CHAPTER 2

Digital Elevation Models and Representation of Terrain Shape

Michael F. Hutchinson and John C. Gallant

2.1 INTRODUCTION

Terrain plays a fundamental role in modulating earth surface and atmospheric processes. This linkage is so strong that an understanding of the nature of terrain can directly confer understanding of the nature of these processes, in both subjective and analytical terms. It is therefore natural to place representations of terrain, in the form of digital elevation models (DEMs), at the center of the flow chart shown in Figure 2.1, reproduced from Hutchinson and Gallant (1999). This flow chart shows DEMs to be at the center of interactions between source data capture and applications. These interactions are supported by DEM generation methods and a steadily increasing range of techniques for DEM interpretation and visualization. Visualization techniques are often used to support interpretations of DEMs and to assess data quality.

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 match the natural scales of terrain-dependent applications. The spatial resolution of a regular-grid DEM can provide a practical index of scale, as well as a measure of information content (Hutchinson 1996). The determination of appropriate scales for hydrological modeling is an active research issue (Zhang and Montgomery 1994, Blöschl and Sivaplan 1995). Incorporation of terrain structure into considerations of spatial scale is also an emerging issue in terrain analysis (Gallant and Hutchinson 1996).

The range of spatial scales of hydro-ecological applications of DEMs and the corresponding common primary topographic data sources are indicated in Table 2.1. Here, DEM resolution is used as an index of scale. The general trend has been to move from broader continental and regional scales, closely allied to the representation of major drainage divisions (Jenson 1991, Hutchinson and Dowling 1991), to

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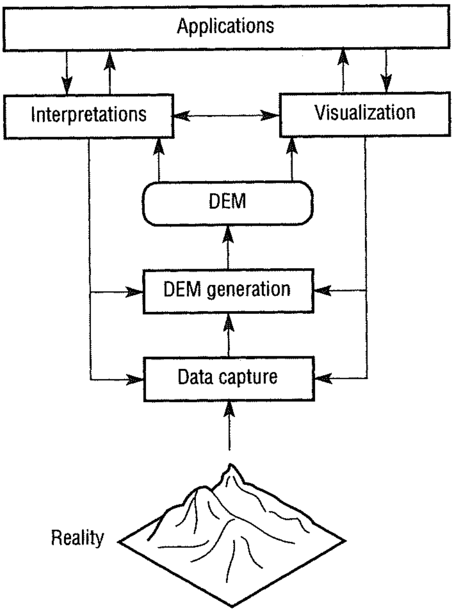


Figure 2.1. The main tasks associated with digital terrain modeling.

mesoscale representations of surface climate (Hutchinson 1995, 1998, Running and Thornton 1996, Daly et al. 1994) and associated flora and fauna (Nix 1986), to finer toposcales suited to the modeling of surface hydrology, vegetation, and soil properties (I. D. Moore et al. 1991, Quinn et al. 1991, Mackey 1996, Gessler et al. 1996, Zhang and Montgomery 1994). This has been accompanied by improvements in methods for representing fine-scale shape and structure of DEMs, supported by the steady increase in the capacity of computing platforms. These finer scale applications are the main focus of this book. At the same time, coarser scale processes, particularly mesoscale climate, can have a significant impact on the spatial distribution of hydrological and ecological processes.

There is naturally some overlap between the divisions shown in Table 2.1, but there is a genuine distinction between fine and coarse toposcale, in terms of common topographic data sources and in terms of modeling applications. Of the applications listed, only representations of surface temperature and rainfall have a direct dependence on elevation. All others depend on measures of surface shape and roughness, as exemplified by the primary and secondary terrain attributes listed in Chapter 1. This underlies the importance of DEMs providing accurate representations of surface shape and drainage structure. This is particularly so in low-relief areas where elevations must be recorded with submeter precision to accurately reflect small elevation gradients.

Though actual terrain can vary across a wide range of spatial scales, in practice, source topographic data are commonly acquired at a particular scale. This places practical limits on the range of DEM resolutions that can be truly supported by a par-

TABLE 2.1 Spatial Scales of Applications of Digital Elevation Models (DEMs) and Common Sources of Topographic Data for Generation of DEMs

Scale	DEM Resolution	Common Topographic Data Sources	Hydrological and Ecological Applications
Fine toposcale	5–50 m	Contour and stream-line data from aerial photography and existing topographic maps at scales from 1:5,000 to 1:50,000 Surface-specific point and stream-line data obtained by ground survey using GPS Remotely sensed elevation data using airborne and spaceborne radar and laser	Spatially distributed hydrological modeling Spatial analysis of soil properties Topographic aspect corrections to remotely sensed data Topographic aspect effects on solar radiation, evaporation, and vegetation patterns
Coarse toposcale	50–200 m	Contour and stream-line data from aerial photography and existing topographic maps at scales from 1:50,000 to 1:200,000 Surface-specific point and stream-line data digitized from existing topographic maps at 1:100,000 scale	Broader scale distributed parameter hydrological modeling Subcatchment analysis for lumped parameter hydrological modeling and assessment of biodiversity
Mesoscale	200 m–5 km	Surface-specific point and stream-line data digitized from existing topographic maps at scales from 1:100,000 to 1:250,000	Elevation-dependent representations of surface temperature and precipitation Topographic aspect effects on precipitation Surface roughness effects on wind Determination of continental drainage divisions
Macroscale	5–500 km	Surface-specific point data digitized from existing topographic maps at scales from 1:250,000 to 1:1,000,000. National archives of ground surveyed topographic data including trigonometric points and benchmarks	Major orographic barriers for general circulation models

Note. DEMs at coarser scales are often obtained by local averaging of finer scale DEM data.

ticular source data set. The following section describes the data sources commonly supporting generation of DEMs at each of the scales listed in Table 2.1. This is followed by an examination of issues arising in the generation of DEMs from these data, including both the quality of source data and the accuracy of generated DEMs. These issues are illustrated by applying the ANUDEM locally adaptive gridding program (Hutchinson 1988, 1989b, 1996) to interpolate digital contours and streamlines, obtained from 1:24,000 scale mapping, to derive the DEM used to calculate the terrain parameters described in Chapters 3 and 4. The choice of DEM resolution is shown to be important in minimizing errors in representation of terrain shape, as measured by various primary terrain attributes, as well as matching the true information content of the source data.

2.2 SOURCES OF TOPOGRAPHIC DATA

Three main classes of source topographic data may be recognized, for which different DEM generation techniques are applicable, as discussed below.

2.2.1 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 gridded DEMs to construct triangulated irregular network (TIN) models (Heller 1990, Lee 1991). The advent of the global positioning system (GPS) has enhanced the availability of accurate ground-surveyed data (Dixon 1991, Lange and Gilbert 1999). Such data are now commonly obtained for detailed surveys of relatively small experimental catchments. They are less often used for larger areas.

2.2.2 Contour and Stream-Line Data

Contour data are still the most common terrain data source for larger areas. Many of these data have been digitized 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 organizations worldwide (Hobbs 1995). Contours can also be generated automatically from photogrammetric stereo models (Lemmens 1988), although these methods are subject to error due to variations in surface cover. A sample contour and stream-line data set, together with some additional point data, is shown in Figure 2.2. 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 undersample the areas between contour lines, especially in areas of low relief, such as the lower right-hand portion of Figure

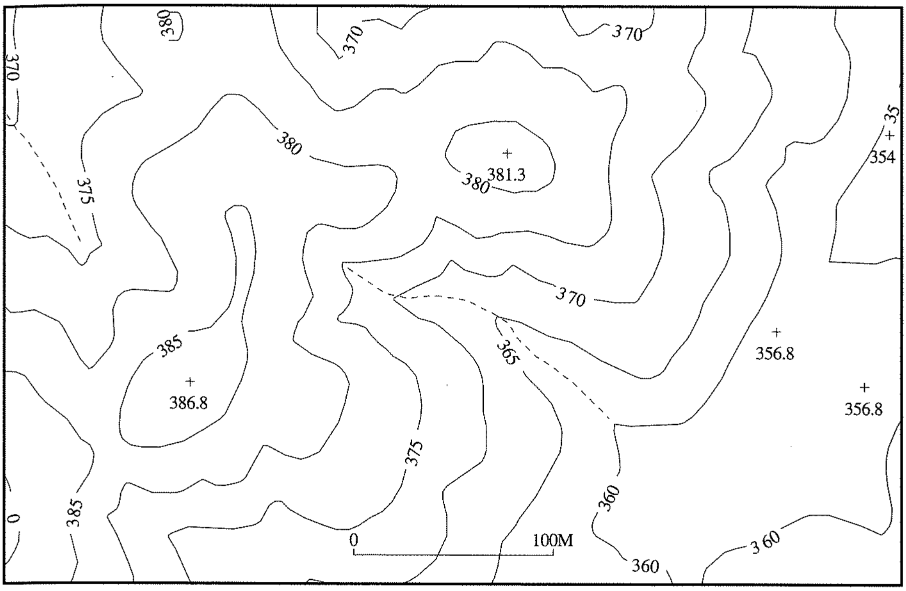


Figure 2.2. Contour, stream, and point elevation data.

2.2. This has led most investigators to prefer contour-specific algorithms over general-purpose algorithms when interpolating contour data (Clarke et al. 1982, Mark 1986).

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.

Streamlines 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, 1989b) can use such streamline data, provided that the stream lines are digitized in the downhill direction. This imposes a significant editing task, which can be achieved by using a Geographic Information System (GIS) with network capabilities.

2.2.3 Remotely Sensed Elevation Data

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

Remote sensing methods can provide broad spatial coverage, but have a number of generic limitations. None of the sensors can reliably measure the ground elevations underneath vegetation cover. Even in the absence of ground cover, all methods measure elevations with significant random errors, which depend on the inherent limitations of the observing instruments, as well as surface slope and roughness (Harding et al. 1994, Dixon 1995). The methods also require accurately located ground control points to minimize 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 meters, but elevation errors can be much larger, up to 100 meters, under unfavorable conditions (Sasowsky et al. 1992, Harding et al. 1994, Zebker et al. 1994, Lanari et al. 1997). Averaging of data obtained from multiple passes of the sensor can reduce these errors, but at greater cost.

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 meters (Dixon 1995). Raw SAR DEMs have occasional large errors and random elevation errors across the whole DEM. They can also have systematic anomalies in the form of spurious ridges along tree-lined watercourses and missing data in areas of topographic shading. Careful filtering and interpolation of such data are required to derive useful representations of surface shape and drainage structure.

2.2.4 Scales of Source Topographic Data

The three main source data types described above may also be characterized according to their usage at different scales, as shown in Table 2.1. Remotely sensed data sources are normally used only at the finest scale. Contour data are normally used at both fine and coarse toposcales. At scales coarser than the toposcale, contour data tend to be too generalized to accurately depict surface shape and drainage structure, and their use at these scales is often supplanted by surface-specific points obtained from coarser scale maps.

Stream lines, at various levels of generalization, are used at all scales except the macroscale, where it is unrealistic to expect DEMs to accurately reflect surface drainage. At this broad scale "happenstance" data, such as benchmarks and trigonometric points recorded in national archives, can be used with profit (Hutchinson and Dowling 1991).

2.3 DEM INTERPOLATION METHODS

Interpolation is required to generate DEMs from surface-specific points and from contour and stream-line data. Since data sets 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 easily adapted 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: triangulation, local surface patches, and locally adaptive gridding. All achieve a degree of local adaptivity to anisotropic terrain structure.

2.3.1 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. Linear interpolation is the simplest case, but a variety of higher order interpolants have been devised to ensure that the interpolated surface has continuous first derivatives (Akima 1978, Sibson 1981, Watson and Philip 1984, Auerbach and Schaeben 1990, Sambridge et al. 1995). Considerable attention has been directed toward methods for constructing the triangulation. The Delauney triangulation is the most popular method and several efficient algorithms have been devised (e.g., Heller 1990, Aurenhammer 1991, Tsai 1993).

Triangulation methods are 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 points are difficult to obtain as primary data. Triangulation methods are sensitive to the positions of the data points and the triangulation needs to be constrained to produce optimal results (Weibel and Heller 1991, Pries 1995). Triangulation methods have difficulties interpolating contour data, which generate many flat triangles, unless additional structural data points along streams and ridges can be provided (Clarke 1990).

2.3.2 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 bivariate spline functions in this way. These methods overcome the computational problems posed by large data sets 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 contour data. An advantage of this method 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.

2.3.3 Locally Adaptive Gridding

Direct gridding or finite difference methods can provide a computationally efficient means of applying high-quality interpolation methods to large elevation data sets. Iterative methods that fit discretized splines in tension have been described by Hutchinson (1989b) and Smith and Wessel (1990). Both methods have their origin in the method developed by Briggs (1974).

Computational efficiency is achieved by using a simple multigrid strategy that optimizes computational time in the sense that it is proportional to the number of interpolated DEM points (Hutchinson 1989b). 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.

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 that have direct relevance for hydrological applications are those imposed by the drainage enforcement algorithm devised by Hutchinson (1989b). 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 that automatically calculates curvilinear 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 that use linear or cubic interpolation along straight lines in a limited number of directions (Clarke et al. 1982, Oswald and Raetzsch 1984, Legates and Willmott 1986, Cole et al. 1990). An analogous approach combining triangulation and grid structures has been described by Aumann et al. (1992).

The result of applying the ANUDEM program (Hutchinson 1997) to the contour, streamline and point data in Figure 2.2 is shown Figure 2.3. The inferred stream and ridge lines are particularly curvilinear in the data sparse, low-relief portion of the map, and there are no spurious depressions. The derived contours also closely match the data contours. This locally adaptive gridding method has overcome problems formerly encountered by gridding methods in accurately representing drainage structure in low-relief areas (Douglas 1986, Carter 1988).

The procedure also yields a generic 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. (1988b) and described in Chapter 3, but they are determined in a more stable manner that incorporates uphill searches on ridges and downhill searches in valleys.

Recent developments in this locally adaptive gridding method include a locally adaptive data smoothing algorithm, which allows for the local slope-dependent

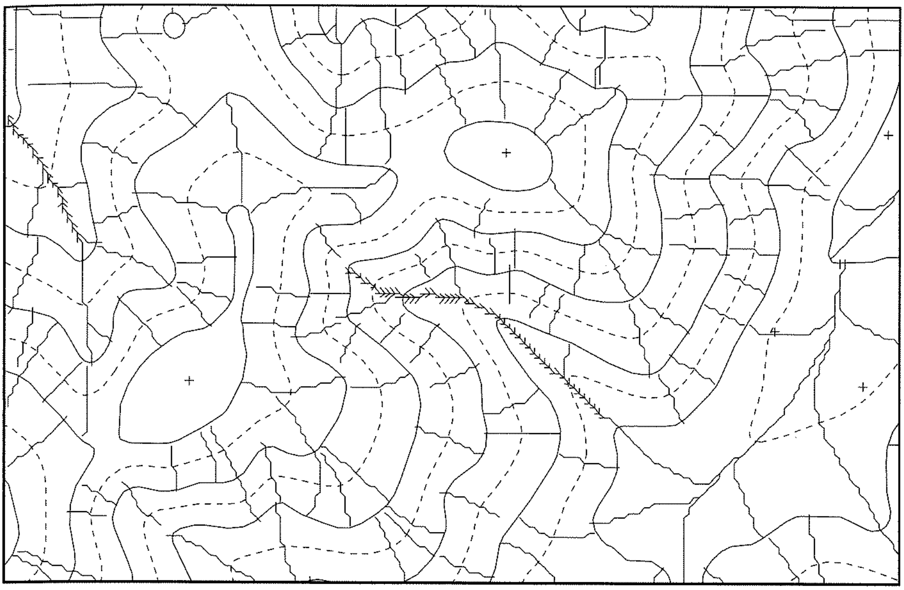


Figure 2.3. Locally adaptive gridding by ANUDEM of the contour, stream, and point data shown in Figure 2.2. Structure lines (ridges and stream lines) are generated automatically by ANUDEM. All contours are derived from the interpolated DEM. Dashed contour lines are shown at elevations midway between the data contour elevations.

errors naturally associated with the finite difference representation of terrain, and a locally adaptive surface roughness penalty, which minimizes profile curvature (Hutchinson 1996). The smoothing method has yielded useful error estimates for gridded DEMs and a criterion for matching grid resolution to the information content of source data.

2.4 FILTERING OF REMOTELY SENSED GRIDDED DEMS

Filtering of remotely sensed gridded DEMs is required to remove surface noise, which can have both random and systematic components. This is usually associated with a coarsening of the DEM resolution. Methods include simple nearest-neighbor subsampling 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 recognized 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-neighbor method to subsample SPOT DEMs, with a spatial resolution of 10 m, to DEMs with spatial resolutions ranging from 20 to 70 m. 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 m and no effective representation of profile curvature could be obtained.

Hutchinson et al. (1997) removed large outliers from airborne SAR data in an area of low relief and then applied moving average smoothing to generate a 50-m-resolution DEM. This provided an accurate representation of surface aspect, except in those areas affected by vegetation cover. Lanari et al. (1997) have applied a Kalman filter to spaceborne SAR data obtained on three different wavelengths. Standard elevation errors ranged between about 5 and 80 m, depending on land surface conditions.

2.5 QUALITY ASSESSMENT OF DEMS

The quality of a derived DEM can vary greatly depending on the source data 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. As indicated in Figure 2.1, 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 nonclassical measures of data quality that offer means of confirmatory data analysis without the use of accurate reference data. Assessment of DEMs in terms of their representation of surface aspect has also been examined by Wise (1998).

2.5.1 Spurious Sinks and Drainage Analysis

Spurious sinks or local depressions in DEMs are frequently encountered and are a significant source of problems in hydrological applications. 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 neighbors. Hutchinson and Dowling (1991) noted the sensitivity of this method in detecting elevation errors as small as 20 m in source data used to interpolate a continentwide DEM with a horizontal resolution of 2.5 km. More subtle drainage artifacts in a DEM can be detected by performing a full drainage analysis to derive catchment boundaries and streamline networks, using the technique of Jenson and Domingue (1988).

2.5.2 Views of Shaded Relief and Other Terrain Attributes

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. 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 slope and aspect in the DEM. Views of other primary terrain attributes, particularly profile curvature, can provide a sensitive assessment of the accuracy of the DEM in representing terrain shape, as discussed in the example in Section 2.8.

2.5.3 Derived Elevation Contours

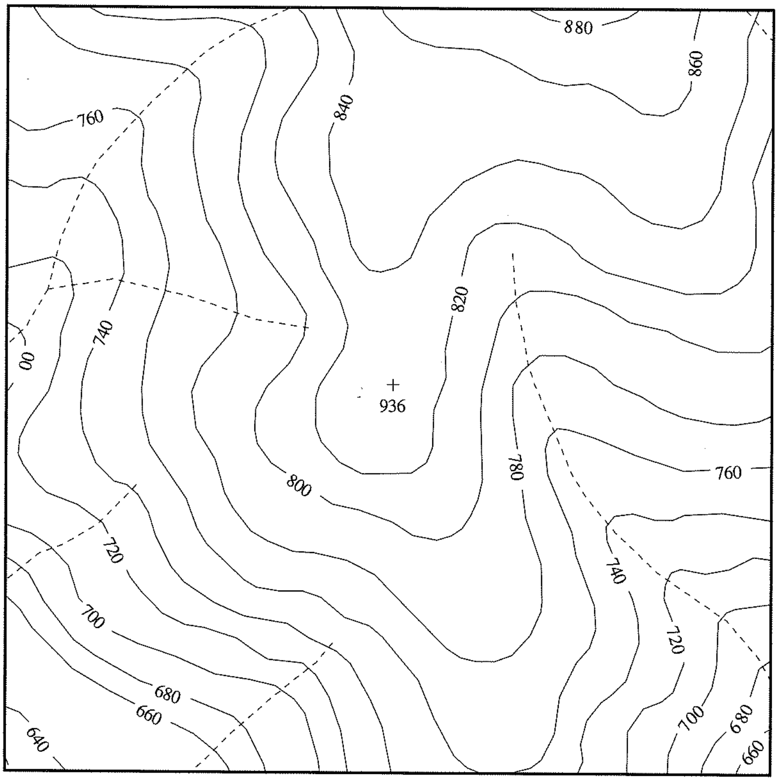
Contours derived from a DEM provide a sensitive check on terrain structure since their position, aspect, and curvature depend directly on the elevation, aspect, and plan curvature, respectively, of the DEM. Derived contours are a particularly useful diagnostic tool because of their sensitivity to elevation errors in source data. Subtle errors in labeling source data contours digitized from topographic maps are common, particularly for small contour isolations, which may have no label on the printed map. A simple example of derived contours indicating a single-point elevation data error is shown in Figure 2.4. It would be difficult to detect this error from only a shaded relief view of the DEM.

2.5.4 Frequency Histograms of Primary Terrain Attributes

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 at the data contour elevations in the elevation histogram. The severity of this bias depends on the interpolation algorithm. Its impact is minimal for applications that depend primarily on drainage analyses that are defined primarily by topographic aspect. The frequency histogram of aspect can be biased toward multiples of 45° and 90° by simpler interpolation algorithms that restrict searching to a few specific directions between pairs of data points.

2.6 OPTIMIZATION OF DEM RESOLUTION

Determination of the appropriate resolution of an interpolated or filtered DEM is usually a compromise between achieving fidelity to the true surface and respecting practical limits related to the density and accuracy of the source data. Determination of the DEM resolution that matches the information content of the source data is desirable for several reasons. It directly facilitates efficient data inventory, since DEM storage requirements are quite sensitive to resolution. It also permits interpre-

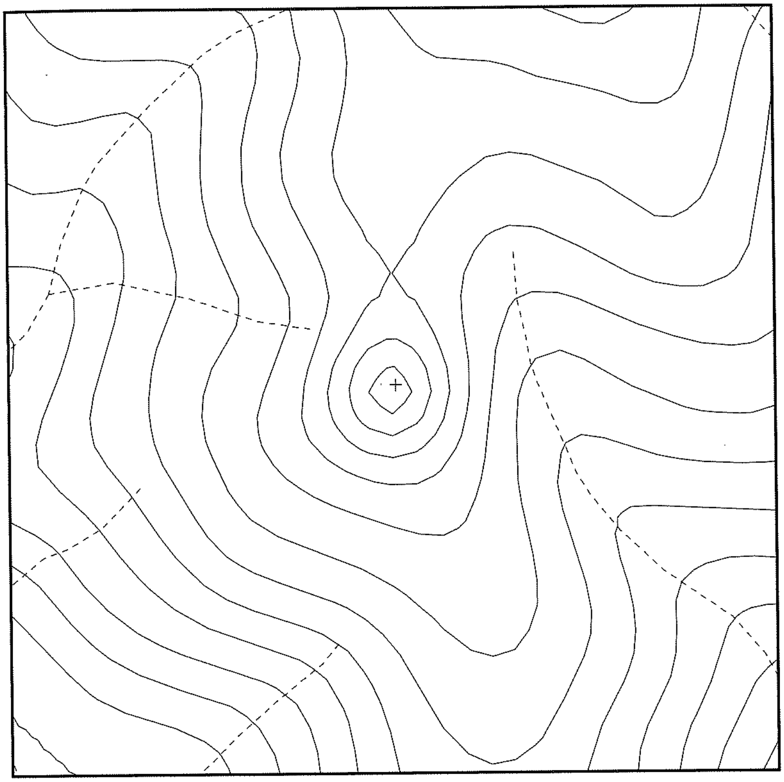


(a)

Figure 2.4. Use of derived contours to detect errors in source data: (a) contour, stream, and point elevation data with one erroneous elevation value; (b) contours derived from a DEM fitted to the erroneous data in (a).

tation of the horizontal resolution of the DEM as an index of information content. This is an important consideration when linking DEMs to other gridded data sets and when filtering remotely sensed DEMs. Moreover, it can facilitate assessment of the scale dependence of terrain-dependent applications, such as the determination of the spatial distributions of soil properties (Gessler et al. 1996).

A simple method for matching DEM resolution to source data information content has been developed by Hutchinson (1996). The method monitors the root mean square slope of all DEM points associated with elevation data as a function of DEM resolution. The optimum resolution is determined by refining the DEM resolution until further refinements produce no significant increase in the root mean square DEM slope. 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. This procedure is used to aid optimization of DEM resolution in the next section.



(b)

Figure 2.4. *(Continued)*

2.7 INTERPOLATION OF THE COTTONWOOD DEM USING ANUDEM

Digital elevation contours and stream-line data were obtained by digitizing 1:24,000 scale topographic maps of the Cottonwood catchment, as shown in Figure 2.5. The area spans approximately 1.4 km west to east, and nearly 3 km north to south. The vertical relief of the catchment, more than 1000 ft, is relatively large. Terrain shape is thus well determined by the elevation contours, which are spaced every 20 ft in the vertical direction. Practical limits on digitizing accuracy are indicated by slight irregularities in position of the closely spaced digitized contours in steeper areas. The lowest slopes are indicated by the more widely spaced contours along stream lines and along ridges defining the catchment boundary.

The ANUDEM program was applied to these data to produce a series of gridded DEMs at horizontal resolutions of 30, 15, and 7.5 m. The root mean square slope criterion, together with views of selected primary terrain attributes derived from the interpolated DEMs, was used to gauge the optimal DEM resolution, which was eventually chosen to be 15 m. A shaded relief view of the chosen 15-m DEM is

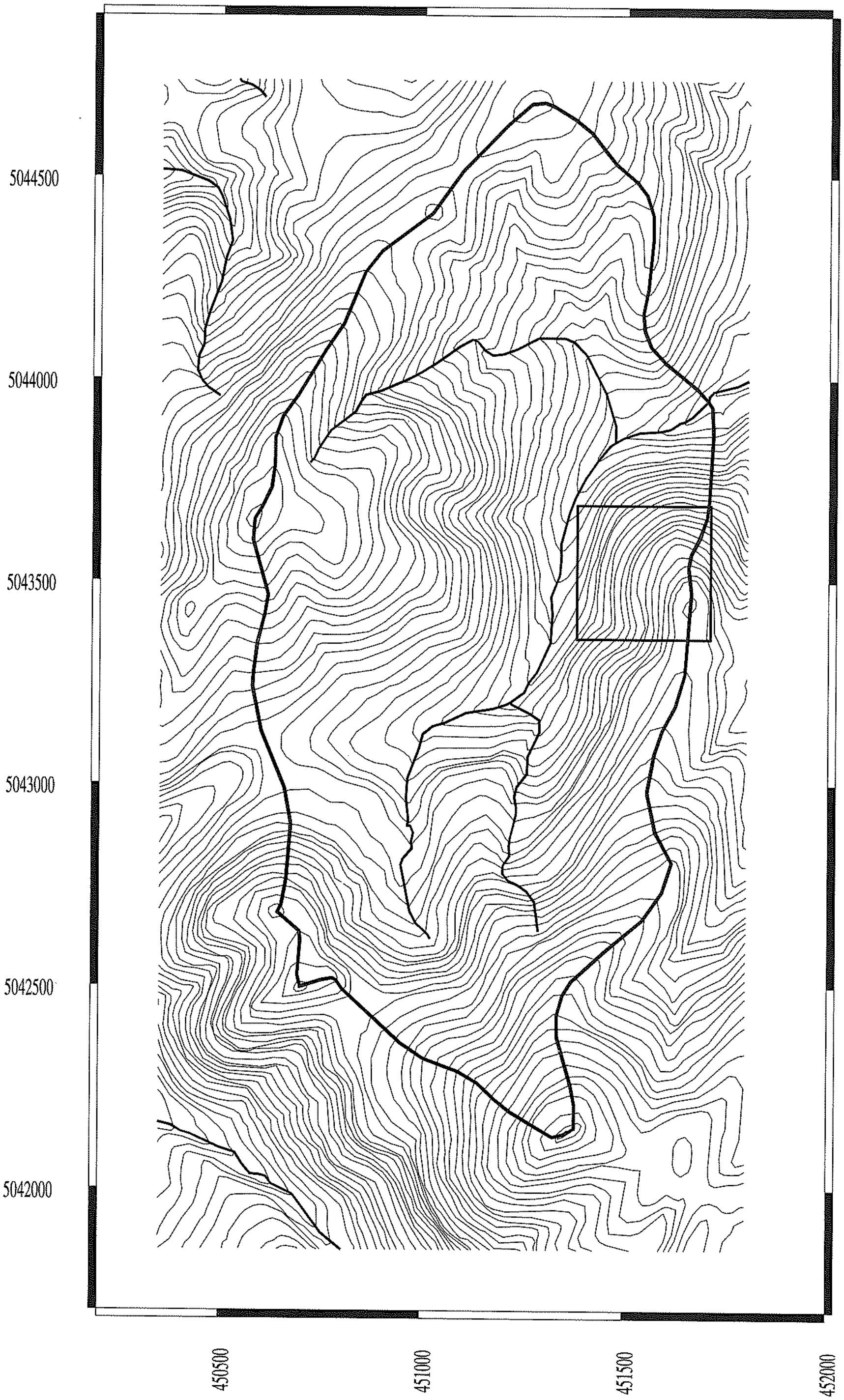


Figure 2.5. Contour and stream-line data for the Cottonwood catchment. The small square indicates the 330 × 330-m subarea used in later analysis.

shown in Figure 2.6 (see color insert). The aim of the procedure was to optimize DEM resolution by matching the true information content of the source data and maximizing surface accuracy. The range of candidate DEM resolutions was specified for consistency with common practice in the United States of calculating 30-m-resolution DEMs from 1:24,000 scale source data (USGS 1999). Practical issues arising in generating the DEM are now described. Optimization of DEM resolution is discussed in Section 2.8.

2.7.1 Specification of ANUDEM Options

Two ANUDEM options merit comment. First, drainage enforcement should be enacted to remove spurious sinks, since it is clear from the data in Figure 2.5 that the entire catchment should drain to the catchment outlet. Second, automatic determination of ridge and stream lines from corners in contour data should also be enacted, since these interpretations are plainly valid for the fine-scale contour data provided here. The effect of this option is that interpolation is defined by minimum curvature in the relatively planar areas away from ridge and stream lines, but the interpolation is constrained by approximate linear descent down each ridge and stream line. This ensures interpolation of curvilinear contour structure between data contour lines, as indicated in the example in Figure 2.4.

2.7.2 Elevation Units and Vertical Precision

Though a DEM with vertical units in meters was eventually required, this was not achieved by first converting the contour elevations in feet to elevations in meters. This would have introduced systematic errors if the converted elevations were stored in integer form, as is common practice. Instead, contour elevations in integer feet were retained and the derived DEM was then simply scaled to have elevations in meters. Provided that the DEM elevations are stored in real (floating point) form, this introduces no significant error.

Storage of DEM elevations in real form is generally recommended, particularly in low-relief areas where elevations in integer meters (or feet) are insufficient to adequately represent drainage direction and other primary terrain attributes. This has been a common problem with some generally available DEMs. In fact, even DEM elevations in higher relief areas, such as the one examined here, should be stored in real form. This maximizes the accuracy of terrain attributes derived from the DEM, particularly slope, aspect, and curvature, which depend on first- and second-order derivatives.

The practice of storing DEM elevations in integer meters (or feet) has arisen from a confusion between precision and absolute accuracy. The precision required for accurate determination of first and second derivatives is much higher than that required to satisfy basic vertical accuracy requirements. This is best indicated by observing that an arbitrary constant systematic error in DEM elevations would have no impact on the accuracy of most derived terrain attributes, even though absolute elevation errors could be arbitrarily large. It is difficult to smooth DEMs with integer vertical precision to recover sensible terrain shape and drainage attributes, especially in low-relief areas.

2.8 ASSESSMENT OF RESOLUTION AND QUALITY OF THE COTTONWOOD DEM

Close inspection of Figure 2.5 reveals probable slight systematic positional errors in the contour data, with some neighboring contour lines distinctly closer than adjacent pairs of contour lines. Such systematic errors are common. They indicate that some data smoothing is required. This is achieved in this case by carefully choosing the DEM resolution using several criteria, all of which relate to accuracy of representation of terrain shape.

2.8.1 Optimization of Resolution Using the Root Mean Square Slope Criterion

The standard approach recommended by Hutchinson (1996) is to monitor root mean square slope of the DEM as a function of DEM resolution. This is shown in Figure 2.7, where the resolutions decrease from left to right by successive halving from 240 to 7.5 m. The last three steps are the candidate DEM resolutions of 30, 15, and 7.5 m with respective root mean square slopes of 27.6, 31.9, and 34.4%. The curve begins to flatten at the last step from 15-m-resolution to 7.5-m-resolution. This suggests that the optimum resolution is approximately 15 m.

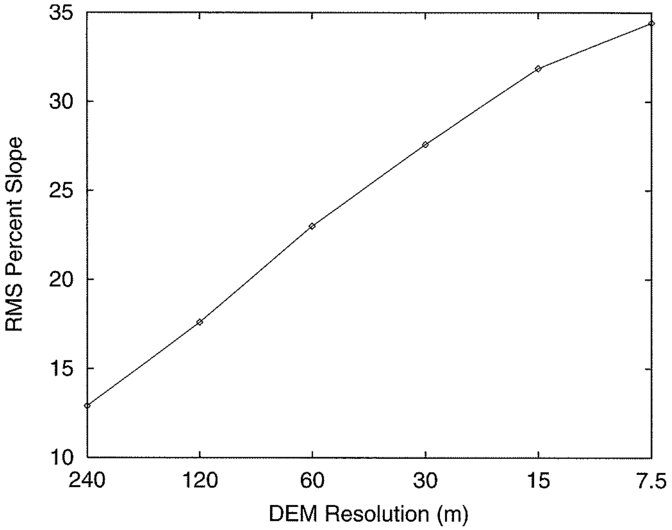


Figure 2.7. Root mean square slope of interpolated DEMs as a function of DEM resolutions successively halved from 240 to 7.5 m.

The flattening in Figure 2.7 is less marked than in Figure 2 of Hutchinson (1996), but this can be attributed to the positional error in the contour data. As the DEM resolution is refined, the fitted DEM comes closer to honoring the data contours. But if the data contours were honored exactly, then the DEM would have spurious variability, which would be reflected in over large values of the root mean square slope.

Additional assessments of DEM quality were made to confirm this choice of resolution. As indicated in Section 2.5, spurious sinks can provide an efficient way of detecting source data errors and assessing the general quality of the drainage structure of the DEM. However, in this case no sinks remained in the DEMs at all resolutions. This indicates the overall quality of the contour data, and its consistency with the stream-line data, as plotted in Figure 2.5. It also indicates the success of the drainage enforcement algorithm associated with the ANUDEM program.

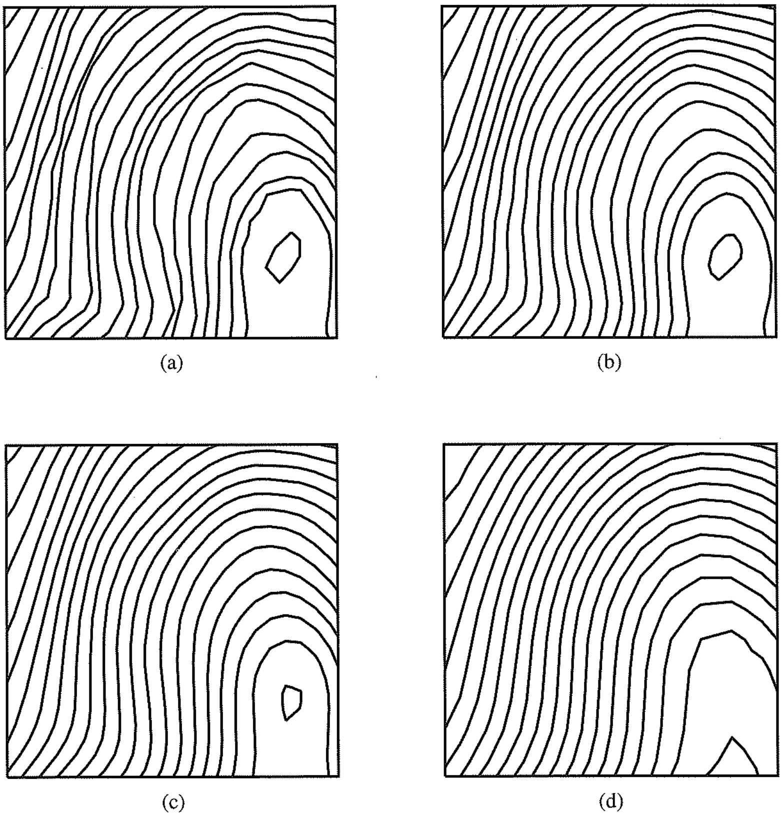
2.8.2 Comparison of Data Contours with Derived Contours

A 330 × 330-m subgrid of each DEM, as indicated in Figure 2.5, was further examined. Figure 2.8 shows the source data contours for this area, and the corresponding contours derived from each of the three candidate DEMs. Both random and systematic positional errors are evident in the data contours. All three sets of derived contours generalize the data contours by varying amounts. The 30-m DEM plainly removes the peak in the lower right-hand corner and is therefore too coarse. This is consistent with the root mean square slope analysis above and the 30-m DEM was omitted from further consideration. The 15- and 7.5-m DEMs, on the other hand, both retain the peak. They appear to vary only in the degree to which they override the systematic positional error evident in the data. It is difficult to determine from these views which of these two resolutions is superior.

2.8.3 Views of Slope and Profile Curvature

Given the above assessment of the contour views in Figure 2.8, it would be difficult to separate the 15- and 7.5-m DEMs in terms of either shaded relief or plan curvature, the latter being directly represented by contour curvature. Views of slope and profile curvature for the two resolutions are therefore shown in Figures 2.9 and 2.10 (see color insert). Slope for the 7.5-m DEM shows only slightly more detail than the 15-m DEM. Thus, as for the contour views in Figure 2.10, it is difficult to separate the two resolutions in terms of their representation of slope.

On the other hand, differences in profile curvature between the two resolutions are quite marked. The linear features in Figure 2.10b are plainly closely associated with the systematic positional error in the data contours. These linear features are completely absent from Figure 2.10a, which shows broader scale variation in profile curvature not tied to any particular data contour. On the grounds that the linear features in the profile curvature in Figure 2.10b are spurious, the optimal DEM resolution was confirmed to be 15 meters. This was consistent with the initial indication given by the root mean square slope analysis shown in Figure 2.7.



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

Figure 2.8. Data elevation contours and derived contours for the 330 × 330-m subarea indicated in Figure 2.5: (a) data contours; (b) contours derived from the 7.5-m DEM; (c) contours derived from the 15-m DEM; (d) contours derived from the 30-m DEM.

2.8.4 Histograms of Elevation and Aspect

To complete the assessments of DEM quality recommended in Section 2.5, histogram plots of elevation and aspect for the whole Cottonwood catchment were prepared for the 15- and 7.5-m-resolution DEMs. These are shown in Figures 2.11 and 2.12. The elevation histograms in Figure 2.11 show the expected small bias toward the data contour elevations, with little difference between the two DEM resolutions.

The aspect histogram for the 15-m-resolution DEM shows no marked bias toward multiples of 45°, with the overall distribution of aspect consistent with the predominant eastern and northwestern downslope orientations of the contour data shown in Figure 2.5. The aspect histogram for the 7.5-m-resolution DEM is consistent with this distribution, but has sharper peaks at multiples of 45°, again indicating some deficiencies with this resolution. However, overall the aspect histograms indicate a relative insensitivity of aspect to DEM resolution. This observation has been made by

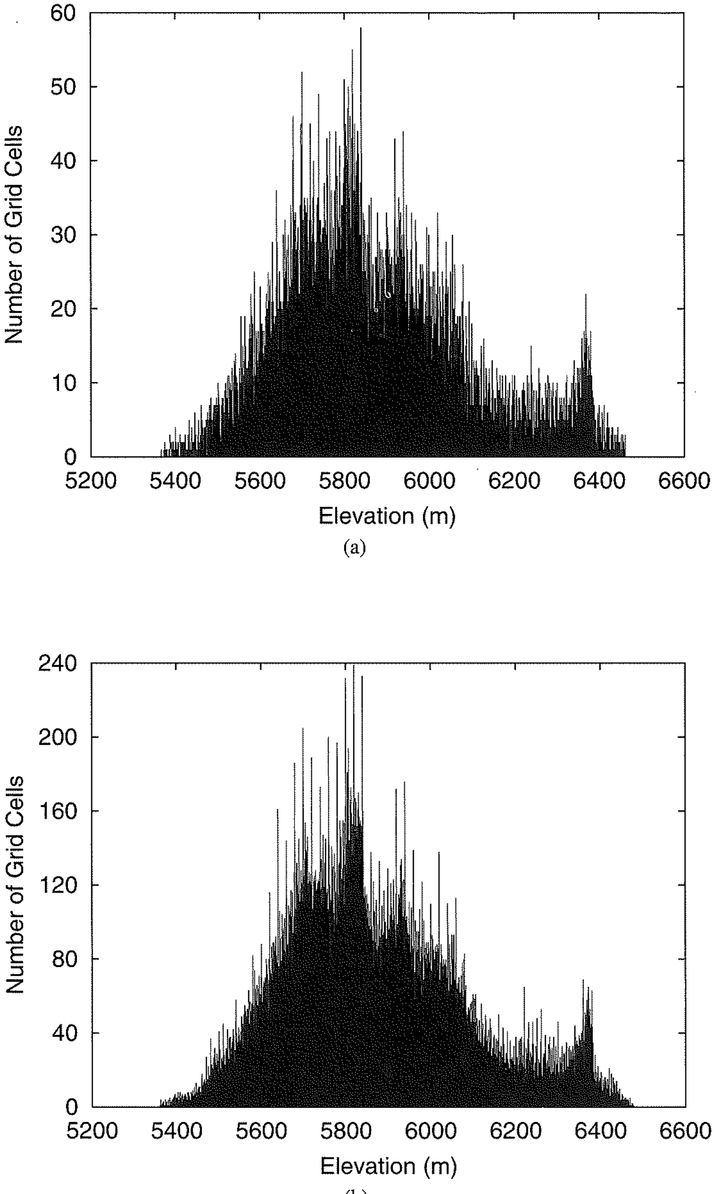
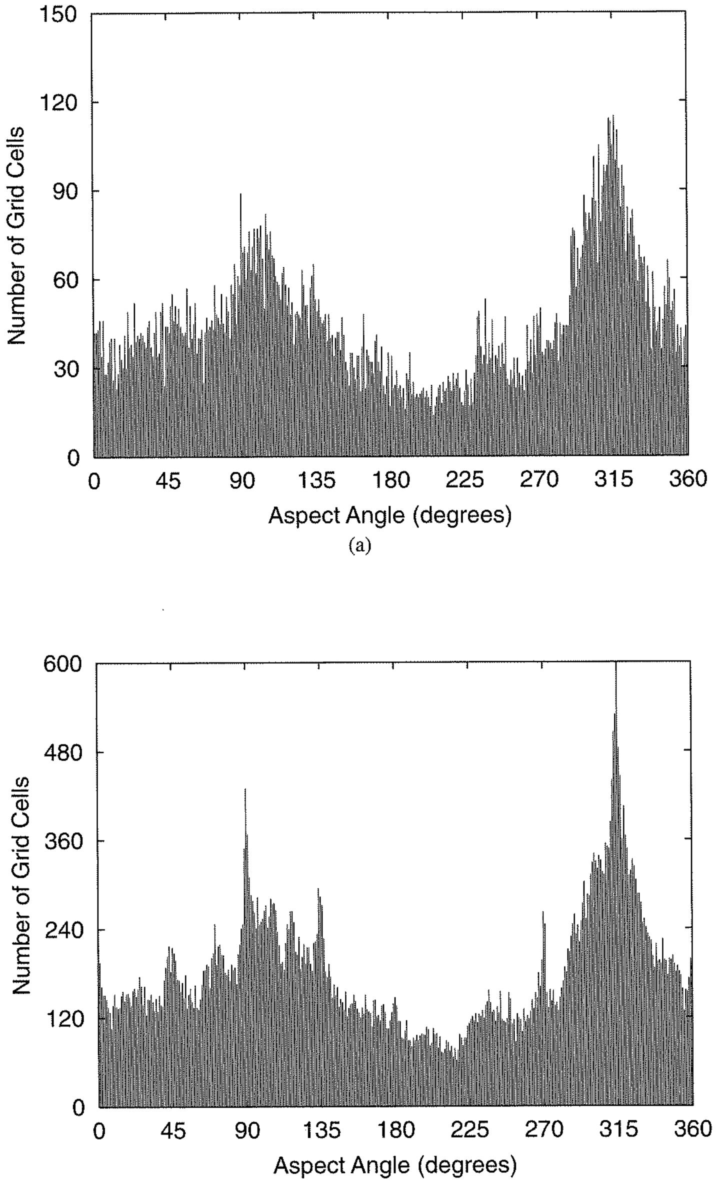


Figure 2.11. Elevation histograms for the Cottonwood catchment from (a) the 15-m DEM and (b) the 7.5-m DEM.



(a)

(b)

Figure 2.12. Aspect histograms for the Cottonwood catchment from (a) the 15-m DEM and (b) the 7.5-m DEM.

several authors. It has implications for the development of iterative terrain interpolation procedures defined in terms of aspect (Hutchinson 1996).

2.8.5 Summary Recommendation

The root mean square slope criterion appears to be a reliable, nongraphical, but nevertheless shape-based, way of matching DEM resolution to the information content of the source contour and stream-line data. This criterion can be refined, especially when source data have positional errors, by examining plots of derived contours and profile curvature. Examination of derived contours can prevent selection of a DEM resolution that is too *coarse* to adequately represent terrain structure. Examination of profile curvature can prevent selection of a resolution that is too *fine,* the latter leading to systematic errors in derived primary terrain attributes. Slope and plan curvature were less sensitive to DEM resolution than profile curvature. The above process of optimizing DEM resolution also illustrates the interactions between source data capture, DEM generation, and applications, as shown in Figure 2.1.

2.9 CONCLUSIONS

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. The locally adaptive ANUDEM gridding procedure is shown to be able to produce such representations from contour, stream-line, and point data. These data are particularly appropriate for producing DEMs at the toposcale, at resolutions ranging from 5 to 200 m, where source contour data tend to accurately reflect terrain shape and drainage structure. The toposcale is also the scale at which applications are governed primarily by terrain shape, as can be directly measured by various primary and secondary terrain attributes that can be derived from the interpolated DEMs.

This success of locally adaptive gridding methods has prompted renewed interest in contour and stream-line data sources, which have wide global coverage. Remotely sensed elevation data sources also hold the promise of providing DEMs with global coverage, but appropriate filtering and interpolation methods that respect surface structure and drainage are required to reduce the inherent errors in these data, particularly in areas with low relief.

The process of producing a DEM from source data requires careful attention to the accuracy of the source data and the quality of the interpolated DEM. Several shape-based measures of DEM quality, which are readily plotted, can greatly assist in assessing DEM quality and in detecting data errors. These measures do not require the existence of separate reference elevation data.

DEM resolution can be optimized to match the true information content of source data as well as to filter positional errors in source data. The root mean square slope criterion, together with plots of derived contours and derived profile curvature, all assisted in determining an optimal resolution of around 15 m for a DEM derived from 1:24,000 scale contour and stream-line data. The optimization procedure clarified the importance of selecting DEM resolution carefully, especially when applications of the DEM depend on sensitive measures of terrain shape, such as profile curvature.

To respect the shape-based needs of applications, elevations of DEMs should be stored in real (floating point) form. DEMs with elevations in integer meters or integer feet have serious deficiencies in representing terrain shape and drainage structure, particularly in areas with low relief.