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Spatial hydrography and landforms

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The structure and function of watersheds and landform systems has been incorporated in a range of GIS applications over the past two decades. Initial work focused on methods of automating the extraction of the geomorphic structure of watersheds from a combination of digital terrain data and satellite imagery. More recent work has continued this activity, but has increasingly concentrated on methods of representation within GIS data models that will support spatial analysis of watershed function as well as form. Of necessity, the associated surface properties of soil and vegetation cover have been included in these data models, and new approaches to inferring and representing the covariance of terrain, soil, and vegetation over a range of scales are under construction. The present state-of-the-art includes object data models that incorporate spatial representations of watersheds along with embedded simulation models to handle queries about the static and dynamic properties of watersheds.

1 INTRODUCTION

This chapter reviews the methods that have been developed to represent and process spatial information on watershed geomorphology. First, the pertinent aspects of surface watersheds are outlined from the perspectives of hydrology and geomorphology, including both the topography and the associated patterns of soil cover and vegetation. The algorithmic bases of methods designed to extract and represent watershed-flow path structure using digital terrain models are reviewed. The discussion of topographic skeletonisation (extraction of channel and ridge networks) is then extended to include recovery and representation of nested sub-catchments and hillslopes, and the subdivision of hillslope systems into discrete zones. More recent work is reviewed that seeks to identify a greater range of watershed landforms in an object format, along with formal schema for their organisation. The association of patterns of soils, vegetation, and landforms through watershed systems is discussed and representation within GIS is appraised. Finally, some recent work has been focused on analysis and representation of watershed form over a range of spatial extents, from small catchments to continental-scale drainage basins. The chapter includes a discussion of the applicability of different approaches, and the form of information that can be extracted and represented, as the focus shifts along this scale range.

Two opposing conceptual models of watersheds have been developed: a model of continuous flow paths and continuous spatial variation of surface attributes; and a model of an exhaustive and mutually exclusive partition of surface area into different discrete land facets. Elements of both continuous and discrete models are often retained within various hydrologic and hydrographic applications. The interaction of these concepts with GIS data models can produce definable bias and inconsistency in spatial representation and analysis. A hybrid model has emerged recently which includes a hierarchical system of embedded sub-catchments, hillslopes, and (potentially) component hillslope positions within which the system of continuous flow paths is defined. Estimation of associated patterns of soil and vegetation by quantification and representation of typical catenary sequences can also be incorporated into a hillslope-based watershed representation and is an interesting current research direction in GIS and spatial environmental modelling. The discussion is extended beyond the spatial domain of individual watersheds to cover methods used to classify and represent a larger range of landforms and systems of landforms. This work builds from the concept of landscape systems or soil-landscapes and embeds knowledge on structure and composition of the surface that has in general not been incorporated into GIS data models in the past.

There have been ample reviews of the techniques developed over the past two decades for channel and ridge network extraction from terrain and image data (e.g. Band 1993; Tribe 1992) and fairly standard methods have been incorporated in commonly-used GIS packages. Discussion is limited here to describing the basic approaches available, the underlying assumptions of the data models, and their shortcomings in different situations. There is a voluminous literature dealing with the extraction of stream networks from digital elevation and remote sensing data that is spread over a range of journals and conference proceedings from different disciplines. A number of these contributions have been motivated by the need to generate watershed structural data for hydrologic or geomorphic research. In addition, stream networks have been very popular systems for the development of machine-vision algorithms. This is partly because of the availability of raster elevation images and partly because of the existence of formal graph models of channel-network patterns in terms of both topology and geometry. This has provided a rich basis for the development and testing of pattern recognition and image analysis techniques. Terrain parameters such as slope, aspect, curvature, and wetness indices are not addressed extensively here (but see Hutchinson and Gallant, Chapter 9).

2 HYDROGRAPHIC NETWORKS AND WATERSHED STRUCTURE

Watersheds can be described as hierarchical systems connected in the direction of flow. Hydrologic and geomorphic stream-, valley- and ridge-networks can be considered to be a topographic skeleton of fluvially eroded landscapes. A rich body of theory has been developed to describe and explain the form, organisation, and function of watersheds based on the topology and geometry of these networks (summarised by Abrahams 1984). More recent work has concentrated on the scaling behaviour of the hierarchical structure of the topographic form of channel networks and associated drainage areas (e.g. Ijjasz-Vasquez et al 1992). A formal model of watershed form incorporates stream networks as tree graphs with drainage sources and junctions defining the tree nodes, and channel links (unbroken stretches of stream channel between the nodes) defining the edge set as introduced by Shreve (1966). The system of drainage partitions flow-paths between each channel link and forms a complementary graph of divide edges and nodes that intersect the channel system at channel junctions. Figure 1 shows an example of the combined graph structures implemented as a topographic skeleton in a portion of the watershed of Onion Creek, a 25 km^2 headwater catchment in the Sierra Nevada of California. The stream network can be extended to define an exhaustive surface partition by incorporating the set of hillslopes or drainage areas draining into each channel link as the leaves of the tree. This produces a spatially exhaustive and mutually exclusive mapping of channel links to drainage areas, and to left- and right-hand hillslopes (relative to the flow direction), facilitating graph functions to aggregate or distribute surface information through the watershed. The computation and labelling of various stream network and drainage area indices are straightforward recursive graph functions. An alternative partitioning of the surface can be gained with Strahler stream coding (Strahler 1957), in which the labelling of a stream reach does not change until a stream of equal (or higher) order is joined. This does not form a mutually exclusive mapping of all drainage areas draining into uniformly labelled stream reaches, as ordered stream segments form nested sub-catchments.

In this model, it is important to note that drainage divides are not necessarily ridges; they may have no topographic expression other than being the line of steepest descent on a hillslope which terminates at a drainage junction. To define a consistent surface topology, the existence of a channel branch requires the existence of a drainage divide between each set of uniquely labelled tributaries, or a tributary and a mainstream. Warntz and Woldenberg (1967) explored

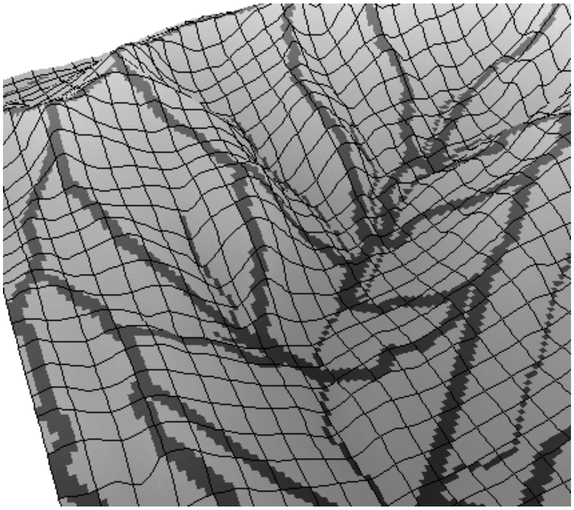

Fig 1. Perspective view of the components of a simple watershed model consisting of nested channel links, divide segments, link drainage areas, and hillslopes. Channel links are thinned, one-pixel-wide chains and divides are un-thinned segments in this image.

the implications of attempting to formalise the complementary nature of divides and channel lines, and Frank et al (1986) repeated the analysis nearly 20 years later. If the drainage lines and divide lines are considered lines of convergent and divergent flow, respectively, and if the drainage lines are extended to the divides at passes, then any ridge junction requires a convergent line, just as any stream junction requires an intermediary drainage divide. Logically, this leads to an infinite sequence of complementary channel and divide lines, unless a stopping criterion is given for the extension of stream sources. However, the conceptual model of drainage basin form that has developed over the past few decades has always incorporated finite extents and terminations of stream sources (Maxwell 1960; Montgomery and Dietrich 1988), negating the need for an infinite hierarchy of ridges and streams. In addition, as mentioned above, drainage divides are not necessarily ridges, such that the assumption of divergent flow in the neighbourhood of a divide is not universally applicable. Defining the upslope terminations of stream channels and valleys is a difficult problem in the field, partially due to the vagueness of landform definition and the continuous variation of surface properties, and a difficult problem in GIS as discussed below (see also Fisher, Chapter 13).

3 HYDROGRAPHIC NETWORK EXTRACTION AND REPRESENTATION

The mass production of digital elevation data has spurred the development of a number of approaches to identifying and organising watershed and other landform information. This section traces the development of the different techniques without delving into the details, which have been summarised elsewhere (Band 1993; Mark 1988; Tribe 1992). The set of image-processing techniques developed over the past three decades to extract watershed-network patterns from digital elevation models (DEMs) and remote-sensing imagery includes:

- classification and pattern-matching algorithms which search for local topographic or image evidence of stream or ridge features in parallel and build the network bottom up;
- global sequential processors that construct space-filling flow patterns over topographic surfaces and generalise the convergent flow system to the connected set of drainage lines;
- knowledge-based techniques that incorporate rules regarding expected drainage-network and landform geometry and topology to infer likely structures from incomplete or noisy data.

The techniques have progressed from simple image-processing algorithms designed to detect the presence of surface-specific points or lines (peaks, pits, valley bottoms, and ridges) to more sophisticated systems that extract the full structure and flow network of a watershed. Object models of watersheds have been implemented recently in which the landforms comprising the watershed are formally defined and instantiated with full object hierarchy and inter-object relations (see Worboys, Chapter 26). Methods to automate the construction of these high-level data models from normally-available DEM and remote-sensing imagery have also been provided.

Topological inconsistencies can exist between the conceptual data model and the implementation in different GIS data structures, which can cascade as a bias into a set of geomorphic and hydrologic applications (see Heuvelink, Chapter 14). The conceptual graph model described above uses a set of surface points, lines, and areas as a well-defined set of discrete areal entities that form an exhaustive partition and connection of the surface. The nodes can be extended to include the set of surface-critical points (peaks, pits, saddles) and stream-channel nodes (drainage junctions and sources) defining the set of ridge- or drainage-line segments, which in turn define the set of discrete drainage areas. In keeping with the graph theoretical model, the set of nodes are 0-dimensional and the edges (stream and divide links) are 1-dimensional. This topology is consistent with a vector or Triangulated Irregular Network (TIN) model of a watershed if a sequence of triangle edges can be defined as the channel and divide lines (e.g. Guercio and Soccodato 1996; Jones et al 1990). However, in raster models stream junctions are grid cells with finite areas and perimeters set by the cell resolution. The fixed dimensions of raster cells produce error in the representation of watershed form, particularly in the area immediately around the stream channel. Computations of surface area of wetted channel, or adjacent riparian areas, both of which are critical to the hydrologic behaviour of the catchment, are biased if standard raster algorithms are used. In Figure 1 the stream channels are represented by a one-pixel-wide chain of grid cells. The cells are 30m resolution, while the channels do not exceed about five metres in this watershed and are incised into the valley bottoms in many areas. Commonly, neither the surface area of the channels nor the topography immediately around the channels can be well represented. Run-off dynamics are sensitive to terrain characteristics at this scale, and they are well beyond the resolution of most DEMs. It is probable that properties of the riparian zone, including channel slope, curvature, and width may need to be determined independently and stored as attribute values rather than being computed from raster methods.

Use of a vector or TIN representation of this area may improve geometrical fidelity. Priestal and Downs (1996) have utilised a combination of raster and vector techniques to minimise the problems of raster representation of stream lines, but in general the critical length scales of the near stream environment are so much less than the rest of the watershed that it is often questionable whether topographic information computed for this region by standard GIS algorithms is sufficiently accurate and unbiased. Perkins et al (1996) have resorted to using an 'imposed stream' algorithm in their DEM-based hydrological model in which a vector representation of the stream is registered to the DEM, but this requires adjustment of the stream to maintain its position in the axis of the valley. Stream-channel properties such as width and cross-sectional area are then prescribed rather than computed from the raster data.

While grid-based methods have obvious disadvantages in comparison to more flexible representations for landform representation, including TIN- and contour-based methods (e.g. O'Loughlin 1990; Weibel and Brandli 1995), they are by far the most commonly used in GIS hydrology- and geomorphology-related projects. This is largely dictated by the availability of raster elevation data, the relative compatibility with remote sensing data, and a history of geomorphic and hydrologic models based on finite difference grids.

3.1 Local parallel processors

The first set of approaches to recognise and extract drainage networks from grid DEMs sought to nominate or classify each pixel into a set of discrete surface forms. Greysukh (1967) assigned grid cells to hill, depression, slope, ridge, ravine, or saddle classes based on the pattern of elevations in the surrounding 3×3 kernel. Templates were designed for pattern recognition of each cell. Peucker and Douglas (1975) tested a series of different local classification techniques based on local templates and found most techniques performed poorly, especially in the presence of terrain data noise. A method that was found to be reasonably efficient was to classify grid cells as concave or convex in order to produce potential stream and ridge cells, without distinguishing the richer set of surface forms. In both of these approaches fully connected drainage or divide networks were not produced because of noise or resolution limitations operating on the local processors. In addition, the local classifications of grid cells were not extended to identify connected landform features.

Toriwaki and Fukumura (1978) began with a similar approach, classifying all grid cells into specific surface features on the basis of local terrain patterns, but extended the surface set to distinguish 'top flats' (plateaux) and 'bottom flats' by progressively searching larger local neighbourhoods until the relative position of the flat could be determined. They also went on to form connected-component regions of the discrete landforms, including both linear and areal elements, using a series of post-classification processes which made use of simple adjacency relations between landforms (e.g. slope and stream). One of these methods involved fusing and then thinning streams and ridges into one-pixel-wide chains, while performing complementary operations on adjacent hillslopes. The result is an exhaustive partition of the surface into discrete landforms which could then be associated according to spatial adjacency.

3.2 Global sequential operators

Band (1986b), Douglas (1986), and Smith et al (1990) started with locally nominated stream and ridge pixels that formed incomplete networks (independently classified grid cells). A second step was used to form fully-connected and fully-labelled stream network structures. Band (1986a) did this by labelling segment ends of thinned linear segments as ‘upslope’ or ‘downslope’ and then extending the downslope nodes to drain through the DEM by steepest descent until another stream pixel was encountered. Starting at the root of the completed channel network, a recursive algorithm was used to climb and label each channel link according to the topologic code proposed by Shreve (1966, 1967). An extension of the fully-encoded stream network to the set of divides delimiting the drainage area of each link was then gained by performing a grey-weighted thinning procedure from each link upslope to the ridges, with the restriction that divides were connected to all stream junctions. This formed an exhaustive partition of the surface into the drainage areas associated with each channel link in a one-to-one mapping that could reference both the links and drainage areas by position in the drainage system. Smith et al (1990) extended the method of linking thinned channel segments into a fully-connected network to handle conditions of low signal-to-noise DEMs by incorporating variable search windows in a restricted direction forward of an active downstream node.

Marks et al (1984) developed a method of recursively labelling a contributing watershed area by progressively climbing a DEM from a designated outlet to all pixels defined as connected by surface drainage based on local aspect. An important feature is the choice of a minimum local slope below which the pixel is considered flat (because of local noise) and connected to all adjacent pixels. The technique included a simple way of identifying and eliminating pits (grid cells that are local minima and therefore do not drain into an adjacent cell) by identifying a pour point and raising the elevation of all pit pixels to that level. O’Callaghan and Mark (1984) devised an iterative procedure of locating and starting at local maxima and progressing downslope, accumulating the number of pixels upslope which are stored as the contributing drainage area in each cell (Figure 2). The result is a space-filling tree graph in which each pixel can be a graph node (branch point). The tree must be pruned to a lower level that will define finite stream segments, and this can be done in a number of ways. The most common method is to choose a threshold to the drainage area to set the limit of the stream channel system (Figure 3), adopting a version of Schumm’s (1956) constant of channel maintenance.

Band (1986a) produced a recursive version of O’Callaghan and Mark’s (1984) method of drainage area accumulation and added a labelling method based on the recursive channel network traverse (Band 1986a) that was extended to include right and left hillslopes draining into each stream link (Band 1989). The basic approach of iterative downslope accumulation or recursive upslope accumulation of drainage area and catchment labelling has been duplicated in various forms by Jenson and Domingue (1988), Martz and Jong (1988), Martz and Garbrecht (1992), Tarboton et al (1988), and a number of others. Jenson and Domingue (1988) popularised the technique by

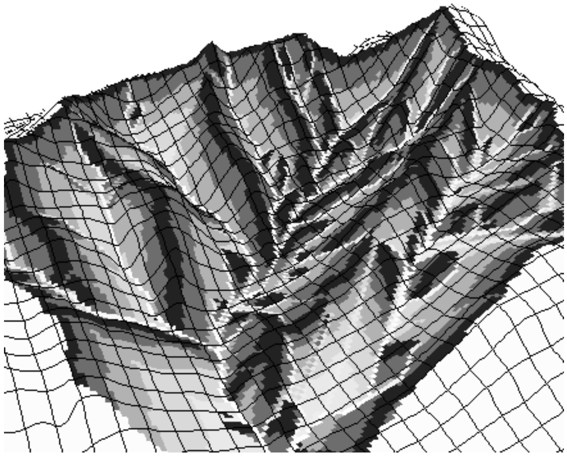

Fig 2. Accumulated drainage area image for a portion of the Onion Creek watershed in California. Each pixel is marked with the number of upslope pixels draining through it using a discrete routing algorithm. Grey scale is stretched for display.

writing and distributing code for personal computer (PC) use. A number of commonly-used GIS currently incorporate similar routines. A novel variant on this approach was developed by Ehlschlaeger (1990) for the Geographic Resource Analysis Support System (GRASS). In this approach a DEM is sorted by increasing elevation and a recursive algorithm branches to all pixels down the sort list (at higher elevation) that are adjacent to the root pixel. This produces a full network of connections from all higher to lower pixels which is then pruned to the drainage pattern using a network optimisation algorithm while accumulating the upslope drainage area (number of pixels). A similar drainage area threshold is used to define a finite stream channel network, along with labelled, associated hillslopes. A similar network optimisation method has been used by Niedda (1996) who points out that the minimisation of cumulative network flow cost is consistent with geomorphic theory of fluvial systems in terms of the dissipation of potential energy.

In the network optimisation all pixels in the DEM are nodes of the graph. The set of edge connections between the nodes must be chosen to minimise $\sum_{ij} c_{ij} x_{ij}$, where the unit cost of a connection (c_{ij}) is proportional to a function of the elevation drop between two adjacent nodes (i and j) and x_{ij} is the quantity of flow between i and j. The x_{ij} are conserved through the accumulation of flow, and in general a constant increment to flow of one is added at each node. This simulates a unit pulse of run-off being added to the full surface. Note that this method allows movement through flat areas or even uphill subject to the global minimisation. The penalty for uphill connections can be set very high, although as shown below this could have important feedback to the full network structure. In many cases the minimum cost algorithm defaults to straight-line segments as minimum-distance solutions if there are not large differences in the gradients along different paths (Plate 34). This solution is not visually intuitive compared to the output of some of the local discrete-drainage-direction algorithms. However, given the data quality of many DEMs this may be a reasonable estimate of flow-paths, and the more irregular nature of the other approaches may simply result from DEM noise.

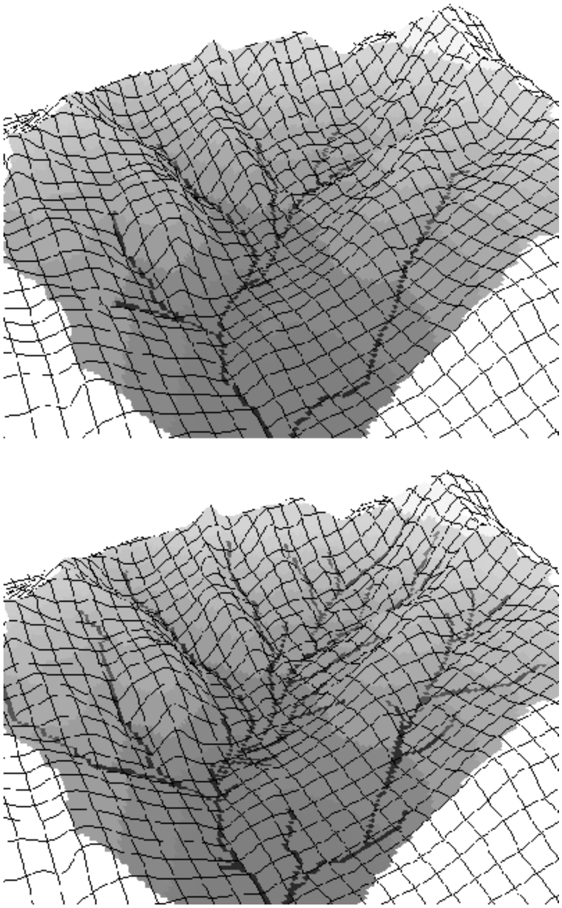

Fig 3. Different extents of the Onion Creek channel network produced by choosing a range of threshold drainage areas to define stream sources.

The method of using a prescribed threshold drainage area to set the stream sources has been criticised as arbitrary, and not reflective of the spatial heterogeneity of the terrain or extent of stream dissection. Tribe (1991, 1992) focused on identifying and extracting valley heads for each valley segment on the basis of local terrain morphology. This approach recognised that what is extracted is actually valley forms as opposed to channel segments, which are probably below the resolution of the DEM. Incorporation of such evidence would improve fluvial network extraction as it is recognised that a spatially-constant drainage area threshold may not be appropriate across a heterogeneous landscape. Evidence of valley head morphology on common high-resolution DEMs (10–100m) appears to be noise sensitive such that the techniques require further development or combination with drainage area information or other ancillary data. Montgomery and Dietrich (1988) proposed a threshold of slope-to-drainage-area gradients for a

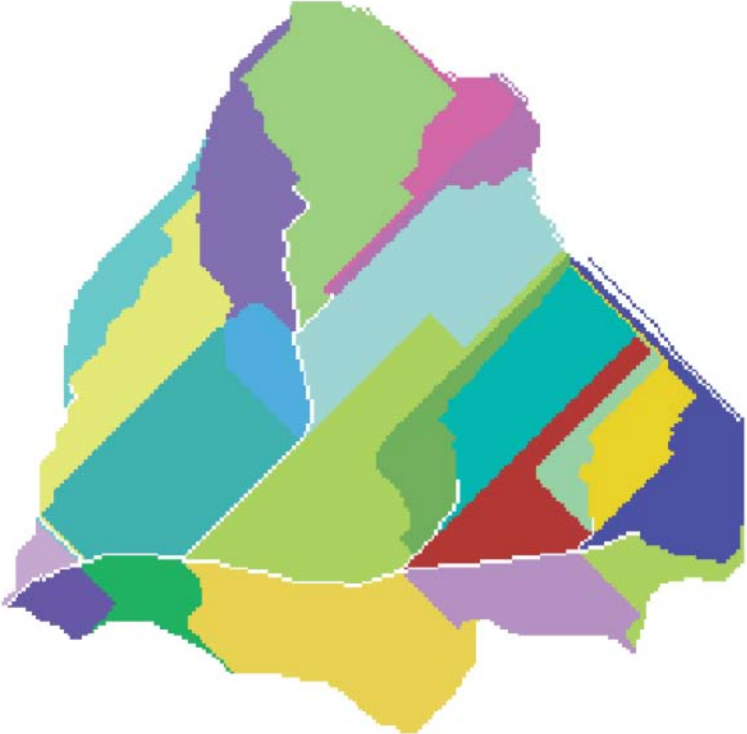

Plate 34

Watershed drainage network and drainage area partition produced by a graph optimisation algorithm in the GRASS algorithm *r.watershed*. Note the bias towards straight-line drainage connections to minimise the cumulative cost function.

stream head based on a combination of empirical and theoretical arguments. Whether valley or stream source areas can be discriminated by various methods on normally-available DEMs with sufficient accuracy depends on both the terrain characteristics and the application requirements.

Another approach to forming the scale of the watershed partition from the accumulated drainage area image is to adapt the degree of dissection (or extent of the network) to the local terrain variability in some key surface property. Lammers (1998) has developed a method whereby a drainage area image is first pruned by applying a very low area threshold, forming an extensive network and numerous small hillslopes. A merge procedure is then run which minimises the within-hillslope spherical variance of the surface normal. Adjacent hillslopes are then merged if the surface normal distributions are similar. This forms a more complex partitioning of the terrain and a more detailed extension of the stream network in dissected terrain. Plate 35 shows this adaptability of stream-network and hillslope extraction for the South Platte drainage basin, where the headwaters drain the Front Range of the Rocky Mountains, while the larger part of the watershed drains the high plains of Colorado and Nebraska. This example used 1 km terrain data which generalises much of the terrain variability, but is appropriate for the regional-scale application.

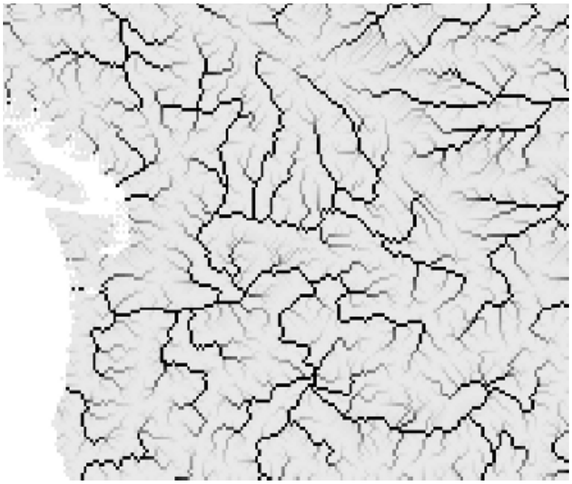

Fig 4. Drainage area accumulation image constructed from ETOPO-5 elevation data (5-minute resolution). Most of the major drainage systems are accurately portrayed with a few exceptions. The low horizontal resolution of the data does not capture accurately the topography of the Fraser River northeast of Vancouver, and the graph optimisation algorithm in GRASS finds a lower cost route for the upper Fraser to drain through the Columbia.

The increasing availability of DEMs covering regional to continental scales (Hutchinson and Gallant, Chapter 9; Hutchinson and Dowling 1991; Jenson 1991) has allowed the application of watershed extraction techniques to continental-scale drainage systems. At this level, a range of physiographic provinces is incorporated, and the performance of the algorithms can be variable, based on local terrain slope and data resolution. A limited amount of work has been published assessing the accuracy of watershed delineation (e.g. Miller and Morrice 1996) and these have generally been limited to areas of moderate to steep relief. In many cases, small errors in local routing where drainage will be connected over a small divide can lead to major topological errors in the connectivity of the network. An example is given in Figure 4 using ETOPO-5 data, a global elevation dataset at five minute resolution (about 10 km in the North–South direction). A portion of the drainage systems extracted for all of North America is shown for the northwest USA and southwestern Canada. While most of the regional drainage is well-represented, portions of the upper watershed of the Fraser River have been connected through the upper Columbia River because of the unresolved narrows of the Fraser Canyon northeast of Puget Sound. In this case, the GRASS4.1 algorithm was used which optimises a flow path. Because of the low resolution of the data and the high penalty associated with traversing the apparent ridge, a major topological error is incurred.

4 LANDFORM FEATURES AND OBJECT-BASED METHODS

The information that can be automatically extracted from low level terrain and image data must be organised into a spatial model commensurate with the watershed representations used by hydrologists and geomorphologists. A number of researchers have added techniques to extract and represent a suite of other topological and geometrical parameters to provide a fuller geomorphometric description of the watershed. Lammers and Band (1990) built a full watershed description from terrain data. Variables were extracted and stored in attribute tables for the set of nodes (stream junctions), lines (stream links), and areas (hillslopes) that constitute the watershed, including stream junction angles, stream link

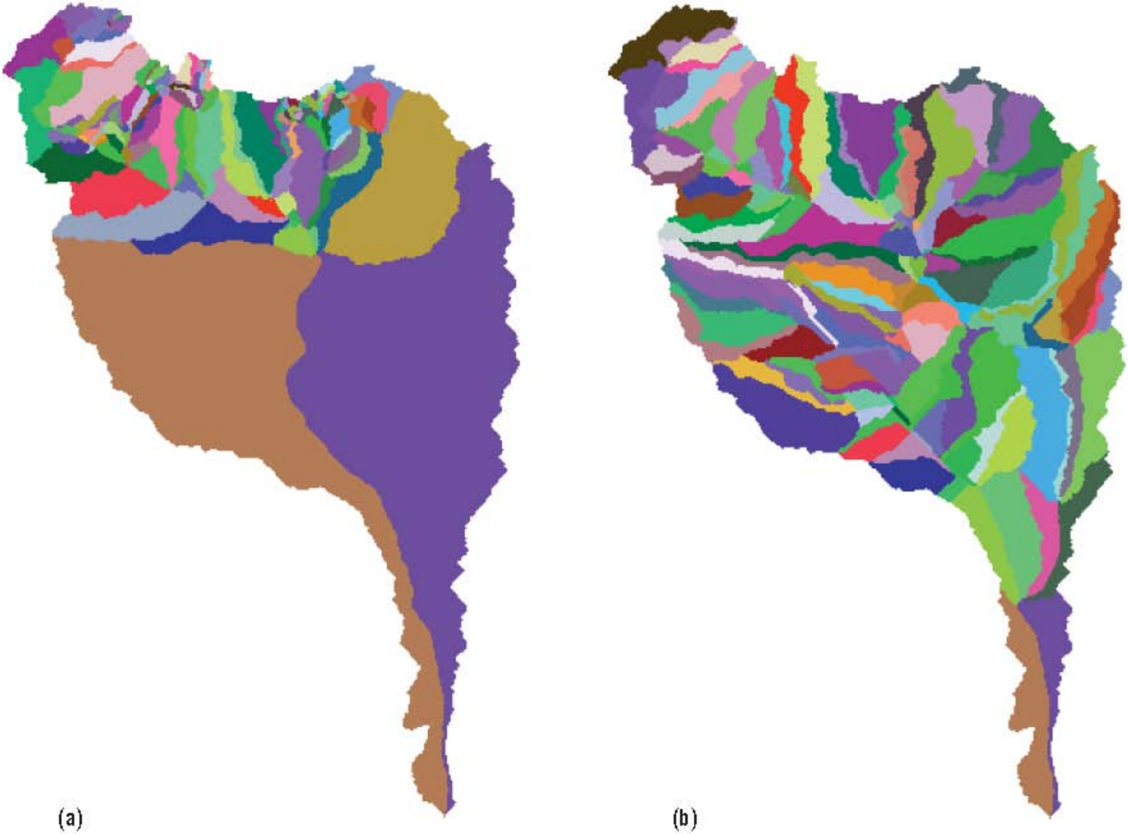

Plate 35 (above)
Partitions of the South Platte River basin produced by two methods of pruning the full drainage direction tree: (**a**) simple thresholding of the drainage area accumulation image; (**b**) adaptively pruning the drainage tree using the surface spherical variance. Both images have approximately the same number of partition units.

lengths, orientation, slope, drainage area, Strahler order and link magnitude, slope area, spherical mean aspect and gradient, as well as inter-feature relations. The tables were expanded to include information on soils and vegetation from co-registered remote sensing images and soil maps to parameterise distributed hydro-ecological models (Band 1993; Band et al 1991; Nemani et al 1993). In this respect, the hydro-ecological models were distributed on a geomorphic base, given by the hillslope organisation of the watershed, rather than the standard grid-cell approach.

Mackay and Band (1994) and Mackay et al (1992) built an object model of the watershed based on the tree-graph channel-link-based model. A hierarchy of objects representing the nested set of channel links, channel (sub)networks, hillslopes, catchments, sub-catchment, and divide segments was constructed from the information derived by the methods of Lammers and Band (1990). A simple graphical interface was designed to facilitate queries regarding object attributes (e.g. slope, area, orientation, soil, vegetation cover), spatial relations (adjacent to, upslope or downslope of), or drainage aggregation. A hydro-ecological simulation system (RHESSys; Band et al 1993) was tightly coupled to the object system so that queries could be expanded to pose hydrological and ecological questions such as expected run-off production, forest productivity, or soil moisture at specified times in response to meteorological input. The object model is undergoing further development to incorporate temporally defined watershed objects such as clear-cuts or other disturbance features (Mackay 1997) and to formalise its object schema (Robinson and Mackay 1995) as shown in Figure 5.

The *r.watershed* routine in GRASS4.1 includes options to compute a series of terrain and landscape variables in the format required to operate distributed run-off and soil erosion models which are incorporated into the spatial analysis package, as well as drainage information linking the set of slopes and sub-catchments. The incorporation of linked or embedded simulation models of watershed runoff and erosion, or ecological processes within a GIS package with the required spatial data preprocessing techniques, significantly extends the functionality of the spatial analysis system.

5 EXTENSION TO LANDFORM SYSTEMS

The set of landforms comprising a watershed can be extended from the channel, ridge, and slope model described above to include a collection of topographically-distinct regions referred to as bottomland, upslope, midslope, floodplains, valleys, mountains, or ridge areas. Unlike the crisply defined set of graph components that comprise the conceptual model of watershed drainage and ridge networks, these entities are not as precisely defined, nor are their extents or spatial relations. However, they are common terms used in a range of applications to distinguish different functional parts of the watershed in terms of hydrologic, geomorphic, and ecological conditions. As such, it is useful to be able to refer to and analyse 'bottomlands' or 'mid-slope position' within a GIS. Dymond et al (1995) extended the set of watershed features by extracting uniform land facets, which are sections of hillslopes stratified by aspect and distance from the stream or valley bottom. This allows the delineation of areas corresponding to ridge, midslope, or toeslope, and may provide a more detailed subdivision of contributing drainage areas and valley sides. The methods work with region-growing algorithms to agglomerate uniform-aspect pixels into terrain facets. For hilly to mountainous areas these techniques seem to be particularly effective in subdividing the drainage areas according to criteria that would be useful for a variety of scientific or management-oriented activities.

With some exceptions (e.g. Toriwaki and Fukumura 1978; Tribe 1991, 1992) many of the watershed characterisations described above have implicitly assumed steep, incised topography composed of V-shaped valley bottoms and sharp ridge tops surrounding simple slope forms. Many of the techniques for flow-path extraction have severe problems in flat areas due to low signal-to-noise ratios for determining appropriate flow directions. Various methods have been used to route water through these areas by searching larger windows (Smith et al 1990), adjusting elevation patterns on the basis of larger neighbourhood topography (Garbrecht and Martz 1996), or other methods of preprocessing and 'correcting' flow directions in identified flat areas or pits. In most cases, however, the channel lines are still constructed as single-pixel-wide chains through the flat regions even if

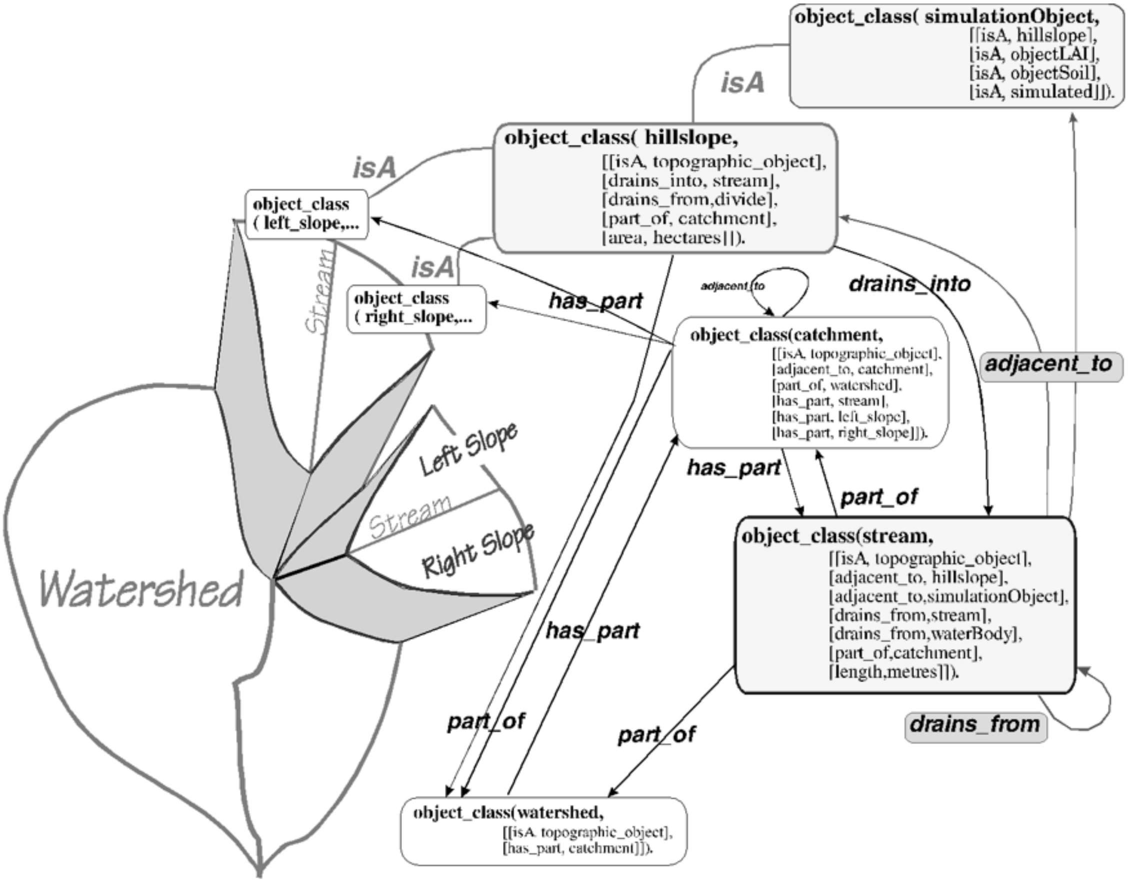

Fig 5. Data model schema defining watershed objects and inter-object relations for the Knowledge-Based Land Information Management System (KBLIMS). (After Robinson and MacKay 1995.)

there are no clearly-defined channels, as in wetlands or open water bodies. It is notable that almost all areas used to develop and demonstrate the channel-network and watershed structure are steeply-sloping fluvial or glacial topographies that are either devoid of lakes or extensive flat bottomland areas or ignore their presence. In areas where these features are ubiquitous, it does not make sense to attempt to ignore their presence as they are dominant features in the landscape. Mackay and Band (1994) addressed the problem of delineating watershed structure in regions dominated by numerous lakes, wetlands, and other flat bottomland features. Rather than attempting to route water through lakes and wetlands, Mackay and Band (1994) and Mackay (1997) first identified all flat regions using a combination of DEM and remote sensing imagery and then labelled them as lake, wetland, or floodplain objects. A version of the recursive climbing algorithm described by Band (1986b, 1989) was used to extract the flow-path structure and contributing drainage areas for all areas not identified as one of these objects. When the algorithm encounters a flat feature it is designed to traverse its perimeter (the set of boundary pixels of the lake or wetland), recursively climbing and accumulating the surrounding drainage areas (Plate 36). The resulting image shows the flow-path structure which is routed just inside the perimeter of each flat. The flow paths within each flat are then dissolved and the total contributing drainage area to each flat along with its surface area and any other attributes that are available (depth, volume, shape) are stored as part of an object description specific to

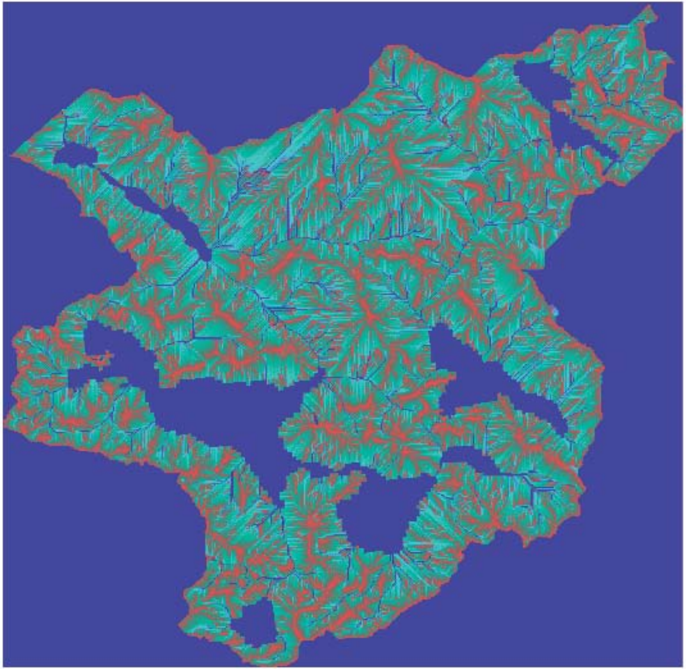

Plate 36

Explicit incorporation of lakes and wetlands into a drainage system involves first identifying and labelling flat bottomland features, then building the upland drainage structure surrounding them rather than attempting to route fictional paths through them. Site is the Turkey Lakes Experimental Watershed, a ten square kilometre catchment in northern Ontario. DEM is 5-metre resolution.

lakes, wetlands, etc. In this regard the flat areas are explicitly recognised and stored as part of the watershed object hierarchy described above and incorporated into the set of watershed objects (Figure 6).

6 UNCERTAINTY IN LANDFORM LABELLING

A persistent problem is the vagueness of landform concepts in terms of spatial boundaries and identification (labelling). This uncertainty in labelling landforms and landform positions translates into surface attribute uncertainty as attributes are often prescribed on a per-category basis. Note that the simple graph model of watersheds as composed of stream lines, divide lines, and hillslopes obviated some of this difficulty by restricting the range and detail of surface features. However, it suffers from being both oversimplified and restrictive compared to real watersheds, or the conceptual models of watersheds used by different communities. Varying attempts have been made to incorporate the degree of similarity of a region to one or more of the conceptual zones, or uncertainty regarding local assignment. The adaptation and use of certainty or similarity measures for zonal or landform labels would be an important function for spatial data models to maintain and use the watershed information generated in an efficient manner.

Some attempts to both infer and represent landform position and landform categories as part of a defined landscape system have been developed recently. These techniques use multiple sources of evidence and incorporate measures of uncertainty in both inferring and representing the landscape system

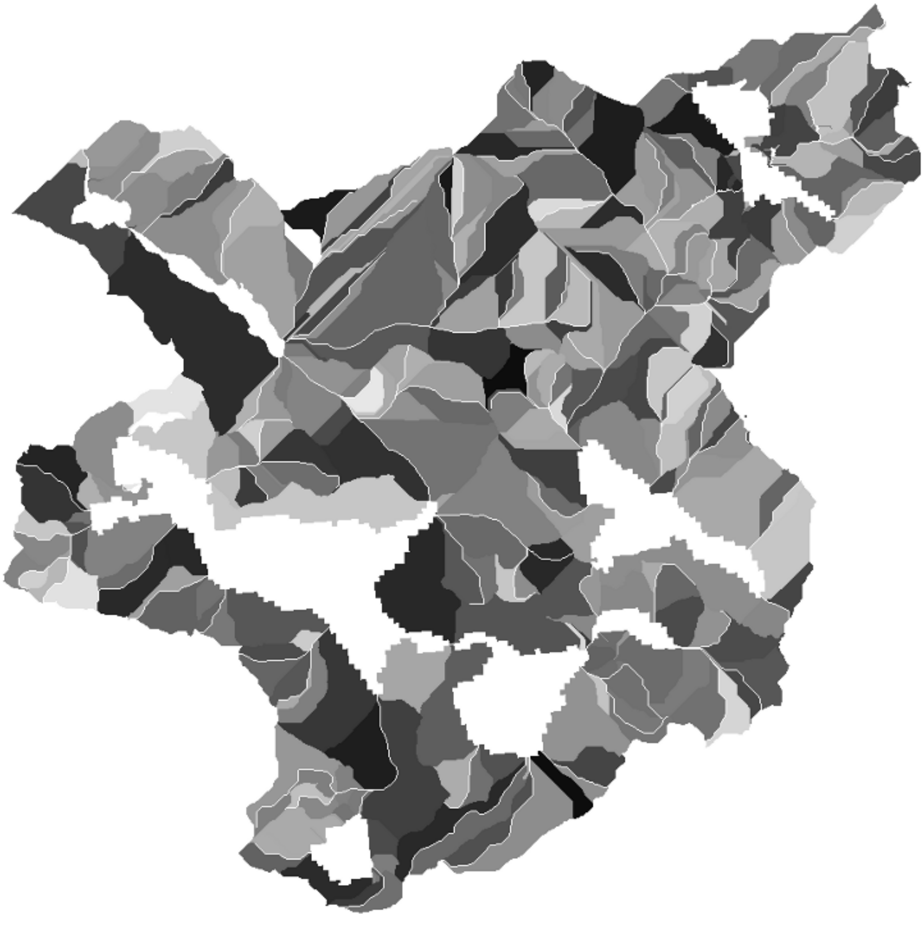

Fig 6. Watershed landform objects incorporating lake, wetland, stream, and slope features into an integrated drainage system.

and components. Skidmore et al (1991) constructed a glossary of the land types characterising different slope positions with characteristic soil/vegetation assemblages for a region of SE Australia. They then used a Bayesian approach to delimit the extents of each land type on the basis of local morphology and terrain position, and were therefore able to infer both the patterns of land components and the characteristic soils expected for the area with known probability. Mackay et al (1992) inferred the presence of types of alpine glacial landforms using mutual evidence theory based on local morphometric characteristics as determined from digital terrain data, and relative position in the landscape. Local evidence of the existence of a cirque within a headwater catchment reinforced the evidence of a glacial trough downslope and vice versa. A certainty measure could then be attached to the landform label for each component as influenced by both local and global information.

7 SOILS AND VEGETATION

The sections above indicate that the extraction of watershed topography and fluvial networks from digital terrain data is reasonably well advanced, at least for hilly to steep terrain, and progress is being made for more gentle topography. For many hydrologic and geomorphic applications, analysis of the composition and structure of a watershed requires information about the patterns of vegetation and soils as well, and their spatial covariance with local topographic form and landscape position. The observation that soils vary in regular patterns within the landscape is old, or even ancient, and it is interesting that this knowledge is just now being built into geographical data models for GIS. The quantification of the relations between topography, vegetation, soils, and climate has been a central concern in physical geography for over four decades. Melton (1958) investigated the correlation structure of a set of variables characterising each of these components using a field- and map-sampling design over a range of watersheds. An important aspect of this and similar research was the collection of field data at similar levels of support. In contrast, a cartographic data layer model typically offers little control over sampling design and the support of the different data layers simply because of the prevalent use of available data, rather than data appropriate to the analysis at hand (see Weibel and Dutton, Chapter 10). In this sense the technology may act as an inadequate alternative to a good sample design (Goodchild and Longley, Chapter 40), and data-overlay-based systems often may not adequately capture covariance structures that may be significant characteristics of the landscape.

Within a landscape system, each landform component at all levels of the hierarchy can be assigned typical patterns of terrain, types of soils, or soil assemblages, as well as vegetation cover characteristic of the landform category. In this respect, the placement of individual landforms and their expected soil and vegetation cover provides a catenary sequence. The presence of one landform can imply the presence of another related landform either at the same level of the hierarchy or at a level above or below. As an example, in the study of Mackay et al (1992) the presence of a cirque implies a glaciated valley downslope, or a tarn and morainal debris within the cirque. This type of knowledge is essential to understanding a landscape as a system, and is contained within the text and legends accompanying maps of the land systems, but has generally not been translated into GIS which are still dominated by a cartographic data model (but see Mitas and Mitasova, Chapter 34).

Of the set of variables that often needs to be incorporated in a description of a landscape, vegetation and other land cover features (cultural features) can be sampled successfully and mapped with the use of remote sensing or aerial photographic techniques at a similar support to the terrain information extracted from terrain data (see Smith and Rhind, Chapter 47). The weak link in the landscape catenary sequence with respect to GIS applications is the state of soils information, as soil information is rarely available at resolutions commensurate with terrain and vegetation information. As soils generally cannot be mapped using remote sensing techniques (with the possible exception of semi-arid to arid areas), their spatial extent is typically mapped in polygon form. Soil polygons are rarely pure, and contain inclusions of other soils which cannot be spatially located but are simply acknowledged in an accompanying soil report in terms of an areal percentage. This arises because of the coarse scale of soil mapping, the ambiguity of the soil classification schemes in general use, and the spatially continuous variation of soil properties in the field in contradiction to the discrete cartographic polygon model (Fisher, Chapter 13). The mismatch of spatial support for soil information relative to topographic and vegetation information produces error in the covariation of these variables when using the standard overlay technique.

Consequently, a number of techniques are in the process of being developed to attempt to improve the information content of soil data relative to that of terrain and vegetation data. These methods are drawn from the concept of soil–landscape modelling, or the catena concept of Milne (1935). The methods that have recently been explored to quantify and represent soil-landscape patterns range from empirical-statistical correlation through to knowledge-based techniques. Moore et al (1993) investigated the correlations of a set of soil properties with a set of terrain variables for a well-studied area in Colorado. Their working hypothesis was that much of the variation in the soils that lie along toposequences is a response to the movement of water over and through the landscape. Their results indicated significant correlations between soil and terrain variables, particularly the compound terrain index $CTI = \ln (A_s / \tan \beta)$, where A_s is the specific catchment area (see Hutchinson and Gallant, Chapter 9) and β is the slope angle, which serves as an indicator of terrain wetness. In terms of areal prediction of soil variables, the methods used were very data-intensive, requiring a large number of soil measurements to develop an adequate database. Gessler et al (1995) extended this work in Australian field sites by building multivariate models of soil properties as simple functions of terrain variables. They found significant explanations of soil depth and *A* horizon depth with surface curvature and the Compound Terrain Index (CTI). Once again, the methods are data intensive and it is unknown how generalisable these relations are beyond the specific dataset employed.

Gessler et al (1996) took a different approach to the soil–landscape problem by attempting to synthesise representative slope profiles in terms of both topography and soil properties. This work uses datasets across a climatic gradient and seeks to identify patterns of specific soil properties along convergent and divergent hillslopes in each environment. In this respect, they identify hillslopes as fundamental objects that can be described in terms of soil patterns associated with more easily observable terrain patterns. If a generalisable set of hillslope soil-terrain behaviour could be identified across observable climatic and geomorphic conditions, this approach may form the basis for extrapolating soil properties across a landscape within a GIS. What is required is a method to encapsulate the knowledge of these typical soil–toposequences in a manner that can be applied to a set of hillslopes extracted by the methods described in the previous section.

Expert systems have also been developed as a method of capturing and representing the knowledge soil scientists have regarding soil-landscape patterns, as an alternative to the demanding sampling procedures required by purely empirical approaches. The Bayesian inference approach of Skidmore et al (1991) was designed to classify landscape elements on the basis of terrain variables in order to infer soil properties. They used schemes developed by local soil scientists and resource managers in southeast Australia to set prior probabilities for each land type, and the typical topographic positions they occupied. Zhu and Band (1994) and Zhu et al (1996) used a fuzzy inference approach to compute membership scores for all grid cells in a raster image for all soil series (or complexes) identified to exist within the area. Figure 7 shows inferred fuzzy memberships for a specific soil complex. The scheme was based on a series of interactive sessions with local soil scientists to attempt to capture and represent their knowledge of soil-landscape patterns by constructing fuzzy membership functions for soil type based on a set of observable landscape variables including terrain, lithology, and canopy cover. The methods worked well in steep, Rocky Mountain topography where terrain-soil relationships are sharp and well defined (and more visualisable to the soil scientists) and less well in more gentle southeast Australian terrain. One of the areas identified as requiring greater development was to incorporate variables that better reflected terrain position, rather than primary terrain variables (e.g. slope, aspect, curvature). These needs were identified by Gessler et al (1996) and Skidmore et al (1991) as being critical to inferring soil variations in gentler topography.

7.1 Extension to larger-area landform systems

A fuller understanding and better categorisation of landforms is gained by placing them within an evolutionary framework such that the formative

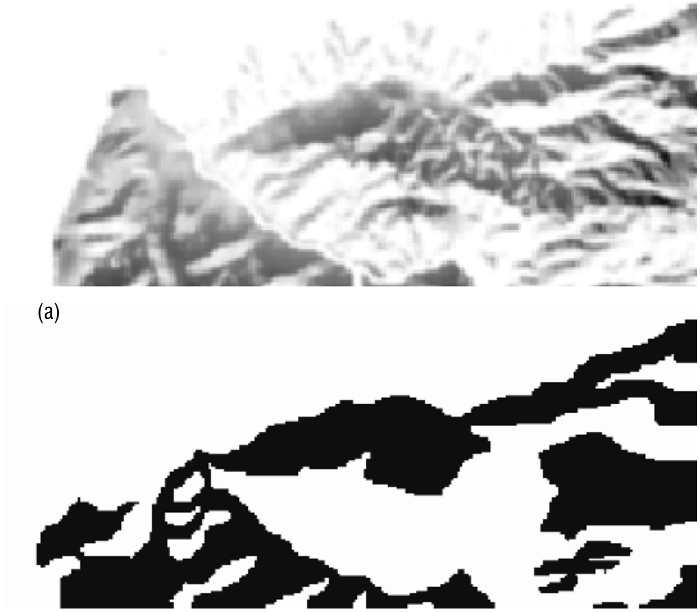

Fig 7. (a) Fuzzy and (b) crisp membership in a soil complex in a watershed of western Montana. The fuzzy memberships are computed on the basis of similarity to a central concept for the soil complex in several terrain and forest cover variables.

processes and relations to adjacent and associated landforms are incorporated. In this respect it is important to catalogue not only what can be inventoried within a landscape at a specific period of time, but what its temporal development has been and what the active processes are that maintain or change the system state (Raper, Chapter 5; Raper and Livingstone 1995). This is the basic approach taken in understanding watershed geomorphology and has been incorporated into a number of land systems that have been developed for resource management at national and other jurisdictional levels. The Soil-Landscape Classifications in Canada, US Forest Service Land Systems, and the Australian Soil and Land Survey (McDonald et al 1990) are examples and are well described by Bailey (1996). Each of these systems is hierarchical in nature, progressively subdividing the landscape into regional to local nested landforms, based on the primary geomorphic processes that have shaped the surface and determined the distribution of surface materials. An advantage of these systems is that they seek to embed knowledge of surficial geomorphology directly within the land-classification scheme. The examples of automating portions of this approach given above were placed in spatial domains of watersheds within which variables such as distance from stream or ridge within hillslopes could be resolved. However, the landscape-systems approach is hierarchical and should extend to much larger regions. Above the level of these small- to medium-size watersheds are large physiographic provinces which combine multiple watersheds and include a mix of dominant geomorphic processes within broader tectonic settings. At these scales, measures pertinent to individual hillslopes are generally well below the resolution of available data, and alternatives must be used. Recognition of landform systems at this level has been attempted by Dikau (1988, 1992), Dikau et al (1995), Fels and Matson (1996), and others. In these cases, initial identification of large-scale physiographic elements is carried out by first identifying geomorphometric parameters at the appropriate scale to distinguish landforms at these levels and the appropriate data resolution for their processing. At global levels an appropriate terrain dataset may be the five-minute elevation data discussed above for recognition of continental-scale features. Classification on the basis of local terrain variables alone is problematic and involves many subjective and interactive decisions regarding thresholds and appropriate variables, which are generally not transferable across different areas or even across different resolutions. Dikau (1992) discusses setting up a formal object hierarchy of landforms that can be aggregated or disaggregated into higher- and lower-level components, respectively. This can aid in identification of individual components, and also ensures consistency with the hierarchical data models used for the land systems. As effective global-scale research and applications using GIS often require a link between continental and local landscape scales, the construction of appropriate object hierarchies for the range of geomorphic systems characteristic of the planet would be an important task.

8 SUMMARY AND DISCUSSION

This chapter has reviewed the methods that have been used to synthesise and represent the geomorphic structure of watersheds and larger landscapes within GIS. Over the past two decades GIS data models have been developed to match more closely the conceptual model of a watershed, progressing from incorporation of the drainage and divide network, to nested sub-catchment and slope systems, to full object models of the watershed. The object models have been integrated with process-based models of hillslope hydrology and ecosystem processes. The catenary system of topographic, soil, and vegetation properties can be combined by standard cartographic overlay, but this method may not preserve significant covariance between these variables. Development and incorporation of soil-landscape models which quantify topographic variation of soils have shown significant progress in the last few years. Like many other areas in GIS, temporal variation in the data model of watersheds has remained rudimentary, although progress is being made in the incorporation of dynamics into surface spatial process and state variables.

There remain certain persistent problems in the recovery and representation of watershed information. The length scales of significant features are highly variable, with a large gap between the length scales of stream-channel and near-stream-channel environments relative to upland areas. Even with resolution-flexible methods of terrain representation such as the TIN, it is difficult to represent the required information content in these variable regions with layer-based models. Landform definitions are often conceptually vague, specifically regarding spatial extent and coverage. Terrain form and properties are typically spatially-continuous and gradational, and do not conform well to cartographic data models which may require spatially-exhaustive and mutually-exclusive thematic coverages. Both the raster and vector models have topological inconsistencies with watershed features which are most critical in the representation of drainage lines and stream channels.

To a certain extent these problems have been mitigated by resorting to object models of the watershed, although the spatial (landform) objects still need to be instantiated into well-defined classes. However, this problem is not just inherent to GIS representations of the watershed but is endemic to any spatial representation (Martin, Chapter 6; Raper, Chapter 5), such as those developed in distributed hydrologic and geomorphic process models. Continued improvement of GIS data models for watersheds and associated landforms should centre on extending the analytical approaches and level of understanding developed in these applications.

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