9

Representation of terrain

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This chapter demonstrates the central role played by representations of terrain in environmental modelling and landscape visualisation. Current trends in digital terrain modelling are discussed. Topographical data sources and digital elevation model (DEM) interpolation and filtering methods are described in relation to the requirements of environmental models. Accurate representation of surface shape and drainage structure is a common requirement, and is facilitated by the development of locally-adaptive, process-based DEM interpolation techniques. The role of traditional contour data sources and remotely-sensed data sources is also examined. Methods for interpreting terrain include terrain parameters, as simplifications of key environmental processes, and a range of terrain features associated with secondary terrain structures. The issue of spatial scale is discussed in relation to the multi-scale requirements of environmental modelling and the identification of scaling properties of DEMs and associated terrain parameters. Multi-scale terrain feature analysis permits the incorporation of terrain structure into analyses of scale.

1 INTRODUCTION

Terrain plays a fundamental role in modulating Earth surface and atmospheric processes. So strong is this linkage that understanding of the nature of terrain can confer understanding of the nature of these processes directly, in both subjective and analytical terms. Thus, analyses and representations of terrain have provided cardinal examples for many activities in GIS and environmental modelling. They have stimulated directly the development of new methods for obtaining digital environmental data (Barnsley, Chapter 32; Dowman, Chapter 31; Lange and Gilbert, Chapter 33), new spatial interpolation methods (Mitas and Mitasova, Chapter 34; Hutchinson 1996), and new methods for assessing data quality (see below). Since 3-dimensional representations of terrain form natural backgrounds for the display of spatially distributed quantities and entities, representations of terrain have also played a prominent role in the development of methods for conceptualisation (Raper, Chapter 5; Weibel and Dutton, Chapter 10) and visualisation (Neves and Câmara, Chapter 39; Kraak, Chapter 11) of 3-dimensional data.

Of central importance for the assessment and management of natural resources is the accuracy and spatial coverage that can be achieved in environmental modelling by incorporating appropriate dependencies on terrain. This particularly applies to improved representations of surface climate (Hutchinson 1995; Running and Thornton 1996) and hydrology (Moore and Grayson 1991) which are key factors in geomorphological and biological applications. This has led to the consideration of the underlying physical processes, and the spatial scales at which they operate, coupled with an increasing focus on explicit mathematical analysis, leading to the development of new methods for representing and interpreting terrain data (Gallant and Hutchinson 1996; see also Heuvelink, Chapter 14). These developments are consistent with key conclusions of the survey of digital terrain modelling by Weibel and Heller (1991), who emphasised a need to combine mathematical and algorithmic approaches with environmental and geomorphological understanding.

Weibel and Heller also asserted that digital terrain modelling had satisfied a number of goals, and that future developments would concentrate on refining current techniques and enlarging their scope. This chapter discusses current developments in terrain modelling in the light of their review, with particular emphasis on methods for the generation and interpretation of DEMs. These are the two areas of terrain representation which are directly related to the modelling of Earth surface processes. Their relationship to the overall context of digital terrain modelling is shown in Figure 1, which is a revised version of Figure 19.1 of Weibel and Heller.

Figure 1 clarifies the main functional connections between the tasks, particularly the interaction between DEM generation and DEM interpretation, and the overriding context provided by a wide range of applications. The issue of spatial scale arises at various points in this scheme. The scale of source data should guide the choice of resolution of generated DEMs and the scales of DEM interpretations should be matched to the natural scales of terrain-dependent applications. Recent developments in terrain features derived from DEMs are seen as having the potential to address issues of both scale and structure in digital terrain analysis.

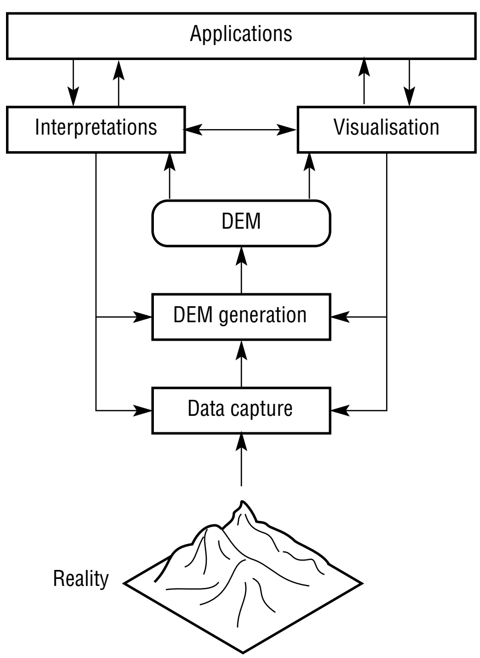


Fig 1. The main tasks associated with digital terrain modelling.

2 CURRENT TRENDS IN DIGITAL TERRAIN MODELLING

The rationale for the revised digital terrain modelling scheme shown in Figure 1 is discussed in relation to current trends in digital terrain modelling and the issues to be addressed in further detail by this chapter.

2.1 Elevation data capture

The role of digital elevation data capture has been enhanced, reflecting recent developments in airborne and spaceborne remote sensing, such as laser and synthetic aperture radar systems, and the development of the Global Positioning System (GPS) for ground data survey (see Lange and Gilbert, Chapter 33). Analysis of the errors associated with these data sources is an essential part of DEM generation.

Elevation contours continue to be the principal data source for the interpolation of DEMs, as well as being useful representations of terrain in their own right. They are widely available from existing topographic maps and, despite inherent sampling biases, can accurately reflect surface structure, particularly if they are coupled with a high-quality interpolation technique.

2.2 DEM generation

The development of methods for interpolation and filtering of DEM data continues to be a central area of digital terrain analysis, but the methods are now applied to a wider variety of data sources. These include traditional data sources such as points, profiles, contours, stream-lines, and break-lines, for which specific interpolation techniques have been developed, and remotely-sensed elevation data, for which various filtering procedures are required. Included in the task of DEM generation is a variety of associated DEM manipulation tasks such as DEM editing, DEM resampling, and data structure conversion between regular grids and triangulated irregular networks (TINs), the two dominant forms of terrain representation.

DEM interpolation methods based on triangulations have been seen as attractive because they can be adapted to various terrain structures and to varying data densities. However, it has been difficult to constrain triangulations to greatest advantage, and TINs can have deficiencies in representing terrain shape parameters such as slope and curvature. On the other hand, techniques for interpolating and analysing regular grids tend to be relatively straightforward, and recent developments in locally adaptive gridding techniques have enhanced the sensitivity of interpolated regular grids to terrain structure, including ridges and streamlines. Interpolation using local spline surface patches can also achieve a degree of local adaptivity to terrain structure.

TINs have seen most use as a data reduction tool, particularly useful in visualisation applications (De Floriani and Magillo, Chapter 38), while regular-grid DEMs have become the dominant vehicle for environmental modelling and natural resources assessment (Band, Chapter 37). Regular-grid DEMs can be readily integrated with remotely-sensed environmental data sources and gridding methods can be adapted to the filtering of noisy remotely-sensed elevation data.

2.3 DEM interpretation

Interpretation of DEMs includes scale analyses, terrain parameters, and a variety of terrain features that can be constructed from DEMs. Many DEM interpretations have been evolved to support hydrological analyses of DEMs, which are also discussed by Band (Chapter 37).

2.3.1 Scale

Scale and resolution enter into terrain analysis in several ways. The most fundamental is the choice of scale or grid resolution, which is analogous to the choice of map scale in cartography (see also Veregin, Chapter 12). The choice is usually a compromise between achieving fidelity to the true surface, and respecting practical limits on the density and accuracy of the source data. Grid resolution can be used as an index of information content. This has important consequences for the construction of meaningful linkages of DEMs with other data sources (Goodchild and Longley, Chapter 40).

The identification of characteristic scales in terrain, and the degree to which surface form changes with scale, is important for deciding on the scales or resolutions required to model terrain-dependent processes. As yet no satisfactory model of the changes of surface form with scale has been developed. The fractal model has been found to be too simplistic for most applications, since a single scaling law does not apply across all scales of interest. The fractal model also does not recognise important structural features such as drainage networks.

2.3.2 Terrain parameters

Terrain parameters, or topographic indices, are descriptions of surface form that can be computed directly at every point on a DEM. A substantial collection of such parameters has been developed to facilitate analyses of surface hydrological and ecological processes (Moore et al 1991). Most terrain parameters depend on the DEM having an accurate representation of surface shape (see also Mitas and Mitasova, Chapter 34). They exhibit scale dependencies which have yet to be fully understood and quantified.

2.3.3 Terrain features

A variety of terrain features have been constructed from DEMs to support terrain-dependent analyses. They are usually associated with secondary terrain structures defined in terms of surface shape and drainage structure. Many of these coincide with common conceptions of landscape features, such as mountain ranges, ridges, catchments, rivers, and valleys.

Dissection of the DEMs into catchments and sub-catchments is an established procedure using the technique of Jenson and Domingue (1988). Terrain can also be dissected into a set of stream tubes bounded by contour lines and flow-lines (Moore et al 1988), particularly suited for hydrological applications. A multi-scale representation of terrain as a collection of overlapping topographic features at different scales has been recently developed by Gallant and Hutchinson (1996).

2.4 DEM interpretation and DEM visualisation

Visualisation techniques may be applied directly to DEMs, as well as to various interpretations of DEMs. Visualisation of DEMs can provide subjective assessments, such as perspective views and intervisibility analyses for various planning and monitoring applications. Intervisibility analyses of DEMs, represented as TINs or as regular grids, are discussed in detail by De Floriani and Magillo (Chapter 38). Visualisations of DEMs draped with various textures can also provide valuable insight into the nature of the processes being represented. They are an essential component of many virtual environment systems (Neves and Câmara, Chapter 39).

Interpretation and visualisation of DEMs can provide assessments of DEM quality which have direct implications for DEM generation and data capture, as indicated in Figure 1. Automated graphical techniques for detection of errors in source data are particularly important since most source topographic datasets are large and contain errors. Non-classical measures of data quality based on visualisation methods offer rare opportunities for confirmatory data analysis (CDA).

2.5 DEM applications

The overriding influence of applications on terrain representation and analysis is indicated in Figure 1. Applications may be found across a wide range of spatial scales, in civil engineering, planning and resource management, Earth sciences, and military studies. The general trend in representations of terrain for environmental modelling has been to move from broader continental and regional scales, closely allied to the representation of major drainage divisions (Jenson 1991), mesoscale representations of surface climate (Hutchinson 1991) and associated flora and fauna (Nix 1986), to finer scales suited to the modelling of surface hydrology, vegetation, and soil properties (Gessler et al 1996; Mackey 1996; Moore and Grayson 1991; Quinn et al 1991). This general trend has been accompanied by improvements in methods for representing fine-scale shape and structure in DEMs, supported by the steady increase in the speed and storage capacity of computing platforms.

This has brought into sharper focus the issue of determining appropriate spatial scales for modelling Earth-surface processes (Steyaert 1993) and for hydrological modelling in particular (Blöschl and Sivaplan 1995). More recently there has been a renewed appreciation of the utility of broader-scale DEMs, with a spatial resolution of about one kilometre, for the purposes of environmental modelling at global level. This has been accompanied by the development of new broader-scale remote-sensing instruments (Barnsley, Chapter 32; Dowman, Chapter 31) and the compilation of global coverages of terrain data (Verdin and Jenson 1996) and Earth-surface data commensurate with this resolution (Steyaert 1996).

3 DEM GENERATION

DEM-generation procedures need to be guided by both the nature of the source data and the intended applications of the generated DEM. For most applications, accurate representation of surface shape and drainage structure is more important than absolute elevation accuracy, particularly in areas with low relief.

3.1 Sources of elevation data

Three main classes of source elevation data may be recognised, for which different DEM-generation techniques are applicable.

3.1.1 Surface-specific point elevation data

Surface-specific point elevations, including high and low points, saddle points, and points on streams and ridges make up the skeleton of terrain (Clarke 1990). They are an ideal data source for most interpolation techniques, including triangulation methods and specially adapted gridding methods. These data may be obtained by ground survey and by manually assisted photogrammetric stereo models (Makarovic 1984). They can also be obtained from grid DEMs to construct TIN models (Heller 1990; Lee 1991). The advent of the GPS has enhanced the availability of accurate ground-surveyed data (Lange and Gilbert, Chapter 33; Dixon 1991), but such data are available only for relatively small areas.

3.1.2 Contour and stream-line data

Contour data are still the most common terrain data source for large areas. Many of these data have been digitised from existing topographic maps which are the only source of elevation data for some parts of the world. The conversion of contour maps to digital form is a major activity of mapping organisations worldwide (Hobbs 1995). Contours can also be generated automatically from photogrammetric stereo models (Lemmens 1988), although these methods are subject to error. A sample contour and stream-line dataset is shown in Figure 2, with some additional point data. Contours implicitly encode a number of terrain features, including points on stream-lines and ridges. The main disadvantage of contour data is that they can significantly under-sample the areas between contour lines, especially in areas of low relief, such as the lower right hand portion of Figure 2. This has led most investigators to prefer contour-specific algorithms over general-purpose algorithms when interpolating contour data (Clarke et al 1982; Mark 1986).

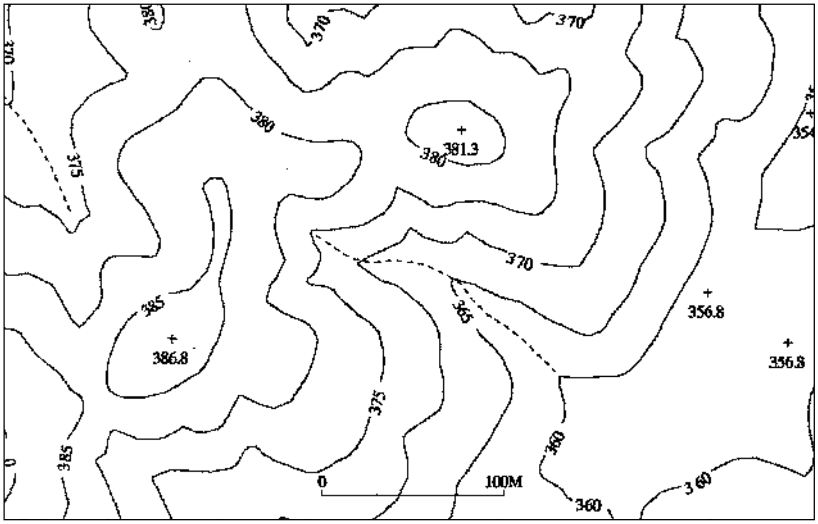


Fig 2. Contour, stream, and point elevation data.

Contour data differ from other elevation data sources in that they imply a degree of smoothness of the underlying terrain. When contours are obtained by manually assisted photogrammetric techniques, the operator can remove the effects of obstructions such as vegetation cover and buildings. Contour data, when coupled with a suitable interpolation technique, can in fact be a superior data source in low-relief areas (Garbrecht and Starks 1995), where moderate elevation errors in remotely-sensed data can effectively preclude accurate determination of surface shape and drainage.

Stream-lines are also widely available from topographic maps and provide important structural information about the landscape. However, few interpolation techniques are able to make use of stream-line data without associated elevation values. The method developed by Hutchinson (1988, 1989) can use such stream-line data, provided that the stream-lines are digitised in the downhill direction. This imposes a significant editing task, which can be achieved by using a GIS with network capabilities.

3.1.3 Remotely-sensed elevation data

Gridded DEMs may be calculated directly by stereoscopic interpretation of data collected by airborne and satellite sensors (Dowman, Chapter 31). The traditional source of these data is aerial photography (Kelly et al 1977) which, in the absence of vegetation cover, can deliver elevations to sub-metre accuracy (Ackermann 1978; Lemmens 1988). Stereoscopic methods have been applied to SPOT imagery (Day and Muller 1988; Konecny et al 1987), and more recently to airborne and spaceborne synthetic aperture radar (SAR). Spaceborne lasers can also provide elevation data in narrow swathes (Harding et al 1994). A major impetus for these developments is the yet unrealised goal of generating high-resolution DEMs with global coverage (Dixon 1995; Zebker et al 1994).

Remote-sensing methods can provide broad spatial coverage, but have a number of generic limitations. None of the sensors can measure the ground elevations underneath vegetation cover reliably. Even in the absence of ground cover, all methods measure elevations with significant random

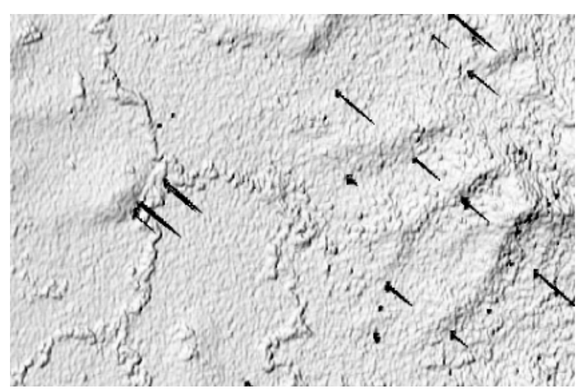


Fig 3. Shaded relief view of a 10-m-resolution DEM obtained from airborne SAR in an area with low relief.

errors, which depend on the inherent limitations of the observing instruments, as well as surface slope and roughness (Dixon 1995; Harding et al 1994). The methods also require accurately located ground control points to minimise systematic error. These points are not always easy to locate, especially in remote regions. Best-possible standard elevation errors with spaceborne systems currently range between 1 and 10 metres, but elevation errors can be much larger, up to 100 metres, under unfavourable conditions (Harding et al 1994; Lanari et al 1997; Sasowsky et al 1992; Zebker et al 1994). Averaging of data obtained from multiple passes of the sensor can reduce these errors.

Airborne SAR data are available for areas of limited extent. Standard elevation errors for DEMs derived from these data can be as small as 1 to 3 metres (Dixon 1995). Figure 3 shows a shaded relief view of a DEM derived from airborne SAR in an area with low relief. The figure shows occasional large errors, evidenced as high points and holes, random elevation errors across the whole DEM, and significant anomalies in the form of spurious ridges along tree-lined watercourses. Careful filtering of such data is required to derive a useful representation of surface shape and drainage structure.

3.2 Interpolation methods

Interpolation (Mitas and Mitasova, Chapter 34) is required to generate DEMs from surface-specific points and from contour and stream-line data. Since datasets are usually very large, high-quality global interpolation methods, such as thin plate splines, in which every interpolated point depends explicitly on every data point, are computationally impracticable. Such methods cannot be adapted easily to the strong anisotropy evidenced by real terrain surfaces. On the other hand, local interpolation methods, such as inverse distance weighting, local Kriging, and unconstrained triangulation methods, achieve computational efficiency at the expense of somewhat arbitrary restrictions on the form of the fitted surface. Three classes of interpolation methods are in use. All achieve a degree of local adaptivity to anisotropic terrain structure.

3.2.1 Triangulation

Interpolation based on triangulation is achieved by constructing a triangulation of the data points, which form the vertices of the triangles, and then fitting local polynomial functions across each triangle (Weibel and Heller 1991; see also Weibel and Dutton, Chapter 10, for a broader discussion of generalisation). Linear interpolation is the simplest case, but a variety of higher-order interpolations have been devised to ensure that the interpolated surface has continuous first derivatives (Akima 1978; Auerbach and Schaeben 1990; Sambridge et al 1995; Sibson 1981; Watson and Philip 1984). Considerable attention has been directed towards methods for constructing the triangulation. The Delaunay triangulation is the most popular method and several efficient algorithms have been devised (e.g. Aurenhammer 1991; Heller 1990; Tsai 1993). The dual of the Delaunay triangulation is the Dirichlet tessellation. Both structures have been used to assess neighbourhood relationships of point data in 2- and 3-dimensional space (Boots, Chapter 36).

Triangulation methods have been seen as attractive because they can be adapted to various terrain structures, such as ridge-lines and streams, using a minimal number of data points (McCullagh 1988). However, these methods are sensitive to the positions of the data points and the triangulation needs to be constrained to produce optimal results (Pries 1995; Weibel and Heller 1991). Triangulation methods are known to have difficulties interpolating contour data, which generate many flat triangles unless additional structural data points along streams and ridges can be provided (Clarke 1990: 204–37). Such data may be obtained by detailed ground or photogrammetric survey, but have not been readily obtained from existing contour maps.

Figure 4(a) shows surface-specific data points selected from corners in the contour data shown in Figure 2 and from stream-lines and ridges inferred from these data by the locally adaptive gridding method described below. The corresponding TIN is shown in Figure 4(b). Using Akima's method to interpolate across the triangles, the TIN is contoured in Figure 4(c) at half the elevation spacing of the data contours. A shaded-relief view is shown in Figure 4(d). This triangulation accurately represents the broad structure of the terrain, but the contour and shaded-relief views reveal minor deficiencies in surface shape. These are typically associated with small narrow triangles which are difficult to avoid. The outstanding feature of this representation is its numerical efficiency, with the number of vertices in the TIN less than one per cent of the number of nodes in the grid DEM shown in Figure 5. Examples of TIN generation from a gridded DEM are shown by Lee (1991), by Weibel and Heller (1991), and by Neves and Câmara (Chapter 39).

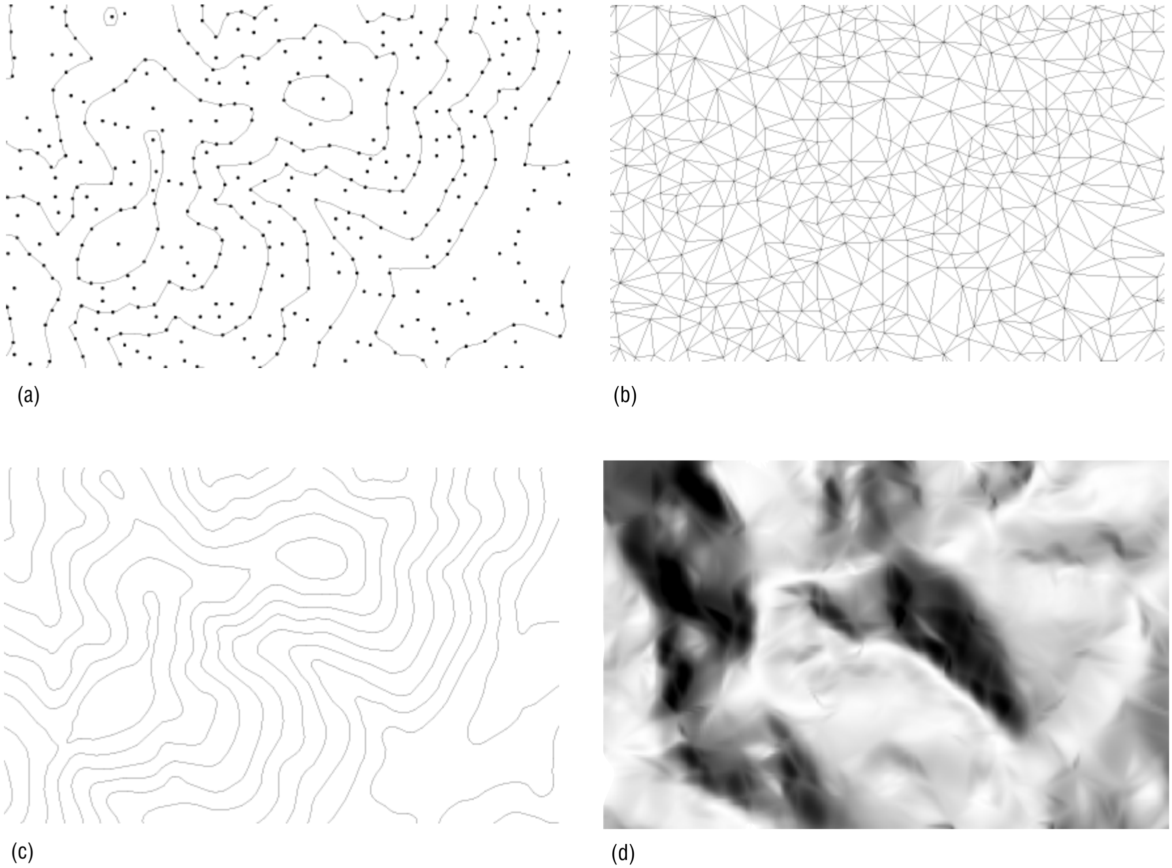


Fig 4. Interpolation of surface-specific elevation data using triangulation: (a) surface-specific points overlaid with the contour data from Figure 2; (b) TIN derived from the surface-specific points; (c) contours interpolated from the TIN; and (d) shaded relief view of the surface interpolated from the TIN.

3.2.2 Local surface patches

Interpolation by local surface patches is achieved by applying a global interpolation method to overlapping regions, usually rectangular in shape, and then smoothly blending the overlapping surfaces. Franke (1982) and Mitasova and Mitas (1993) have used respectively thin plate splines and regularised splines in tension in this way: see also Mitas and Mitasova (Chapter 34). These methods overcome the computational problems posed by large datasets and permit a degree of local anisotropy. They can also perform data smoothing when the data have elevation errors. There are some difficulties in defining patches when data are very irregularly spaced and anisotropy is limited to one direction across each surface patch. Nevertheless, Mitasova and Mitas (1993) have obtained good performance on sparsely-distributed contour data. An advantage of this method for applications is that topographic parameters such as slope and curvature, as well as flow-lines and catchment areas, can be calculated directly from the fitted surface patches which have continuous first and second derivatives (Mitasova et al 1996). Local surface patches can also be readily converted into regular grids.

3.2.3 Locally adaptive gridding

Direct gridding or finite-difference methods can provide a computationally efficient means of applying high-quality interpolation methods to large elevation datasets. Iterative methods which fit discretised splines in tension have been described by Hutchinson (1989) and Smith and Wessel (1990). Both are based on the method developed by

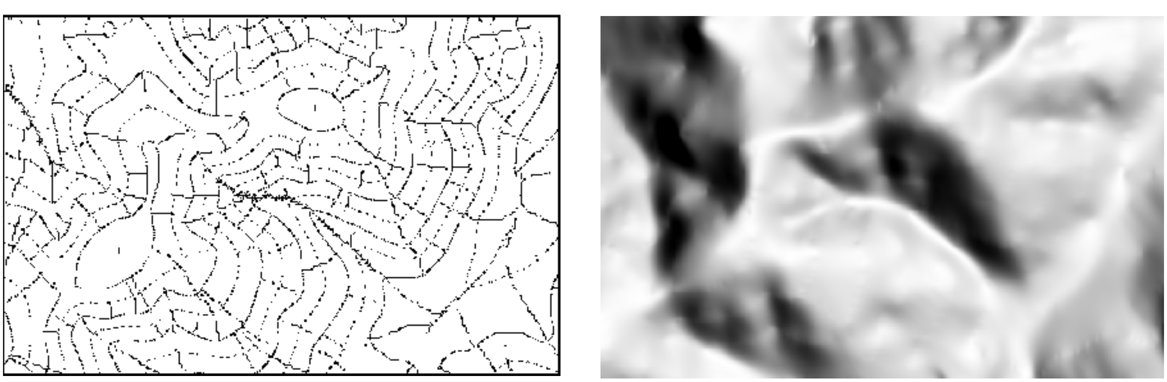
Briggs (1974). Computational efficiency is achieved by using a simple multi-grid strategy. The use of splines in tension is indicated by the statistical nature of actual terrain surfaces (Frederiksen et al 1985; Goodchild and Mark 1987). It overcomes the tendency of minimum-curvature splines to generate spurious surface oscillations in complex areas and has been similarly applied to interpolation of elevation by local surface patches.

Former limitations in the ability of general gridding methods to adapt to strong anisotropic structure in actual terrain surfaces, as noted by Ebner et al (1988), have been largely overcome by applying a series of locally-adaptive constraints to the basic gridding procedure. These constraints can be applied between each pair of adjacent grid points, allowing maximum flexibility. Constraints which have direct relevance for hydrological applications are those imposed by the drainage enforcement algorithm devised by Hutchinson (1989). This algorithm removes spurious depressions in the fitted DEM, in recognition of the fact that sinks are usually quite rare in nature (Band 1986; Goodchild and Mark 1987). This can significantly improve the drainage quality and overall structure of the fitted DEM, especially in data-sparse areas.

A related locally-adaptive feature is an algorithm which automatically calculates ridge- and stream-lines from points of locally maximum curvature on contour lines (Hutchinson 1988). This permits interpolation of the fine structure in contours across the area between the contour lines in a more reliable fashion than methods which use linear or cubic interpolation along straight lines in a limited number of directions (Clarke et al 1982; Cole et al 1990; Legates and Willmott 1986; Oswald and Raetzsch 1984). A partly similar approach, combining triangulation and grid structures, has been described by Aumann et al (1992). The result of applying the locally-adaptive gridding procedure to the contour and stream-line data in Figure 2 is shown in Figure 5. The inferred stream-lines and ridges are curvilinear, particularly in the data-sparse, low-relief portion of the figure, and there are no spurious depressions. The derived contours closely match the data contours and the shaded-relief view confirms that the surface has no fine-scale artefacts. The locally-adaptive method has overcome problems formerly encountered by gridding methods in accurately representing drainage structure in low-relief areas (Carter 1988; Douglas 1986).

The procedure also yields a systematic classification of the landscape into simple, connected, approximately-planar terrain elements, bounded by contour segments and flow-line segments. These are similar to the elements calculated by Moore et al (1988), but are determined in a more stable manner which incorporates both uphill and downhill searches, depending on the shape of the terrain.

Recent developments in this locally-adaptive gridding method include a locally-adaptive data-smoothing algorithm, which allows for the local slope-dependent errors associated with the finite-difference representation of terrain, and a locally-adaptive surface roughness penalty, which minimises profile curvature (Hutchinson 1996). The smoothing method has yielded useful error estimates for grid DEMs and a criterion for matching grid resolution to the information content of source data.



(a) (b)

Fig 5. Locally-adaptive gridding of the contour and stream-line data shown in Figure 2: (a) structure lines (ridges and stream-lines) generated by the gridding method and contours derived from the fitted DEM; and (b) shaded relief view of the fitted DEM.

3.3 Filtering of remotely-sensed grid DEMs

Filtering of remotely-sensed grid DEMs is required to remove surface noise, which can have both random and systematic components. Filtering is usually associated with a coarsening of the DEM resolution. Methods include simple nearest-neighbour sub-sampling techniques and standard filtering techniques, including median and moving-average filtering in the spatial domain, and low-pass filtering in the frequency domain. Several authors have recognised the desirability of filtering remotely-sensed DEMs to improve the representation of surface shape.

Sasowsky et al (1992) and Bolstad and Stowe (1994) used the nearest-neighbour method to sub-sample SPOT DEMs, with a spatial resolution of 10 metres, to DEMs with spatial resolutions ranging from 20 to 70 metres. This generally enhanced the representation of surface shape, although significant errors remained. Giles and Franklin (1996) applied median and moving-average filtering methods to a 20-m-resolution SPOT DEM. This similarly improved representation of slope and solar-incidence angles, although elevation errors were as large as 80 metres and no effective representation of profile curvature could be obtained.

Hutchinson et al (1997) removed the large outliers from the airborne SAR data shown in Figure 3 and applied moving-average smoothing to generate a 50-metre-resolution DEM with accurate representation of surface aspect, except in those areas affected by vegetation cover. Lanari et al (1997) have applied a Kalman (moving-average) filter to spaceborne SAR data obtained on three different wavelengths. Standard errors ranged between about 5 and 80 metres, depending on land surface conditions.

The data in Figure 3 indicate that standard filtering techniques are not sufficient adequately to reduce error. Points associated with random large data errors and systematic errors attributable to surface cover need to be detected and replaced by interpolation. This process would be assisted by making use of techniques which enforce appropriate drainage conditions on the filtered DEM.

3.4 DEM quality assessment

The quality of a derived DEM can vary greatly depending on the data source and the interpolation technique. The desired quality depends on the application for which the DEM is to be used, but a DEM created for one application is often used for other purposes. Any DEM should therefore be created with care, using the best available data sources and processing techniques. Efficient detection of spurious features in DEMs can lead to improvements in DEM generation techniques, as well as detection of errors in source data.

Since most applications of DEMs depend on representations of surface shape and drainage structure, absolute measures of elevation error do not provide a complete assessment of DEM quality. A number of graphical techniques for assessing data quality have been developed. These are non-classical measures of data quality which offer means of confirmatory data analysis without the use of an accurate reference DEM. Assessment of DEMs in terms of their representation of surface aspect has been examined by Wise (1997).

Spurious sinks or local depressions in DEMs are frequently encountered and are a significant source of problems in hydrological applications (Band, Chapter 37). Sinks may be caused by incorrect or insufficient data, or by an interpolation technique that does not enforce surface drainage. They are easily detected by comparing elevations with surrounding neighbours. Hutchinson and Dowling (1991) noted the sensitivity of this method in detecting elevation errors as small as 20 metres in source data used to interpolate a continent-wide DEM with a horizontal resolution of 2.5 kilometres. More subtle drainage artefacts in a DEM can be detected by performing a full drainage analysis to derive catchment boundaries and stream-line networks, using the technique of Jenson and Domingue (1988).

Computing shaded relief allows a rapid visual inspection of the DEM for local anomalies that show up as bright or dark spots. It can indicate both random and systematic errors, as shown in Figures 3 and 4(d). It can identify problems with insufficient vertical resolution, since low-relief areas will show as highly visible steps between flat areas. It can also detect edge-matching problems (Hunter and Goodchild 1995). Shaded relief is a graphical way of checking the representation of slopes and aspects in the DEM. These can also be checked by standard statistical analysis if there is an accurate reference DEM or accurately surveyed ground data (Bolstad and Stowe 1994; Giles and Franklin 1996; Sasowsky et al 1992).

Contours derived from a DEM provide a sensitive check on terrain structure since their position, aspect, and curvature depend directly on the elevation, aspect, and plan curvature respectively of the DEM. Derived contours are a particularly useful diagnostic tool because of their sensitivity to elevation errors in source data. Subtle errors in labelling source-data contours digitised from topographic maps are common, particularly for small contour isolations which may have no label on the printed map. An example is shown in Figure 6, which also shows the utility of plotting sinks. The contours in Figure 6(b) and (c) were derived from a DEM calculated by the locally-adaptive gridding procedure described above.

Other deficiencies in the quality of a DEM can be detected by examining frequency histograms of elevation and aspect. DEMs derived from contour data usually show an increased frequency of contour elevations in the elevation histogram. The severity of this bias depends on the interpolation algorithm. The frequency histogram of aspect can be biased towards multiples of 45 and 90 degrees by interpolation algorithms that restrict searching to a few specific directions between pairs of data points.

4 DEM INTERPRETATION

4.1 Scale

4.1.1 Matching the resolution of grid DEMs to source data

Determination of the DEM resolution which matches the information content of the source data is desirable for several reasons. It directly facilitates efficient data inventory. It also permits interpretation of the horizontal resolution of the DEM as an index of information content. This is an important consideration when linking DEMs to other grid datasets and when filtering remotely-sensed DEMs. Moreover, it can facilitate the assessment of scale dependencies in terrain-dependent applications.

A simple method for matching DEM resolution to source data information content has been developed as part of the locally-adaptive gridding technique of Hutchinson (1996). The method monitors the root-mean-square slope of all DEM points associated with elevation data. The optimum DEM grid spacing is determined by refining the DEM spacing until further refinements produce no significant increase in the root-mean-square DEM slopes. The method is particularly appropriate when source data have been obtained in a spatially-uniform manner, such as elevation contours from topographic maps at a fixed scale, or from remotely-sensed gridded elevation data.

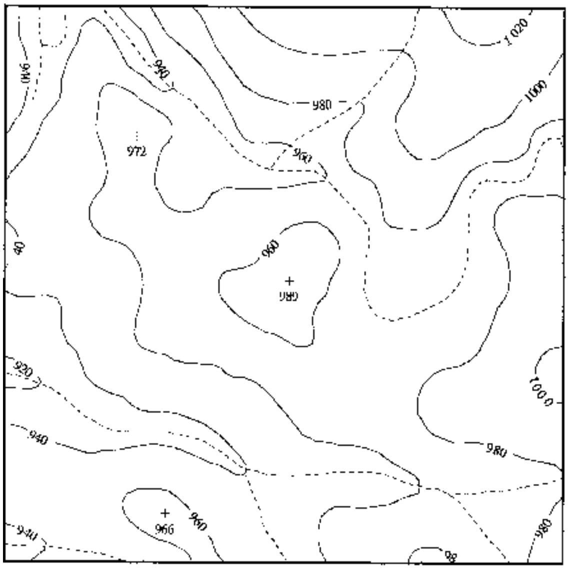
4.1.2 Spectral and fractal analyses of scale

Understanding of the scaling characteristics of land-surface elevation is useful for identifying characteristic scales and predicting how sensitive the surface is to changes in resolution. This scaling behaviour can be studied using measures that are sensitive to the magnitude of variation at different spatial scales, such as the variogram (Oliver and Webster 1986) and the Fourier power spectrum (Mulla 1988; Pike and Rozema 1975). The power spectrum can discriminate degrees of smoothness that are indistinguishable using variograms (Gallant et al 1994).

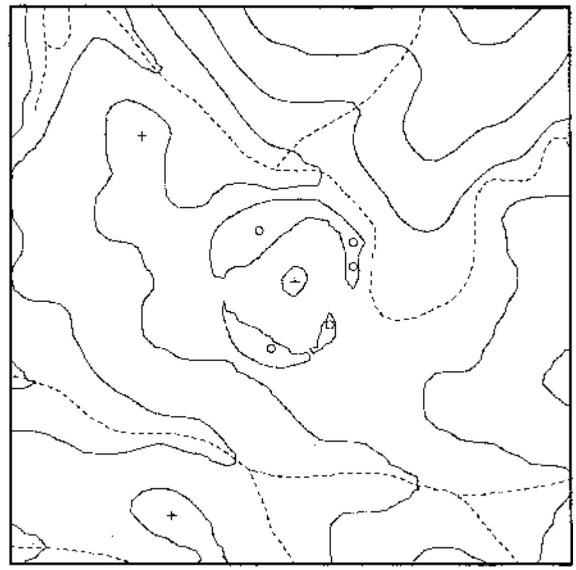
The fractal model of scaling asserts that variance changes with scale according to a power-law function. This translates to a straight line in the logarithmic plot of the power spectrum with the magnitude of the slope between 1 and 3. A single scaling exponent across all scales is acknowledged to be unrealistic (Burrough 1981; Mandelbrot 1977; Mark and Aronson 1984) and several straight segments with different slopes are considered to satisfy the fractal model, provided the slopes are in the allowable range.

Figure 7 shows the power spectra of two DEMs in an area with moderate relief, one at 5-m resolution from 1:10 000-scale contours and stream-lines and the other at 20-m resolution from 1:25 000-scale data. These are the optimum resolutions for the source data, as determined by the procedure described above. Multiple straight lines are apparent in both spectra but, apart from the broadest-scale segment, the spectral slopes are too steep to be interpreted as fractal surfaces. The steep spectral slope indicates low fine-scale variance relative to coarse-scale variance.

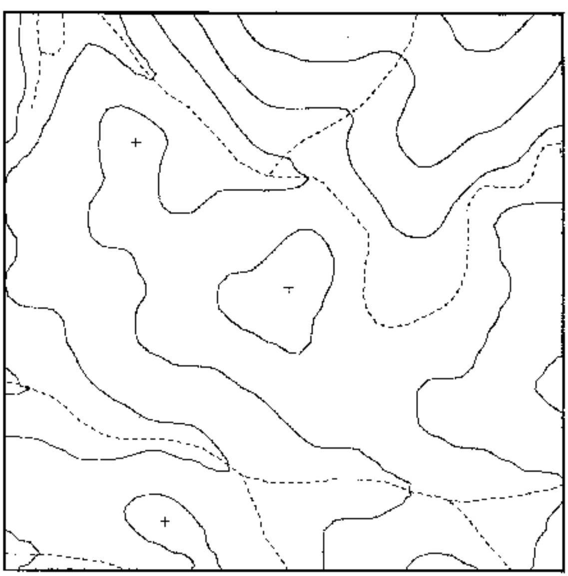
Figure 7 also demonstrates that the spectral slope at fine scale is sensitive to both DEM resolution and the scale of the source data. Coarser-scale source data and coarser DEM resolution result in a smoother surface and steeper spectral slopes. However, the common increase in spectral slope at about 200-m wavelength for both curves is likely to be a function of the actual topography, related to hill-slope length and drainage density.



(a)



(b)



(c)

Fig 6. Use of drainage artefacts and derived contours to detect errors in source data: (a) contour and stream-line data with one contour label in error by one contour interval; (b) contours and spurious sinks, denoted by small circles, derived from a DEM fitted to the erroneous data in (a); and (c) contours derived from a DEM fitted to corrected data.

4.2 Terrain parameters

Terrain parameters, or topographic indices or attributes, are descriptive parameters of land-surface form that can be measured on the real surface and computed from a DEM. They have been developed as simplifications of specific Earth-surface processes in order to characterise the spatial variability of these processes across the landscape (Moore et al 1991; Speight 1980; Zevenbergen and Thorne 1987). Some parameters, such as slope and curvature, are defined in terms of local surface shape while others, such as specific catchment area, topographic wetness index, and flow length, are dependent on the shape of the surface some distance away from the reference location.

The more commonly used terrain parameters and their hydrological applications are described by Moore et al (1991, 1993) and Wilson and Gallant (1997). Slope and aspect modulate solar insolation, evaporation, and surface-water flow rates. Plan curvature and specific catchment area are parameters that describe the accumulation of surface water, closely related to the formation of streams and to the processes of soil erosion and soil aggradation. A 3-dimensional perspective view of specific catchment area derived from the DEM in Figure 5 is shown in Plate 4.

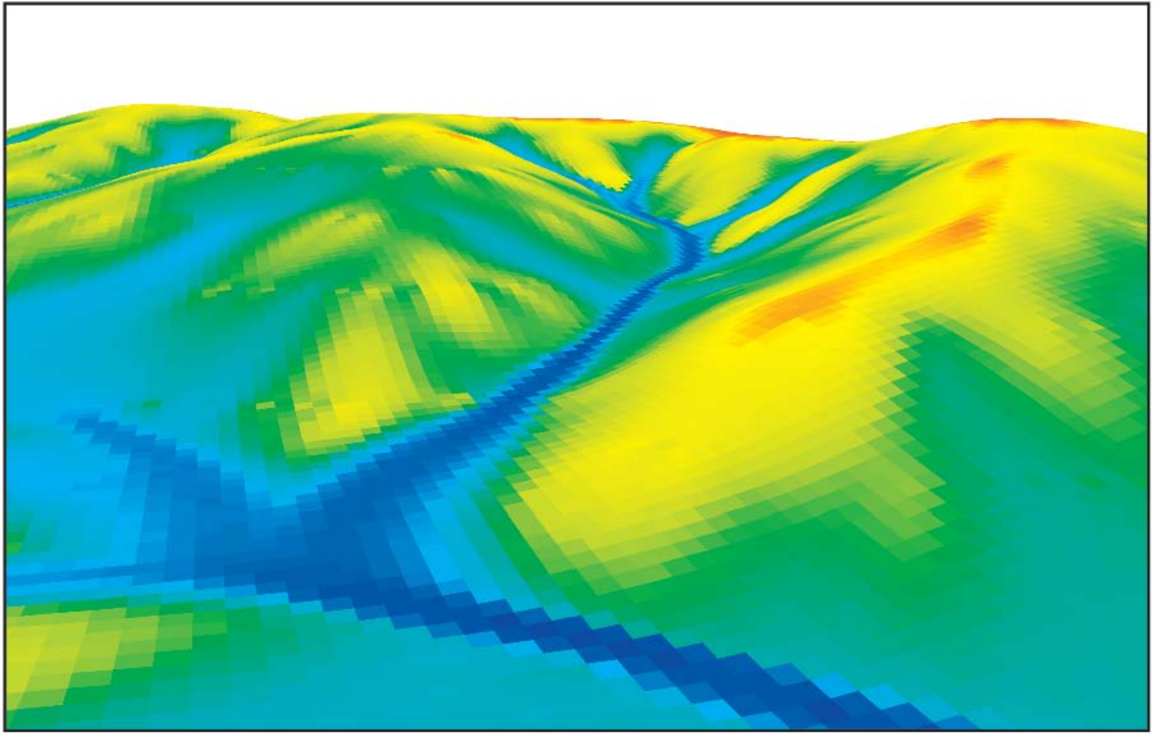


Plate 4 Three-dimensional view of the DEM in Figure 5 of Chapter 9 overlaid with specific catchment area.

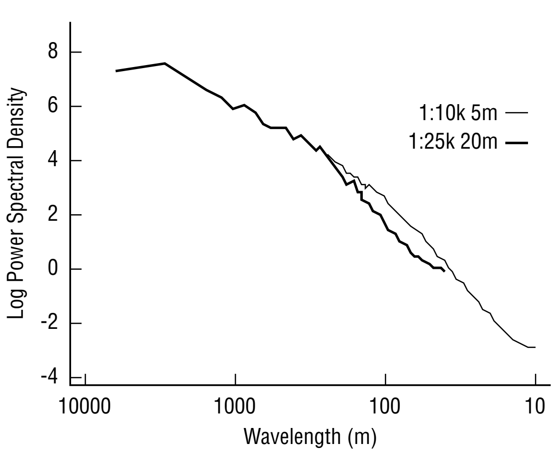


Fig 7. Terrain power spectra for DEMs at 5-m and 20-m horizontal resolutions.

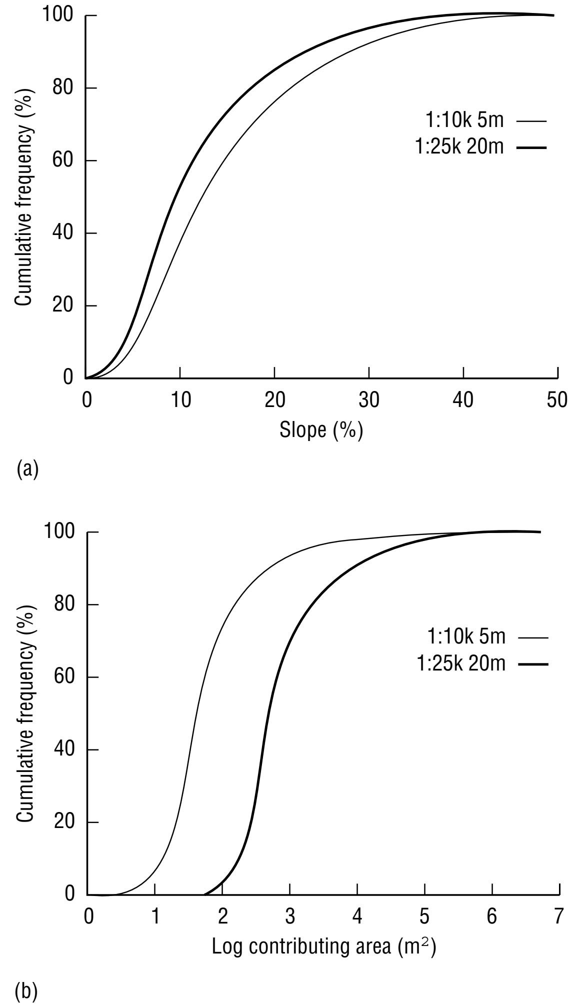


Fig 8. Cumulative distributions of terrain parameters derived from DEMs with horizontal resolutions of 5 and 20 metres: (a) slope; and (b) specific catchment area.

The sensitivity of terrain parameters to DEM resolution has been demonstrated by Moore et al (1993). As DEM resolution becomes coarser, surface detail is lost, leading to reduced slopes and curvatures, and an increasingly simplified drainage network. This behaviour must be considered when using terrain parameters to represent landscapes in applications. In view of the absence of a satisfactory theory of scale dependence, comparisons between different landscapes are feasible only when the terrain surfaces are represented at the same resolution. The effects of changing DEM resolution and source-data scale on the cumulative distributions of slope and specific catchment area are shown in Figure 8.

4.3 Features

Three methods of dissecting the landscape into area features are described. Further classifications of landscapes into line and area features related to surface hydrology are described by Band (Chapter 37).

4.3.1 Catchments and sub-catchments

Catchments and sub-catchments form natural hierarchical dissections of landscapes. They can be readily calculated from DEMs, across a wide range of spatial scales, provided the DEMs represent surface drainage accurately. In contrast to many terrain parameters, they are robustly defined with respect to DEM resolution. Figure 9 shows a catchment determined from two coarse-scale continent-wide DEMs, with resolutions of 1/40th and 1/20th degree (approximately 2.5 and 5 kilometres). The two boundaries are in close agreement with the boundary determined from the 250-m-resolution DEM used to produce Figure 10.

Sub-catchments also form a natural unit for modelling and characterising biological and hydrological activity. Grouping environmental attributes across sub-catchments can greatly reduce model complexity, typically by around two orders of magnitude (Lewis et al 1991). The sub-catchments in Figure 10 were calculated using the technique of Jenson and Domingue (1988) to contain a minimum of 200 grid cells.

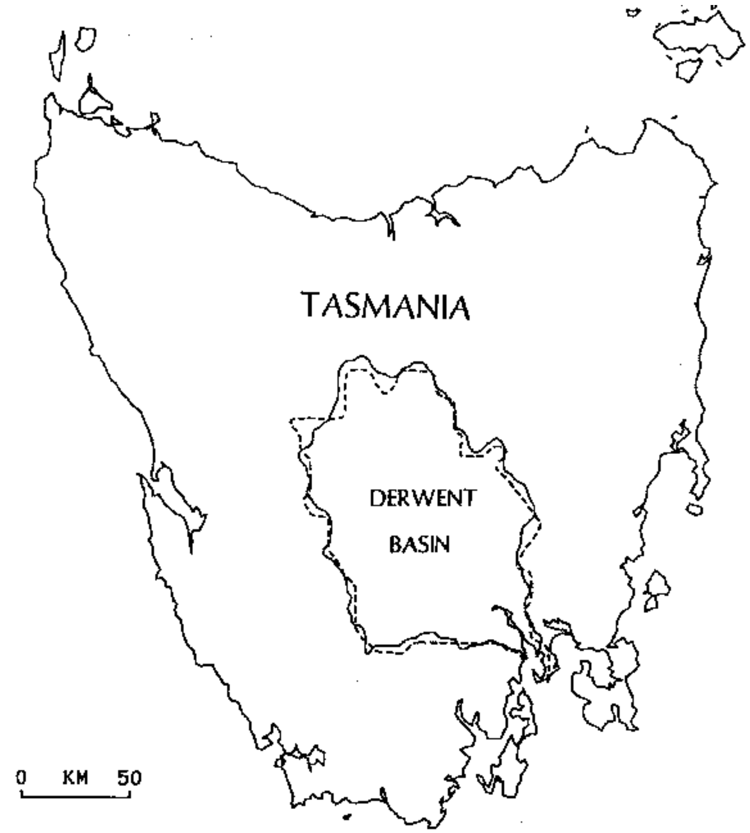


Fig 9. The Derwent River catchment of Tasmania, after Figure 2 of Hutchinson and Dowling (1991). The solid line denotes the boundary calculated from a 1/40th-degree DEM. The dashed line denotes the boundary calculated from a 1/20th-degree DEM.

4.3.2 Contour-flowline networks

Terrain surfaces can be dissected into small essentially planar elements bounded by contour lines and flow-lines (Moore et al 1988). This produces a natural discretisation of the landscape that reflects the convergence and divergence of surface water flow. This structure simplifies hydrological analyses, which become essentially 1-dimensional on each flow element. An efficient distributed-parameter dynamic hydrological model based on this structure has been developed by Grayson et al (1995).

Figure 11 shows a network of elements derived from contours using the TAPES-C program (Moore and Grayson 1991). The TOPOG program (Vertessy et al 1993) operates in a similar fashion. The elements are constructed by taking fixed-size steps along the lowest contour and successively connecting flow-lines to the next-highest contours. The flow-lines are ideally orthogonal to every contour and follow the line of steepest descent across the landscape. In practice, straight line segments are used so the segments tend not to be orthogonal to contours at both ends, particularly where the contours are sharply curved. Hilltops and saddle points must be carefully specified to provide the connectivity required by the model (Dawes and Short 1994).

Current methods for defining the elements are stable for divergent topography, where flow-lines converge in the uphill direction, but unstable for convergent topography where flow-lines converge downhill. The construction of flow-lines in valley bottoms is therefore difficult and frequently produces large and uneven elements. Contour data often need to be augmented with intermediate contours to produce satisfactory elements.

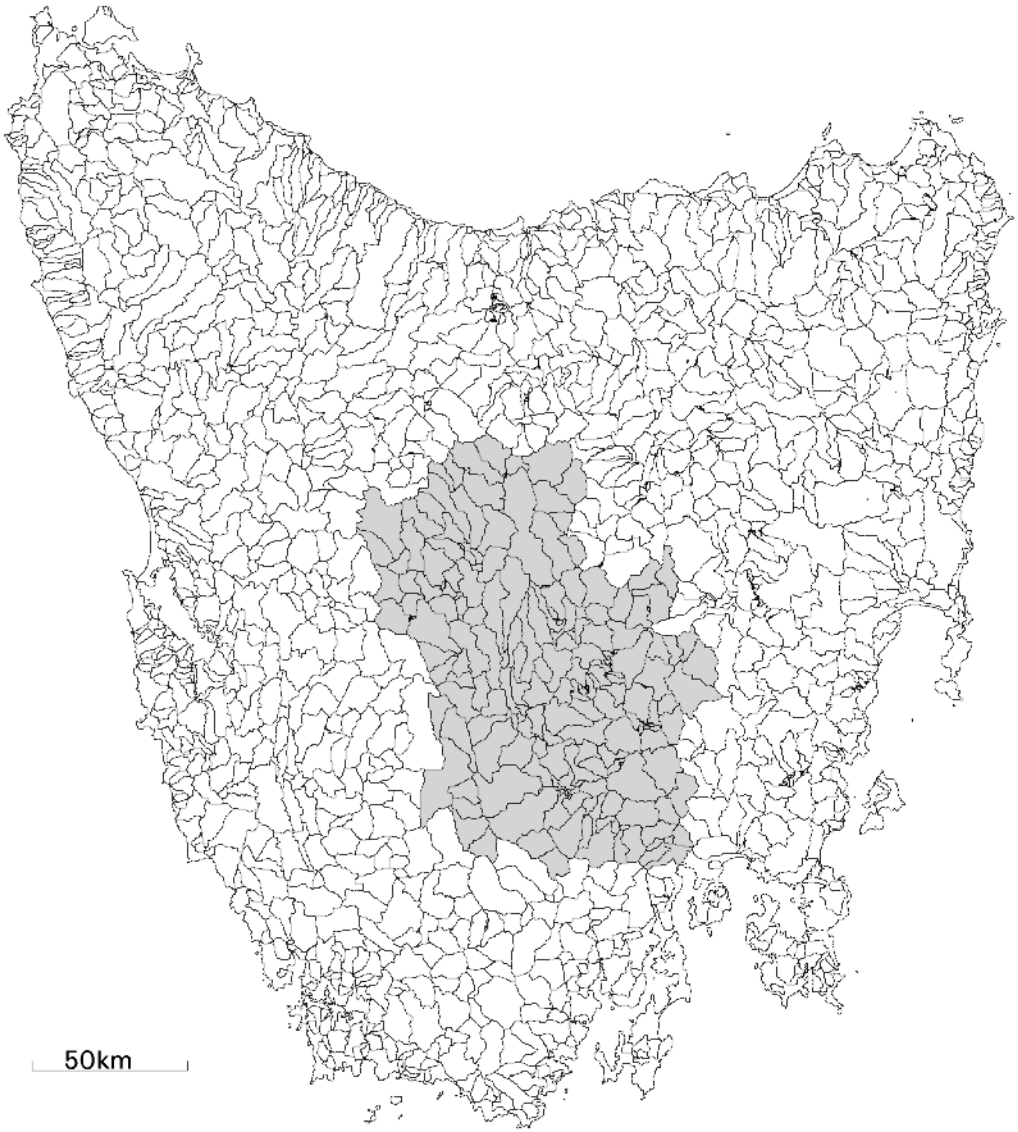


Fig 10. Sub-catchments calculated from a 250-m-resolution DEM for Tasmania overlaid with the Derwent catchment shown in Figure 9.

Because of these difficulties the method is usually restricted to well-defined catchments with limited interior complexity.

4.3.3 Multi-scale feature model

The extraction of particular topographic features from surface representations, usually grid DEMs or contour maps, has received attention from many authors, including Band (1986), Graff and Usery (1993), O'Callaghan and Mark (1984), Speight (1974), and Tribe (1992). However, there have been few attempts to automate an explicit representation of terrain using such features. A method inspired by wavelet methods and the shortcomings of fractal analysis has been developed by Gallant and Hutchinson (1996). It represents terrain as a

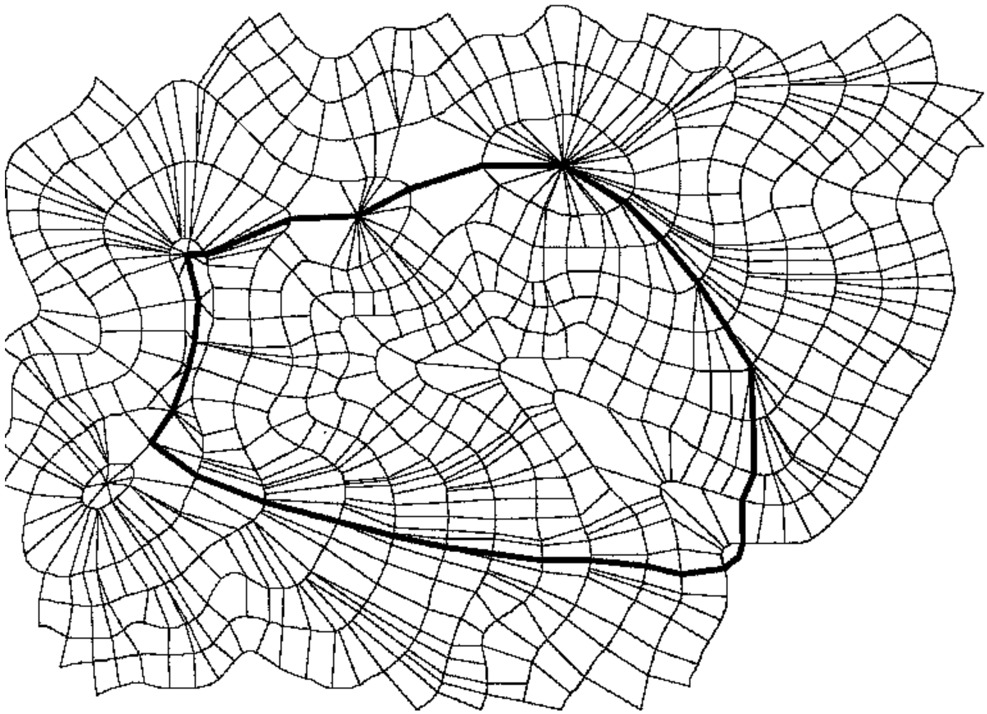


Fig 11. Finite elements bounded by refined contours and flow-lines for the area shown in Figure 2.

collection of features at different scales. These features differ from sub-catchment and contour-based features in having overlapping elliptical coverages. They have a bell-shaped profile form that blends smoothly to zero at the feature boundary.

Each feature is specified by six parameters describing spatial location, length, width as a fraction of length, orientation, and height, which may be negative. A grid DEM can be decomposed into these features using an iterative technique that repeatedly detects features, using the wavelet-based correlation-detection algorithm developed by Watson and Jones (1993), to remove them from the surface and detect new features from the residual surface.

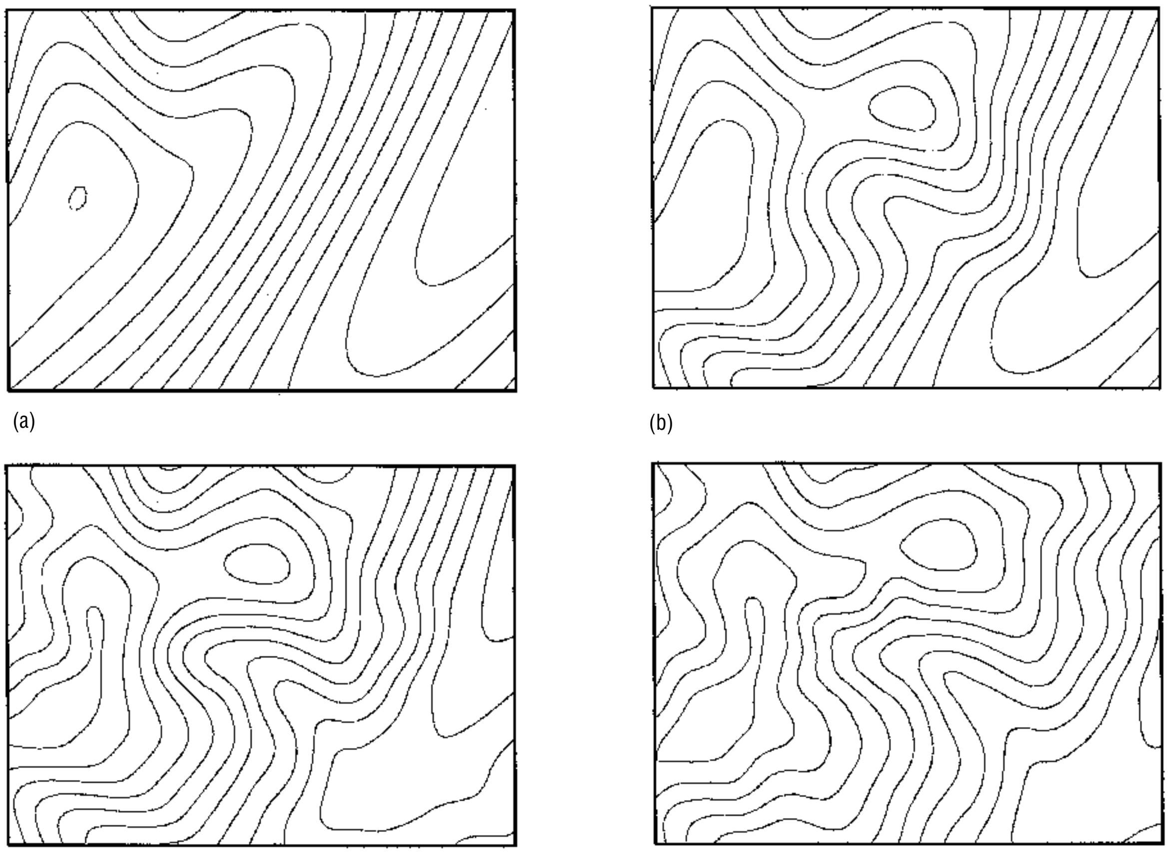
Figure 12 illustrates this technique with a progressively-refined representation of the catchment shown in Figure 5. The four broadest-scale features define a ridge and valley within which the catchment is embedded. Adding further features improves the representation of topographic structure until detailed catchment structure is represented using just 34 features. This representation uses fewer parameters than the TIN shown in Figure 4, but provides a more accurate representation of surface shape.

The particular value of this representation is that the length and height parameters capture scale directly, facilitating study of the scaling properties of terrain and of the connections between scale and shape. The representation permits generalisation of the surface by removal of fine-scale features, and refinement of particular areas by addition of new features based on additional site data. These features may also be used to obtain information about shape and orientation of the terrain surface.

5 SCALES OF APPLICATIONS OF DEMS IN ENVIRONMENTAL MODELLING

Steyaert (1993) and others have recognised the need to identify appropriate scales for modelling various Earth-surface processes and the need for effective methods to integrate data and analyses across different scales. Accordingly, applications of grid DEMs in environmental modelling are best described in relation to their spatial resolution.

The finest DEM spatial resolutions, from 5 to 50 metres, are typically used for spatially-distributed



(a) (b) (c) (d)

Fig 12. Progressively refined positive wavelet feature analysis of the DEM shown in Figure 5: (a) 4 features; (b) 7 features; (c) 18 features; and (d) 34 features.

hydrological modelling (Binley and Beven 1992; Zhang and Montgomery 1994) and analysis of soil properties (Gessler et al 1996). The determination of appropriate spatial scales for hydrological modelling is an active research issue (Blöschl and Sivaplan 1995). DEMs at this scale can also be used to make aspect-based corrections to remotely-sensed data (Ekstrund 1996; Hinton 1996). These applications are distinguished by their dependence on accurate representation of terrain shape.

Fine mesoscale or 'toposcale' DEMs, with spatial resolutions from 50 to 200 metres, are used to model aspect-related microclimatic variations, particularly in solar radiation, evaporation, and associated vegetation patterns (Mackey 1996; Wigmosta et al 1994). This scale is appropriate for broader-scale distributed-parameter hydrological models which incorporate remotely-sensed land-cover data (Kite 1995). It is also appropriate for defining sub-catchment units for lumped-parameter hydrological models and assessments of biodiversity (Lewis et al 1991).

Mesoscale DEMs, with spatial resolutions from 200 metres to 5 kilometres, are appropriate for topographically-dependent representations of surface temperature and rainfall, key determinants of biological activity. For these variables elevation is more important than surface shape, giving rise to temperature and precipitation elevation lapse rates, so that the spatial distributions of these variables are truly 3-dimensional. Precipitation is best described by a model which permits spatially-varying elevation lapse rates (Hutchinson 1995), as illustrated in Plate 5. There are secondary aspect effects related to prevailing wind directions (Daly et al 1994), and local

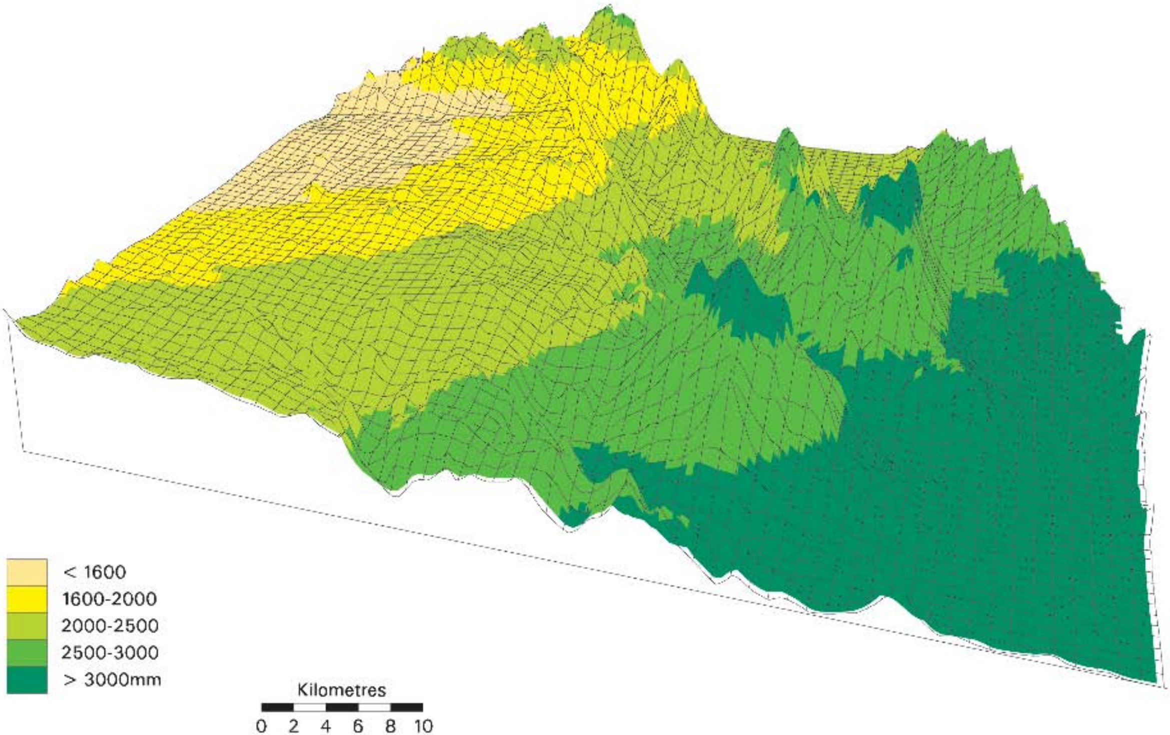


Plate 5 Annual mean precipitation overlaid on a 250-m resolution DEM for an area of length approximately 25 km.

relief at this scale can be used to assist the interpolation of surface windspeeds (Weiringa 1986). This scale is also useful for determining continental-scale drainage structure (Hutchinson and Dowling 1991; Hutchinson et al 1996; Jenson 1991), and for providing fundamental terrain and climatic constraints on agricultural productivity (as discussed by Wilson in Chapter 70).

Macro scales with spatial resolutions from 50 to 500 kilometres are used for broad-scale atmospheric modelling. The DEMs used in these applications are very generalised and accuracy is not critical. Terrain shape is still significant in terms of defining major orographic barriers. DEMs at much finer resolutions are required to distribute the outputs of these broad-scale models spatially (Steyaert 1996).

6 CONCLUSION

This chapter has demonstrated the central role played by representations of terrain in environmental modelling and landscape visualisation. An important theme for providers of source topographic data and DEM interpolation methods is the need by most applications for accurate representations of terrain shape and drainage structure.

This has prompted the development of locally-adaptive process-based interpolation methods and a renewed interest in contour and stream-line data sources which represent surface shape explicitly. Remotely-sensed elevation data sources hold the promise of providing DEMs with global coverage, but filtering methods which respect surface structure and drainage need to be developed to reduce the inherent errors in these data, particularly in areas with low relief.

Spatial scale has become an important issue. The need for multi-scale representations of Earth-surface processes is now recognised, as is the need for representations of terrain to have spatial scales consistent with these processes. The scaling properties of DEMs and various associated terrain parameters have yet to be determined satisfactorily. Spectral analyses of terrain reveal some information about terrain structure, but associated fractal models of scale have been found to have shortcomings. A multi-scale feature model shows promise in incorporating relevant aspects of shape and drainage structure into terrain scale analyses.

References

Ackermann F 1978 Experimental investigation into the accuracy of contouring from DTM. *Photogrammetric Engineering and Remote Sensing* 44: 1537–48

Akima H 1978 A method of bivariate interpolation and smooth surface fitting for irregularly distributed data points. *ACM Transactions on Mathematical Software* 4: 148–59

Auerbach S, Schaeben H 1990 Surface representation reproducing given digitised contour lines. *Mathematical Geology* 22: 723–42

Aumann G, Ebner H, Tang L 1992 Automatic derivation of skeleton lines from digitised contours. *ISPRS Journal of Photogrammetry and Remote Sensing* 46: 259–68

Aurenhammer F 1991 Voronoi diagrams – a survey of fundamental geometric data structure. *ACM Computing Surveys* 23: 345–405

Band L E 1986b Topographic partition of watersheds with digital elevation models. *Water Resources Research* 22: 15–24

Binley A, Beven K 1992 Three-dimensional modelling of hill-slope hydrology. *Hydrological Processes* 6: 347–59

Blöschl G, Sivaplan M 1995 Scale issues in hydrological modelling: a review. *Hydrological Processes* 9: 313–30

Bolstad P V, Stowe T 1994 An evaluation of DEM accuracy: elevation, slope, and aspect. *Photogrammetric Engineering and Remote Sensing* 60: 1327–32

Briggs I C 1974 Machine contouring using minimum curvature. *Geophysics* 39: 39–48

Burrough P A 1981 Fractal dimensions of landscapes and other environmental data. *Nature* 294: 240–2

Carter J R 1988 Digital representations of topographic surfaces. *Photogrammetric Engineering and Remote Sensing* 54: 1577–80

Clarke A L, Grün A, Loon J C 1982 The application of contour data for generating high fidelity grid digital elevation models. *Proceedings AutoCarto 5*. Falls Church, ASPRS: 213–22

Clarke K C 1990 *Analytical and computer cartography*. Englewood Cliffs, Prentice-Hall

Cole G, MacInnes S, Miller J 1990 Conversion of contoured topography to digital terrain data. *Computers and Geosciences* 16: 101–9

Daly C, Neilson R P, Phillips D L 1994 A statistical-topography model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology* 33: 140–58

Dawes W, Short D 1994 The significance of topology for modelling the surface hydrology of fluvial landscapes. *Water Resources Research* 30: 1045–55

Day T, Muller J-P 1988 Quality assessment of digital elevation models produced by automatic stereo matchers from SPOT image pairs. *International Archives of Photogrammetry and Remote Sensing* 27: 148–59

Dixon T H 1991 An introduction to the global positioning system and some geological applications. *Reviews of Geophysics* 29: 249–76

Dixon T H (ed.) 1995 *SAR interferometry and surface change detection*. RSMAS Technical Report TR 95-003, University of Miami

Douglas D H 1986 Experiments to locate ridges and channels to create a new type of digital elevation model. *Cartographica* 23: 29–61

Ebner H, Reinhardt W, Hössler R 1988 Generation, management and utilisation of high-fidelity digital terrain models. *International Archives of Photogrammetry and Remote Sensing* 27: 556–65

Ekstrund S 1996 Landsat TM-based forest damage assessment: correction for topographic effects. *Photogrammetric Engineering and Remote Sensing* 62: 151–61

Franke R 1982b Smooth interpolation of scattered data by local thin plate splines. *Computers and Mathematics with Applications* 8: 273–81

Frederiksen P, Jacobi O, Kubik K 1985 A review of current trends in terrain modelling. *ITC Journal* 1985: 101–6

Gallant J C, Hutchinson M F, Moore I D, Gessler P E 1994 Estimating fractal dimensions: an empirical approach. *Mathematical Geology* 26: 455–81

Gallant J C, Hutchinson M F 1996 Towards an understanding of landscape scale and structure. *Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modelling*. Santa Barbara, NCGIA. CD

Garbrecht J, Starks P 1995 Note on the use of USGS level 1 7.5-minute DEM coverages for landscape drainage analyses. *Photogrammetric Engineering and Remote Sensing* 61: 519–22

Gessler P E, McKenzie N J, Hutchinson M F 1996 Progress in soil-landscape modelling and spatial prediction of soil attributes for environmental models. *Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modelling*. Santa Barbara, NCGIA. CD

Giles P T, Franklin S E 1996 Comparison of derivative topographic surfaces of a DEM generated from stereographic SPOT images with field measurements. *Photogrammetric Engineering and Remote Sensing* 62: 1165–71

Goodchild M F, Mark D M 1987 The fractal nature of geographic phenomena. *Annals of the Association of American Geographers* 77: 265–78

Graff L H, Usery E L 1993 Automated classification of generic terrain features in digital elevation models. *Photogrammetric Engineering and Remote Sensing* 59: 1409–17

Grayson R B, Blöschl G, Moore I D 1995 Distributed parameter hydrologic modelling using vector elevation data: Thales and TAPES-C. In Singh V P (ed.) *Computer models of watershed hydrology*. Highland Ranch, Water Resources Publications: 669–96

Harding D J, Bufton J L, Frawley J 1994 Satellite laser altimetry of terrestrial topography: vertical accuracy as a function of surface slope, roughness, and cloud cover. *IEEE Transactions on Geoscience and Remote Sensing* 32: 329–39

Heller M 1990 Triangulation algorithms for adaptive terrain modelling. *Proceedings, Fourth International Symposium on Spatial Data Handling*. Columbus, International Geographical Union: 163–74

Hinton J C 1996 GIS and remote sensing integration for environmental applications. *International Journal of Geographical Information Systems* 10: 877–90

Hobbs F 1995 The rendering of relief images from digital contour data. *The Cartographic Journal* 32: 111–16

Hunter G J, Goodchild M F 1995b Dealing with error in spatial databases: a simple case study. *Photogrammetric Engineering and Remote Sensing* 61: 529–37

Hutchinson M F 1988 Calculation of hydrologically sound digital elevation models. *Proceedings, Third International Symposium on Spatial Data Handling.* Columbus, International Geographical Union: 117–33

Hutchinson M F 1989 A new procedure for gridding elevation and streamline data with automatic removal of spurious pits. *Journal of Hydrology* 106: 211–32

Hutchinson M F 1991 The application of thin plate smoothing splines to continent-wide data assimilation. In Jasper J D (ed.) *Data assimilation systems*. BMRC Research Report No. 27. Melbourne, Bureau of Meteorology: 104–13

Hutchinson M F 1995b Stochastic space-time weather models from ground-based data. *Agricultural and Forest Meteorology* 73: 237–64

Hutchinson M F 1996 A locally adaptive approach to the interpolation of digital elevation models. *Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modelling*. Santa Barbara, NCGIA. CD

Hutchinson M F, Dowling T I 1991 A continental hydrological assessment of a new grid-based digital elevation model of Australia. *Hydrological Processes* 5: 45–58

Hutchinson M F, Gessler P E, Xu T, Gallant J C 1997 Filtering Wagga TOPSAR data to improve drainage accuracy. In Milne A K (ed.) *Proceedings, International Workshop on Radar Image Processing and Applications*. Canberra, CSIRO: 80–3

Hutchinson M F, Nix H A, McMahon J P, Ord K D 1996 The development of a topographic and climate database for Africa. *Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modelling*. Santa Barbara, NCGIA. CD

Jenson S K 1991 Applications of hydrologic information automatically extracted from digital elevation models. *Hydrological Processes* 5: 31–44

Jenson S K, Domingue J O 1988 Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric Engineering and Remote Sensing* 54: 1593–1600

Kelly R E, McConnell P R H, Mildenberger S J 1977 The Gestalt photomapping system. *Photogrammetric Engineering and Remote Sensing* 43: 1407–17

Kite G W 1995 The SLURP model. In Singh V P (ed.) *Computer models of watershed hydrology*. Highland Ranch, Water Resources Publications: 521–62

Konecny G, Lohmann P, Engel H, Kruck E 1987 Evaluation of SPOT imagery on analytical instruments. *Photogrammetric Engineering and Remote Sensing* 53: 1223–30

Lanari R, Fornaro G, Riccio D, Migliaccio M, Papathanassiou K, Moreira J, Schwabisch M, Dutra L, Puglisi G, Franceschetti G, Coltelli M 1997 Generation of digital elevation models by using SIR-C/X-SAR multifrequency two-pass interferometry: the Etna case study. *IEEE Transactions on Geoscience and Remote Sensing* 34: 1097–114

Lee J 1991 Comparison of existing methods for building triangular irregular network models of terrain from grid digital elevation models. *International Journal of Geographical Information Systems* 5: 267–85

Legates D R, Willmott C J 1986 Interpolation of point values from isoline maps. *The American Cartographer* 13: 308–23

Lemmens M J P M 1988 A survey on stereo matching techniques. *International Archives of Photogrammetry and Remote Sensing* 27: V11–V23

Lewis A, Stein J L, Stein J A, Nix H A, Mackey B G, Bowyer J K 1991 *An assessment of regional conservation adequacy: Tasmania*. Forestry and Timber Inquiry Consultancy Series No. FTC91/17. Canberra, Resource Assessment Commission

Mackey B G 1996 The role of GIS and environmental modelling in the conservation of biodiversity. *Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modelling*. Santa Barbara, NCGIA. CD

Makarovic B 1984 Structures for geo-information and their application in selective sampling for digital terrain models. *ITC Journal* 1984: 285–95

Mandelbrot B B 1977 *Fractals: form, chance, and dimension*. San Francisco, Freeman

Mark D M 1986 Knowledge-based approaches for contour-to-grid interpolation on desert pediments and similar surfaces of low relief. *Second International Symposium on Spatial Data Handling*. Columbus, International Geographical Union: 225–34

Mark D M, Aronson P B 1984 Scale-dependent fractal dimensions of topographic surfaces: an empirical investigation with application to geomorphology and computer mapping. *Mathematical Geology* 16: 671–83

McCullagh M J 1988 Terrain and surface modelling systems: theory and practice. *Photogrammetric Record* 12: 747–79

Mitasova H, Hofierka J, Zlocha M, Iverson L 1996 Modelling topographic potential for erosion and deposition using GIS. *International Journal of Geographical Information Systems* 10: 629–41

Mitasova H, Mitas L 1993 Interpolation by regularised spline with tension: I. Theory and implementation. *Mathematical Geology* 25: 641–55

Moore I D, Grayson R B 1991 Terrain-based catchment partitioning and runoff prediction using vector elevation data. *Water Resources Research* 27: 1177–91

Moore I D, Grayson R B, Ladson A R 1991. Digital terrain modelling: a review of hydrological, geomorphological, and biological application. *Hydrological Processes* 5: 3–30

Moore I D, Lewis A, Gallant J C 1993 Terrain attributes: estimation of scale effects. In Jakeman A J, Beck M B, McAleer M (eds) *Modelling change in environmental systems*. New York, John Wiley & Sons Inc.: 189–214

Moore I D, O'Loughlin E M, Burch G J 1988 A contour-based topographic model for hydrological and ecological applications. *Earth Surface Processes and Landforms* 13: 305–20

Mulla D J 1988 Using geostatistics and spectral analysis to study spatial patterns in the topography of southeastern Washington State, USA. *Earth Surface Processes and Landforms* 13: 389–405

Nix H A 1986 A biogeographic analysis of Australian elapid snakes. In Longmore R (ed.) *Atlas of elapid snakes of Australia*. Australian Flora and Fauna Series No.7. Canberra, Australian Government: 4–15

O'Callaghan J F, Mark D M 1984 The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics, and Image Processing* 28: 323–44

Oliver M A, Webster R 1986 Semi-variograms for modelling the spatial pattern of landform and soil properties. *Earth Surface Processes and Landforms* 11: 491–504

Oswald H, Raetzsch H 1984 A system for generation and display of digital elevation models. *Geo-Processing* 2: 197–218

Pike R J, Rozema W J 1975 Spectral analysis of landforms. *Annals of the Association of American Geographers* 65: 499–516

Pries R A 1995 A system for large-scale image mapping and GIS data collection. *Photogrammetric Engineering and Remote Sensing* 61: 503–11

Quinn P F, Beven K J, Chevallier P, Planchon O 1991 The prediction of hill-slope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological Processes* 5: 59–79

Running S W, Thornton P E 1996 Generating daily surfaces of temperature and precipitation over complex topography. In Goodchild M F, Steyaert L T, Parks B O, Johnston C, Maidment D, Crane M, Glendinning S (eds) *GIS and environmental modelling: progress and research issues*. Fort Collins, GIS World Books: 93–8

Sambridge M, Braun J, McQueen H 1995 Geophysical parameterisation and interpolation of irregular data using natural neighbours. *Geophysical Journal International* 122: 837–57

Sasowsky K C, Peterson G W, Evans B M 1992 Accuracy of SPOT digital elevation model and derivatives: utility for Alaska's North Slope. *Photogrammetric Engineering and Remote Sensing* 60: 1327–32

Sibson R 1981 A brief description of natural neighbour interpolation. In Barnett V (ed.) *Interpreting multivariate data*. Chichester, John Wiley & Sons: 21–36

Smith W H F, Wessel P 1990 Gridding with continuous curvature. *Geophysics* 55: 293–305

Speight J G 1974 A parametric approach to landform regions. *Special Publication Institute of British Geographers* 7: 213–20

Speight J G 1980 The role of topography in controlling throughflow generation: a discussion. *Earth Surface Processes and Landforms* 5: 187–91

Steyaert L T 1993 A perspective on the state of environmental simulation modelling. In Goodchild M F, Parks B O, Steyaert L T (eds) *Environmental modelling with GIS.* New York, Oxford University Press: 16–30

Steyaert L T 1996 Status of land data for environmental modelling and challenges for geographic information systems in land characterisation. In Goodchild M F, Steyaert L T, Parks B O, Johnston C, Maidment D, Crane M, Glendinning S (eds) *GIS and environmental modelling: progress and research issues*. Fort Collins, GIS World Inc.: 17–27

Tribe A 1992 Problems in automated recognition of valley features from digital elevation models and a new method toward their resolution. *Earth Surface Processes and Landforms* 17: 437–54

Tsai V 1993 Delaunay triangulations in TIN creation: an overview and linear-time algorithm. *International Journal of Geographical Information Systems* 7: 501–24

Verdin K L, Jenson S K 1996 Development of continental scale digital elevation models and extraction of hydrographic features. *Proceedings, Third International Conference/ Workshop on Integrating GIS and Environmental Modelling*. Santa Barbara, NCGIA. CD

Vertessy R A, Hatton T J, O'Shaugnessy P J, Jayasuroya M D A 1993 Predicting water yield from a mountain ash forest catchment using a terrain analysis based catchment model. *Journal of Hydrology* 150: 665–700

Watson D F, Philip G M 1984 Triangle based interpolation. *Mathematical Geology* 16: 779–95

Watson G H, Jones J G 1993 Positive wavelet representation of fractal signals and images. In Crilly A J, Earnshaw R A, Jones H (eds) *Applications of fractals and chaos*. Berlin, Springer-Verlag: 117–35

Weibel R, Heller M 1991 Digital terrain modelling. In Maguire D J, Goodchild M F, Rhind D W (eds) *Geographical information systems: principles and applications*. Harlow, Longman/New York, John Wiley & Sons Inc. Vol. 1: 269–97

Weiringa J 1986 Roughness-dependent geographical interpolation of surface wind speed averages. *Quarterly Journal of the Royal Meteorological Society* 112: 867–89

Wigmosta M S, Vail L W, Lettenmaier D P 1994 A distributed hydrology-vegetation model for complex terrain. *Water Resources Research* 30: 1665–79

Wilson J P, Gallant J C 1997 Terrain-based approaches to environmental resource evaluation. In Lowe S N, Richards K S, Chandler J H (eds) *Landform monitoring, modelling and analysis*. Chichester, John Wiley & Sons: 219–40

Wise S 1997 The effect of GIS interpolation errors on the use of digital elevation models in geomorphology. In Lowe S N, Richards K S, Chandler J H (eds) *Landform monitoring, modelling, and analysis*. Chichester, John Wiley & Sons: Chapter 7

Zebker H A, Werner C, Rosen P A, Hensley S 1994 Accuracy of topographic maps derived from ERS-1 interferometric radar. *IEEE Transactions on Geoscience and Remote Sensing* 32: 823–36

Zevenbergen L W, Thorne C R 1987 Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms* 12: 47–56

Zhang W, Montgomery D R 1994 Digital elevation model grid size, landscape representation, and hydrologic simulation. *Water Resources Research* 30: 1019–28