now strongly dependent on engineering judgment. Many of the limitations of present GIS capabilities are more related to limitations of data collection and reduction and current hardware capabilities, than to the software architectures used for GIS data handling. Based on current progress in these areas, the optimism of those involved in development of hydrologic applications of GIS appears justified.

GIS DATA TYPES

Topographic Data

One of the capabilities of a GIS most important to hydrologic applications is the description of the topography of a region. Techniques used in the computer description of topography are called digital elevation models (DEM's). Some spatial information is not directly described by elevation, and can be described as topologic data. Topologic data define how the various pieces of the region are connected. Topology can be described as the spatial distribution of terrain attributes. DEM and GIS representations of topologic data are part of the general grouping of digital terrain models (DTM's). An example of hydrologic topology is the collection of lines describing a stream network. Another is the collection of points delineating subregions of a watershed. Both forms of information are related to topography, but may be defined in a topological sense based on the topographic portion of the GIS database.

Topologic Data

While topographic data fit within the general classification of topologic data, there are significant hydrological attributes not related to land surface elevation. The more obvious of these are catchment areas, flow lengths, land slope, surface roughness, soil types, and land cover. These attributes help to describe the ability of a region to store and transmit water. Some topologic attributes are tied to the concept of a watershed unit. The most basic of these is the description of the watershed boundary. Given a drainage point, the topography alone can be used to define those areas that should drain to the point. Average slope and drainage path networks are related, topographically derived, topologic attributes. These attributes are useful in determining watershed attributes such as time of concentration, flow potential energies, and determining watershed attributes such as time of concentration, flow potential energies, and flow attenuation. The sorting and manipulation capabilities of a GIS are well suited to extracting such attributes.

GIS DATA HANDLING APPROACHES

Raster or Grid-Based Data

The first applications of GIS in hydrologic modeling utilized grid cell or raster storage of information. The grid is made up of regularly spaced lines, and the enclosed area of each rectangle is described in terms of its center coordinates. It is important to note that there may be different grid scales for different attributes of the terrain, although following the scale of the available data is the obvious first choice. For attributes that are largely homogeneous, the use of the rigid resolution necessary for a DEM would require the storage of large amounts of redundant data. The reduction in data storage from the use of several grid scales comes at the cost of the complexity of translation between the scales to relate the data.

An inherent problem in hydrologic modeling with grid DEM data is the production of nonphysical depressions due to noise in the elevation data affecting interpolation schemes used to describe variation in elevation between raster points. The result is an unwanted termination of drainage paths in pits. The problem is particularly acute for relatively flat areas. The situation is complicated however by the existence of naturally pitted topography, sometimes called pothole regions. The methods are sufficiently flexible to allow accurate flow path delineation even with filling of real depressions.

Grid-based Flow Pattern

Most of the raster based GIS systems contain routines, which determine the flow direction over land surface terrain using pour point model. Water on grid cell is permitted to flow to one of its eight neighboring cells. By taking a grid of terrain elevations, determine the slope of the line joining each cell with each of its neighboring cells, a grid of flow directions is created with one direction for each cell which represents the direction of steepest descent among the eight permitted choices. The concept of grid based flow pattern is represented in Figs. 1(a), 1(b), 1(c) and 1(d). The grid in figure 1(c) is shown as a set of arrows but infect is stored in GIS as a grid of numbers where each flow direction has a unique identifying number. By assigning water flow to one of its eight neighboring cells, equivalent one dimensional flow network is constructed by connecting the cell centers in the direction of flow as shown in Fig. 1(d). There is thus a duality between the grid and equivalent flow network and one might call the network so created a hybrid grid-network.

Triangular Irregular Networks

An alternate approach to producing DEM's relies upon determination of significant peaks and valley points into a collection of irregularly spaced points connected by lines. The lines produce a patchwork of triangles known as a triangular irregular network (TIN). Most typically the triangles are treated as planar facets, but smoother interpolation is possible. The problems of depressions and interrupted drainage paths are partly avoided with a TIN as the path of water movement follows the slope of a plane or flows down the edge between two triangles. Due to the fact that triangle networks from points are nonunique, several algorithms have been developed to produce them from sets of points. The most widely used is known as Delauney triangulation based on a principle of maximizing the minimum angle of all triangles produced by connector lines to nearest neighbor points. One of the main TIN systems available commercially is *ARC / INFO.*

Vector- or Contour-Based Line Networks

The third major form of representing topography is contour line mapping. The contours can be represented digitally as a set of point-to-point paths (vectors) of a common elevation. When an entire map is stored in this digital form it is called a digital line graph (DLG). Most commercially available GIS's have the ability to transform between DLG'S, grid DEM'S, and TIN DEM'S. The chief advantage of the approach is that an important hydrologic attribute (steepest descent path) is inherent in the resulting data structure.

USE OF REMOTELY SENSED DATA

Data for a GIS can be collected from ground surveys, digitizing existing maps, digitally recorded aerial photography, satellite imaging data, or combinations of these. A problem of the scale of accuracy arises when these data are used in combination, so there is a disincentive to mix them. Aerial photography is the oldest of techniques for determining topology from a remote location. Satellites have been used for several decades for remote sensing, and the potential for applications in hydrology were quickly recognized. Many hydrologically significant parameters that can be obtained through remote sensing include, land cover, vegetation properties, thermal and moisture indices, snow cover, and imperviousness. Most of these are obtained through satellite imagery. However, not all information from satellites is imagery. Satellites are often used for communication of hydrologic data from land-based sensors to analysis centers. This data can be entered into a GIS with little processing, while imagery requires considerably more processing.

HYDROLOGIC MODELING APPROACHES IN GIS CONTEXT

Rainfall-Runoff Models

Prediction of surface runoff is one of the most useful hydrologic capabilities of a GIS system. The prediction may be used to assess or predict aspects of flooding, aid in reservoir operation, or be used to aid in the prediction of the transport of water-borne contaminants. The types of models that have been applied with a GIS will be classified as lumped parameter, physics based (implying full spatial distribution and modeling for runoff related attributes), or some combination of the two.

Lumped Parameter Models

The basic unit of a lumped parameter model is normally taken to be a sub-basin of the total watershed being considered. Each sub-basin is taken as a hydrologic response unit, so that all attributes must be averaged or consolidated into unit-level parameters. The distinction between lumped parameter and distributed models is not as clear as might be desired, because the sub-basin may be taken to be arbitrarily small. Furthermore, the point-by-point descriptions of processes such as infiltration, inter-flow, and overland flow are sometimes modeled as separately contributing processes in a sub-basin. In this way, processes in complex terrain are modeled physically as simple plane (or square bin) processes occurring separately from each other. The U.S. Army Corps of Engineers hydrologic model HEC-1 is an example of a model classified here as a lumped parameter model, but can effectively operate as a distributed model through small sub-basins and/or kinematic wave routing options. Several authors have cited GIS applications of HEC-1. SCS runoff curve number estimation from raster data describing land use and soil type also falls under this category.

Physics Based Models

The lumped parameter model use empirical approaches to describe the runoff phenomenon. In comparison, a physics-based model uses some form of balance equation defined at all points to model runoff flows. The most common approach is the application of the Saint Venant equations of shallow water flow, which conserve water momentum and volume. When interflow is considered, Darcy's law of porous medium flow is used. When applied to a two-dimensional surface, these balance equations are second order partial differential equations in time and space, which must be solved by approximation methods. The solution approach is generally dictated by the form in which the data is stored. For example, grid data lends itself to application of finite difference methods, while TIN data is better suited to finite element methods.

General Indices

In some cases complete rainfall/runoff response need be described to provide the necessary hydrologic information. General indices of the tendency to produce runoff may be sufficient. Decision-making can be based on simple maps of terrain properties. It is in these applications that GIS methods can be most quickly and efficiently applied. Further, the map data produced can be saved for future use in actual rainfall runoff prediction if they are stored in a form appropriate to the model to be used. Two such indices are given below:

- Imperviousness
- Natural Land Cover

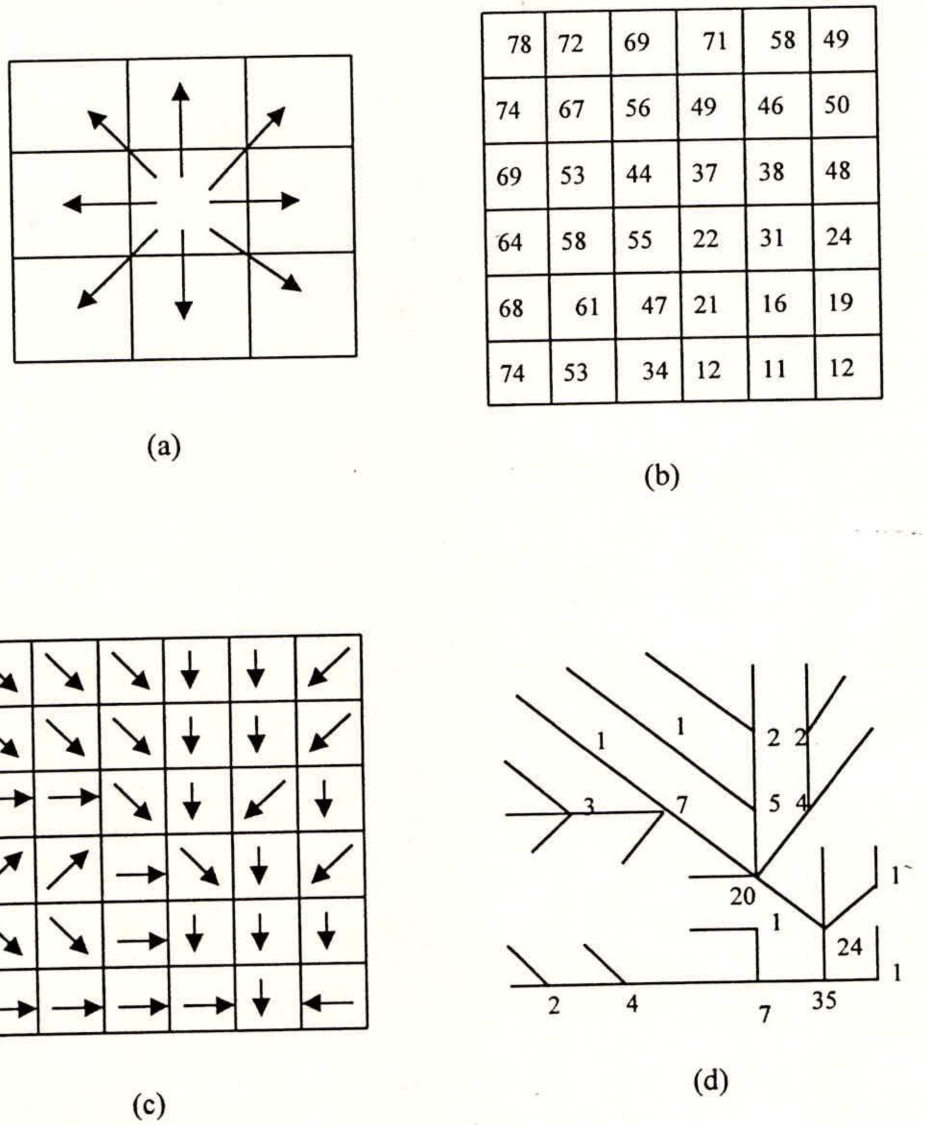

Fig. 1 Watershed terrain analysis using grid GIS method: (a) the eight direction pour point model; (b) a grid of terrain elevations; (c) the corresponding grid of flow directions; (d) the equivalent network showing flow accumulation.