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GIS and Land-Surface–Subsurface Process Modeling

IAN D. MOORE,
A. KEITH TURNER,
JOHN P. WILSON,
SUSAN K. JENSON, AND
LAWRENCE E. BAND

Generic, knowledge-based modeling techniques that are transportable across environments are rapidly becoming the basis of analytical methods used to examine and resolve complex resource and environmental issues. Models can incorporate descriptions of the key processes that modulate system performance or behavior with varying degrees of sophistication. A modeling framework provides a basis for evaluating options. Knowledge-based methods allow a variety of hypotheses to be explored and permit the calibration of physical system parameters from observations and prior knowledge. A generic framework is needed for the development of response strategies that can be applied to a variety of institutional arrangements, human settlement patterns, landscapes, and weather and climate input patterns.

Information systems and databases for addressing resource and environmental issues must be capable of integrating spatial information to representative and environmentally diverse landscapes. They also must be capable of integration with models and other analytical tools used for analysis. Geographic information systems that incorporate and spatially relate biophysical and socioeconomic data are an exciting new tool for manipulating and accessing these data.

There are many physical, biological, economic, and social models in use today. Richardson (1984) presents examples and describes the classification and characteristics of some of these "disciplinary-based" models. Some of the most interesting research being carried out today is aimed at developing integrated biophysical–socioeconomic models, databases and information systems to drive them, and decision support systems that permit their use by politicians, policy-makers, and managers who often lack intimate knowledge of the models being used.

This chapter is restricted to an examination of models of surface and subsurface processes operating at the "landscape" scale (i.e., the macro- and mesoscale). The domains dealt with by both subsurface and surface models and GIS technology are spatially distributed over a landscape; so the two technologies have a natural affinity. Moore and Gallant (1991) describe a variety of methods of classifying models. We will concentrate on computer-based, distributed parameter, semiempirical and physically based hydrological models. The hydrologic cycle provides the link between the physical, chemical, and biological processes within all the compartments of the earth (Eagleson, 1991). We will review how models of surface and subsurface processes can be interfaced with GIS to provide more robust and effective research and management tools for resource and environmental management. We attempt to address several key issues including: (1) problems of model and database structure; (2) the effects of scale and accuracy on GIS databases; (3) incompatibilities between the scales of many physically based models of land surface/subsurface processes, databases, and the intended end uses of model outputs; and (4) the specific problem of soil properties for environmental modeling, their spatial variability, and the constraints they place on land surface process modeling in particular.

MODELING AND GIS—APPLICATIONS AND PROBLEMS

The growing societal significance of non-point-source pollution, hazard identification, land resource assessment, and resource allocation problems at a variety of

scales has fueled, to a degree, the development of spatially distributed surface/subsurface modeling technologies. These problems range from the development of site-specific management strategies to regional and national policy. GIS provide the technology to store and manipulate the spatial relational data demanded by many of these models.

GIS technology has been integrated with several surface/subsurface models in recent years. Several applications explore water quality in one or two dimensions at the catchment scale. The Simulator for Water Resources in Rural Basins (SWRRB) has been linked via a decision support system (Arnold and Sammons, 1989). The Finite Element Storm Hydrograph Model (FESHM) (Hession et al., 1987; Shanholtz et al., 1990), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) (Engel et al., 1991), and Agricultural Non-Point Source pollution (AGNPS) (Engel et al., 1991; Panuska et al., 1991) models have also been linked to a variety of GIS and image processing systems. These systems include the Geographical Resources Analysis Support System (GRASS), the Earth Resources Data Analysis Systems (ERDAS), and ARC/INFO, as well as several terrain analysis software packages. The next chapter illustrates how these linkages can be made. Specifically, it shows how a spatial decision support system can be interfaced with an agricultural non-point-source water quality model and the ease with which resource managers can examine alternative management options using this integrated technology. Methods for predicting areas at risk from catastrophic mass movement (i.e., landslides) in "young" landscapes and populated areas have combined GIS and modeling technologies in Europe, China, and other areas (Aste, 1988; Corominas et al., 1990; Noverraz, 1990; Carrara et al., 1991). GIS technology that incorporates physical models and spatial databases characterizing climate, soil nutrient status, and hydrology has provided valuable insights into the forcing functions that determine the distribution and abundance of flora and fauna in "natural" ecosystems (Verner et al., 1986; Turner and Gardner, 1990; Lees and Ritman, 1991; Mackey, 1991; Norton and Moore, 1991).

At a larger scale, the United States Environmental Protection Agency (USEPA) is using the DRASTIC index (Aller et al., 1985) as a screening tool to provide regional assessments of the vulnerability of ground water to pollution and for planning ground water monitoring programs. DRASTIC is a weighted numerical scheme that considers depth to ground water (D), net recharge rate (R), aquifer media (A), soil characteristics (S), topography (T), impact of the vadose zone (I) and hydraulic conductivity of the aquifer (C) and is well suited to GIS implementation. These assessments assist in determining resource allocation among the various regions for the USEPA's ground water pollution programs. There is also great potential for using integrated modeling and GIS technologies in national resource assessments such as the appraisal of soil, water and related resources on nonfederal land required under the Soil and Water Conservation Act of 1977 (USDA, 1989) and in implementing the conservation title of the Food Security Act of 1985.

Three-dimensional GIS-based systems are being developed to visualize and model three-dimensional space and handle the huge amounts of data that are generated in subsurface and Earth system studies. They have been used to study subsurface contamination at hazardous waste disposal sites, nuclear waste repositories, and petroleum spills (Fisher and Wales, 1990, 1991, 1992). The method can provide information where an adequate sampling density is too costly and allows conditions to be predicted in areas with no data and where nonintrusive survey techniques must be used (Fisher, 1991).

Although powerful, GIS-based environmental modeling approaches have characteristics and problems that may constrain their integration. These features are discussed next.

Mathematical models

Mathematical models integrate existing knowledge into a logical framework of rules and relationships. They represent one method of formalizing knowledge about how a system behaves (Moore and Gallant, 1991). Mathematical models range from simple empirical equations such as linear regression equations (functional models) to sets of complex differential equations derived from fundamental physics (physically based models).

There are at least two reasons for developing a mathematical model: (1) to assist in the understanding of the system that it is meant to represent, that is, as a tool for hypothesis testing; and (2) to provide a predictive tool for management (Grayson et al., 1992; Beven, 1989). These two purposes can be quite distinct. Hillel (1986, p. 42) identified four principles that should guide model development:

1. Parsimony: "A model should not be any more complex than it needs to be and should include only the smallest number of parameters whose values must be obtained from data";
2. Modesty: "A model should not pretend to do too much", "there is no such thing as THE model";
3. Accuracy: "We need not have our model depict a phenomenon much more accurately than our ability to measure it"; and
4. Testability: "A model must be testable" and we need to know "if it is valid or not, and what are the limits of its validity."

Many models of surface and subsurface flow processes arguably violate these guidelines. The quandary modelers

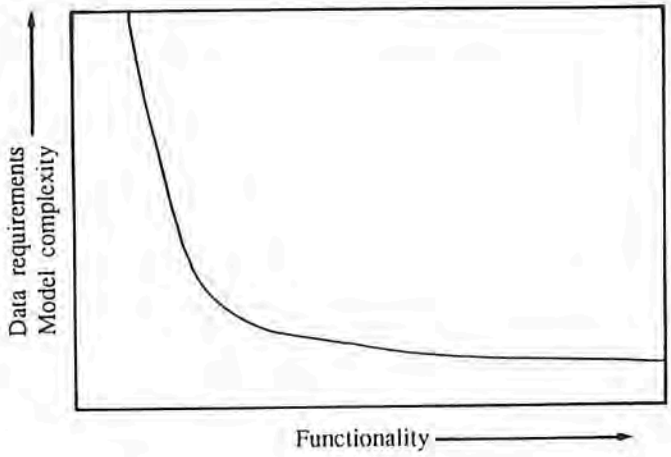

Figure 19-1: Data requirements and model sophistication versus model functionality.

often face was addressed by Denning (1990, pp. 497–498). He stated that "simplifying assumptions can introduce rather than resolve computational complexities, a possibility that looms larger for systems with many variables and for models with many simplifications" and that "it is easy for us to ignore these complexities by persuading ourselves that the model is real or that the simplifying assumptions are of no consequence." He later went on to say that "our drive to use scientific models to resolve world problems might not reflect the hubris of science. We need to ask ourselves whether some of the models of complex phenomena we seek to construct would gain us anything if we could find them." Figure 19-1 represents the tradeoff that inevitably must be made between model functionality or ease of use and data requirements or the sophistication of the process descriptions represented in the model. This tradeoff is an important consideration when attempting to interface surface/subsurface modeling techniques with GIS.

Some problems and limitations of distributed parameter, physically based mathematical models, and particularly hydrological models, were discussed by Klemes (1986), Beven (1989), Moore and Hutchinson (1991) and Grayson et al. (1992). In summary:

1. It is not clear that point-based equations adequately describe three-dimensional, spatially heterogeneous and time-varying systems in real landscapes;
2. Because of system nonlinearities, effective parameters at the grid scale may not be the same as spatially averaged values;
3. A priori estimation of model parameters is dependent on the initial method and scale of measurement;
4. Model structure can significantly influence parameter values; and
5. The ability to validate is dependent on the errors of both inputs and outputs, and requires different types of data than are traditionally available (Moore and Hutchinson, 1991).

Beven (1989, p. 157) concluded that "future developments in physically based (hydrological) modeling must take account of the need for a theory of the lumping of subgrid scale processes; for closer correspondence between equations and field processes; and for rigorous assessment of uncertainty in model predictions." Furthermore, "for a good mathematical model it is not enough to work well. It must work well for the right reasons. It must reflect, even if only in a simplified form, the essential features of the physical prototype" (Klemes, 1986, p. 178S).

Geographic information systems

Agencies adopting GIS should be aware that this technology creates a need to import data from outside the organization, often with little control by the agency. Even within an organization, one may find the need to integrate functions that were kept separate in the past. Many agencies have rushed to develop GIS with a view that it would be a panacea for providing solutions to their problems. Often the expectations of GIS technology are too high. Unfortunately, many GIS are simply being used as cartographic tools for displaying the basic input data in the form of colored maps. Many organizations are not realizing the full capabilities of this technology due to a lack of generic, knowledge-based (physically based) approaches for analyzing and interpreting data. These capabilities must be added by the user to versatile GIS such as ARC/INFO that provide a "toolbox" from which the user can build specific applications. Such approaches allow realistic answers to questions that might be asked, such as: "where are high erosion hazard zones located in a landscape?" Two other problems concerned with the implementation of GIS technology are that: (1) half-digested secondary data are often being input into them; and (2) data obtained at different scales are used with no consideration of scale effects. Primary data that modulate landscape processes and biological responses should be used as far as possible, and subjective data should be avoided. As ideas and concepts change and evolve, subjective data are often rendered useless.

Until recently GIS have been used most commonly as a cartographic tool to map essentially two-dimensional (2D) land surface phenomena such as land use, vegetation, or soil series boundaries. An extension of this tradi-

tional approach is required in soils and geological applications where representation of the vertical dimension (e.g., in characterizing soil horizons and geologic stratigraphy) is necessary and linkages to various data manipulation procedures require 3D data. Some of the most exciting developments in GIS are in the areas of topologically oriented 2D, 3D (space), and 4D (time) analyses and visualization (Gessler, 1991). These techniques have huge potential applications in the geological, soil, limnological, oceanic, and atmospheric sciences. These new GIS systems are perhaps best developed in the geological sciences, where they are called "geoscientific information systems" (GSISs) to differentiate the geologically oriented 3D and 4D systems from traditional 2D GIS products (Turner et al., 1990; Turner, 1991). In Chapter 21 Fisher illustrates how 3D GIS can be used to facilitate hazardous waste site investigations.

DATA AND MODEL STRUCTURES

Correct use of a model requires an understanding of both the biophysical system being studied and the operation of the model (Gersmehl et al., 1987a). Furthermore, a certain level of compatibility is required between the structure and spatial scale of the model and the database(s) needed to drive the model. Choosing a model is a "third-level" task. The first task consists of phrasing intelligent questions, and the second is to gather the appropriate data. All three levels must be linked (Gersmehl et al., 1987a). The problems and dangers in attempting to match spatial databases and quantitative models in land resource assessment are outlined by Burrough (1989).

There are at least two possible ways of representing topological data in a GIS: raster and vector representations (Burrough, 1986). These structures are described in detail in Chapters 3, 7 and 8. Raster structures are perhaps the simplest because entities are represented implicitly, whereas vector entities are explicitly stored in a linked database. Many low-cost GIS and large-scale environmental applications that use satellite data are based on a raster system. Vector systems usually incorporate topological structuring, which greatly increases their robustness and analytical capabilities. However, with vector systems much effort is expended in defining polygons for individual data layers and spatial operations (e.g., overlay, buffer) on two or more data layers.

Areal attribute data developed for either raster- or vector-based GIS may be stored in two ways: as a tag (classificatory) that describes each spatial unit as a whole based on the dominant attribute within it, or as a count that is an inventory of the frequency of occurrence of some phenomenon as a whole (Gersmehl et al., 1987a). Table 19-1 outlines the characteristics of the two methods. Gersmehl et al. (1987a) recommend that data collected by one method should not be used in models or to answer questions that require data of the other type.

Data problems and issues

Surface and subsurface models may require climatic/weather input data and model parameters derived from measurements of: (1) topography; (2) soil physical and chemical properties; (3) geology, including physical, chemical, and aquifer properties, and ground water characteristics; (4) land cover or land use; and (5) hydrography and water quality data. These data have vastly different temporal and spatial scales of variability and measurement. Often the scale and method of measurement are not directly compatible with the scale needed by a model. Furthermore, modeling applications require data georeferenced to a common system of grids, polygons, lines, or points. Often the lack of the necessary data to run the model or on which to estimate model parameters places the greatest constraints on the choice of model for a particular application.

Data required for biophysical modeling may be measured at a point (e.g., precipitation, soil properties, stream discharge) or over an area (e.g., remotely sensed land cover). Often point data are spatially interpolated before they are stored in GIS or used in surface and subsurface process modeling. Techniques commonly used to interpolate point data spatially include: (1) qualitative methods based on transfer by analogy, which is the dominant paradigm in soil survey; (2) local interpolation methods; (3) moving average methods; (4) kriging; and (5) partial thin plate (or Laplacian) smoothing splines (Moore and Hutchinson, 1991; McKenzie, 1991). Kriging has probably become the most widely used quantitative method of interpolating a variety of surface and subsurface data. Partial thin plate splines are formally related to kriging methods but offer some distinct advantages. The main advantage is that partial thin plate splines do not require the estimation of a spatial covariance or semivariogram function.

Different measurement and interpolation techniques characterize different biophysical phenomena occurring in landscapes, and these in turn raise different problems and issues as illustrated by the following discussion.

Climate/weather

Climate and weather variables are usually measured at a point. The gauging network is usually highly irregular, and the sampling density is nonuniform and often sparse. The records are often incomplete and of variable length. Precipitation is one of the most spatially and temporally variable types of climate data, and so we will use it as an example. Many hydrological models require hourly or even finer-resolution rainfall intensity data to drive them,

Table 19-1: Comparison of count and tag methods of data storage (reproduced from Gersmehl et al., 1987a)

Criterion	Count	Tag
Primary purpose	Regional inventory	Parcel classification
Question asked	How much of resource *R* is in area *X*?	What is the major resource in area *X*?
Typical answers	*X* has 50 ha cropland or 30 ha of *X* is woodland	*X* is a dense stand of eucalypt or *X* is mainly land capability class IV
Data scaling	Quantity measured (ratio data)	Category assignment (nominal data)
Data cell coding method	Each data cell is tabulated on the basis of the resource at the center (or some random point) within the cell	Each data cell is categorized on the basis of the areally (or economically) dominant resource within the cell
Method tries to maximize	Statistical validity in the aggregate	Descriptive accuracy in the particular
User is willing to sacrifice	Proper description of some individual tracts of land	Accurate tabulation of small or odd-shaped resource areas
What can (often does, even should) happen	The sample point "hits" a tiny woodlot in a big field and the entire cell is recorded as woodland	Narrow floodplain is "lost" from the data record because it is too small to dominate any data cells
Ideal procedure	Use enough sample points to make a valid count of even the least abundant resource	Use small enough cells to keep them homogeneous for even the smallest resource areas
Real-world compromise	Use sampling theory to limit error for major resources	Use cell size that can "capture" most major resources
Inevitable result	Point-count methods misclassify parcels	Area-tag methods miscalculate totals

but only daily data are commonly available from the National Weather Service. In addition, most models require some form of areal precipitation estimate rather than a point estimate. In recognition of these difficulties, hydrologists have derived several crude methods for estimating areal precipitation. They include Thiessen (i.e., Voronoi polygons), isohyetal, and reciprocal-distance-squared methods (Chow et al., 1988). None of these methods provides good estimates of the spatial distribution of temporally varying, fine time-resolution rainfall intensities on a catchment. Nor do they effectively handle the effects of moving storm cells. Recent developments in weather radar may overcome some of these problems, but it is not yet a fully developed technology.

Stochastic weather generators such as CLIGEN (Nicks, 1985; Nicks and Lane, 1989) and CLIMATE.BAS (Woolhiser et al., 1988) are being linked to crop growth, hydrological, erosion, and crop-productivity models such as SWRRB (Arnold et al., 1990), Water Erosion Prediction Project (WEPP) (Lane and Nearing, 1989), and Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1983, 1984). They generate sequences of daily or hourly weather data (precipitation, maximum and minimum temperature, solar radiation, etc.) at a point as a function of the statistical moments of the historical data (e.g., monthly averages of daily means and standard deviations). The parameters of Nicks's model have been developed for nearly 200 stations in the United States.

Hutchinson (1989b) has recently developed monthly climatic surfaces for Australia (EStimation Of CLIMate—ESOCLIM) by interpolating irregularly spaced and variable record length historical climate data as a function of latitude, longitude, and elevation using thin plate smoothing splines. This method is particularly attractive because it allows the variance of the climate variable to be spatially varied. It also allows the mapping of the parameter values of the weather generator described. Running et al. (1987) and Hungerford et al. (1989) developed MTCLIM, a mountain microclimate simulator, that interpolates minimum and maximum daily air temperature, precipitation, humidity, vapor pressure deficit, and solar radiation over mountainous terrain from base station records by adjusting for elevation and aspect-related effects. MTCLIM provides information at a level of accuracy and precision necessary to operate forest ecosystem models over a growing season. ESOCLIM is being used to isolate climatic influences on forest structure (Mackey, 1991) and flora and fauna distribution and abundance. Both the ESOCLIM and MTCLIM techniques could be easily imbedded in the data analysis subsystem of a GIS.

Topography

Water and wind are the main erosive agents and transporting mechanisms for land surface processes. The distribution of water is also a major factor determining the distribution and abundance of flora and fauna in a landscape. Topography is a major determinant of these erosion and transport processes. Surface process models typically

Table 19-2: Primary topographic attributes that can be computed by terrain analysis from DEM data (adapted from Speight, 1974, 1980; Moore et al., 1991)

Attribute	Definition	Significance
Altitude	Elevation	Climate, vegetation, potential energy
Upslope height	Mean height of upslope area	Potential energy
Aspect	Slope azimuth	Solar insolation, evapotranspiration, flora and fauna distribution, and abundance
Slope	Gradient	Overland and subsurface flow velocity and runoff rate, precipitation, vegetation, geomorphology, soil water content, land capability class
Upslope slope	Mean slope of upslope area	Runoff velocity
Dispersal slope	Mean slope of dispersal area	Rate of soil drainage
Catchment slope*	Average slope over the catchment	Time of concentration
Upslope area	Catchment area above a short length of contour	Runoff volume, steady-state runoff rate
Dispersal area	Area downslope from a short length of contour	Soil drainage rate
Catchment area*	Area draining to catchment outlet	Runoff volume
Specific catchment area	Upslope area per unit width of contour	Runoff volume, steady-state runoff rate, soil characteristics, soil water content, geomorphology
Flow path length	Maximum distance of water flow to a point in the catchment	Erosion rates, sediment yield, time of concentration
Upslope length	Mean length of flow paths to a point in the catchment	Flow acceleration, erosion rates
Dispersal length	Distance from a point in the catchment to the outlet	Impedence of soil drainage
Catchment length*	Distance from highest point to outlet	Overland flow attenuation
Profile curvature	Slope profile curvature	Flow acceleration, erosion/deposition rate, geomorphology
Plan curvature	Contour curvature	Converging/diverging flow, soil water content, soil characteristics

* All attributes except these are defined at points within the catchment.

require topographic-based data defining catchment and subcatchment boundaries, drainage areas, land slopes, slope lengths, slope shape, channel slopes, aspects, channel networks, and cell or land unit connectivities that define how water moves through a landscape (Table 19-2). For example, approximately one third of the input parameters required by the AGNPS water quality model are terrain based (Young et al., 1989). Panuska et al. (1991) have shown how digital terrain modeling techniques can be interfaced with the AGNPS model to derive terrain-based model parameters automatically.

Topographic attributes can be divided into primary and secondary (or compound) attributes. Primary attributes are directly calculated from elevation data and include variables such as elevation, slope, and aspect. Compound attributes involve combinations of the primary topographic attributes and are physically based or empirically derived indices that characterize the spatial variability of specific processes occurring in the landscape. Table 19-2 lists the key primary topographic attributes and their significance in surface and subsurface process modeling. Moore et al. (1991) and Moore and Nieber (1989) describe a series of compound attributes used to characterize the spatial distribution of selected hydrological, geomorphological, and ecological processes. This approach is discussed in more detail later using two examples: the spatial distribution of soil water content and erosion potential in complex terrain.

These topographic attributes can be computed from a digital elevation model (DEM) using a variety of terrain analysis techniques and stored as a digital terrain model (DTM) as part of a GIS (Moore et al., 1991). It may be more efficient to include a terrain analysis technique within the analysis system of a GIS and compute terrain attributes from DEM data rather than store the large number of terrain attributes within the GIS. It is possible to compute the primary terrain attributes by either fitting a surface defined by some function $F(x,y,z)$ to the DEM

and using elementary geometry to derive the attributes or by using finite difference techniques directly with the DEM. Methods that fit a surface sequentially to local regions of the DEM are called local interpolation methods, while those that fit a surface to the entire DEM are called global methods. Generally, global methods are computationally intractable except for small areas. Moore et al. (1991) present equations for calculating slope and aspect from surfaces fitted using local interpolation methods to a range of DEM structures. The equations are simple and easy to implement within a GIS and produce identical results to finite differencing methods, depending on the form of the finite differencing scheme used. The presentation of these relationships is beyond the scope of this paper.

The ideal structure for a DEM depends on the intended use of the data and how it might relate to the structure of a model. Figure 19-2 illustrates the three principal ways of structuring a DEM (Moore et al., 1991):

1. Grid-based methods may use a regularly spaced triangular, square, or rectangular mesh or a regular angular grid, such as the 3 arcsecond spacing used by the U.S. Defence Mapping Agency. The choice of grid-based method relates primarily to the scale of the area to be examined. The data can be stored in a variety of ways, but the most efficient is as z coordinates corresponding to sequential points along a profile with the starting point and grid spacing also specified.
2. Triangulated irregular networks (TINs) usually sample surface-specific points, such as peaks, ridges, and breaks in slope, and form an irregular network of points stored as a set of x, y and z coordinates together with pointers to their neighbors in the net (Peucker et al., 1978; Mark, 1975).
3. Vector or contour-based methods consist of digitized contour lines and are stored as digital line graphs (DLGs) in the form of x,y coordinate pairs along each contour line of specified elevation. These can be used to subdivide an area into irregular polygons bounded by adjacent contour lines and adjacent streamlines (Moore et al., 1988; Moore and Grayson, 1991). The method is based on the stream path analogy first proposed by Onstad and Brakensiek (1968).

The most widely used data structures consist of square grid networks because of their ease of computer implementation and computational efficiency (Collins and Moon, 1981). However, they do have several disadvantages (Moore et al., 1991). They cannot easily handle abrupt changes in elevation. The size of grid mesh affects the results obtained and the computational efficiency (Panuska et al., 1991). The computed upslope flow paths used in hydrological analyses tend to zigzag and therefore are somewhat unrealistic. This produces a lack of precision in the definition of specific catchment areas. Since regular grids must be adjusted to the roughest terrain, redundancy can be significant in sections with smooth terrain (Peucker et al., 1978). Triangulated irregular networks are more efficient and flexible in such circumstances. Olender (1980) compares triangulated irregular networks with regular grid structures. Grid-based DEMs generally provide the most efficient structures for estimating terrain attributes. Contour-based methods require an order of magnitude more data storage and do not provide any computational advantages. With TIN structures, there can be difficulties in determining the upslope connection of a facet. These can be overcome by visual inspection and

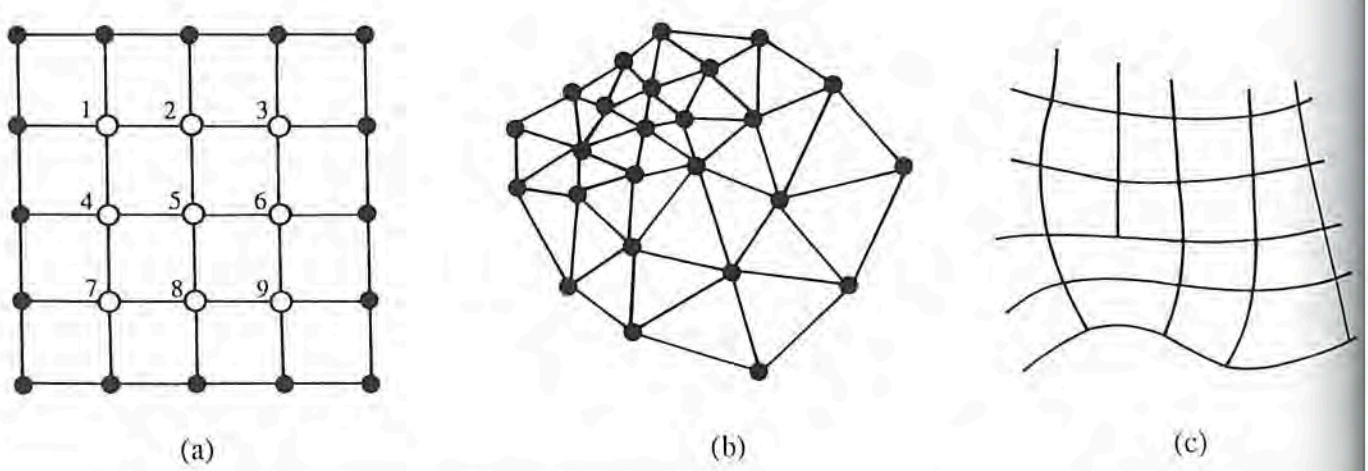

Figure 19-2: Methods of structuring an elevation data network: (a) square-grid network showing a moving 3 × 3 submatrix centered on node 5; (b) triangulated irregular network (TIN); and (c) vector- or contour-based network (adapted from Moore et al., 1991)

manual manipulation of the TIN network (Palacios-Velez and Cuevas-Renaud, 1989). The irregularity of the TIN makes the computation of attributes more difficult than for the grid-based methods.

Contour lines can be digitized automatically using the processes of raster scanning and vectorization (Leberl and Olson, 1982) or manually by using a flat-bed digitizer and software packages. Individual contours can be digitized and retained in contour form as DLGs or interpolated onto a regular grid or TIN. Similarly, spot heights can be digitized and analyzed as an irregular network or interpolated onto a regular grid. Hutchinson (1989a) describes a new efficient finite difference method of interpolating grid-DEMs from contour line data or scattered surface-specific point elevation data (ANUDEM). The method was used to develop the continent wide DEM for Australia that is described by Hutchinson in Chapter 39. The most common method of performing a contour-to-TIN transformation is via Delaunay triangulation (McLain, 1976).

Digital elevation data are available in several forms for selected areas in the United States. They can be obtained from the Earth Science Information Center (ESIC) of the U.S. Geological Survey (USGS). DEMs are available on a 30 m square grid for 7.5 minute quadrangle coverage, which corresponds to the 1:24,000 scale map series quadrangle. DEMs based on a 3 arcsecond spacing have been developed by the Defense Mapping Agency for 1 degree coverage, which is equivalent to the 1:250,000 scale map series quadrangle, and are also available from the ESIC. Digital contour lines are available as digital line graphs (DLGs) for certain 7.5 and 15 minute topographic quadrangles, the 1:100,000 scale quadrangle series, and 1:2,000,000 scale maps published by the USGS. A 30 arcsecond DEM is now available for the conterminous United States from the National Geophysical Data Center of the National Oceanic and Atmospheric Administration (NOAA). Stereo images available from the French Earth observation satellite SPOT can be used to produce orthophotos and DEMs in much the same way as conventional air photography. Satellite data have the advantage that they can be purchased in digital form and directly accessed by computers. However, they also requires special software for processing.

A new source of global elevation information will be provided by the U.S. Defense Mapping Agency's Digital Chart of the World (DCW) product. The DCW will contain fully structured and attributed vector data from the 1:1,000,000 Operational Navigation Charts (ONCs). It will be available on CDROM. For much of the world where DEMs are not available, the DCW hypsography and hydrography can be gridded to produce DEM data sets. The prototype DCW CDROM contains the vector data from the E-1 ONC map covering the United Kingdom. The hypsography and hydrography for a two-degree square area from 51 to 53 N and 0 to 2 W was gridded using ANUDEM (Hutchinson, 1989a) and compared to ETOPO5 (5 arcminute global DEM) and Defense Mapping Agency's three-arcsecond DEM for the area. Plate 19-1 illustrates the three DEMs and the DCW vector data. Major features are readily apparent in the DCW DEM, indicating that this will be a promising new source of topographic information.

Many published DEMs are derived from topographic maps; so their accuracy is dependent on the quality of the original source of the data and of the methods of interpolation. The most accurate DEMs produced by the U.S. Geological Survey are generated by linear interpolation of digitized contour maps. They have a maximum root mean square error of one-half contour interval and an absolute error no greater than two contour intervals in magnitude (USGS, 1987). The USGS DEMs are referenced to "true" elevations from published maps that include points on contour lines, benchmarks, or spot elevations (USGS, 1987). However, these "true" elevations also contain errors. All DEMs have inherent inaccuracies not only in their ability to represent a surface but also in their constituent data. It "behooves users to become aware of the nature and the types of errors" (Carter, 1989). The USGS DEM data are classified as Level 1, 2, or 3 in quality (USGS, 1987), with Level 3 data being the most accurate. The USGS does not currently produce Level 3 elevation data.

Soils

The U.S. Department of Agriculture Soil Conservation Service Soils-5 database provides information on the characteristics and interpretive properties of 13,788 soil series identified in the United States. These data are derived from the USDA-SCS County Soil Surveys that are mapped at scales ranging from 1:15,000 to 1:20,000, depending on the age of the survey. As an example application, the soil data required by the SWRRB model were derived from the Soils-5 database and are available on computer diskettes (Arnold et al., 1990). Lytle discusses the digital soils databases for the United States in more detail in Chapter 38.

The boundaries of mapping units in the County Soil Surveys are being digitized and stored in vector form using a variety of GIS software, but most commonly GRASS (U.S. Army, 1987), in many State Offices of the USDA-SCS. In Minnesota, Robert and Anderson (1987) have developed a Soil Survey Information System (SSIS) based on digitized County Soil Survey data. It has many of the features of a GIS. SSIS can retrieve, sort, display, highlight, and print soil survey information, as well as display and overlay other digitized data (such as vegetation cover) and develop and display interpretive maps. The system has been used to develop crop equivalent ratings, to prepare farm conservation plans and to help individual farm-

ers and extension agents make better judgments on fertilizer and herbicide application rates using simple analytical models such as the Universal Soil Loss Equation (Wischmeier and Smith, 1978).

Specific soil property data within Soils-5 are presented as ranges. The values of some variables, particularly those describing the hydraulic properties of the soil, can vary by an order of magnitude. This limits the use of Soils-5 data to certain agro-forestry applications and macro-scale or basin-scale hydrological models (such as SWRRB) where there is a high degree of lumping of model parameter values and to large temporal scales probably exceeding one day. These data cannot be used directly, for example, in a model that might calculate infiltration, runoff, and subsurface water movement using physically based process descriptions such as the Richards equation (Richards, 1931) or even the greatly simplified Green–Ampt equation (Mein and Larson, 1973). In recognition of these major constraints, considerable effort has been directed towards developing methods of inferring air and water properties of soils using surrogates derived from soil morphological properties available from soil surveys (Rawls et al., 1982, 1983; McKeague et al., 1984; McKenzie and MacLeod, 1989; Williams et al., 1990; McKenzie et al., 1991). The most common surrogates used are soil texture, organic matter, soil structure, and bulk density. These methods have only been partly successful because the surrogates are usually measured at scales too coarse to capture the variability in the parameters used by the models (compare the variability of soil texture/soil series on a county soil map with the variability of infiltration and hydraulic conductivity that display great variability over distances of less than 10 m). Methods that also include landform descriptors derived from DEMs (e.g., Dikau, 1989) show potential for overcoming these problems (Moore et al., 1991; McKenzie, 1991).

In late 1991 the USDA-SCS National Soil Survey Laboratory in cooperation with the Blackland Research Center at Texas A&M University released the "Soil Pedons of the United States" database on CDROM. This includes laboratory data from the National Soil Survey Laboratory (16,000 pedons), soil description data (8,000 pedons), and mineralogy data for individual, geo-referenced pedons (Dyke, 1991). These data with DTMs and suitable spatial interpolation techniques may provide parametric methods of estimating specific soil properties for input into macro- and meso-scale models of land surface processes.

Geology

A major impediment to environmental modeling is the lack of coordinated mapping programs to produce geologic maps and digital databases at consistent scales. The lack of established standards is another problem, as is the inability of geologists working on adjoining map sheets to agree on feature locations and naming conventions. The basic areal unit for unconsolidated and surficial geologic materials can often be assumed to coincide with the surface drainage basin or catchment. For consolidated and bedrock material this is rarely true (Pfannkuch et al., 1987). Furthermore, most traditional 2D geological mapping is based on chronology (i.e., age) rather than lithology. Chronology often does not provide sufficient differentiation of physical and chemical geological properties needed in subsurface modeling.

The development of geologic conceptual models is the major process in subsurface characterization and poses unique demands on both data management and visualization (Turner, 1989). The procedure of using multiple working hypotheses is a fundamental tenet of geology. Given the sparseness of geological data, geoscientists must develop one or more "most probable" scenarios, or conceptual models, in order to expand measured data to create a continuous model of the entire subsurface. A variety of data types must be combined and synthesized. This requires a centralized database capable of handling a variety of data. The geoscientist using such a system desires to interact with the database in ways that retain the spatial relationships and allow 3D visualization.

During many geological investigations existing 2D geological maps and associated cross sections form an important data source. Two-dimensional mapping of surficial geology is also required for many types of biophysical modeling (such as water balance studies). Sometimes geology can be used as a surrogate when soils data are not available. Two-dimensional surficial and bedrock geology maps are commonly available at scales of 1:500,000 and 1:250,000, but more detailed maps are available for some local areas. Major sources of 1D data include borehole log records, well-pumping data, and water-depth data collected by the USGS and the petroleum industry. All these data sources must be incorporated into a 3D data structure for subsequent analysis and modeling activities. The methods for such incorporation are still under development. For example, environmental site characterization at uncontrolled hazardous waste sites typically involves the collection of data and development of a conceptual model of a site's geology, hydrogeology, and contaminant nature and extent. These investigations result in the generation of graphical and tabular data of different types and formats. Data integration, correlation, and synthesis are necessary for the development and testing of the required 3D computerized conceptual model(s). In addition, site data are often subjected to quality assurance and quality control (QA/QC) procedures. These range from prescribed adherence-related QC attributes, through sample collection and analysis techniques, to statistical verification techniques for identifying outliers and calculating parameter uncertainty. QA/QC procedures are often a prerequisite to data input into higher-level assessment and design activities, such as site characterization, feasibility

studies, hazard assessments, and remedial design activities.

To accommodate the types of data flow and data uses described, the data management system must satisfy the following general data management requirements (Nasser and Turner, 1991):

1. Provide the capability to store, retrieve, manipulate, and view 1D, 2D, and 3D graphical objects in any user-defined viewplane in the 3D space;
2. Provide a direct link between the 1D, 2D, and 3D objects and their attributes through a relational database management system;
3. Accommodate the QA/QC procedures, including the level of confidence of the data being used and the RDBMS storage of data validation results;
4. Allow a user-defined, interactive graphical technique for the transition from the first dimension (borehole) into the second dimension (cross section) and then into the third dimension (3D solid block or 3D physical conceptual model);
5. Provide the tool to slice interactively through the created 3D object in any user-defined viewplane in 3D space;
6. Allow easy update of the created 3D model to take account of recently collected data; and
7. Provide application tools to support volumetric interpretive activities.

Typical application tools include spatial analysis, 3D statistical parameter estimation and interpolation (e.g., hydraulic conductivity interpolation by kriging analysis of measured hydraulic conductivity data), and integration of several 3D models to evaluate the possible relationship between these models (e.g., integration of a 3D contaminant plume model with a 3D hydrogeological model).

Land cover

Land cover (LC) is a critical component of most surface/subsurface models, whether they deal with plant growth, hydrology, erosion, or salinization. Land cover is a more useful variable than land use (LU) because land use is an economic concept and a given land use can be associated with a variety of land covers (Gersmehl et al., 1987). In addition, land cover is a dynamic quantity that often exhibits great seasonal variation. Some models, particularly crop-growth models, simulate vegetation canopy development, often via leaf area index (LAI), and so do not require land cover input data directly. Traditional sources of data include the USGS 1:100,000 (urban areas) and 1:250,000-scale (rural areas) LU/LC polygon maps and GIRAS digital data files. The USGS maps combine land use and land cover into a single classification that has four levels that range from very broad to detailed (Anderson et al., 1976). The major problem with these data is that they were collected for once-over cover of the conterminous United States and represent only a snapshot in time. The temporal incompatibilities associated with adjacent maps greatly limit their utility.

Land cover data are most commonly obtained from satellite imagery such as Landsat Thematic Mapper (TM) and Multi-Spectral Scanner (MSS) or SPOT1 and visual air photo interpretations. Satellite imagery is relatively inexpensive, can be rapidly processed and can provide data on the temporal variation in land cover. Landsat-5, for example, allows scenes of the same area to be obtained every 16 days, cloud cover permitting. The Advanced High Resolution Radiometer (AVHRR) satellites operated by the National Oceanic and Atmospheric Administration provide frequent large-area coverage with approximately 1 km resolution. A "greenness" measure derived from these data is frequently used to represent vegetation conditions. These data are composited at the EROS Data Center to provide digital biweekly United States greenness data sets. The availability of these kinds of data provides a basis for time series representations of land cover. Loveland describes these AVHRR derived data sets in more detail in Chapter 37.

Classification of land cover from satellite images is subject to misinterpretation because of problems with rectification and because spectral data cannot distinguish small features and can overlap in complex ways. The ambiguities in the interpretations can be reduced by using the terrain and soils data contained within a GIS to assist in the classification. Visual air photo interpretations are generally more accurate, particularly in urban areas, but are very expensive and time consuming to process (Gersmehl, 1987). Satellite data are provided in raster form, whereas data from air photo interpretations are usually provided in vector form.

Hydrography

Stream systems and channels are linear features and have a hierarchical organization based on the gravity flow of water. These features are best represented as vector data files. Discharge and water quality are measured at specific points along these linear features at different time scales. Mean daily discharge data are available through the USGS stream gauging database and databases maintained by some state agencies. Each stream gauge has a unique 8-digit number ordered in the downstream direction. These stream gauging records are of variable length and often contain missing records. Water quality is measured at a limited number of sites on a monthly or less frequent basis and provides only a snapshot in time. Furthermore, the water quality variables measured are inconsistent and because of the poor temporal cover are almost unusable for modeling purposes.

Many states also hold other hydrographic data, including information concerning lakes, wetlands, and coastal zones. Minnesota has MLMIS40 watershed boundary files, MLMIS40 water orientation files (all 40-acre parcels of land that adjoin or contain water), Systems for Water Information Management (SWIM) lake summary files (location, physical characteristics, water chemistry, use, diversion and other permits, development along shore line, public access, fishing resources), and River Kilometer Index (RKI) files (identifies all streams and ditches and records their lengths) (Brown et al., 1987). For modeling applications where runoff needs to be routed through a channel and lake network, data such as channel geometry, bed roughness and slope, channel stability conditions over short distances are required, but rarely available.

The "blue lines" drawn on topographic maps are a conservative representation of the stream network as they only represent permanently flowing or major intermittent or ephemeral streams (Mark, 1983). This is unfortunate because first-order channels are a major source of surface runoff in many environments. Rogers and Singh (1986) found that in Pennsylvania the number and distribution of first-order channels were inversely proportional to basin soil infiltration capacity and controlled surface runoff hydrograph shape, respectively. Not surprisingly, there has been an increasing effort directed towards the development of automatic, computer-based channel network models that use digital elevation data as their primary input. Hydrological, geomorphological, and biological analyses using GIS and remote sensing technology and computer-based cartographic systems can be more easily integrated with these methods than traditional manual methods, with a high degree of objectivity. Excellent reviews of channel network analysis are presented by Jarvis (1977), Smart (1978), Abrahams (1984), Mark (1988), and Tarboton et al. (1989).

Mark (1988) identified several algorithms for determining total accumulated drainage at a point for application to grid-based DEMs. Some are computationally impractical to implement from an operational and computational efficiency point of view. One of the first algorithms developed, Collins' (1975) method, required that the elevation data be sorted into ascending order. Although several efficient sorting algorithms are now available, the method is not practical for large elevation matrices compared to the alternative techniques to be described. A second and probably the most commonly used algorithm for determining drainage or contributing areas and stream networks was proposed by O'Callaghan and Mark (1984). After producing a depressionless DEM, they use the resulting drainage direction matrix, which gives the flow direction from a node to one of eight nearest neighbors (D8 algorithm—see Figure 19-2a, which shows the eight nearest neighbors to the central node 5), and a weighting matrix to determine a drainage accumulation matrix iteratively that represents the sum of the weights of all elements draining to that element. The element weights range from 0.0 (no runoff from the element) to 1.0 (entire element contributes to runoff). The drainage direction of each individual element is the flow direction from the element to one of its eight nearest neighbors based on the direction of steepest descent. If all the weights equal one, then the drainage accumulation matrix gives the total contributing area, in number of elements, for each element in the matrix. Streams are then defined for all elements with an accumulated drainage area above some specified threshold. A similar, but faster and more operationally viable, method of defining stream channels and drainage basins has been developed by Jenson and Domingue (1988) and is being widely used. Band (1986a, 1989) describes another variation of O'Callaghan and Mark's (1984) algorithm. Methods that use the D8 nearest-neighbor algorithm to assign drainage directions tend to produce parallel lines along preferred directions. Fairfield and Leymarie (1991) overcame this problem by introducing a quasirandom component to the D8 algorithm. Freeman (1991) and Quinn et al. (1991) recently developed algorithms that pass cell drainage to multiple downslope cells using a weighting factor calculated as a function of slope.

Band (1986b) describes another approach that uses Peucker and Douglas' (1975) algorithm for marking convex and concave upward points as ridge and stream points. For each element the highest of the neighboring eight elements is marked, and after two sequential sweeps (forward and backward) through the elevation matrix the unmarked elements identify the drainage courses. Similarly, identifying the lowest of the eight neighboring elements defines ridge lines that are approximations to the drainage divides. The drainage and ridge lines may not be continuous and may consist of multiple adjacent lines that must be interpolated and thinned to one-element-wide continuous lines. A connected channel network is developed using a steepest decent method that includes an elementary pit removal algorithm that often breaks down in flat terrain. In the final step each stream junction element is defined as a divide, thus anchoring the divide graph to the stream network, and the divide network is refined. Thus subcatchments are defined for each stream link. The method requires initial smoothing of the DEM but does have the advantage that no arbitrary threshold area needs to be specified (Tarboton et al., 1989).

Model structures

There are six model structures commonly found in surface/subsurface models, and most are based on topography: (1) lumped models that spatially integrate the entire area being modeled; (2) models based on identifiable hydrological response units (HRUs) consisting of so-called "homogeneous" subcatchments; (3) grid-based

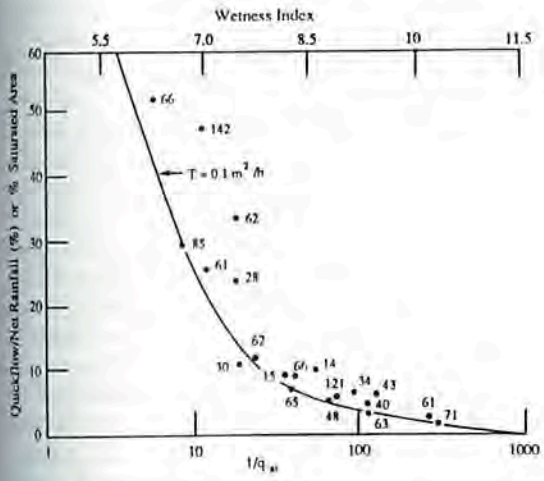

Figure 19-3: Percentage saturated source area as a function of wetness index [$\ln(A_s/\tan\beta)$] and average subsurface drainage rate per unit area, q_{at}, for a small catchment in south eastern Australia (adapted from Moore et al., 1986). The measured percentage of quickflow to net rainfall for individual storm events is plotted as the solid points and the net rainfall is shown for each storm. T is the catchment average transmissivity.

models; (4) TIN-based models; (5) contour-based models; and (6) 2D and 3D groundwater models. Types (2) and (3) to (5) could be viewed as extremes of the representative elemental area (REA) concept proposed by Wood et al. (1988) and are compatible with the DEM structures illustrated in Figure 19-2. The models presented as examples in this section can generally be classed as distributed-parameter, physically based models.

Lumped models

Lumped models are among the simplest forms of model. A major concern in using a lumped model is that it is probably not possible to obtain a single value of a spatially variable parameter that allows a model to predict the mean response of the modeled area (Moore and Gallant, 1991). Spatial integration to the catchment scale is difficult because of the typical nonlinear catchment response (Goodrich and Woolhiser, 1991). For example, Milly and Eagleson (1987) examined the effects of spatial variability of soil and vegetation on spatially and temporally averaged hydrologic fluxes. Only where there was little initial variability could an equivalent homogeneous soil reproduce the average behavior. Similarly, Addiscott and Wagenet (1985) warn that "gross over- or underestimates of solute and water movement may result from ignoring [parameter variations in the horizontal plane]" when applying leaching models.

If one process in a landscape dominates the response, it may be possible to use a simple lumped model to simulate the behavior if a quasidistributed representation of the effect of that process can be incorporated into the model. Moore et al. (1986) adopted this approach in their development of a lumped model of the dynamic hydrological response of a forested catchment in southeastern Australia. The response of the catchment was dominated by saturation overland flow. They used a distribution function of fraction of saturated source area versus mean base flow as the basic input to the model controlling the simulation of the effect on catchment runoff of the expansion and contraction of zones of surface saturation (Figure 19-3). This function was estimated using O'Loughlin's (1986) steady-state method of computing the wetness index [$\ln(A_s/\tan\beta)$, where A_s is the specific catchment area and β is the slope at a point] versus percent saturated area relationship (and in the process fitted the mean catchment transmissivity) from a DEM and historical rainfall-runoff data. This relationship, with the assumption of successive steady states in the time domain, provided the basic structure of a simple lumped-parameter model of forested catchment hydrological response.

HRU models

In hydrological modeling the traditional method of dealing with complex landscapes has been to subdivide them into "less complex" units or subcatchments. This approach finds its best expression in the Finite Element Storm Hydrograph Model (FESHM) (Ross et al., 1979; Hession et al., 1987). The model has two discretization schemes. The first divides a catchment into hydrological response units (HRU) determined by soil types and land use or land cover, as illustrated in Figure 19-4. This subdivision provides the basis for the computation of spatially distributed rainfall excess and infiltration. The second scheme divides the catchment into interconnected overland flow elements and channels based on topography and surface flow paths. Area-weighted HRU rainfall excess is then routed from successive elements to the catchment outlet. A limitation of this two-phase approach is the separation of the rainfall excess production mechanism from the overland flow routing mechanism. In practice interactions and feedbacks between the two mechanisms occur and sometimes can be significant (e.g., runoff-runon problem). The vast majority of hydrological and water quality models developed before the mid-1980s are based on some variation on this structure.

Over the past 5 years the Information Support Systems Laboratory at Virginia Tech in cooperation with the Virginia Division of Soil and Water Conservation have been pioneering the linkage of GIS and hydrological modeling and water quality modeling technology. For example, they have linked FESHM and other water quality models with both PC-ARC/INFO and VirGIS (Virginia Geographic

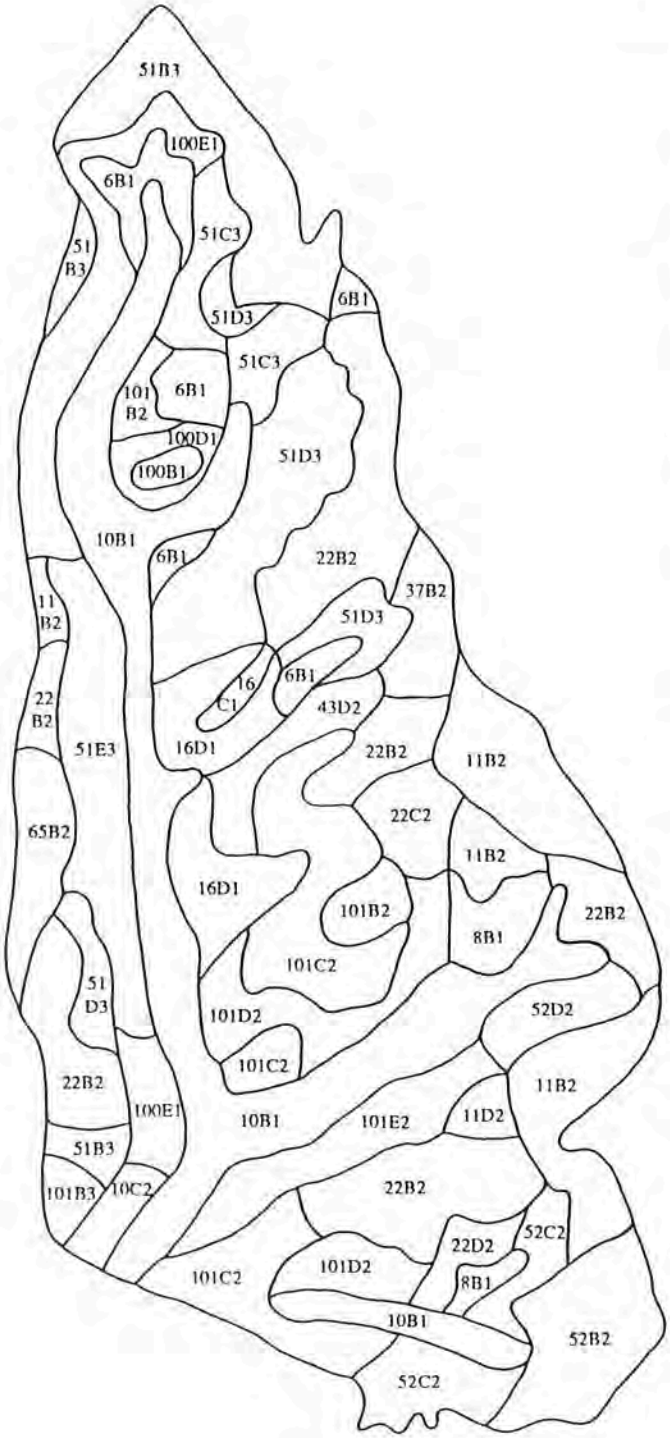

Figure 19-4: Subdivision of the Powells Creek catchment into hydrologic response units (HRU) on the basis of soil types (reproduced from Ross et al., 1982).

Information System). Also, they have built state-wide databases that these models can access (Hession et al., 1987; Shanholtz et al., 1990; Desai et al., 1990). In an evaluation of FESHM, Hession et al. (1987) concluded that "GIS technology did not provide for the entire range of management and manipulation of data desired for creating FESHM input files." A digital map-based hydrologic modeling system that can develop databases for topography, soils, land use, and point and radar-predicted rainfall using GIS has been developed by Johnson (1989). A variety of hydrologic models representing a range of processes with varying degrees of sophistication has been parameterized using this approach.

The following three model structures can be viewed as a scaling down and a merging of the basic HRU and routing element structure concepts. The apparent belief (or hope) is that successively smaller landscape units can be treated as internally homogeneous or uniform and that the spatial variability of the landscape is captured by the between unit variability. As the spatial scale of discretization decreases, the data and computational requirements of the models expand, almost exponentially. Hence the need for integrating fine resolution models with GIS.

Grid-based models

Grid or cellular approaches to subdividing the landscape provide the most common structures for modern dynamic, process-based hydrological models (Figure 19-2a). Some examples of models based on this structure include the ANSWERS (Beasley and Huggins, 1982), AGNPS (Young et al., 1989), and the very detailed Système Hydrologique Européen model (SHE) (Abbot et al., 1986). AGNPS is a semiempirical, peak flow surface water quality model and does not route the flow as such. SHE employs a two-dimensional form of the diffusion wave equations to partition flow. ANSWERS derives a weighting factor by partitioning a cell based on the line of maximum slope. A problem with these approaches is that the flow paths are not necessarily down the lines of greatest slope; so the resulting estimates of flow characteristics (e.g., flow depth and velocity) are difficult to interpret physically. ANSWERS uses a preprocessing program, ELEVAA, to generate slope steepness and aspect from grid-based DEMs for input into the model. Panuska et al. (1991) linked a grid-based terrain analysis method and grid-based DEMs with the AGNPS model via interface routines to generate the terrain-based parameter file. Terrain-based attributes represent about one-third of the input parameters required by the model. The use of grid structures for these models has a major benefit in that it allows pixel-based remotely sensed data, such as vegetation types and cover (i.e., canopy) characteristics, to be used to estimate the model parameters in each element or cell because of the inherent compatibility of the two struc-

tures.

Beven and Kirkby (1979) have developed a physically based, topographically driven flood forecasting model, TOPMODEL, that is beginning to be widely used. The model is based on the variable contributing theory of runoff generation and predicts the soil water deficit pattern and the saturated source area from a knowledge of topography and soil characteristics (Beven, 1986). Recent versions of TOPMODEL also consider Hortonian overland flow (Beven, 1986; Sivapalan et al., 1987). Beven and Wood (1983), Beven et al. (1984), Hornberger et al. (1985), Kirkby (1986), and Beven (1986) describe applications and developments of the model. Sivapalan et al. (1987) and Wood et al. (1988) used the model to examine hydrological similarity. They developed a series of dimensionless similarity parameters, one of which included a scaled soil-topographic parameter that was recently used to account for partial area runoff with the Geomorphic Instantaneous Unit Hydrograph (Sivapalan and Wood, 1990). An excellent review of the issues of similarity and scale in catchment storm response is presented by Wood et al. (1990). Band and Wood (1986, 1988) used grid-based DTMs to partition a catchment first into a set of stream link drainage areas and then extracted separate distribution functions of $\ln(A_s/\tan\beta)$, where A_s is the specific catchment area and β is the slope angle, for each subcatchment. The separate parameterization of each link catchment area revealed substantial differences in the $\ln(A_s/\tan\beta)$ distributions, and therefore in the hydrological response between typical exterior link and interior link catchments. The TOPMODEL approach is most commonly driven by a grid-based method of analysis but can easily be adapted to contour-based methods.

Several geomorphological models have been developed to simulate landscape evolution on geologic time scales. Landscapes are modeled as "open dissipative systems," where sediment transport is the dissipative process and the state equation for elevation is the sediment mass continuity equation, written in the form (Willgoose et al., 1989a,b):

$$\frac{\partial z(x,y,t)}{\partial t} = \text{sources} - \text{sinks} + \text{spatial coupling} \quad (19\text{-}1)$$

where $z(x,y,t)$ represents the land surface that is twice continuously differentiable in space (x,y) and once continuously differentiable in time, t (Smith and Bretherton, 1972). The spatial coupling is achieved via sediment transport that is usually expressed as a function of slope, β, and discharge, Q. This in turn is spatially linked via the water continuity equation (usually the overland flow equations). Examples of the processes represented in these models include: tectonic uplift (sources), bedrock weathering, rockfall, slow mass movement (creep), rain splash and overland flow erosion and sediment transport (Kirkby, 1971; Smith and Bretherton, 1972; Ahnert, 1987; Willgoose et al., 1989a,b). Models of the evolution of both 1D hillslopes (e.g., Kirkby, 1971; Smith and Bretherton, 1972; Ahnert, 1976) and 2D landscapes (Smith and Bretherton, 1972; Ahnert, 1987; Willgoose et al., 1989a,b, 1990, 1991) have shown that the shape of the final hillslope or landscape is dependent on the form of the governing sediment transport equation. Most models, such as Ahnert's (1987) SLOP 3D model, which simulates a wide range of landscape processes, do not specifically account for the linkages between the land system and the channel network. Hillslopes are equally dependent on the boundary conditions, and this is a deficiency when the hillslopes and channels do not interact. Willgoose et al. (1989a,b, 1990, 1991) recently developed a channel network and catchment evolution model that attempts to account for these interactions. However, in their model interactions are restricted to a parameterization of channel initiation that is prescribed and is not based on sediment continuity. Channels are fixed in position and cannot move laterally, nor can divides. This is an area that requires more research. All the 2D landscape evolution models developed to date are driven by grid-based DEMs.

TIN-based models

TINs (Figure 19-2b) have also been used for dynamic hydrological modeling (e.g., Palacios-Velez and Cuevas-Renaud, 1986, 1989; Silfer et al., 1987; Vieux et al., 1988; Maidment et al., 1989; Goodrich, 1990; Jones et al., 1990; Djokic and Maidment, 1991; Goodrich et al., 1991). Vieux et al. (1988) minimized the problems of using TINs for dynamic modeling by orienting the facets so that one of the three edges of a facet formed a streamline and there was only one outflowing edge. However, this required a priori knowledge of the topography, which was obtained from a contour map, thereby detracting from the advantages of the TIN method. For the more common case where the facets are not oriented so that the junction between facets forms a streamline, the modeling of the flow on the facets is not trivial because of the variable boundary conditions (i.e., either one or two inflowing and outflowing edges). A method of distributing the inflow and/or outflow for each facet to downslope facets under these conditions is described by Silfer et al. (1987). Maidment et al. (1989) solved the 2D St. Venant equations for flow on the facets using the TIN-based catchment discretization method of Jones et al. (1990). Djokic and Maidment (1991) linked a TIN surface terrain model with a GIS that defined stormwater intakes and drainage networks to model stormwater flow in an urban environment. Recently, Goodrich et al. (1991) have adapted a 2D kinematic cascade model to predict overland flow on a TIN representation of the land surface. Their method performs a within TIN facet finite element discretization based on a conformal rotation in the direction of steepest

slope. This allows a 1D system of equations to be solved in a 2D domain. The TIN representation was an outgrowth of approaches proposed by Palacios-Velez and Cuevas-Renaud (1986, 1989).

Contour-based models

Contour- or isohypse-based methods of partitioning catchments (Figure 19-2c) and terrain analysis provide a natural way of structuring hydrological and water quality models because the partitioning is based on the hydraulics of fluid flow in the landscape. It is essentially a vector technique and was first proposed by Onstad and Brakensiek (1968), who termed it the stream path or stream tube analogy. Contour lines are assumed to be equipotential lines and pairs of orthogonals to the equipotential lines form the stream tube. An element is bounded by adjacent pairs of contour lines and stream lines (Figure 19-2c). With this form of partitioning only 1D flow occurs within each element, allowing water movement in a catchment to be represented by a series of coupled 1D equations. The equations can be solved using a 1D finite-differencing scheme.

Terrain Analysis Programs for the Environmental Sciences-Contour version–TAPES-C (Moore et al., 1988b; Moore and Grayson, 1991) and TOPOG (Dawes and Short, 1988) are examples of computer-based terrain analysis methods that use this approach. The applications oriented TOPOG is based on the concepts and methods first developed in TAPES-C, which can be considered the original research version. Both analysis packages have their origins in the work of O'Loughlin (1986).

Kozak (1968) and Onstad (1973) used this method to examine the distributed runoff behavior of small catchments. In each case the catchment partitioning was carried out by hand. The applications of Onstad and Brakensiek (1968) and Kozak (1968) involved small catchments with very simple topographies, while that of Onstad (1973) was for a simple hypothetical symmetric catchment. Tisdale et al. (1986) used this technique with an implicit 1D kinematic wave equation to examine distributed overland flow and achieved good accuracy when compared to steady-state solutions for flow depth and discharge over a hypothetical cone-shaped catchment. They found the method to be computationally faster than 2D finite element modeling methodologies, because it solves simpler model equations, while retaining an equivalent physical realism. Moore and Grayson (1991), Moore et al. (1990), and Grayson (1990) present two simple process-oriented hydrological models that simulate saturation overland flow and Hortonian overland flow using a contour-based network of elements and the kinematic wave equations for routing subsurface and overland flow between elements. In the solutions of the kinematic equations, the models use the slope and area of each element, the widths of the element on the upslope and downslope contours bounding the element, the flow path length across the element, and the connectivity of the elements calculated by the TAPES-C terrain analysis suite of programs (Moore et al., 1988b; Moore and Grayson, 1991).

Two- and three-dimensional ground water models

In most hydrogeological projects, the primary purpose of the subsurface characterization is to provide improved ground water flow and contaminant transport estimates. Finite element or finite difference numerical ground water models are the main methods used to simulate 2D and 3D ground water flow. There has been much debate concerning these two procedures (Faust and Mercer, 1980; Fetter, 1980). The finite difference method is widely used because it has a more easily understood intuitive basis, requires simpler data input, uses efficient numerical solution methods, and involves easier programming. The USGS MODFLOW model is the most widely used finite difference model (McDonald and Harbaugh, 1988). Finite difference has two major disadvantages: It may be inaccurate for some problems, and it cannot handle complex geometries in its relatively regular grids. The finite element method addresses these disadvantages, but at the price of more complex data entry requirements and more difficult programming (Poeter, 1983).

The ability of the finite element method to define complex geometries and its ability to evaluate internal flow heterogeneities more accurately has made it the logical choice for modeling applications that require more precision. Fortunately, some powerful 3D finite element ground water models have been developed recently. One example is the Coupled Fluid Energy and Solute Transport (CFEST) program developed at the Battelle Pacific Northwest Laboratories (Gupta et al., 1987). CFEST was designed to evaluate pressure or head, temperature, and solute concentrations for large, multilayered, natural hydrological systems using finite element methods. CFEST can simulate flow in a horizontal plane, in a vertical plane, or in a fully 3D region. Both steady-state and transient simulations are possible.

ROLE OF GIS IN SUBSURFACE MODELING

The heterogeneities of an aquifer must be known in order to simulate or predict the transport of contaminants in a ground water system, or the depletion of water resources within an aquifer. Researchers have focused on the inherent uncertainties associated with definitions of the subsurface, including the measurable properties and features at all scales of interest. To determine these properties exactly, every part of the region of interest would have to be tested. Stochastic modeling approaches have been used to

solve the problem of subsurface uncertainties. A stochastic phenomenon or process is one that when observed under specified conditions does not always produce the same results. Stochastic methods are used extensively for reservoir characterization in the petroleum industry (Augedal et al., 1986; Haldorsen et al., 1987).

Many deterministic and/or stochastic geologic process simulation computer models have been developed for a number of geological environments. These models combine deterministic components, often using empirical formulae, with stochastic components to introduce a suitable level of complexity or uncertainty into the results. Measures of statistical or geometrical properties have demonstrated that these models replicate real systems. Use of these models can be considered a type of expert system. The expertise of many geologists is incorporated in the model formulation and the thought processes of experienced geologists are emulated to develop a conceptualization of subsurface conditions from limited data.

Domenico and Robbins (1985) and Domenico (1987) described methods, termed inverse plume analysis, that determined aquifer and contaminant source characteristics from the spatial distribution of contaminant concentration within a contaminant plume. Inverse plume analysis techniques determine the three orthogonal dispersivities, the center of mass of the contaminant plume, and the contaminant source strength and dimensions from contaminant concentration data and assumed aquifer characteristics. The original technique was restricted to isotropic and homogeneous aquifers, but Belcher (1988) has applied the method to heterogeneous aquifers.

For features such as bedding planes, the third dimension can be represented by surfaces that can be contoured or displayed as isometric views. Because the elevation of the surface is not an independent variable, these systems are best defined as "2.5D" systems and can only accept a single elevation value for any surface at any given location (Turner, 1989). Several important geologic structures that cause repetition of a single horizon at a given location, such as folds or faults, cannot be represented by these systems. In contrast, true 3D systems, containing three independent coordinate axes, can accept repeated occurrences of the same surface at any given location.

The ability to create and manipulate 3D images rapidly can materially assist understanding of the subsurface environment and aid in testing hypotheses for conceptual model development. For example, the geologic characterization of a given natural system is traditionally a complex task that requires the correlation and synthesis of a large amount of multidisciplinary data. The process usually involves manually developing a series of cross sections based on geologic correlations of borehole data. The representation of these cross sections and the resulting 3D conceptual model is often achieved through development of pseudo-3D fence diagrams that cannot be fully visualized by the often nonexpert decision maker. Further, development of new cross sections across the model in different directions in 3D space cannot be readily created based on the already developed cross sections or resulting fence diagram. Usually, the scientist must manually interpolate geologic data in space. This process becomes very tedious when the geologist is faced with updating and modifying the conceptual model to incorporate newly collected data or to test different hypotheses to conceptualize the system. The 3D spatial visualization capabilities of some existing GIS appear to offer promising tools to resolve the data management and 3D spatial visualization problems. However, the existing systems are immature, and none fully provides all the required data management and spatial capabilities. The prototype systems use distinctly different approaches:

1. Interactive volume modeling (IVM), developed by Dynamic Graphics Inc., which uses 3D contouring (Paradis and Belcher, 1990; Belcher and Paradis, 1991);
2. A prototype geoscience demonstration system developed by Intergraph Corporation based on nonuniform rational B-splines (NURBS) techniques currently used in their computer-aided design applications (Fisher and Wales, 1990, 1992); and
3. 3D component modeling developed by Lynx Geosystems for mine design and planning applications (Houlding, 1988; Houlding and Stokes, 1990).

Three-dimensional GIS alone cannot solve the hydrogeological analysis problems. The process of hydrogeological analysis can be considered in terms of four fundamental modules:

1. Subsurface characterization;
2. Three-dimensional GIS;
3. Statistical evaluation and sensitivity analysis; and
4. Ground water flow and contaminant transport modeling.

The 3D GIS must, therefore, be used in combination with the remaining modules that use many developed analytical tools. Figure 19-5 summarizes these concepts by showing the dominant information flows and cycles among these modules.

The process starts when the geologist investigator combines geological experience with limited field data to begin the subsurface characterization process (Figure 19-5). The subsurface characterization module contains a variety of analytical techniques, including geological process simulation models that may combine both stochastic and deterministic elements.

The information generated by the subsurface characterization module is linked directly to the 3D GIS module. This feedback loop is an important consideration in de-

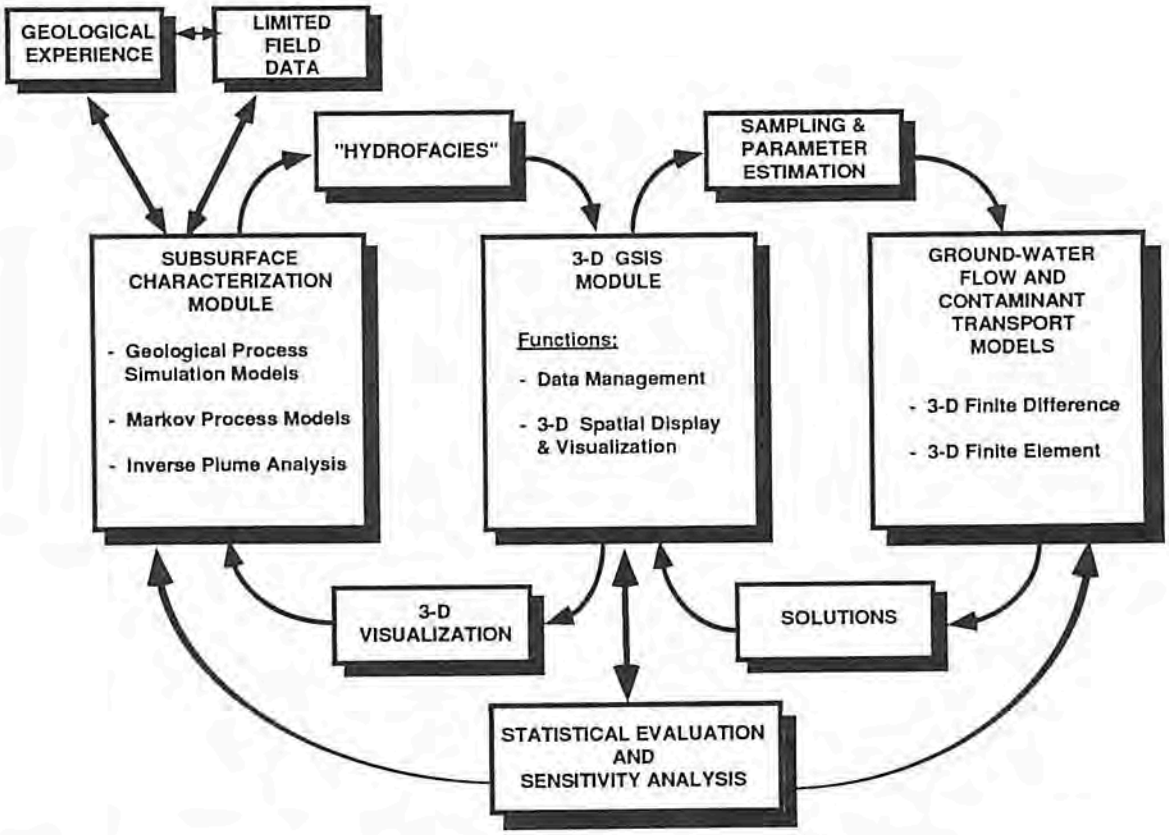

Figure 19-5: Information flow and the role of 3D GSIS for hydrogeology (after Turner, 1989).

fining appropriate interfaces between the GIS and the analytical tools within the subsurface characterization module. The interfaces must be designed to provide both data management and spatial visualization support. Several iterations are expected before the most probable subsurface conditions are defined. Sometimes a unique solution may not be achievable, and two, or more, alternative characterizations may be used.

Once a suitable subsurface characterization has been defined, the analysis continues with a second cycle. In this cycle 3D GIS is used to support appropriate ground water or contaminant transport models (Figure 19-5). This involves the creation of finite-difference or finite-element meshes by sampling from the database. The definition of an optimal mesh has been examined by Stam et al. (1989).

Figure 19-5 shows a strong linkage between the 3D GIS module and a module labeled "Statistical Evaluation and Sensitivity Analysis." This module contains methods for assessing the usefulness and reasonableness of the subsurface characterizations. The investigator can continue the analysis of the hydrogeological conditions only when the subsurface conditions are clearly defined and shown to be statistically acceptable. The spatial visualization capabilities of the 3D GIS are one way of making such reasonableness assessments. In addition, other more numerical approaches, including standard statistical screening methods and geostatistical techniques such as kriging (Olea, 1975; Clark, 1979; Lam, 1983), are usually required. Kriging assumes the data are time invariant. Another method, Kalman filtering, allows both time and spatial variation in the data (van Geer, 1987). These methods have been used for optimizing sampling networks, but appear to have special utility in analyzing seasonally varying contaminant data. The use of such techniques and the analytical methods contained within the other modules allows for a second level of information cycling and feedback (Figure 19-5). An important question that is often posed in groundwater contamination modeling studies concerns the sensitivity of the answers to variations or uncertainties in the input parameters. This sensitivity analysis requires the combined use of all the modules shown in Figure 19-5.

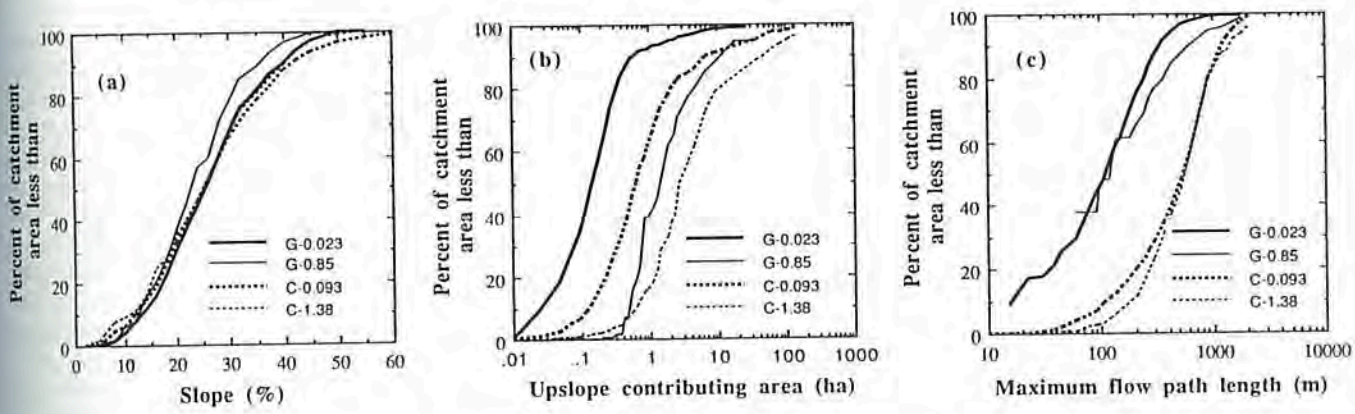

Figure 19-6: Examples of slope (a), upslope contributing area (b), and maximum flow path length (c) distributions computed from (G) grid- and (C) contour-based DEMs and terrain analysis methods for a range of average element sizes (numbers) (adapted from Panuska et al., 1991).

ROLE OF GIS IN SURFACE PROCESS MODELING

There are four major scale-related issues that influence the use of GIS in environmental modeling of surface processes: (1) GIS cell or polygon (element) size; (2) the method of analysis used to derive the attribute values (e.g., slope, aspect, etc.) or the method of measurement (soil physical and hydraulic characteristics); (3) merging data with different resolutions, accuracies, and structures; and (4) scale differences between model process representation and data available for model parameterization. Space does not allow in-depth discussion, but presentation of examples of the problems and (often ignored) difficulties in integrating GIS and surface process modeling may provide some perspective on the effects of scale.

Effects of scale and method of analysis

Panuska et al. (1991) examined the sensitivity of topographic attributes computed from different DEM structures for a range of element sizes on the 210 ha north fork of the Cottonwood Creek catchment in southwestern Montana. They considered grid- and contour-based DEMs and computed slope, upslope contributing area, and maximum flow path length using the TAPES-G and TAPES-C programs (Moore et al., 1991; Moore and Grayson, 1991), respectively. The average element sizes ranged from 0.023 to 1.38 ha. Representative cumulative frequency distributions of the three attributes are presented in Figures 19-6a–c. The numbers in the figures refer to the mean element size in hectares. More detailed results are presented in Panuska and Moore (1991). The computed topographic attribute distributions varied in sensitivity depending on the choice of DEM and terrain analysis method used and on element size. Overall, the slope distributions appeared to be the most stable (Figure 19-6a). However, at scales approaching the natural periodicities of the landscape or hillslope lengths (100–300 m), one might expect these relationships to break down. For the Cottonwood Creek catchment this occurs at grid sizes of about 130–140 m.

At a larger scale, the effect of DEM scale on slope for three different spatial resolutions for the conterminous United States and for the Elmira 1:250,000 scale map covering the Chemung area (40 to 43.3 N, 74 to 77.3 W) has been evaluated by Jenson (1991). The slope of each cell was calculated as the slope of a line connecting it with the cell of lowest elevation of its eight neighboring cells. The results are summarized in Figure 19-7. Increases in

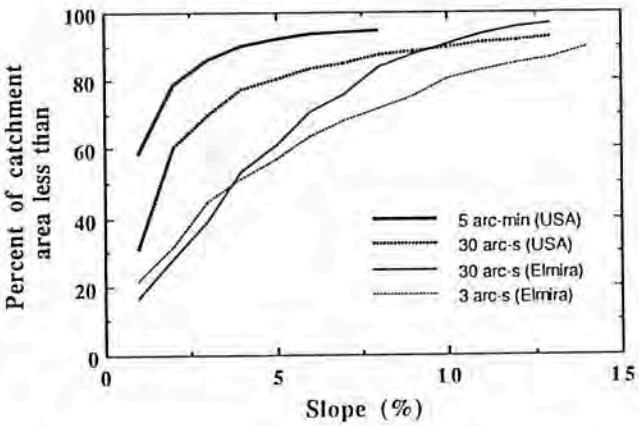

Figure 19-7: Comparison of slopes computed from DEMs of the conterminous US (thick lines) and Elmira 1:250,000 scale map sheet (thin lines) at various resolutions (adapted from Jenson, 1991).

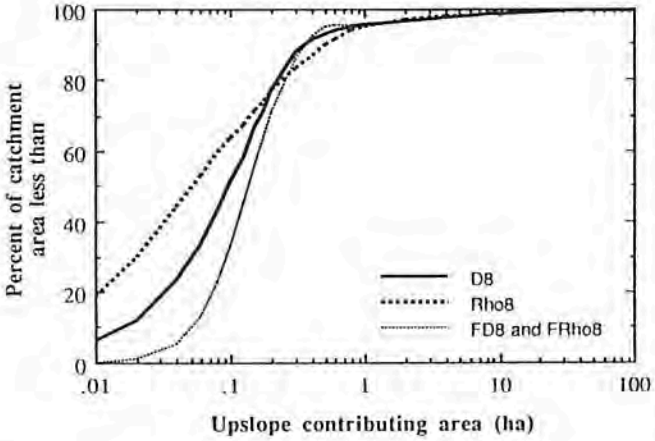

Figure 19-8: Upslope contributing area frequency distributions computed by the D8 (O'Callaghan and Mark, 1984; Jenson and Domingue, 1988), Rho8 (adapted from Fairfield and Leymarie, 1991), FRho8 and FD8 (adapted from Freeman, 1991, and Quinn et al., 1991) element connectivity algorithms from a 10 × 10m grid based DEM.

cell size produce lower slope values, which is consistent with the trends shown in Figure 19-6a at a finer scale.

Both the upslope contributing area and maximum flow path length distributions calculated by the two methods of analysis described depend on the computed connectivity of individual elements (i.e., the topology), but slope calculations were independent of this connectivity. The connectivity of the elements for the grid-based analysis depended highly on the element size, particularly in regions of high flow convergence or divergence (in valleys or ridges). Large element sizes could not account for the same degree of detail as could smaller element sizes. For example, the 90 m grid DEM predicted two flow paths along the edges of the valley in the upper part of the catchment, rather than one flow path along the valley floor (Panuska and Moore, 1991). The D8 algorithm developed by O'Callaghan and Mark (1984), and implemented by Jenson and Domingue (1988), was used to derive the element connectivity for the grid-based terrain analysis (TAPES-C) results presented here.

Figure 19-8 illustrates the impact that the form of the element connectivity algorithm can have on the distribution functions of attributes such as upslope contributing area computed from grid-based DEMs. Upslope contributing area is a basic attribute needed by most hydrological and water quality models. In Figure 19-8 a 0.01 ha square element (10 m grid-DEM) is used to estimate the element connectivities using three different approaches: (1) flow from an element to only one of eight nearest neighbors (Figure 19-2a), based on the direction of steepest descent—O'Callaghan and Mark (1984) and Jenson and Domingue's (1988) D8 algorithm; (2) Fairfield and Leymarie's (1991) modification of this algorithm to include a stochastic component when the D8 algorithm computes flow directions in N-E, S-E, S-W, and N-W directions—Rho8 algorithm; and (3) an adaption of the algorithms proposed by Freeman (1991) and Quinn et al. (1991) that allows flow to be distributed to multiple nearest-neighbor elements in upland areas above defined channels and the Rho8 or D8 algorithms below points of channel initiation—FRho8 and FD8 algorithms, respectively. The D8 and Rho8 algorithms cannot represent flow divergence or catchment spreading (Speight, 1974). In the FRho8 and FD8 algorithms the proportion of flow or upslope contributing area assigned to multiple downslope nearest neighbors is determined on a slope weighted basis. The FRho8 and FD8 algorithms require the specification of a critical upslope contributing area for channel initiation. It is our belief that the FRho8 algorithm is the better approximation of reality for grid-based methods of analysis. One advantage of contour-based methods of analysis (TAPES-C, Moore et al., 1988; Moore and Grayson, 1991; TOPOG, Dawes and Short, 1988) is that they explicitly represent both flow convergence and divergence.

Scale generalization

In many GIS applications there is an implicit assumption that the geographic areal units (raster cells or polygons) can be considered homogeneous in terms of attribute values. However, in many landscapes and at many scales of investigation this assumption is not valid. Jenson (1991) demonstrated that slopes calculated from raster elevation data vary significantly depending on cell size and data source, for example (Figure 19-7). If the topographic data from the three sources illustrated in Plate 19-1 were used for different parts of a catchment to build a GIS database for the entire catchment, the slopes would vary artificially within the database according to the variable topographic source data.

The challenge of merging data from different sources, and with different resolutions, accuracies, and data structures arises for most categories of data including topography, soils, and land cover. Land surface/subsurface models that incorporate multiple attributes as inputs add to this challenge because different parameters vary in different ways across landscapes (space). Loague (1988), for example, examined the impact of spatially variable rainfall and soil information on runoff predictions. Detailed hydraulic conductivity and rainfall data were aggregated to coarser resolutions, and subsequent impacts on hillslope runoff were assessed. The hydraulic conductivity data appeared to be more critical than rainfall information, although different runoff variables (peak rate, time to peak, runoff

volumes, etc.) were also found to require different spatial scales.

The appropriate scale (areal unit) may vary with the type of landscape for many attributes as well. Panuska et al. (1991) noted that all DEMs are different representations of the actual land surface and that the accuracy with which a DEM represents the land surface depends on the accuracy and resolution of the original survey data. Hence, the smallest element size produces the most accurate representation of the terrain only if the dimensions of the element are greater than the horizontal resolution of the primary elevation data and if elevation differences between neighboring points are greater than the vertical resolution of the data. The adequacy of a DEM, therefore, depends on the characteristics of the terrain. For example, rolling terrain with moderate relief can be better represented by a larger element sized DEM than can a dissected catchment with sharp ridges, ravines, and abrupt changes in slope or elevation.

There are also the problems that arise because of scale differences between model process representation and the data available for model parameterization. Goodrich and Woolhiser (1991), in their recent review of catchment hydrology, stressed the need to continue experimental studies that explore spatial and temporal variability of catchment characteristics, states, and rainfall patterns. Consistent treatment of these processes and the validation of models requires that observational and model scales be commensurate. What little is known about the variability of water flow direction, solar insolation, infiltration, and a host of other physical processes, indicates a need to explore these phenomena over large numbers of events in a large variety of geographic settings.

Physically based, spatially distributed process representation

While the problems noted in the previous section mean that it may not be possible to move to a scale at which within-element variance is negligible, it is possible to store distributional information on important model parameters or indices (e.g., the attribute distributions presented in Figure 19-6a,c). It is useful to seek indices that scale system behavior from knowledge of areal mean or representative values over a given area. An example is the relationship between a mean wetness index and soil water content in a catchment. These parameters serve as similarity indices as they scale system behavior.

Many advances in the representation of surface and subsurface processes in the past 20 years have been in the characterization and mathematical description of processes at the plot scale. We can now successfully simulate point processes such as interception, infiltration, and evapotranspiration using equations derived from fundamental physics. The grey area occurs at the hillslope or catchment scale, what we will call the meso-scale. Since the first computer-based models were developed in the early 1960s, scientists have been attempting to use micro-scale process descriptions in meso-scale system models. Many meso-scale processes (e.g., hydrological processes) are highly nonlinear. Part of the drive behind the development of spatially distributed, physically based models (such as those described in the previous section) has been the belief that the sequential task of dividing a landscape into smaller units, elements, or grids that are assumed to be homogeneous, predicting the response of each element, and then aggregating the response (routing flow from element to element) will allow these nonlinearities and the spatially variable hydrological response to be predicted. Over the past 10 years evidence indicates that this approach has been only partially successful.

So why are meso-scale models important? Many solutions to environmental problems such as soil erosion and non-point-source pollution involve changes in management strategies of landscapes at the hillslope or catchment scale. In many parts of the world, resource agencies have been adopting the philosophy of "total catchment management." Physically based, distributed-parameter models (e.g., hydrological and water quality models) are being viewed as essential tools in developing and evaluating these land and water management strategies. But is this modeling approach the most effective method of fulfilling these needs, given the data and model constraints discussed above? An alternative approach that is more consistent with the available data, the management questions being posed (as opposed to the scientific rigor of the models) and the precision with which these question need (and can) be answered may be preferred.

We propose an index approach that is based on simplified representations of the underlying physics of the processes but includes the key factors that modulate system behavior (such as topography). The converse of this is that all other factors that are not explicitly accounted for by the index have low variance within the landscape. With this approach we sacrifice some physical sophistication to allow improved estimates of spatial patterns in landscapes (Moore et al., 1991). The method must be able to operate at different levels of sophistication depending on the availability of possible input data and the spatial resolution of those data. These simplified models are based on, and can operate with, what Nix (1981) termed "minimum data sets." Care must be taken in developing these techniques as simplifying assumptions can introduce rather than resolve computational complexities (Denning, 1990). The basic approach can be illustrated by examining two important hydrologic issues: (1) the distribution of soil water content in a landscape—a major factor determining the biophysical behavior of landscapes; and (2) the susceptibility of landscapes to erosion by water—an important issue in the recently enacted Food Security legislation in the United States.

Spatial distribution of soil water content

Hydrological prediction at the micro- and meso-scales is intimately dependent on the ability to characterize the spatial variability of soil water content. Soil water content and related soil properties exhibit extreme variability over distances of 1–100 m. This is supported by many reports in the literature (Brutsaert, 1986; Sharma et al., 1987; Webster, 1985; Yates and Warrick, 1987; Wilson and Luxmoore, 1988; Loague and Gander, 1990). Brutsaert (1986) posed an important question: How meaningful can a soil water index be at this scale? Several factors affect soil water content, including:

1. Soil characteristics: saturated hydraulic conductivity, thickness of the hydrologically active zone (A horizon), effective porosity, and the occurrence of deep percolation and preferential flow;
2. Topography: local slope (measure of hydraulic gradients), specific catchment area (measure of the potential maximum water flux), plan curvature (a measure of the rate of flow convergence and divergence), profile curvature (water concentrates where slopes flatten out), and aspect and topographic shading (which with slope influence the radiation regime and therefore evapotranspiration);
3. Vegetation: annual variation in surface cover and water use characteristics; and
4. Weather: net rainfall, net radiation and temperature.

In mountainous or hilly terrain soil, water distribution is controlled by vertical and horizontal water divergence and convergence, infiltration recharge, and evapotranspiration. The latter two terms are affected by solar insolation and vegetation canopy that vary strongly with exposure in semiarid areas. The divergence/convergence term is dependent on hillslope position. Most index approaches for predicting the spatial distribution of soil water can be expressed as:

$$\chi_i = \ln\left[\frac{T_e}{T\tan\beta}\frac{\sum_j \mu_j a_j}{b}\right]_i = \ln\left[\frac{1}{\tan\beta}\frac{\sum_j \mu_j a_j}{b}\right]_i + \left[\ln(T_e) - \ln(T_i)\right] \tag{19-2}$$

where χ is the wetness index, a_j is the area, b_i is the outflow width, μ_j is an area weighting coefficient, β_i is the slope, and T_i is the transmissivity (depth integrated hydraulic conductivity) of the ith or jth element and $\ln(T_e)$ is the areal average value of $\ln(T_i)$ (Moore and Hutchinson, 1991). This index was developed for predicting saturated source areas and depths to water tables. However, there is a conceptual jump required to apply these same relationships to the prediction of soil water spatial variability.

The most common form of Eq. (19-2) assumes that the weighting function, μ_j, is spatially uniform and equal to one (Beven and Kirkby, 1979; O'Loughlin, 1986; Moore et al., 1988b), so that Eq. (19-2) reduces to:

$$\chi_i = \ln\left[\frac{A_s T_e}{T\tan\beta}\right]_i = \ln\left[\frac{A_s}{\tan\beta}\right]_i + \left[\ln\left(T_e\right) - \ln\left(T_i\right)\right] \tag{19-3}$$

where A_s is the specific catchment area (catchment area draining across a unit width of contour). This index considers only topographic (first term) and soil factors (second term) and is derived from simple catchment drainage theory. In Eq. (19-3) A_s is a measure of the steady-state subsurface drainage flux, but assumes uniform infiltration over the entire catchment. The simplest method of accounting for vegetation evapotranspiration effects on the wetness index is to assume that

$$\mu_i = \mu = 1 - \frac{E}{P-R} \tag{19-4}$$

where E is the actual evapotranspiration, P is the precipitation, and R is the direct surface runoff plus deep drainage loss on a seasonal or annual basis. This approach assumes that evapotranspiration is spatially invariant. The lumped catchment term $E/(P-R)$ can be estimated directly from an analysis of long-term catchment precipitation and runoff records. For example, forested catchments along the south-east coast of Australia have an average value of $E/(P-R)$ of about 0.70–0.95. This index can only characterize soil water distribution in a landscape if evapotranspiration is conservative over the land area (to maintain stationary mean soil water content).

A GIS can be used to partition the region into areas of uniform evapotranspiration, E, such as hillslope facets. Band and Nemani (1990), Band (1991), and Band et al. (1991) took this approach, assuming that Eq. (19-3) controls the variability within hillslopes while canopy and microclimate variations dominate between hillslopes. An alternative approach is to recast Eq. (19-4) in the following form to account for spatially variable infiltration and evapotranspiration (Moore and Hutchinson, 1991):

$$\mu_i = 1 - f_i\frac{E_p}{(P_i - R_i)}\left[1 - \left(\frac{\theta_{fc}-\theta}{\theta_{fc}-\theta_{wp}}\right)_i^{C/E_p}\right] \quad \text{for } \theta_i \le \theta_{fc,i} \tag{19-5}$$

$$\mu_i = 1 - f_i\frac{E_p}{(P_i - R_i)} \quad \text{for } \theta_i > \theta_{fc,i}$$

where E_p is the potential evapotranspiration on an unshaded horizontal surface, f_i is the ratio of the solar radiation on a sloping surface to that on a horizontal surface (0.5–1.2) and is a function of slope, β, aspect, η, and topographic shading, θ is the actual soil water content, θ_{fc} is the field-capacity soil water content, θ_{wp} is the wilting-point soil water content, and C is a constant. These equa-

tions would typically be applied on a seasonal or annual basis for examining the spatial distribution of "average" soil water content. The f_i term accounts for the effect of topography on E_p and assumes that E_p is directly proportional to the solar radiation received by the land surface. The term involving θ, θ_{fc} and θ_{wp} is simply an empirical expression for the κ factor, written in terms of the soil water content and the evaporative demand (Kristensen and Jensen, 1975), in the following equation relating actual evapotranspiration, E, to the potential evapotranspiration, E_p:

$$E = \kappa E_p \tag{19-6}$$

As a first approximation, the soil water content can be related to the wetness index via an empirical equation of the form:

$$\theta = b_1\chi + b_2 \tag{19-7}$$

where b_1 and b_2 are fitted constants. Using the form of the weighting function given by Eq. (19-5), the wetness index, χ, appears on the left- and right-hand (via the μ term) side of Eq. (19-2) and must be solved iteratively. The solution technique is most efficient if it begins with the element of highest elevation and finishes with the element of lowest elevation at the catchment outlet. Plates 19-2a and 19-2b show the patterns of soil water distribution in a small catchment in Montana predicted using Eqs. (19-4) and (19-5), respectively. In both cases the values of the parameters were somewhat arbitrarily chosen to give a median soil water content of 0.27 $m^3\ m^{-3}$.

Estimation of the spatial variation in soil water content using Eqs. (19-2) and (19-5) requires the estimation of local slope, aspect, flow paths (determines how the individual elements are connected), and topographic shading, which are all topographic attributes; field-capacity and wilting-point soil water contents and net rainfall (P–R), which are soil and weather attributes; and average catchment-wide potential evapotranspiration, which is a vegetation–weather attribute. Here we assume that the spatial scale of variation in E_p is much greater than that of the other variables, and so can logically be ignored. For large catchments this assumption may be invalid and so it may be desirable to use spatially distributed values of E_p, based on vegetation distribution. Equation (19-3) is a single equation that is an order of magnitude simpler than most distributed-parameter, physically based models, but accounts for the major factors affecting soil water content. However, the question remains as to how to estimate the distributed values of the soil attributes that are parameters in the equation.

Because of the difficulties associated with direct measurement or estimation of the spatial variability of soil properties, many people have used only topographic attributes to characterize soil water distribution. Moore et al. (1988a) found a strong correlation between $\ln(A_s/\tan\beta)_i$ and surface soil water distribution on a small fallow catchment near Wagga. They found a linear combination of aspect and $\ln(A_s/\tan\beta)_i$ to be the best predictor. Burt and Butcher (1986) found that plan curvature, $PLANC_i$, performed almost as well as $\ln(A_s/\tan\beta)_i$, but that the compound index $PLANC_i{*}\ln(A_s/\tan\beta)_i$ was best. Wood et al. (1990) demonstrate that the variation in the topographic variable, $\ln(A_s/\tan\beta)_i$, is far greater than the local variation in transmissivity, $\ln(T_i)$. The topographic variable alone is therefore a useful approximation. However, during interstorm periods the mean transmissivity, $\ln(T_e)$, plays a dominant role.

One rationale for only using topographic attributes to predict soil water content is that in many landscapes pedogenesis of the soil catena occurs in response to the way water moves through the landscape. Therefore, it can be hypothesized that the spatial distribution of topographic attributes that characterize these flow paths inherently captures the spatial variability of soil properties at the meso-scale as well. One of the most exciting new areas of research is the attempt to verify this hypothesis by examining the correlation between topographic attributes and soil properties. Parallel research is also underway aimed at exploring the correlation between topographic attributes and vegetation distribution in undisturbed landscapes. Climate, parent material, topography, vegetation, and other biotic agents are the dominant soil-forming process, but climate and parent material probably exert control at scales larger than we are considering here.

From the foregoing arguments we hypothesize that only net rainfall (P–R) and the spatial variability of topographic attributes need to be considered to provide adequate estimates of the spatial variability of soil water content. The other parameters can be spatially lumped, with little or no loss in predictive ability. For example, the variability in net rainfall has been ignored in the application of the index approach to field measurements (Burt and Butcher, 1986; Moore et al., 1988a), and this may be satisfactory for steady-state applications. Similarly, spatially distributed soil parameters have often been ignored because they are rarely available for applications in operational hydrology.

Care must be exercised in applying static indices like those described to predict the distribution of a dynamic process like soil water content that shows hysteretic effects, especially when threshold changes occur in the area of saturation. Because of fluctuating rainfall intensities and the short duration of rainfall events compared to the travel time of subsurface throughflow, the subsurface flow regime in a natural catchment rarely reaches steady state. Barling (1992) has observed that during storm events subsurface flow is only affected by a small proportion of the contributing area directly upslope. He has also observed that initial surface saturation does not necessarily occur at points with the largest $\ln(A_s/\tan\beta)$ values. Iida (1984) recognized this problem and proposed a hydrolog-

ical method of estimating the effect of topography on saturated throughflow that involved the calculation of a subsurface flow travel time-specific area curve, $a_s(t)$, where $a_s(t_e)=A_s$ and t_e is the time to equilibrium. The time required for water to move from any point E to F along a flow line or stream tube is given by:

$$t_{EF} = \frac{\gamma}{k}\int_F^E \frac{ds}{\sin\beta\ \cos\beta} \tag{19-8}$$

where s is the horizontal component between E and F, k is the saturated hydraulic conductivity, and γ is the effective porosity. Iida assumed spatially uniform soil properties but did demonstrate the effects of slope angle, plan curvature, and profile curvature on the shape of the time–area curve. Barling (1992) has automated Iida's method and integrated it into Equation (19-2) to derive a spatially and temporally varying wetness index. This approach must still be validated.

Spatial distribution of erosion by water

A second example further illustrates the efficiency of the index approach. The physical potential for sheet and rill erosion in upland catchments can be evaluated by the product *RKLS*, a component of the universal soil loss equation (USLE), where R is a rainfall and runoff erosivity factor, K is a soil erodibility factor, and LS is the length–slope factor that accounts for the effects of topography on erosion (Wischmeier and Smith, 1978). The USLE is an empirical equation that includes terms representing the dominant factors affecting erosion by water. To predict erosion at a point in the landscape, the LS factor can be written as:

$$LS = (n+1)\left(\frac{A_s}{22.13}\right)^n\left(\frac{\sin\beta}{0.0896}\right)^m \tag{19-9}$$

where A_s is the specific catchment area, β is the local slope in degrees, $n=0.4$, and $m=1.3$. This equation was derived from unit stream power theory by Moore and Burch (1986). It is more amenable to landscapes with complex topographies than the original empirical equation because it explicitly accounts for flow convergence and divergence through the A_s term in the equation (Moore and Nieber, 1989). The erosion potential can be normalized using the concept of an allowable soil loss, E_a, to give the erodibility index, $RKLS/E_a$. This index can be mapped based on the topographic attributes of slope and specific catchment area, and soil and climatic attributes via K, E_a and R (Moore and Nieber, 1989). Each of these variables could be a primary data layer in a GIS. In the United States, highly erodible land is defined as land with an erodibility index greater than 8. This definition is used to identify land that can be bid into the Conservation Reserve Program (CRP) and taken out of production for 10 years. Plate 19-3 maps the erosion potential over two small catchments in southern Minnesota. It illustrates how a GIS with a simple knowledge-based analysis system can facilitate the land management decision-making process by efficiently identifying highly erodible land.

Vertessy et al. (1990) developed an erosion hazard index, derived in part as an abstraction of the physically based erosion model proposed by Rose et al. (1983a) and Rose (1985). The index is a useful diagnostic function that integrates, in a simple way, the effect of soil properties, vegetative cover, and runoff on the entrainment of soil particles by overland flow. The erosion hazard index, H, is given by:

$$H = P\eta \tag{19-10}$$

where

$$P = \text{stream power} = \rho g q \tan\beta \tag{19-11}$$
$$\eta = \text{entrainment efficiency} = \alpha_1 e^{-\alpha_2(1-C_r)}$$

and ρ is the density of water, g is the acceleration due to gravity, q is the overland flow discharge per unit width, β is the local slope, $1-C_r$ is the fraction of surface cover in contact with the ground, and α_1 and α_2 are constants that depend on soil type and surface management. The values of α_1 range from 0.2 to 0.7 for cultivated soils (Rose, 1985) and 0.05 to 0.06 for arid zone pasture (Rose et al., 1983b; Silburn, 1991). Increasingly sophisticated versions of the erosion hazard index can be obtained depending on the sophistication of the assumptions and model used to estimate the spatial variation of q. The simplest approach is to assume spatially uniform, steady-state rainfall excess over a catchment—the same assumption used to derive Eq. (19-9). With this assumption the erosion hazard index becomes:

$$H = \rho g A_s i \tan\beta\ \alpha_1 e^{-\alpha_2(1-C_r)} \tag{19-12}$$

where i is the rainfall excess rate. Vertessy et al. (1990) applied a more sophisticated version of the model that assumed runoff was generated from saturated source areas, which could be predicted as a function of topographic and soil attributes. Equation (19-12) is a function of topographic (A_s and β), soil (α_1 and α_2) and surface cover (C_r) attributes for a given rainfall excess regime, all of which could be data layers in a GIS.

SOIL PROPERTIES FOR SPATIALLY DISTRIBUTED ENVIRONMENTAL MODELING

Soil physical and chemical property data are essential for modeling surface and subsurface phenomena. The lack of these data at the required spatial resolution is probably the greatest impediment to the successful application of modeling and GIS technologies to analyzing resource and

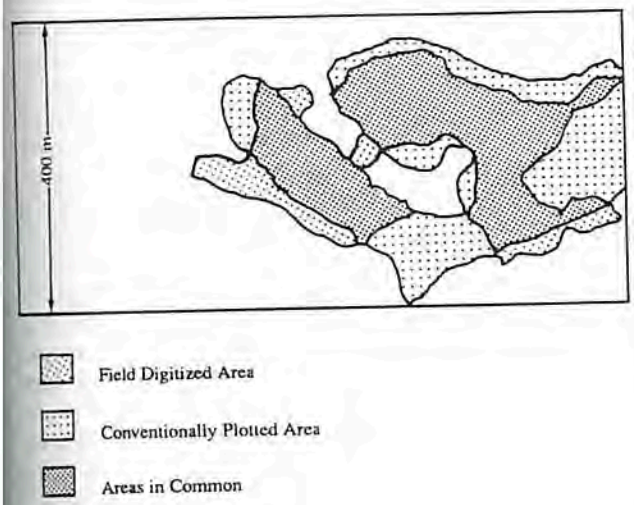

Figure 19-9: Comparison of boundaries between two soil series mapped using conventional soil survey techniques and by field digitizing using GPS (adapted from Long et al., 1991).

environmental problems. Until recently soil scientists have emphasized the vertical relationships of soil horizons and soil-forming processes rather than the horizontal relationships that characterize traditional soil survey (Buol et al., 1989). Soil spatial patterns have been captured and displayed as choropleth maps with discrete lines representing the boundaries between map units, which implies homogeneity within map units (Gessler, 1990). Two problems follow from this approach: (1) the lines drawn on the soil survey maps may not accurately depict the boundaries between map units [Figure 19-9, for example, shows the variations between map boundaries produced with traditional soil survey and global positioning system (GPS) technology within a 129 ha field in northern Montana]; and (2) the inferred homogeneities do not exist for many physical and chemical attributes needed for environmental modeling (see earlier discussion).

The prescribed standard accuracy for delineating soil boundaries in detailed soil surveys is 30 m (100 ft). However, significant errors can occur depending on the base map quality, the map reading skill and aptitude of the soil surveyor, and terrain conditions (Long et al., 1991). The global positioning system (Dixon, 1991) offers a relatively inexpensive, time-efficient, and accurate method of positioning on a base map, navigating to predetermined sites, and field digitizing soil boundaries compared to conventional positioning used in soil survey (particularly when surface features are difficult to observe from the ground), such as aerial photographs, and topographic maps (Long et al., 1991). In an evaluation of GPS errors, Long et al. (1991) concluded that positions measured by GPS receivers operating in autonomous mode (single receiver) are comparable with the accuracy of positions from 1:24,000 scale topographic maps. In differential mode (two receivers) the accuracy is within 5 m. GPS survey and digital terrain analysis technologies overlap and offer ways of reducing, or at least quantifying, the relational errors in point and vector land surface data that are used in environmental modeling and GIS.

From a soil science and hydrologic modeling perspective, there is considerable merit in using the soil horizon as the basic entity for modeling and quantifying soil properties in three-dimensional space rather than the map unit or soil series (Gessler, 1991). The hydrologically active zone generally corresponds to the A horizon, but varies greatly in thickness and in physical and chemical properties. It is possible to use soil series and pedon data as a basis for horizon-oriented, three-dimensional modeling and visualization of soil patterns. In one of the first applications of its kind, Gessler et al. (1989) used the horizon information within a GIS to analyze soil–vegetation–landuse patterns in southwest Wisconsin. To develop this horizon-based approach for modeling and quantifying soil properties in space requires the development of useful horizon classes by: (1) determining the distribution and arrangement of horizons in space; and (2) characterizing the chemical, physical, and biological properties of the horizon, for which recent work using fuzzy set theory shows potential (Powell et al., 1991; McBratney and DeGruitjter, 1992; McBratney, 1992).

The theory of similar media has been used to develop methods for micro-scaling of hydraulic properties and infiltration equations (Miller, 1980; Warrick, 1990). The variability of measured soil hydraulic data has been reduced by as much as 80% using these techniques. Tyler and Wheatcraft (1990) demonstrated that the power-law soil water retention function was a fractal process and could be analyzed using fractal scaling theory. An excellent review of scaling theory in soil physics is provided by Hillel and Elrick (1990).

In the past 10 years there have been many attempts to characterize the meso-scale spatial variability of measured soil attributes (Webster, 1985; Yates and Warrick, 1987; Loague and Gander, 1990). These attempts have concentrated on the characterization of patterns, rather than on the linking of pattern to process. Two techniques are commonly used: quantitative methods using kriging, which relate the spatial covariance function to the spatial separation of the data, and methods that relate soil properties to qualitative measures of landscape position such as toe-slopes and interfluves (an attempt to account for process). Both techniques require large databases, and their results are not transferable. Kriging techniques ignore pedogenesis, while methods based on landscape position have lacked a consistent quantitative framework.

Kriging has shown that spatial correlation lengths of soil properties, such as saturated hydraulic conductivity, are on the order of only tens of meters. Digital terrain modeling methods offer another way of stratifying measured soil properties based on the way the soil catena develops in response to water movement in the landscape (i.e., process) and quantifiable landscape units. Better correlations may possibly be obtained using kriging or partial splines if wetness index or plan curvature were included as independent variables. The incorporation of these variables via a parametric submodel of a partial thin plate spline is attractive. In this way, broad changes with position can be accounted for by a smooth dependence on the two spatial variables (x,y), and the parametric submodel can account for more local, process-based effects. This approach was successfully applied to the interpolation of temperature at the macro-scale by Hutchinson (1991).

A recent approach is to organize the land surface according to a formal geomorphological model of landform and interlandform relations (Speight, 1974; Weibel and DeLotto, 1988; Dikau, 1989; Lammers and Band, 1990; Gessler, 1990; Mackay et al., 1991). Instead of dealing with pixels, flow tubes, or triangular facets, there are advantages in using integrated systems of hillslopes, floodplains, and ridgelines. The geomorphological position of a site strongly influences soil and other important properties. For example, Dikau (1989) demonstrated how digital terrain analysis could be applied to quantitative relief form analysis to define basic relief units for geomorphological and pedological mapping. The main topographic attributes used to define these relief units were slope, plan curvature, and profile curvature (Figure 19-10). This approach provides a systematic and methodological basis for derivation of complex relief units. It may be possible to

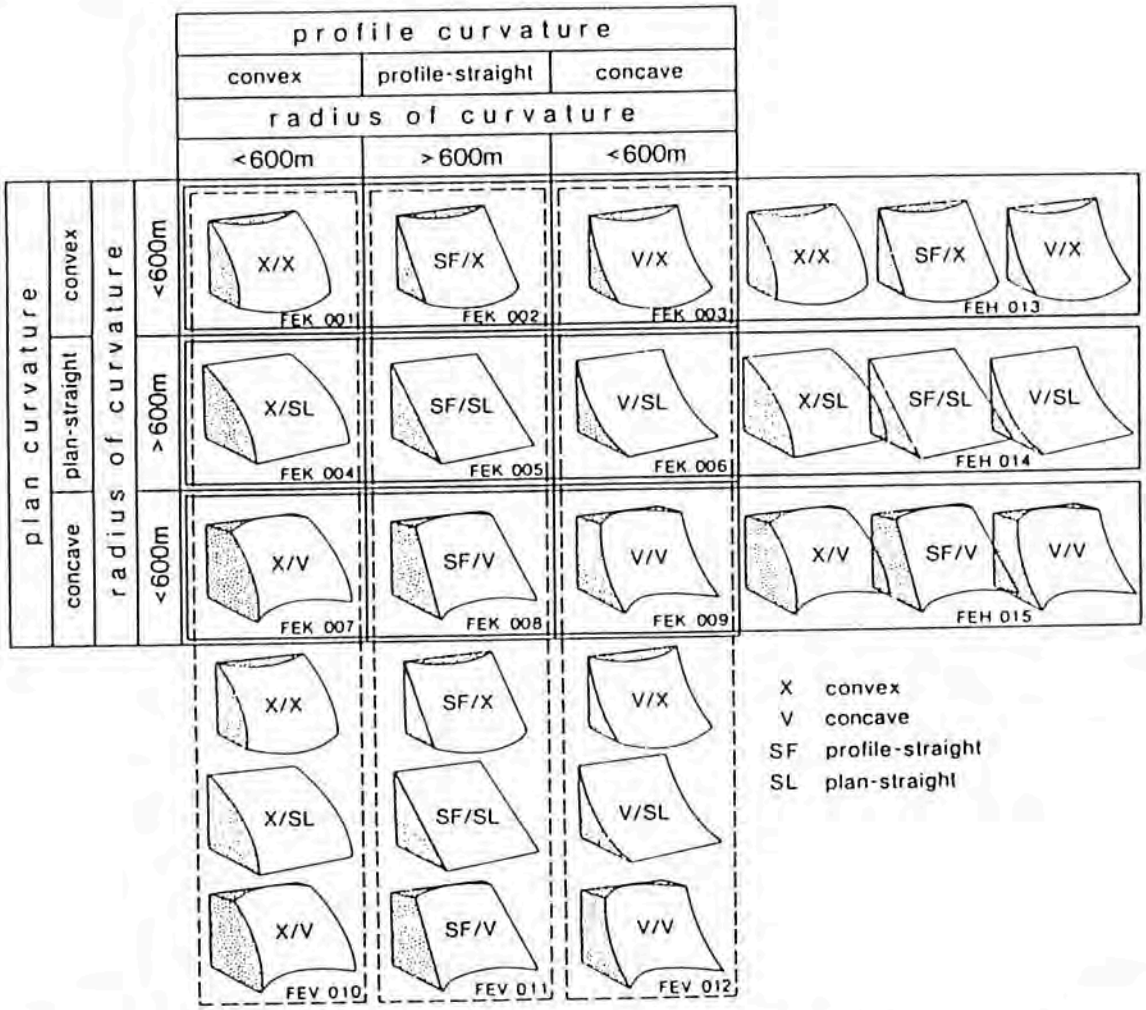

Figure 19-10: Classification of land form elements by plan and profile curvature for the determination of geomorphological relief units (reproduced from Dikau, 1989).

use these relief units to stratify the measured soil attributes and separate the micro- and meso-scale spatial variabilities.

Lammers and Band (1990) developed techniques for producing a set of landform files describing the morphometry, catchment position, and surface attributes of hillslopes and stream channels comprising a drainage basin. At this stage, these landforms can be said to comprise a "feature model" of the basin. Mackay (1990) and Mackay et al. (1991) extended the feature model by encapsulating the landform features derived from DTMs into a formal object model of the terrain, consisting of distinct object (landform) classes. Morphometric information on each landform object can be drawn from lower-level C programs, while a PROLOG model manipulates and addresses the objects and provides a graphical interface for object manipulation for the user. Mackay (1990) used this system to search for glacial features such as cirques or troughs based on local morphometry and global position. Mackey et al. (1991) used similar systems to structure and represent terrain knowledge for forested ecosystem applications.

RECOMMENDATIONS AND CONCLUSIONS

The overarching theme of this discussion has been integration: integration with respect to scientific disciplines, modeling, GIS technology, and data. The skills and resources necessary to build and operate effective models of environmental systems transcend individual disciplines. Today we need to be part hydrologist, geologist, soil scientist, geomorphologist, geographer, ecologist, biologist, atmospheric physicist, mathematician, statistician, and computer scientist. If we are concerned about how our models are used in decision-making and in the formulation of policy, then we should add sociologist and economist to this list. The recent literature is replete with references to multidisciplinary and transdisciplinary approaches, coupling of hydrologic and atmospheric models, and hybrid data structures. These integrative and innovative areas of research are, to us, the most promising and challenging areas requiring attention. New institutional and research structures that foster problem-oriented transdisciplinary research need to be encouraged. Often the traditional disciplinary division of academic institutions is an impediment to this type of activity. In particular, the biophysical science and spatial processing communities need to continue to join forces to provide the next generation of hybrid tools. For instance, elevation data can be generated from either map-based information or from stereo remotely sensed data. A hybridization of the two approaches could exploit both kinds of source materials.

Because the integration of modeling and GIS technology requires transdisciplinary skills, there is great potential for misuse and abuse of the technology. In addition, because of skill limitations, GIS technology is often solely used as a cartographic tool and so is not being fully utilized. There is thus a need for expanded training and education in the use of these tools. Training programs for users of these technologies are both lengthy and expensive. Training and education of a different sort is also required for the public at large. They need to understand what these systems can and cannot accomplish if they are to be accepted in various debates and forums, including legal challenges, which are so common in many environmental controversies. Furthermore, scientists have to make the effort to transfer their findings to the public in ways that can be easily understood.

A review of current GIS capabilities and their ability to support environmental modeling activities suggests that improved functionality is needed. The following issues are recommended for additional research and discussion:

1. *Emphasis on pattern as a function of process.* Models of land surface/subsurface phenomena that are linked with GIS should emphasize the identification of pattern as a function of process.
2. *Support for a broad spectrum of projects* dealing with land, water, and atmospheric environments at a variety of scales, including the site-specific, local, regional, and global scales.
3. *A variety of data interpolation algorithms are required.* GIS databases must incorporate the primary data that characterize the processes that modulate landscape and biological responses. The aggregation of data should be left to specific users since different users and applications may dictate different spatial scales of aggregation. Subjective and half-digested secondary data should be avoided as far as possible.
4. *Easy data input and output,* realizing that data may be derived from a very diverse suite of sources, and data may have to be exported for use by a variety of simulation models. This may be facilitated by some forms of expert systems.
5. *GIS should be supported by database management systems* that support two critical functions: (i) provide an "audit trail," or genealogy of the data; and (ii) provide methods of assessing data accuracy and uncertainty.
6. *Broadly accepted data standards.* Standards must be economically achievable, nonproprietary, and be enforceable if they are to be useful.
7. *Support interactive manipulation of model data.* Real-time data manipulation is desirable for the user to be able to add or delete certain data (e.g., an individual well, or some new information) and see how this addition or deletion affects the model.
8. *Provide ways for measuring model accuracy and/or defining the uncertainty in the results.* It is necessary to provide not only numerical values on data uncertainty,

but also to define the uncertainty associated with alternative interpretations. Monte Carlo techniques have been used in the past.

9. *Detailed field studies that explore the spatial and temporal variability of landscape processes must be continued.* These must be made available to the larger scientific community for continued model development and testing, especially the determination of proper model component process representation, the scales over which the processes are valid, and the integration of processes (Goodrich and Woolhiser, 1991).
10. *Improved soil survey and attribute mapping.* Current soils mapping techniques discard the pedon attribute data once a map unit line is drawn. Modern soil survey must use the pedon data as the primary information transfer mechanism (Burrough, 1986; Gessler, 1990). Also, soils attributes must be related to terrain, climate, vegetation/soil biology, parent material (which can be characterized in a GIS), and time.
11. *Improved spatial accuracy of relational data collected in the field.* This can be greatly aided by using global positioning system (GPS) technology.

New technology will only be adopted if it offers substantial time and financial savings over more traditional methods. Such time savings may be of great benefit in some environmental assessment and monitoring situations. Several issues need to be addressed if there is to be widespread adoption of GIS technology:

1. *Systems must become cheaper.* The environmental applications field is characterized by large numbers of smaller companies, and decentralized and relatively small groups of larger firms and Federal and state government agencies. These arrangements cannot support very expensive systems. However, they offer a large and diverse market for more modestly priced systems (e.g., the USDA-Soil Conservation Service's adoption of GRASS).
2. *There must be greater system integration.* For the reasons stated, environmental users cannot justify buying two or three systems to achieve the desired functionality; they require the functionality in a single system.
3. *Lower unit costs will yield an increased user base.* The anticipated reductions in the cost of acquiring GIS technology will encourage the acquisition of units into the smaller offices typical of the environmental consulting world. This will lead to much greater feedback, to the broad acceptance of technology, and to other benefits.
4. *There must be faster processing of 3D models.* Environmental projects often operate on short time frames, so rapid turnaround is critical.

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