

DIGITAL TERRAIN MODELLING: A REVIEW OF HYDROLOGICAL, GEOMORPHOLOGICAL, AND BIOLOGICAL APPLICATIONS

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ABSTRACT

The topography of a catchment has a major impact on the hydrological, geomorphological, and biological processes active in the landscape. The spatial distribution of topographic attributes can often be used as an indirect measure of the spatial variability of these processes and allows them to be mapped using relatively simple techniques. Many geographic information systems are being developed that store topographic information as the primary data for analysing water resource and biological problems. Furthermore, topography can be used to develop more physically realistic structures for hydrologic and water quality models that directly account for the impact of topography on the hydrology. Digital elevation models are the primary data used in the analysis of catchment topography. We describe elevation data sources, digital elevation model structures, and the analysis of digital elevation data for hydrological, geomorphological, and biological applications. Some hydrologic models that make use of digital representations of topography are also considered.

KEY WORDS Basin topography Digital elevation models Terrain analysis Hydrologic models

INTRODUCTION

The demands placed on hydrologic models have increased considerably in recent times. Although it was once sufficient to model catchment outflow, it is now necessary to estimate distributed surface and subsurface flow characteristics, such as flow depth and flow velocity. These flow characteristics are the driving mechanisms for sediment and nutrient transport in landscapes and unless they can be predicted reasonably well, water quality models cannot be expected to adequately simulate sediment and nutrient transport. The control exerted by topography on the movement of water within the landscape is fundamental to the prediction of these flow characteristics. A great deficiency of many hydrologic and water quality models currently in use is their inability to represent the effects of three-dimensional terrain on flow processes and the spatial variability of hydrologic processes without gross, and often unrealistic, simplifications. In response to this challenge, methods are being developed to digitally represent terrain in hydrologic models.

In addition to these complex models, used largely for research into catchment processes, there is a demand for simpler techniques to assist with day-to-day land management. Action agencies responsible for land and water management in many parts of the world are being required to identify those areas of land susceptible to various types of environmental hazard and degradation such as erosion, sedimentation, salinization, non-point source pollution, and water logging (Herndon, 1987) and to assess and manage biological productivity

and diversity within landscapes. A number of hydrologically-based, topographically-derived indices appear to be particularly powerful and useful for determining this susceptibility to hazard (Moore and Nieber, 1989). Many geographic information systems and resource inventory systems are being developed storing topographic information as primary data for use in analysing water resource and biological problems.

This paper reviews the availability of digital elevation data and its accuracy, digital representation of topography, analysis of the digital data for hydrological, geomorphological, and biological applications, and describes some models that make use of digital representations of topography. We use examples from Australia and the United States of America in our discussions because of our familiarity with hydrologic research and practice in these two countries.

DIGITAL ELEVATION MODELS

A Digital Elevation Model (DEM) is an ordered array of numbers that represents the spatial distribution of elevations above some arbitrary datum in a landscape. It may consist of elevations sampled at discrete points or the average elevation over a specified segment of the landscape, although in most cases it is the former. DEMs are a subset of Digital Terrain Models (DTMs) which can be defined as ordered arrays of numbers that represent the spatial distribution of terrain attributes.

The acquisition, storage, and presentation of topographic information is an area of active research. Generally, raw elevation data in the form of stereo photographs or field surveys, and the equipment to process these data, are not readily available to potential end users of a DEM. Therefore, most users must rely on published topographic maps or DEMs produced by government agencies such as the United States Geological Survey (U.S.G.S.) or the Australian Surveying and Land Information Group (AUSLIG—formerly the Division of National Mapping).

This section describes the three major methods of structuring a DEM, the sources of elevation data in Australia and the United States, how DEMs are commonly produced and gives some indication of their quality. The section concludes with a discussion of some simple techniques for analysing elevation data for the estimation of topographic attributes such as slope and aspect and gives examples of methods that can be applied to each of the three DEM structures.

Data networks for Digital Elevation Models

When discussing the use of DEMs it is important to consider the way in which the surface representation is to be used. The ideal structure for a DEM may be different if it is used as a structure for a dynamic, hydrologic model than if it is used to determine the topographic attributes of the landscape.

There are three principal ways of structuring a network of elevation data for its acquisition and analysis, as illustrated in Figure 1. Triangulated Irregular Networks (TINs) usually sample surface specific-points, such

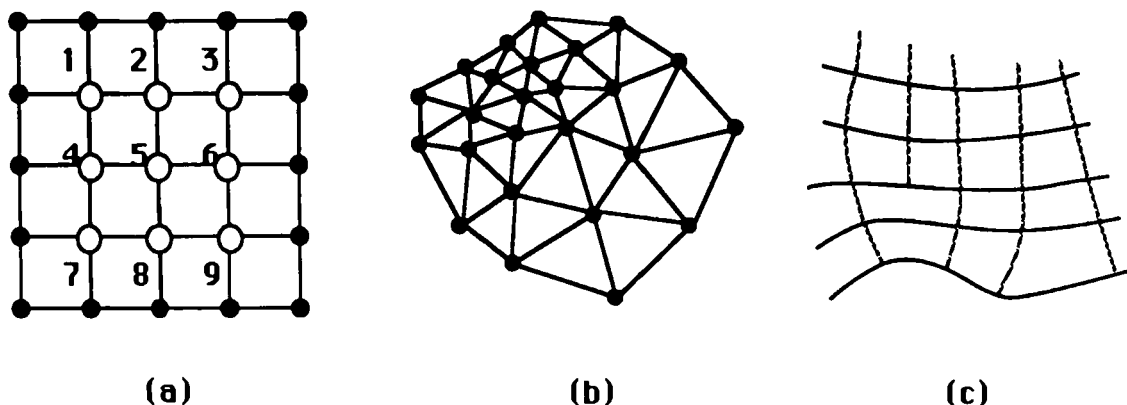


Figure 1. Methods of structuring an elevation data network: (a) square-grid network showing a moving 3×3 submatrix centred on node 5; (b) triangular irregular network-TIN; and (c) contour-based network

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 neighbours in the net (Peucker *et al.*, 1978; Mark, 1975). The elemental area is the plane joining three adjacent points in the network and is known as a facet. Grid-based methods may use a regularly-spaced triangular, square, or rectangular mesh or a regular angular grid, such as the 3 arc-second spacing used by the U.S. Defence Mapping Agency. The choice of grid-based method is related 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. The elemental area is the cell bounded by three or four adjacent grid-points for regular triangular and rectangular grid-networks, respectively. 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, 1988; Moore and Grayson, 1989, 1990) and are 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, including: (1) they cannot easily handle abrupt changes in elevation, although Franke and Nielson (1983) discuss possible ways of modelling these discontinuities; (2) the size of grid mesh affects the results obtained and the computational efficiency (Panuska *et al.*, 1990); (3) the computed upslope flow paths used in hydrologic analyses tend to zig-zag and therefore are somewhat unrealistic; and (4) precision is lacking 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), whereas triangulated irregular networks are more efficient and flexible in such circumstances. Olender (1980) compares triangulated irregular networks with regular grid structures.

Topographic attributes such as slope, specific catchment area, aspect, plan, and profile curvature can be derived from all three types of DEMs. Methods of doing this and potential uses of these and other compound attributes are discussed in detail later. However, the most efficient DEM structure for the estimation of these attributes is generally the grid-based method. 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, although these can be overcome by visual inspection and manual manipulation of the TIN network (Palacios and Cuevas, 1989). The irregularity of the TIN makes the computation of attributes more difficult than for the grid-based methods.

For dynamic hydrologic modelling, there are quite different considerations. Mark (1978) noted that grid structures for spatially partitioning topographic data are not appropriate for many geomorphological and hydrological applications. He stated that 'the chief source of this structure should be the phenomena in question, and not problems, data, or machine considerations, as is often the case'. Hydrologic models simulate the flow of water across a surface so the elemental areas of the DEMs should reflect this requirement. Contour-based methods have important advantages in this regard (Moore, 1988; Moore and Grayson, 1989, 1990) because the structure of their elemental areas is based on the way in which water flows on the land surface. Orthogonals to the contours are streamlines so the equations describing the flow of water can be reduced to a series of coupled one-dimensional equations.

Digital elevation data sources

Digital elevation data are available for selected areas in the United States from the National Cartographic Information Center (NCIC) in several forms (Dept. Interior-U.S.G.S., 1987). DEMs are available on a 30 m square grid for 7.5 minute quadrangle coverage, which is equivalent to the 1:24000-scale map series quadrangle. These data are produced by the U.S.G.S. for the NCIC from: (1) Gestalt Photo Mapper II (Kelly *et al.*, 1977); (2) manual profiling from photogrammetric stereomodels; (3) stereomodel digitizing of contours; and/or (4) digital line graph data. DEMs based on a 3 arc-second spacing have been developed by the Defense Mapping Agency (DMA) for 1 degree coverage, which is equivalent to the 1:250000-scale map series quadrangle. Line map data in digital form, known as Digital Line Graph (DLG) data, are available for 7.5 minute and 15 minute topographic quadrangles, the 1:100000-scale quadrangle series, and 1:2000000-

scale maps. A 30 arc-second DEM is now available for the conterminous United States from the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA).

Moore and Simpson (1982) developed a coarse resolution DEM of Australia with a 6 minute (10 km) grid spacing and the Australian Survey and Land Information Group (AUSLIG) is currently developing a 1:1000000-scale grid DEM using a 18 arc-second grid-spacing (i.e. approximately 500 m) (Trezise and Hutchinson, 1986). Recently, [Hutchinson and Dowling \(1991\)](#) developed a 1.5 minute grid DEM of Australia. Both the 1.5 minute and 18 arc-second DEMs were developed using the procedures described by Hutchinson (1989a) which use both spot height data and stream line data. At the global scale, a 5 minute global DEM is available from NGDC-NOAA.

As noted above, direct photogrammetric techniques are available to produce DEMs from stereophoto pairs. With the Gestalt Photomapping system, photo coordinates of control points are measured and their locations and elevations input (Kelly *et al.*, 1977). A least squares solution is used to produce a stereo model that can be processed off-line to generate a DEM. Stereo images available from the French earth observation satellite, SPOT (Le Systeme Pour l'Observation de la Terre), can be used to produce orthophotos and DEMs in much the same way as conventional air photography. Satellite data has the advantage that it can be purchased in digital form and directly accessed by computers.

If digital elevation data for a particular study area are not available they can be derived by digitizing existing topographic maps. Contour lines can be digitized automatically using the processes of raster scanning and vectorization (Leberl and Olson, 1982) or by manually using a flat-bed digitizer and software packages. A variety of low-cost flat-bed digitizers and software packages are now available for most personal computers. 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 analysed as an irregular network or interpolated onto a regular grid.

[Hutchinson \(1988, 1989a\)](#) describes a new efficient finite difference method of interpolating grid DEMs from contour line data or scattered surface-specific point elevation data. The method is innovative in that it has a drainage enforcement algorithm that automatically removes spurious sinks or pits and calculates stream lines and ridge lines from points of locally maximum curvature on contour lines. The most common method of performing a contour to TIN transformation is via Delaunay triangulation ([McLain, 1976](#)), but this method can produce poorly configured triangular facets where a facet edge crosses a contour segment or all three vertices are on the same contour. Christensen (1987) developed a parallel pairs procedure as part of a medial axis transformation method that overcomes these problems.

Digital elevation model quality

Many published DEMs are derived from topographic maps so their accuracy can never be greater than the original source of the data. For example, the most accurate DEMs produced by the U.S.G.S. are generated by linear interpolation of digitized contour maps and have a maximum root mean square error (RMSE) of one-half contour interval and an absolute error no greater than two contour intervals in magnitude (Dept. Interior U.S.G.S., 1987). Care must be exercised when fitting mathematical surfaces to DEMs as the resulting models give the appearance of 'generating' data, but the accuracy of the data is unknown. The U.S.G.S. DEMs are referenced to 'true' elevations from published maps that include points on contour lines, bench marks, or spot elevations (Dept. Interior-U.S.G.S., 1987). However, these 'true' elevations also contain errors. It is therefore apparent that all DEMs have inherent inaccuracies not only in their ability to represent a surface but also in their constituent data and it 'behoves users to become aware of the nature and the types of errors' (Carter, 1989).

The quality of the U.S.G.S. DEM data are classified as Level 1, 2, or 3 (Dept. Interior-U.S.G.S., 1987). Level 1 is the standard format and has a maximum absolute vertical error of 50 m and a maximum relative error of 21 m. Most 7.5 minute quadrangle coverage is classified as Level 1. Level 2 data have been smoothed and edited for errors. DEMs derived by contour digitizing are classified as Level 2. These data have a maximum error of two contour intervals and a maximum root mean square error (RMSE) of one half of a contour interval. Level 3 data have a maximum error of one contour interval and a maximum RMSE of one third of a contour interval—not to exceed 7 m. The U.S.G.S. does not currently produce Level 3 elevation

data. The vertical accuracy of the Gestalt Photomapping system is 0.022 per cent to 0.03 per cent of the aircraft flying height and is therefore capable of producing a DEM of level 3 accuracy (Kelly *et al.*, 1977). Konecny *et al.* (1987) showed that SPOT stereoscopic data may be used for topographic mapping up to a scale of 1:25000 and is capable of producing a DEM with a grid spacing of 500 m and a root mean square error of 7.5 m.

The errors contained in the U.S.G.S. grid-based DEMs were classified by Carter (1989) as either global or relative. Global errors are systematic errors in the DEM that can usually be corrected by applying transformations including linear or nonlinear translation, rotation, and scaling to the whole DEM. Like Carter, the authors have found mismatching elevations along the boundaries of adjacent 7.5 minute DEMs to be the most pervasive global errors. Relative errors occur when a few elevations are in 'obvious error relative to the neighbouring elevations' (Carter, 1989). The errors in DLG data include artificial peaks and blocks of terrain extending above the surrounding terrain, particularly along ridge lines. These errors may be due to deficiencies in the interpolation algorithms that produced the DLG data or to an excessive spacing between sampled coordinate pairs along the line data. Thapa (1990) describes a method of optimal compression of DLG data that may overcome some of these problems.

Analysis of elevation data

The topographic attributes of a landscape can be calculated directly from a DEM using only the point values without the assistance of surface fitting, smoothing operations or the assumptions of continuity (Collins, 1975). This approach has limited usefulness, is restricted to grid-based DEMs, and does not produce physically realistic results particularly in the calculation of flow directions in flat areas (Douglas, 1986).

The most common method of estimating topographic attributes involves fitting a surface to the point elevation data using either linear or nonlinear interpolation. The sequential steepest slope algorithm developed by Leberl and Olson (1982) is an example of a linear interpolation technique for generating grid elevation data. The interpolation is carried out firstly along ridge and drainage lines and then elevations are interpolated for all other points in the grid using ridge, drainage, and contour lines as lines of known elevation. Barnhill (1983) classifies nonlinear surface fitting methods in two ways: as local or global and patch or point schemes. Global methods utilize all or most of the elevation data to characterize the surface at a point and have the advantage of preserving continuity. Their chief disadvantage is their high computational cost which is proportional to n^3 , where n is the number of data points (Hutchinson, 1989a). For local methods, the fitted surface (often a simple polynomial) at a point depends only on nearby data and the computational costs are proportional to n (Hutchinson, 1989a). Patch surfaces consist of small curved patches that are joined together smoothly, whereas point methods construct the surface using only information given at discrete points.

A wide variety of methods are available for fitting elevation surfaces to point data and some are described by Hutchinson (1984). They include: kriging (Gandin, 1963; Matheron, 1973; Delfiner and Delhomme, 1975; Jupp and Adomeit, 1981; and Dubrule, 1984), for which numerous commercial packages are available; local interpolation methods (surveyed by Barnhill and Boehm, 1983); moving average methods; and spline interpolation (Dubrule, 1984; Hutchinson, 1984). More recently, Hutchinson (1988, 1989a) has developed an iterative finite difference interpolation method for use with irregularly distributed data that has the efficiency of a local method without sacrificing the advantages of the global methods. This method uses a nested grid strategy that calculates grid DEMs at successively finer resolutions.

Most digital terrain analysis methods are based on grided data structures and for these local interpolation methods are the simplest and easiest to implement. This approach has been used by Evans (1980), Zaslavsky and Sinai (1981), Mark (1983), Jenson (1985, 1987), Zevenbergen and Thorne (1987), Jenson and Domingue (1988), and Moore and Nieber (1989). One simple grid-based local interpolation method that appears very promising is Snyder *et al.*'s (1984) sliding polynomials. It has the advantage over methods like Zevenbergen and Thorne's (1987) in that the continuity of the fitted function and its first and second derivatives are preserved between adjacent patches.

One problem with the analysis of digital elevation data for hydrologic applications is the definition of drainage paths when the DEM contains depressions or flat areas. Some depressions are data errors while

others are natural features or excavations (Jenson and Domingue, 1988; Hutchinson, 1989a). The hydrologic significance of depressions depends on the type of landscape represented by the DEM. In some areas, such as the prairie pot-hole region in the upper Midwest of the United States, surface depressions dominate the hydrologic response of the landscape. In areas with coordinated drainage, depressions are an artifact of the sampling and generation schemes used to produce the DEM. In landscapes with natural depressions, the numerical filling of depressions in the DEM is used as a method of determining storage volumes and to assign flow directions that approximate those occurring in the natural landscape once the depressions are filled by rainfall and runoff (e.g. Moore and Larson, 1979). Mark (1983) discusses the smoothing of data sets to remove depressions, but this has the disadvantage of affecting all the elevations in the data set and will not remove large depressions.

O'Callaghan and Mark (1984) and Jenson (1987) proposed algorithms to produce depressionless DEMs from regularly spaced grid elevation data. If the depressions are hydrologically significant then their volume can be calculated. Jenson and Domingue (1988) used the depressionless DEM as a first step in assigning flow directions. Their procedure is based on the hydrologically realistic algorithm discussed by Mark (1983) and O'Callaghan and Mark (1984), but is capable of determining flow paths iteratively where there is more than one possible receiving cell and where flow must be routed across flat areas. Hutchinson's (1988, 1989a) method, which was briefly described earlier, includes an automatic drainage enforcement algorithm that removes spurious sinks or pits. This can greatly simplify the task of obtaining a depressionless DEM.

If a surface defined by the function $F(x, y, z)$ is fitted to the DEM, then a number of hydrologically important topographic attributes can be derived from this function at the point (x_0, y_0, z_0) . As an example, we will now demonstrate how two of these attributes, aspect and the maximum slope can be determined from the function $F(x, y, z)$ using elementary geometry. We will then briefly describe three elementary local-point methods of representing surfaces using triangulated irregular networks, square-grid networks, and contour-based networks, respectively.

The fitted surface The equation of the tangent plane to the point (x_0, y_0, z_0) is

$$\frac{\partial F}{\partial x} \Big|_{x=x_0} (x - x_0) + \frac{\partial F}{\partial y} \Big|_{y=y_0} (y - y_0) + \frac{\partial F}{\partial z} \Big|_{z=z_0} (z - z_0) = 0 \quad (1)$$

Now, if we let

$$a = \frac{\partial F}{\partial x} \Big|_{x=x_0}; b = \frac{\partial F}{\partial y} \Big|_{y=y_0}; d = \frac{\partial F}{\partial z} \Big|_{z=z_0} \quad (2)$$

then the equation of the plane tangent at the point (x_0, y_0, z_0) is

$$a(x - x_0) + b(y - y_0) + d(z - z_0) = 0 \quad (3)$$

or

$$\frac{a}{d}x + \frac{b}{d}y + z + \frac{c}{d} = 0 \quad (4)$$

where $c = -ax_0 - by_0 - dz_0 = \text{constant}$. The partial derivatives defined by Equation 2 may be estimated directly from the analytical form of $F(x, y, z)$ or, if the DEM uses a square grid, as finite differences. The maximum slope angle, β , is defined as the intersecting angle of the tangent plane with the horizontal plane (i.e. $z = 0$) and is given by

$$\cos \beta = \left| \frac{d}{\sqrt{a^2 + b^2 + d^2}} \right| \text{ or } \tan \beta = \left| \frac{\sqrt{a^2 + b^2}}{d} \right| \quad (5)$$

The aspect is the orthogonal to the tangent to (x_0, y_0, z_0) in the horizontal plane (i.e. with $z = z_0 = \text{constant}$). Simplifying Equations 1 to 4 with $z = z_0 = \text{constant}$, the equation of the tangent to (x_0, y_0, z_0) in the horizontal plane is

$$y = -\frac{a}{b}x - \frac{c}{b} \quad (6)$$

where $c = -ax_0 - by_0 = \text{constant}$. This is the equation of a line with slope $-a/b$, so the slope of its orthogonal is b/a . Therefore, the aspect, ψ , measured in degrees clockwise from north is

$$\psi = 180 - \arctan\left(\frac{b}{a}\right) + 90\left(\frac{a}{|a|}\right) \quad (7)$$

when x is positive east and y is positive north.

Triangulated irregular network Tajchman (1981) divided the landscape into a triangulated irregular network and represented the surface of each triangular segment or patch by a plane. The equation of a plane determined by three points $P_1(x_1, y_1, z_1)$, $P_2(x_2, y_2, z_2)$, and $P_3(x_3, y_3, z_3)$ is $z = Ax + By + C$, where the constants A , B , and C are determined by simultaneous solution of the equation at P_1 , P_2 , and P_3 . Following from Equations 1 to 7, the slope, β , of this plane in the aspect direction is given by

$$\beta = \arctan[(A^2 + B^2)^{1/2}], \quad (8)$$

and the aspect of the plane, ψ , is given by

$$\psi = 180 - \arctan\left(\frac{B}{A}\right) + 90\left(\frac{A}{|A|}\right) \quad (9)$$

where y is positive north and x is positive east, and the area of the triangular segment in the horizontal plane, A_h , is given by

$$A_h = \pm 0.5(x_1y_2 + x_2y_3 + x_3y_1 - x_1y_3 - x_2y_1 - x_3y_2) \quad (10)$$

Tajchman (1981) used modifications of these relationships to examine the distribution of slope and azimuth classes and their interrelationships over the Little Run catchment in the Appalachian Mountains. Because the surface is assumed to be planar this method does not provide point estimates of slope or aspect, but rather estimates 'average' values over each triangular segment. For similar reasons, the method cannot be used to calculate topographic attributes such as profile and plan curvature because the second derivatives of the surface functions do not exist. More complex techniques that use piece-wise continuous curved patches, such as those described by Barnhill and Boehm (1983), do have these capabilities.

Regular grid network Evans (1980) fitted a 5-term quadratic polynomial to the interior grid point of a moving 3×3 square-grid network such as that shown in Figure 1a. Heerdegen and Beran (1982) used this scheme to calculate a variety of distributed catchment topographic attributes including slope, aspect and plan, and profile curvature. Zevenbergen and Thorne (1987) modified this method by fitting the following quadratic polynomial to this moving grid.

$$z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I \quad (11)$$

This 9-term polynomial exactly fits all 9 points in the 3×3 moving grid, whereas Evan's (1980) 5-term polynomial does not. Determining the values of the coefficients in this equation is simplified by having a

uniform grid, which allows the coefficients to be expressed solely as functions of the grid-point elevations and the grid-spacing, λ . The slope, β , aspect, ψ , profile curvature, ϕ , plan curvature, ω , and curvature, χ , which is the Laplacian- ∇^2 of the function defining the surface (Zaslavsky and Sinai, 1981), of the mid-point in the moving grid can then be calculated using the following relationships.

$$\beta = \arctan[(G^2 + H^2)^{1/2}] \quad (12)$$

$$\psi = 180 - \arctan\left(\frac{H}{G}\right) + 90\left(\frac{G}{|G|}\right) \quad (13)$$

$$\phi = -2 \frac{DG^2 + EH^2 + FGH}{G^2 + H^2} \quad (14)$$

$$\omega = 2 \frac{DH^2 + EG^2 - FGH}{G^2 + H^2} \quad (15)$$

$$\chi = \omega - \phi = 2E + 2D \quad (16)$$

The plan area in the horizontal plane characterized by each node or grid-point is $A_h = \lambda^2$. Jenson and Domingue (1988) describe a computationally efficient algorithm for estimating flow directions and hence catchment areas and drainage path lengths for each node in a regular grid DEM based on the concept of a depressionless DEM which was described earlier. They assume that water flows from a given node to one of eight possible neighbouring nodes, based on the direction of steepest descent. Moore and Nieber (1989) combined this algorithm with Zevenbergen and Thorne's (1987) approach to estimate a wide variety of hydrologically significant topographic attributes.

Contour-based networks Moore *et al.* (1988a), Moore (1988) and Moore and Grayson (1989, 1990) have developed a method of computing contour-based networks for topographic analysis. Their scheme, called TAPES-C, Topographical Analysis Program for the Environmental Sciences—Contour, partitions a catchment into irregularly shaped elements or patches such as is shown in Figure 1c. These elements are bounded by equipotential lines on two sides (contour lines) and streamlines, that are orthogonal to the equipotential lines on the other two sides (no flow boundaries). Both the contours and the streamlines or flow trajectories between contours are approximated by short straight line segments. Streamlines are computed using two criteria: (1) minimum distance between adjacent contours, that is applied in ridge areas; and (2) orthogonals to the downslope contour, that is applied in valley areas. Application of the two criteria is determined by the plan curvature. The two criteria are used in an attempt to overcome the error caused by using straight line segments to define streamlines. Bell (1983) has developed a program, SLOPROFIL.2, for constructing contour orthogonals from user specified points on a square-grid network. It has considerable potential for simplifying Moore and Grayson's (1990) scheme. Hutchinson's (1988) scheme can also be used to simplify this task by interpolating intervening contour lines with respect to the stream line and ridge line structures.

TAPES-C computes the average slope of each element as

$$\beta = \frac{\kappa (L_u + L_d)}{2 A_h} \quad (17)$$

where κ is the contour interval, L_u and L_d are widths of the element along the upslope and downslope contours, respectively, and A_h is the area of the element in the horizontal plane. Aspect, ψ , is calculated at the midpoint of the lower contour segment of each element as the downslope direction orthogonal to the contour at that point. The plan curvature, ω , is computed using a finite difference approximation to successive x, y coordinate pairs along each contour. The area A_h is calculated using trapezoidal numerical integration. TAPES-C also determines the connectivity between upslope and downslope elements in the network and this is used to compute the specific catchment area and drainage path length for each element.

HYDROLOGICALLY, GEOMORPHOLOGICALLY, AND BIOLOGICALLY SIGNIFICANT TOPOGRAPHIC ATTRIBUTES

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 and slope. Compound attributes involve combinations of the primary attributes and are indices that describe or characterize the *spatial variability of specific processes occurring in the landscape* such as soil water content distribution or the potential for sheet erosion. These attributes can be derived empirically but it is preferable to develop them through the application and simplification of the underlying physics of the processes. In the past we have been able to model specific point processes in considerable detail but have not been able to represent the spatial variability of these processes very successfully. With the index approach we sacrifice some physical sophistication to allow improved estimates of spatial patterns in the landscape.

In this section we describe a range of topographic attributes and indices, their underlying assumptions and limitations and the hydrological, geomorphological, and biological processes they attempt to characterize. We also outline their physical basis, but do not attempt to give detailed derivations—the interested reader should refer to the cited literature for these.

We envisage that the topographic indices described below could be used in a variety of ways. The primary indices can be used directly in processes modelling (e.g. slope and aspect can be used in the estimation of energy budgets) or the compound indices can be used as surrogates of very complex hydrological, geomorphological, and biological processes (e.g. use of the wetness and radiation indices to predict the spatial distribution of different plant species). In many cases it is not possible to carry out direct measurements of these environmental processes because of physical, time, or economic constraints. Elevation data are usually accessible, and through the terrain analysis methods described above, topographic attributes can be readily calculated without these constraints.

In many developing countries there is a general lack of environmental data for planning projects, but the first information obtained is usually a topographic map. From this elevation data, topographic attributes can be calculated and used in the planning of data collection networks (i.e. hydrological monitoring, soil surveys, biological surveys), and in the initial planning of agricultural and forestry developments (as an example, see Srivastava and Moore, 1989). As additional environmental data become available, these data can be used to provide improved estimates of the terrain-based indices. For example, the susceptibility of the landscape to sheet and rill erosion can be initially estimated using only topographic data. As hydrological and soils information become available, this information can be integrated into the predictions and finally, as information on vegetation and cover is developed, the full Universal Soil Loss Equation ([Wischmeier and Smith, 1978](#)) or a complete physically-based erosion model can be used. Hence, in such situations we see different layers or levels of data being developed over time with elevation data and the related topographic attributes constituting a minimum data set. Adoption of this approach by international development agencies has the potential for achieving major cost savings, particularly during the critical initial planning and implementation stages of a project.

Primary topographic attributes

Speight (1974) described over 20 topographic attributes that can be used to describe landform. A series of hydrologically related primary topographic attributes, adapted from Speight (1974, 1980), is presented in Table I. The attributes identified with an asterisk in this table can only be appraised along drainage lines while the others are spatially distributed properties. These can theoretically be evaluated at every point in the catchment, although the values of many become unstable (i.e. have increasing error) close to the drainage lines. The primary topographic attributes that can be easily estimated using the computer-based methods described above include slope, β ; aspect or azimuth, ψ ; specific catchment area, A_s , that is defined as the upslope area draining across a unit width of contour ([Speight, 1980](#)); flow path length, γ ; profile curvature, ϕ ; and plan curvature, ω .

Slope or slope steepness has always been an important and widely used topographic attribute. Many land capability classification systems, some of which are described by Morgan (1986), utilize slope as the primary

Table I. Primary topographic attributes (adapted from Speight, 1974, 1980)

Attribute	Definition	Hydrologic significance
Altitude	Elevation	Climate, vegetation type, potential energy
Upslope height	Mean height of upslope area	Potential energy
Aspect	Slope azimuth	Solar irradiation
Slope	Gradient	Overland and subsurface flow velocity and runoff rate
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
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	Impedance of soil drainage
Catchment length*	Distance from highest point to outlet	Overland flow attenuation
Profile curvature	Slope profile curvature	Flow acceleration, erosion/deposition rate
Plan curvature	Contour curvature	Converging/diverging flow, soil water content

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

means of ascribing class, together with other factors such as soil depth, soil drainability, and soil fertility (Moore and Nieber, 1989). Dimensionless slope and flow path (i.e. slope steepness and length) are included as parameters in the Universal Soil Loss Equation-USLE, which was the basis for quantifying sheet and rill erosion by water in the recent assessment of the United States National Resources Inventory (National Research Council, 1986). These two primary topographic attributes are being commonly used to assess erosion hazard. Moore and Thornes (1976) developed LEAP- Land Erosion Analysis Programs to examine the spatial distribution of slope length, slope steepness, and the plan curvature for assessing 'topographic erosion potential'. More recently, Bork and Rohdenburg (1986) have developed a 'Digital Relief Model' for estimating and displaying the distributed morphographic parameters mentioned above.

Hydrologically, the specific catchment area, A_s , is a measure of surface or shallow subsurface runoff at a given point on the landscape, and it integrates the effects of upslope contributing area and catchment convergence and divergence on runoff. For the ideal case of temporally and spatially uniform rainfall excess, the steady-state discharge per unit width, q , is directly proportional to A_s . Even though this ideal condition rarely exists in the natural environment this assumed relationship is used extensively in hydrology. Examples include the application of the Rational formula, many applications of the USDA-Soil Conservation Service curve number technique, and most spatially lumped hydrologic models.

Soil water content has been related to curvature ($R^2 = 0.81$) by Zaslavsky and Sinai (1981), slope, aspect, and specific catchment area by Moore *et al.* (1988b) and slope and plan curvature by Burt and Butcher (1986). Zaslavsky and Sinai (1981) observed that in their experimental catchment soil water contents were higher in hollows even though there was no water table, perched water, or impermeable layer. Moore and

Burch (1986a) and others also demonstrated that profile curvature is an important determinant of erosion and deposition processes at the hillslope scale.

Since the pioneering work of [Whittaker \(1967\)](#), there has been a concerted effort to describe the vegetation continuum in terms of environmental gradients. The term 'phytogeomorphology' was coined by Howard and Mitchell (1985) in recognition of the interdependence of plants and landforms. They state that phytogeomorphology 'reflects those sensitive landform-vegetation attributes that are visibly dominant in the landscape'. Vegetation characteristics such as species composition, total basal area, and growth habitat, have been correlated with gradient position defined by environmental scalars. These environmental scalars may include primary topographic attributes such as altitude, slope and aspect, or derived attributes such as radiation indices ([Austin et al., 1983, 1984](#)) which are discussed later.

In many cases altitude is used as an indirect means of accounting for spatial variations in temperature and/or precipitation. Improved estimates of the spatial distribution of climatic variables, including mean seasonal and annual rainfall (isohyetal maps) and monthly mean daily maximum and minimum temperature, can be obtained from 'thin plate' smoothing spline surfaces that fit the historical climatic data in terms of irregularly spaced elevation data ([Hutchinson, 1989b](#); [Hutchinson and Bischof, 1983](#)). Hutchinson's method is particularly attractive because it allows the variance of the dependent parameter to be spatially varied. For example, [Hutchinson and Bischof \(1983\)](#) assumed that mean rainfall was distributed independently with variance σ^2/n , where σ is the local standard deviation estimate derived from the historical data and n is the number of years of record.

Elevation and a series of temperature and precipitation attributes derived from these elevation-based climate gradients have been used to develop a numerical classification scheme for examining the environmental domain of rainforest structural types in the wet tropics World Heritage Property of northeast Queensland, Australia ([Mackey et al., 1989](#)). [Mackey and Norton \(1989\)](#) argue that physical environmental data such as elevation, slope, aspect, and catchment area can be used as indices of species diversity and forest structure and should be included in the recently proposed Australian National Forest Inventory.

Dispersal area, which [Speight \(1974\)](#) indicated was related to the soil drainage rate, cannot be calculated in a manner that is consistent with the estimation of specific catchment area with existing grid-based methods of analysis. These methods have no provision for drainage from one node in the grid to multiple nodes downslope in areas where flow is diverging. However, contour-based methods can directly calculate dispersal area because they partition a catchment using streamlines.

Analytically derived compound topographic indices

Soil water content and surface saturation zones The most commonly used hydrologically-based compound topographic attribute or index is

$$w_T = \ln\left(\frac{A_s}{T \tan \beta}\right) \text{ or } w = \ln\left(\frac{A_s}{\tan \beta}\right) \quad (18)$$

where T is the transmissivity when the soil profile is saturated and w_T and w are both often referred to as wetness indices. The form represented by w assumes uniform soil properties; i.e. that the transmissivity is constant throughout the landscape and equal to unity. [Beven and Kirkby \(1979\)](#) and [O'Loughlin \(1986\)](#) derived slightly different forms of the wetness index, but both relate it to the spatial distribution and size of zones of saturation or variable source areas for runoff generation. Runoff from saturation zones is a threshold process and areas producing saturation overland flow can be identified using a threshold wetness index. Because significant percolation of soil water to ground water occurs only when the soil water content exceeds field capacity, a threshold concept could possibly be used to also relate the potential for ground water recharge and non-point source pollution to the wetness index ([Moore and Nieber, 1989](#)).

[Moore et al. \(1988b\)](#) found a strong correlation between the distribution of w and the distribution of surface soil water content in a small fallow catchment. [Burt and Butcher \(1986\)](#) found that the product of wetness index and plan curvature ($w\omega$) produced the best correlations, whereas in the study of [Moore et al.](#)

(1988b) a linear relationship involving the wetness index, w , and aspect, ψ , performed best. Jones (1986, 1987) discusses the usefulness and limitations of the wetness index as an indicator of the spatial distribution of soil water content and soil water drainage. Care must be exercised in applying a static index like w or w_T 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 (Burt and Butcher, 1986).

Examining the surface water chemistry of the Llyn Brianne catchments in Wales, Wolock and Musgrove (1988) found that the mean value of the distribution of w_T , ξ , was highly correlated with the slope of the discharge-hydrogen ion concentration relationship ($r^2 = 0.88$). Wolock *et al.* (1989) called ξ a flow path partitioning index and also derived a second variable, t_r , an index of soil contact or residence time for percolating water in catchments, where

$$t_r = b_{ave} n_{ave} e^{\xi} \quad (19)$$

and b_{ave} and n_{ave} are the areally averaged soil depth and porosity, respectively. They found a strong positive correlation between lake alkalinity, an indicator of catchment acidification response, and the flow path partitioning and soil contact time indices of 145 lakes fed by separate catchments in the northeastern United States. This analysis is based on the assumption that catchments that produce higher proportions of saturated overland flow are less able to buffer acid rain and yield lower pH runoff than other catchments.

The location of salt scalds and zones susceptible to dry-land salinization appears to be correlated with the distribution of the wetness index (Bullock and Williams, personal communication). Strong correlations also exist between the wetness index and vegetation distribution in the national estate forest areas of southeastern Australia (Nix and Mackey, personal communication). Moore *et al.* (1986b) showed how the wetness index versus per cent saturated source area relationship, together with observed stormflow data, could be used to estimate the effective transmissivity of a small forested catchment. This analysis used an analogy with Theis' (1935) graphical method for determining the transmissivity of a ground water aquifer under conditions of unsteady flow.

Precipitation Precipitation often falls at a considerable inclination due to the effects of wind. As a result the precipitation incident on a hillslope may deviate widely from measurements made in conventional raingauges with horizontal orifices (Sharon, 1980; Sevruk, 1982, 1986; Folland, 1988; Sharon *et al.*, 1988). Accurate estimates of the rainfall intensity are necessary if accurate estimations of rain-dependent processes such as infiltration and interception are to be made. Folland (1988) developed a numerical model of the raingauge exposure problem that accounts for the interaction between wind speed and direction, raindrop size and the physical characteristics of the collector. He used this model to design a 'flat champagne glass'-shaped collector that minimized collection errors. The range of systematic precipitation measurement errors are discussed by Sevruk (1986, 1987).

Topographic position also affects precipitation measurement errors and a crude but simple method of accounting for these and wind induced errors follows. Sharon (1980) used Fourcade's (1942) equation to develop a correction factor, C_f , to adjust rainfall measurements made using a gauge with a horizontal orifice, P_o , to rainfall on an inclined surface, defined in terms of per unit of projected horizontal area, P_a , on the basis of the topographic attributes of slope, β , and aspect, ψ , and the inclination of the rainfall vector, ϵ , measured from the zenith in the direction from which rain is falling, ϕ .

$$C_f = \frac{P_a}{P_o} = 1 + \tan \beta \tan \epsilon \cos(\psi - \phi) \quad (20)$$

In practice ϵ is dependent on raindrop size and windspeed and ϕ will vary during a storm. The values of these variables can be inferred from wind speed and direction measurements and effective drop sizes that are related to rainfall intensity. Sharon showed that for rainfall inclined at 40° , C_f varies from 0.52 on the lee side to 1.48 on the windward side of a 30° slope and concluded that Equation 20 is accurate providing the rainfall vector can be specified within narrow limits. These effects even occur at the microtopographical scale on

cultivated fields with ridges (Sharon *et al.*, 1988). Sharon (1980) also found that the variations of hydrological rainfall between windward and lee slopes are 'reduced near wind-exposed ridges, owing to systematic small-scale variations of meteorological rainfall and of rain inclination'.

Solar radiation dependent processes The surface energy budget is a driving force for evaporation and transpiration processes occurring at the land surface and is highly dependent on topography. Evapotranspiration accounts for a major part of the total water budget of a catchment. The potential solar radiation ratio, $F = R_o/R_{oh}$, which is the ratio of the potential solar radiation on a sloping surface to that on a horizontal surface, has been used widely in hydrological and ecological contexts as an approximate method of examining the spatial distribution of radiation across a catchment (Lee, 1978; Moore *et al.*, 1988a). The potential solar radiation is the radiation received at a sloping site in the absence of the atmosphere and can be expressed as:

$$R_o = \frac{24I}{\pi r^2} \cos \phi \cos \delta (\sin \eta - \eta \cos \eta) \quad (21)$$

where I is the solar constant, δ is the solar declination, r is the ratio of the earth-sun distance to its mean, and ϕ and η are functions of the terrestrial latitude and the topographic attributes of slope, β , and aspect, ψ (Lee, 1978). Equation 21 can be numerically integrated over any time period ranging from one day to one year to estimate the seasonal potential solar radiation on an inclined surface. Hence, on a given catchment, the variation in potential solar radiation over the catchment is a function of only slope, aspect, and the time of year.

The major shortcoming of the above approach is that it ignores all atmospheric effects which tend to reduce the contrast between sloping and horizontal sites (Fleming, 1987). The total shortwave radiation received on an inclined surface, R_t , actually consists of three components: direct— R , diffuse— R_d , and reflected— R_r radiation (Gates, 1980; Bristow and Campbell, 1985; Flint and Childs, 1987).

$$R_t = R + R_d + R_r \quad (22)$$

This relationship can be approximated by:

$$R_t = (R_{th} - R_{dh})F + R_{dh}f + R_{th}(1 - f)\mu \quad (23)$$

where R_{th} and R_{dh} are the total and diffuse radiation on a horizontal surface, respectively, f is the fraction of the sky which can be seen by the sloping surface [$= \cos^2(\beta/2)$], μ is the albedo of the surrounding area, and β is the slope angle (Paltridge and Platt, 1976; Bristow and Campbell, 1985). The total and diffuse radiation on a horizontal surface are often expressed as functions of the total and diffuse transmittances of the atmosphere and the potential solar radiation on a horizontal surface, R_{oh} . These transmittances are functions of the thickness and composition of the atmosphere, particularly the water vapour (i.e. cloudiness), dust, and aerosol content (Lee, 1978; Hounam, 1963). Several models for predicting total shortwave radiation in mountainous terrain have recently been evaluated by Isard (1986). The reader is referred to the above citations and to Kondratyev (1977) for an in depth discussion of these relationships.

Equation 23 ignores the effect on computed radiation input to a surface of shading from direct sunlight by surrounding terrain at enclaved sites. Failure to account for this effect can have a significant impact on the ability to predict snowmelt processes and snowpack conditions in alpine regions and on the ability to correlate vegetation diversity and distribution to radiation. Solutions of the horizon problem are computationally intensive because they cannot be calculated from elevation data restricted to the immediate neighbourhood of a point (Dozier and Bruno, 1981). However, Dozier and Bruno (1981) present a solution scheme with an efficiency proportional to n , where n is the number of data points, for use with grid-based DEMs. Dozier (personal communication) has recently extended this method to provide estimates of direct, diffuse, and reflected radiation and Duguay (1989) has adapted it for the estimation of net radiation

(shortwave and longwave) in mountainous terrain. An approximate radiation index that accounts for diffuse and direct radiation and to a limited extent, the horizon problem, is also reported by Fleming (1987) and has been used by Austin *et al.* (1983, 1984) and Mackey *et al.* (1989). An excellent review of radiation modelling is provided by Duguay (1989).

Vegetation diversity and biomass production have been shown to be related to radiation input in the United States (Hutchins *et al.*, 1976; Tajchman and Lacey, 1986). Hutchins *et al.* (1976) found that slopes receiving greater amounts of solar radiation had higher temperatures and greater evaporative demand which was reflected in less dense tree stands and less well developed vegetation. The distributions of vegetation and solar radiation in small mountainous catchments near Hokkaido, Japan are highly correlated (Takahashi, 1987) and Austin *et al.* (1983, 1984) have shown that the distribution and zonation of eucalypt species in southeastern Australia is related to altitude, rainfall, and annual radiation index. The radiation index in combination with the wetness index also has potential for characterizing biological distribution and species diversity (Moore *et al.*, 1988a).

Snowmelt processes also respond to radiation inputs and are sensitive to topographic position (i.e. elevation, slope, and aspect). Slope and aspect maps derived from DEM data can be used in conjunction with multispectral scanner (MSS) data and maps of the areal extent of snow cover, obtained from Advanced Very High Resolution Radiometer (AVHRR) satellite data, to estimate areal snow water equivalent at a resolution of approximately 500 m (Carroll and Yates, 1989). Leavesley and Stannard (1989) are developing a distributed-parameter, energy-budget, snowmelt-runoff model that uses digital terrain analysis and geographic information systems to provide objective basin characterization procedures. They are specifically using slope and aspect in their energy budget calculations and use elevation data in the computation of lapse rates for air-temperature and precipitation extrapolation.

Erosion processes Stream power, $\Omega = \rho g q \tan \beta$, where ρg is the unit weight of water and q is the discharge per unit width, is the time rate of energy expenditure and has been used extensively in studies of erosion, sediment transport and geomorphology as a measure of the erosive power of flowing water. The compound topographic index $A_s \tan \beta$ is, therefore, a measure of stream power since q is often assumed to be proportional to A_s . Moore *et al.* (1988b) found that the indices $A_s \tan \beta$ and w (i.e. $A_s/\tan \beta$), when used together, were good predictors of the location of ephemeral gullies in a small fallow agricultural catchment. For example, on a semiarid catchment in Australia ephemeral gullies formed where $w > 6.8$ and $A_s \tan \beta > 18$ (Moore *et al.*, 1988b) and on a small catchment in the island of Antigua in the Caribbean they formed where $w > 8.3$ and $A_s \tan \beta > 18$ (Srivastava and Moore, 1989). The threshold values of the indices differ because of differences in soil properties. Thorne *et al.* (1986) developed the index $A_s \omega \tan \beta$, where ω is the plan curvature, to identify the location of ephemeral gullies. They also proposed the following equation for predicting the cross-sectional area of an ephemeral gully, X_a , after one year of development:

$$X_a = 0.2(A_s \omega \tan \beta)^{0.25} \quad (24)$$

The stream power index, or its derivatives, could be used to identify places where soil conservation measures that reduce the erosive effects of concentrated surface runoff, such as grassed waterways, should be installed (Moore and Nieber, 1989).

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, 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). To predict erosion at a point in the landscape the LS factor can be written as:

$$LS = (n + 1) \left(\frac{A_s}{22.13} \right)^n \left(\frac{\sin \beta}{0.0896} \right)^m \quad (25)$$

where $n = 0.4$ and $m = 1.3$. This equation was derived from unit stream power theory by Moore and Burch (1986b) and 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, $RKLS/E_a$, which can be mapped on the basis of the topographic attributes of slope and specific catchment area, and soil and climatic attributes via K , E_a , and R (Moore and Nieber, 1989).

Soil properties There have been numerous attempts to relate soil properties, soil erosion class, and to a lesser extent, productivity to landscape position in the pedology and soil survey literature (e.g. Walker *et al.*, 1968; Daniels *et al.*, 1985; Stone *et al.*, 1985; Kreznor *et al.*, 1989). For example, organic matter content and A horizon thickness, B horizon thickness and degree of development, soil mottling, pH and depth to carbonates, and water storage have all been correlated to landscape position (Kreznor *et al.*, 1989). Most of these studies use general mapping units such as head slopes, linear slopes, and footslopes to characterize soil position, rather than the specific topographic attributes described above. However, Walker *et al.* (1968) did attempt to correlate a range of depth characteristics, such as thickness of the A horizon, to slope, aspect, curvature, elevation, and flow path length (distance to hillslope summit), although there was much unexplained variance which he attributed to relic features such as the prior streams postulated by Butler (1950).

A 1989 USDA–Soil Conservation Service task force on ‘The Utility of Soil Landscape Units’ concluded that future soil surveys must include more information on the shape of the land surface and that these landform parameters should reflect the combined effects of both the hydrological and erosional processes taking place at different locations in the landscape, as proposed by Moore *et al.* (1986a). Digital elevation models were seen as the basic data for providing this information that would be delivered through geographic information systems.

Information systems and the display of topographic attributes and indices

Information systems and data bases for addressing resource and environmental problems must, by necessity, be capable of integrating spatial information to representative and environmentally diverse landscapes and must be capable of being interfaced with models and other analytical tools used for analysis. Geographic Information Systems (GISs) are an exciting primary tool for manipulating, storing, and accessing this data because they: integrate spatial and other information within a single system; offer a consistent framework for analysing the spatial variation across landscapes; allow geographic knowledge to be manipulated and displayed in a variety of forms including maps; and allow connections to be made between entities based on geographic proximity and characteristics that are vital to understanding and managing activities and resources (Unwin and Wilson, 1990).

In Australia and elsewhere there has been a rush by many organizations responsible for resource development, conservation, and the environment to develop GISs with a view that they will be a panacea for providing solutions to their assessment and management problems. However, in many cases ‘half digested’ secondary data are being input into them and data obtained at quite different scales are being used with no consideration of scale effects. Primary data that modulate landscape processes and biological responses, such as the primary topographic attributes described above, should be used as far as possible to construct the basic data sets that a GIS needs to access. As ideas and concepts change and evolve subjective data are often rendered useless. What is also often lacking within a GIS are knowledge-based (i.e., physically-based) approaches for analysing and interpreting data. Such approaches allow realistic answers to questions that might be asked, such as: ‘Where are high erosion hazard zones located in a landscape?’ The compound topographic indices described above or even the more complex hydrological, geomorphological, and biological models that are described later do provide this knowledge-based approach and can be imbedded within the data analysis subsystems that any GIS must have. Most GISs are based on a pixel or cellular structure so that the grid-based methods of terrain analysis described here can provide the primary geographic data for them and can be integrated within these analysis subsystems.

One of the reasons that GIS technology has been readily adopted is because it allows spatial information to be displayed in integrative ways that are readily comprehensible and visual. The spatial distribution of

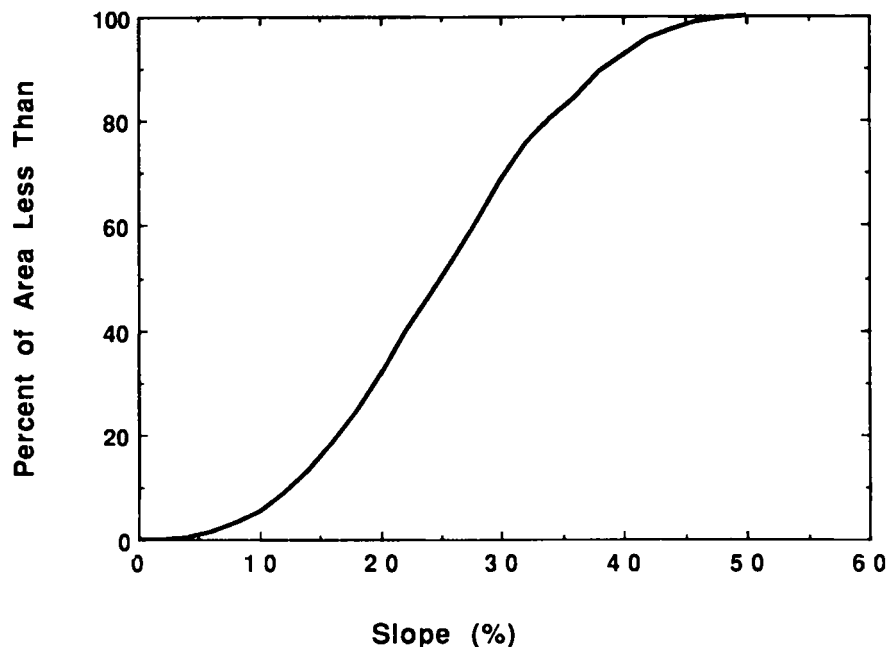


Figure 2. Areal weighted cumulative frequency distribution of slope, in per cent, of a 210 ha subcatchment of the Cottonwood Creek in Montana

topographic attributes and indices can be displayed as isoline or coloured planimetric maps, coloured isometric projections or numerically in the form of cumulative, areally weighted, frequency distributions. Examples of the distribution of slope classes on a 210 ha subcatchment of the north fork of Cottonwood Creek in southwestern Montana ($45^{\circ}32'N$, $111^{\circ}39'E$) are presented as a cumulative frequency distribution and as a grey-scale superimposed on an isometric projection of the 30 m grid-based DEM of the catchment in Figures 2 and 3, respectively. These types of presentation allow the reader to quickly get a 'feel' for the spatial variability of a wide variety of processes occurring in a catchment.

BASIN DELINEATION AND STREAM NETWORKS

Depending on the scale, drainage basins, catchments, or subcatchments are the fundamental unit for the management of land and water resources. Many distributed parameter hydrologic models, such as the Stanford Watershed Model-SWM (Crawford and Linsley, 1966) and the Finite Element Storm Hydrograph Model-FESHM (Ross *et al.*, 1979), use the partitioning of catchments into subcatchments or landunits, each having a single soil mapping unit and landuse type, as a means of crudely representing spatially varying catchment characteristics within the structures of the models. In FESHM these are called hydrological response units. The subdivision of the landscape into catchments and subcatchments is performed around the stream network and these areas are defined on the basis of the drainage network above the catchment outlet and above interior nodes or junctions where upstream channels join, respectively. 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). In the last ten years 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 geographic information systems 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).

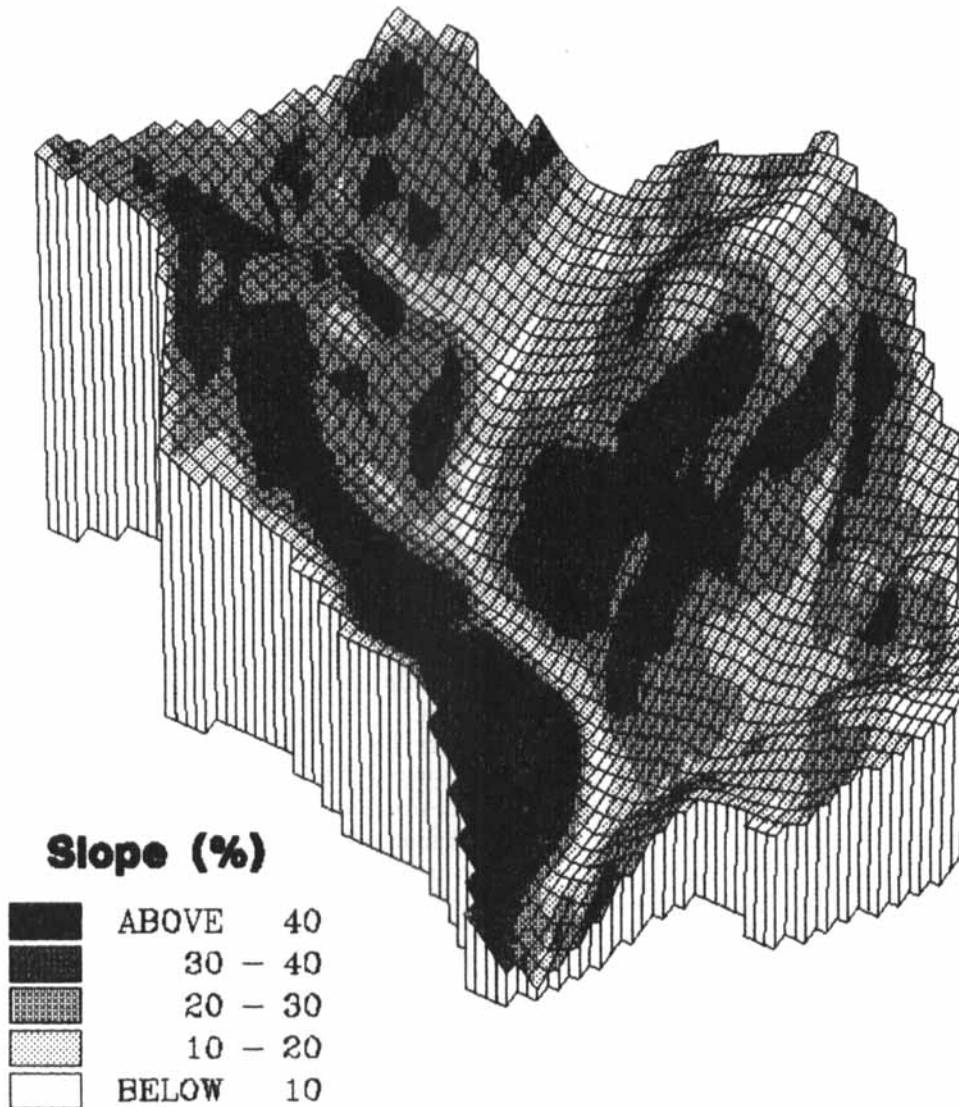


Figure 3. Spatial distribution of slope classes superimposed on an isometric projection of the 30 m DEM of a 210 ha subcatchment of the Cottonwood Creek in Montana

Mark (1988) identified several algorithms for determining total accumulated drainage at a point for application to grid-based DEMs. However, some are computationally impractical to implement from an operational and computational efficiency point of view. One of the earliest algorithms proposed, Collins' (1975) method, requires the elevation data to be sorted into ascending order and although a number of efficient sorting algorithms are now available, the method is not practical for large elevation matrices compared to the alternative techniques described below. 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 and a weighting matrix to iteratively determine a drainage accumulation matrix that represents the sum of all 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) and the drainage direction of each individual element is the flow direction from the element to one of its eight nearest neighbours 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 somewhat similar, but faster and more operationally viable method of defining stream channels and drainage basins has been developed by Jenson (1985) and Jenson and Domingue (1988) and is being widely used. Another variation of O'Callaghan and Mark's (1984) algorithm is described by Band (1989).

Another approach that uses Puecker and Douglas' (1975) algorithm for marking convex and concave upward points as ridge and stream points, respectively, is described by Band (1986). For each element the highest of the neighbouring eight elements is marked and after one sweep through the elevation matrix the unmarked elements identify the drainage courses. Similarly, identifying the lowest of the eight neighbouring elements defines ridge lines which 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 tends to break 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 need be specified (Tarboton *et al.*, 1989).

None of these methods accurately predict where stream channels initiate. Channel heads may advance and retreat depending on discharge cycles (Dietrich *et al.*, 1987) so their location is dynamic. Channel initiation is controlled by four processes: incision by Hortonian overland flow, incision by saturated overland flow, seepage erosion, and shallow landsliding (Dunne, 1980; Montgomery and Dietrich, 1989). Montgomery and Dietrich (1989) found that local valley slope at channel heads is inversely related to source area and source-basin length as well as specific catchment area at the channel head. In first-order catchments there is also an inverse relationship between the geometric properties of source-basin length and drainage density. On steep slopes channel head location is controlled by subsurface flow-induced instability; at abrupt channel heads on gentle slopes it is controlled by seepage erosion; and gradual channel heads are controlled by saturation overland flow (Montgomery and Dietrich, 1989). Wilson *et al.* (1989) also indicate that soil failure, and hence channel initiation, is more likely to occur in hollow areas with well coupled stormflow systems in both the bedrock and the overlying colluvium where high positive pore pressures exist. Channel initiation is a very important process in the evolution of landscapes but is poorly represented in many geomorphological models of landscape evolution. Some dynamic geomorphological models are described below.

SOME TOPOGRAPHICALLY-BASED HYDROLOGIC AND GEOMORPHOLOGIC MODELS

The period from about 1960 to 1975 can be viewed as the era of 'hydrologic modelling' in which many developments in the hydrological sciences occurred because of the growing awareness of the deficiencies of the old methods of analysis and the increasing availability of digital computers. This led to the use of numerical methods in hydrology and hydrologic modelling. The first version of the Stanford Watershed Model (SWM) was released in 1962 and a subsequent version, the Mark IV SWM (Crawford and Linsley, 1966), released in 1966, has probably become the most widely used hydrologic model over the last 25 years. Hydrologic models developed at this time were generally concerned with predicting water quantities, such as runoff volumes and discharges, at a catchment or subcatchment outlet. During this era there was a rapid development of mathematical descriptions of many individual hydrologic processes that were incorporated into many hydrologic models. Most hydrologic models were essentially lumped parameter models, or at best only crudely accounted for spatially variable processes and catchment characteristics.

The decade between about 1975 and 1985 can be viewed as the 'transport modelling era' during which time environmental problems became a top priority, including all forms of pollution. During this era transport models were seen as the best way of predicting water pollution. Many of the hydrologic models developed in the late 1960s and early 1970s were used as the flow components in these transport models, often with little modification. These models poorly account for the effects of topography on catchment

hydrology where flow convergence and divergence has a major impact on observed and predicted flow depths and velocities and are generally incapable of providing realistic spatially distributed estimates of these hydrologic characteristics. Spatially variable flow characteristics such as flow depth and velocity are the driving mechanisms for sediment and nutrient transport in landscapes and unless they can be predicted reasonably well water quality modelling cannot be successful and the results from these models may be inappropriate for making land-use planning and management decisions.

The last five years has seen an increasing emphasis on the need to predict spatially variable hydrologic processes at quite fine resolutions. We are now in the era of 'spatial modelling'. Digital elevation data and remotely sensed catchment characteristics such as vegetation cover are now viewed as essential data inputs to the new generation of hydrologic and water quality models. Furthermore, we are beginning to see major changes in the basic structures of hydrologic models that allow them to more readily use this spatial input data and predict spatially distributed landscape processes. This section identifies and discusses a series of hydrologic and geomorphological models that have been built around grid-, TIN- and contour-based DEM networks.

Models using grid-based structures

Grid or cellular approaches to subdividing the landscape provide the most common structures for dynamic, process-based hydrologic models. Some examples of models based on this structure include the Areal Nonpoint Source Watershed Environment Response Simulation model-ANSWERS (Beasley and Huggins, 1982), the AGricultural Non-Point Source pollution model-AGNPS (Young *et al.*, 1989) and the very detailed Systeme Hydrologique Europeen 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. In ANSWERS, a weighting factor is derived by partitioning a cell on the basis of the line of maximum slope. A problem with these approaches is that the flow paths are not necessarily down the line 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, ELEVA, to generate slope steepness and aspect from grid-based DEMs for input into the model. Panuska *et al.*, (1990) interfaced a grid-based terrain analysis method and grid-based DEMs with the AGNPS model to generate the terrain-based model parameters which represent about one-third of the input parameters for the model. 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 structures.

The Geomorphic Instantaneous Unit Hydrograph-GIUH, first proposed by Rodriguez-Iturbe and Valdez (1979) and adapted by Gupta *et al.* (1980, 1986), Rosso (1984) and others, is becoming one of the most commonly used methods of determining the rainfall-runoff response of catchments. The method assumes runoff is generated uniformly throughout a catchment, but has more recently been adapted to include both Hortonian (Diaz-Granados *et al.*, 1984; Gupta *et al.*, 1986, and others) and partial area (Sivapalan and Wood, 1990) runoff generation. The GIUH parameterizes the Instantaneous Unit Hydrograph-IUH, which relates catchment response to rainfall excess, via the characteristics of the channel network expressed by Horton's (1945) laws through the Strahler (1952) ordering scheme of channel networks. On the basis of the assumptions of linearity, time invariance and a lumped system, the catchment discharge, $Q(t)$, can be expressed in terms of the rainfall excess rate, $i(t)$, and the IUH, $u(t)$, as

$$Q(t) = \int_0^t u(t - \tau) i(\tau) d\tau \quad (26)$$

Following from Rosso (1984), a useful analytical form of the IUH is the two-parameter gamma probability density function:

$$u(t) = [k\Gamma(\alpha)]^{-1} (t/k)^{\alpha-1} \exp(-t/k) \quad (27)$$

where $\Gamma(\cdot)$ is the gamma function and α and k are shape and scale parameters, respectively, that can be estimated empirically from the geomorphic structure of the catchment where:

$$\alpha = 3.29(R_B/R_A)^{0.78}R_L^{0.07} \text{ and } k = 0.7[R_A/(R_BR_L)]^{0.48}v^{-1}L \quad (28)$$

and v is the mean streamflow velocity, L is the mean length of higher order streams and R_A , R_B and R_L are Horton's area, bifurcation, and length ratios, respectively. The product of the peak discharge and time to peak of the GIUH, U^* , can be shown to be a function of catchment geomorphology only, such that:

$$U^* = 0.58(R_B/R_A)^{0.55}R_L^{0.05} \quad (29)$$

In Equations 29 and 30 the three geomorphic ratios are defined as:

$$R_B = N_i/N_{i+1} \quad R_L = L_i/L_{i-1} \quad R_A = A_i/A_{i-1} \quad (30)$$

where N_i , L_i , and A_i are the number of streams, the mean length of the streams, and the mean basin area, respectively, of order i (Horton, 1945). These quantities can be easily determined from the structure of the channel network determined from a DEM of the catchment using the methods briefly described in the previous section.

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 at the core of the model is the relationship:

$$S_i = m\xi - m\ln[A_s/(T_i \tan \beta)]_i + S \quad (31)$$

where S_i is the soil storage deficit at point i , m is a recession parameter, ξ is the mean value of the $\ln[A_s/(T_i \tan \beta)]$ distribution for the catchment (the flow path partitioning index), T is the transmissivity, and S is the mean value of S_i for the entire catchment. This equation permits the prediction of the soil water deficit pattern and the saturated source area (when $S_i \leq 0$) 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). Applications and developments of the model are described by Beven and Wood (1983), Beven *et al.* (1984), Hornberger *et al.* (1985), Kirkby (1986), and Beven (1986). Sivapalan *et al.* (1987) used the model to examine hydrologic similarity and developed a series of dimensionless similarity parameters, one of which included a scaled soil-topographic parameter which was recently used to account for partial area runoff with the GIUH (Sivapalan and Wood, 1990). 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 modelled 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.*, 1989):

$$\frac{\partial z(x, y, t)}{\partial t} = \text{sources} - \text{sinks} + \text{spatial coupling} \quad (32)$$

where $z(x, y, t)$ represents the land surface which 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 which is usually expressed as a function of slope, β , and discharge, Q , which 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; and Willgoose *et al.*, 1989). The evolution of both one-dimensional hillslopes (e.g. Kirkby, 1971; Smith and Bretherton, 1972; Ahnert, 1976) and two-dimensional landscapes (Smith and Bretherton, 1972; Ahnert, 1976, 1987; and Willgoose *et al.*, 1989, 1990) 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 (1976, 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. However, Willgoose *et al.* (1989, 1990) recently developed a channel network and catchment evolution model that does account for these interactions. All the two-dimensional landscape evolution models developed to date are driven by grid-based DEMs.

Models using TIN-based structures

TINs have also been used for dynamic hydrologic modelling (e.g. Silfer *et al.*, 1987; Vieux *et al.*, 1988; Maidment *et al.*, 1989; Goodrich and Woolhiser, 1989; Palacios and Cuevas, 1989). Vieux *et al.* (1988) minimized the problems of using TINs for dynamic modelling 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 modelling 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). Goodrich and Woolhiser (1989) divided each facet into 15 subelements and applied a two-dimensional finite element solution of the kinematic equations. Maidment *et al.* (1989) solved the two-dimensional St. Venant equations for flow on the facets.

Models using contour-based structures

As noted earlier, contour-based methods of partitioning catchments provide a natural way of structuring hydrologic and water quality models. This method was first proposed by Onstad and Brakensiek (1968), who termed it the stream path analogy. With this form of partitioning only one-dimensional flow occurs within each element, allowing water movement in a catchment to be represented by a series of coupled one-dimensional equations. The equations can be solved using a one-dimensional finite-differencing scheme.

This method has been used by Kozak (1968) and Onstad (1973) to examine the distributed runoff behaviour 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. Recently, Tisdale *et al.* (1986) used this technique together with an implicit one-dimensional 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 two-dimensional finite element modelling methodologies, because it solves simpler model equations, while retaining an equivalent physical realism. Moore and Grayson (1990), Moore *et al.* (1990), and Grayson (1990) present two simple process-oriented hydrologic 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 described earlier.

Adopting an approach similar to TOPMODEL, Moore *et al.* (1986b) used O'Loughlin's (1986) steady-state, contour-based method of computing the $\ln(A_s/\tan \beta)$ versus per cent saturated area relationship (and in the process fitted the mean catchment transmissivity) to simulate the saturated source area expansion and contraction as a function of catchment wetness. This relationship, together with the assumption of successive steady-states in the time domain, provided the basic structure of a simple lumped-parameter model of

forested catchment hydrologic response. In the model runoff was assumed to occur via subsurface flow and saturation overland flow.

FRactal Dimension of Landscapes

The idea that different processes dominate hydrologic and geomorphic response at different scales is implicit in the literature describing the modelling of these systems. In the preceding sections of this paper we have attempted to show how these processes relate to land form and the characteristics of the stream network. The last decade has seen an explosion in the application of fractal theory to the characterization of topographic surfaces (Goodchild, 1980; Mark and Aronson, 1984; Clarke, 1986; Culling and Datko, 1987; Roy *et al.*, 1987; Huang and Turcotte, 1989 and others) and river networks (Tarboton *et al.*, 1988; Hjelmfelt, 1988; La Barbera and Rosso, 1989 and others). Natural topographic surfaces show remarkable similarity to synthetic fractal surfaces generated by fractional Brownian processes with fractal dimensions, D , ranging from 2.1 to 2.3 (Mandelbrot, 1975, 1982; Goodchild, 1982). Most landscapes can only be considered to be fractal in a statistical sense. The application of fractal theory in hydrology, geomorphology, and biology is in its infancy and there is great potential for major advances in this area of research in the coming years.

The topological dimension, D_t , familiar from Euclidean geometry is 1.0 for a curve and 2.0 for a surface, whereas the corresponding fractal or Hausdorff-Besicovitch dimension, D , can range from 1.0-2.0 and 2.0-3.0, respectively. Fractals embody the concept of 'space-filling'. River networks and landscapes, which can be visualized as a series of branching lines and folded surfaces, respectively, are said to be 'space-filling' if their fractal dimensions are 2 and 3, respectively. Fractal dimensions have been defined by spectral analysis using Fourier transforms (e.g. Frederiksen, 1981; Voss, 1985; Huang and Turcotte, 1989) and by variograms (e.g. Goodchild, 1980; Mark and Aronson, 1984; Roy *et al.*, 1987) which can be written as

$$E[(z_i - z_{i+d})^2] = d^{2H} \quad (33)$$

where d is the distance between points i and $i + d$, z is the observed value at the two points (e.g. the elevation of the land surface), and Culling and Datko (1987) called H the Hurst scaling parameter which ranges from 0.0-1.0. The fractal dimension is then

$$D = (D_t + 1) - H \quad (34)$$

Goodchild (1980) presents examples of simulated surfaces with fractal dimensions ranging from 2.1 (smooth surfaces) to 2.7 (rough surfaces).

In natural landscapes D appears to be constant for only limited areas over limited ranges of scales (Goodchild, 1980). Mark and Aronson (1984) computed the surface variograms for 17 7.5 minute U.S.G.S. DEMs from Pennsylvania, Oregon, and Colorado in the United States and found at least two different values of D . At small scales, for distances between 0.4 and 1.8 km, D ranged from < 2-2.48; at intermediate scales, for distances up to 4-7 km, D ranged from 2.39-2.8; while in some cases at larger scales the surface variograms displayed periodicities. They suggest that the breaks represent characteristic horizontal scales at which different surface processes operate. Similar results were obtained by Culling and Datko (1987) who suggested that D ranges from 2.0 to 2.3 at the hillslope scale and from 2.4 to 2.6 at scales associated with the drainage network. Huang and Turcotte (1989) found the mean fractal dimension of the state of Arizona to be 2.09. Roy *et al.* (1987) calculated fractal dimensions of fluvial, summit, and glacial areas in eastern North America of 2.13, 2.10, and 2.21, respectively, but found that the values of D varied spatially within the DEM and with elevation. Roy *et al.* also attribute the higher fractal dimensions obtained by Mark and Aronson to the sampling plan used which creates biases towards the longer scales.

If a surface is self-similar then the fractal dimensions of the surface and of profiles along the surface should differ by unity. However, Huang and Turcotte (1989), using spectral analysis techniques, found the mean two-dimensional fractal dimension to be 2.09, and the one-dimensional fractal dimension to be 1.52 ($H = 0.48$). The process is Brownian for $H = 0.5$.

Both Tarboton *et al.* (1988) and La Barbera and Rosso (1989) have examined the fractal dimensions of river networks and compared them with those derived from Horton's (1945) laws. The fractal dimension of individual rivers range from 1.1–1.2 and that of the network as a whole is about 2.0, implying that the network is space filling which is 'consistent with classical fluvial geomorphology and the popular random topology model' (Tarboton *et al.*, 1988). Hjelmfelt (1988) and La Barbera and Rosso (1989) demonstrated that if channel networks are fractal, then a length or drainage density measurement, L_1 , at scale d_1 is related to that (L_2) measured at scale d_2 by:

$$L_2/L_1 = (d_2/d_1)^{1-D} \quad (35)$$

They refer to Pilgrim's (1986) work on design flood procedures in Australia which incorporates a series of parameters that are related to the topology of the river network and hence dependent on scale. Equation 35 can be equated to the empirical map scale adjustment relationship proposed by McDermott and Pilgrim (1982), producing a value of D of 1.09, which is consistent with the fractal dimension of an individual stream (Hjelmfelt, 1988).

SUMMARY AND CONCLUSIONS

The relative magnitudes of many hydrological, geomorphological, and biological processes operating in natural landscapes are sensitive to topographic position. Indices of these processes can be developed as functions of distributed soil, vegetation, and, particularly, topographic attributes. Computerized methods of terrain analysis for use on small inexpensive personal computers have the capability of quickly and efficiently deriving these topographic attributes. This paper attempts to introduce some of the basic concepts involved in terrain analysis using digital elevation data and demonstrate the usefulness of the technique for hydrological, geomorphological, and biological applications. These techniques have the potential for widespread application to resource evaluation, planning, and management. Finally, these methods provide the opportunity for realistically representing the three-dimensional nature of natural landscapes in hydrologic and geomorphologic modelling under the constraints of maintaining physical rigour, simplifying the governing equations that must be solved, and reducing the computational requirements.

This review has been divided into five sections. The first section discusses the general characteristics of digital elevation models and describes the three major methods of structuring a DEM (grid-, TIN- and contour-based methods), the sources of elevation data in Australia and the United States, how DEMs are commonly produced, and gives some indication of their quality. The section concludes with a discussion of some simple techniques for analysing elevation data for the estimation of topographic attributes such as slope and aspect and gives examples of methods that can be applied to each of the three DEM structures.

In the second section we describe a range of topographic attributes and indices, their underlying assumptions and limitations and the hydrological, geomorphological, and biological processes they attempt to characterize. We also outline their physical basis, but do not attempt to give detailed derivations. The use of grid-based DEMs for this form of analysis is recommended because grid-based DEMs are the most commonly available form of digital elevation data, the methods of analysis are computationally efficient and simple and this structure is compatible with remotely sensing techniques and geographic information systems.

The third section briefly describes methods of delineating drainage basins and stream networks using DEMs, which is necessary for many land and water management and planning activities. The fourth section describes a number of hydrologic and geomorphic models that are structured around the form of the DEM network. Grid-based hydrologic and geomorphic models are the most common for the reasons identified in the previous paragraph. However, contour-based models offer significant computational advantages in that they allow the complex two- and three-dimensional flow and transport equations to be reduced to a series of coupled one-dimensional equations. A number of TIN-based models have also been developed in recent years. The development of these models is still in its infancy. There is a real need for a comparison using common data sets of models that use these three structures. In particular, there is a need to evaluate the

ability of these models to realistically predict spatially distributed flow processes—especially the ability to predict flow depths and velocities. Unfortunately, very little spatial data of this type exists.

The fifth and final section briefly addresses the question of scale and introduces some very recent work on the application of fractal theory for characterizing land form and stream networks. To date there has been little consideration of the effects of scale on the computed values of the topographic attributes and indices described in this paper. For many applications they need to be computed at the scale appropriate for particular processes occurring in the landscape. If these scale effects are not considered, then the computed attributes may be meaningless or the processes of interest may be masked so that the intended use of these attributes may not be realized. Future research needs to determine the appropriate scale for analysing certain types of hydrologic, climatic, biological, and land degradation problems in the context of their correlation with terrain attributes.

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