CHAPTER 3

Primary Topographic Attributes

John C. Gallant and John P. Wilson

3.1 TAPES-G: TERRAIN ANALYSIS ON GRIDDED DEMS

A gridded digital elevation model (DEM) represents the terrain surface as a regular lattice of point elevations. A grid can also be thought of as a tessellation using square tiles with the point elevation at the center of the square, as shown in Figure 3.1; the tiles should not be thought of as being flat with a constant elevation. The shape of the surface is represented by the change in elevations between adjacent lattice points.

The DEM lattice is nearly always aligned along geographic axes (N-S and E-W) and usually has equal spacing in both directions. When the DEM coordinates are length units, such as meters or feet, the spacing between DEM points is the same over the entire DEM, making analysis quite straightforward. Some DEMs (particularly at broad scales) use geographic coordinates (degrees, minutes, and seconds) and the actual distance between points varies across the DEM. Analysis of these DEMs must recognize this variable spacing. Most terrain-analysis programs, TAPES-G included, do not recognize the variable spacing of DEMs in geographic coordinates, so this type of DEM is difficult to work with unless it is projected to a regular grid in real coordinates before analysis. Unfortunately this type of transformation almost invariably results in the disturbance of surface drainage pathways, resulting in sinks (local minima). A better alternative is to project the source data and regenerate the DEM, but this is not always possible. This last strategy was used with ANUDEM (Hutchinson 1989b) to derive the 100- and 200-m DEMs from 1° to 2° USGS 3-arc-second DEMs used in Chapter 5, for example.

3.1.1 Surface Derivatives

Most of the primary topographic attributes listed in Table 1.1 can be determined locally from the derivatives of the topographic surface. These derivatives measure the

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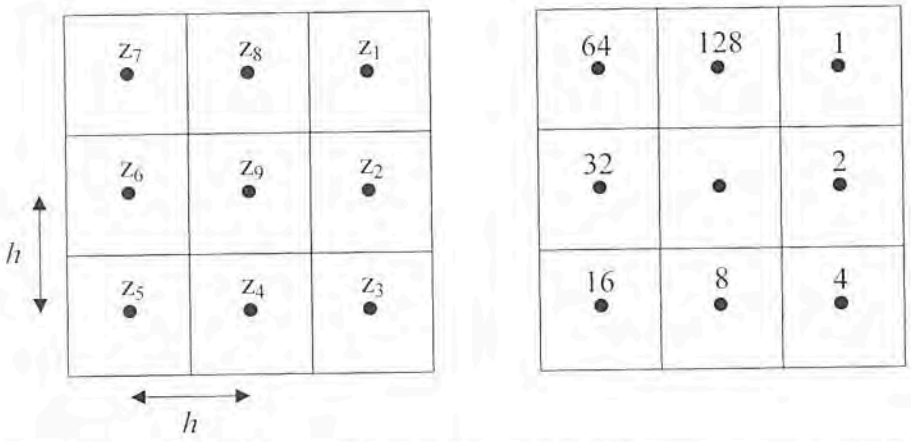

Figure 3.1. 3×3 subgrid for gridded DEM showing (a) node numbering convention and (b) flow direction numbering convention.

rate at which elevation changes in response to changes in location (x and y). The derivatives are estimated using centered finite differences:

$$z_x = \frac{\partial z}{\partial x} \approx \frac{z_2 - z_6}{2h} \tag{3.1}$$

$$z_y = \frac{\partial z}{\partial y} \approx \frac{z_8 - z_4}{2h} \tag{3.2}$$

$$z_{xx} = \frac{\partial^2 z}{\partial x^2} \approx \frac{z_2 - 2z_9 + z_6}{h^2} \tag{3.3}$$

$$z_{yy} = \frac{\partial^2 z}{\partial y^2} \approx \frac{z_8 - 2z_9 + z_4}{h^2} \tag{3.4}$$

$$z_{xy} = \frac{\partial^2 z}{\partial x\, \partial y} \approx \frac{-z_7 + z_1 + z_5 - z_3}{4h^2} \tag{3.5}$$

$$p = z_x^2 + z_y^2 \tag{3.6}$$

$$q = p + 1 \tag{3.7}$$

Equations 3.1 and 3.2 are the first-order derivatives that describe the rate of change of elevation with distance along the x and y axes, or the slope in those directions; these slope values can be positive or negative. Equations 3.3 and 3.4 are the second derivatives that describe the rate of change of the first derivative in the x and y directions, or the curvature in those directions. Equation 3.5 is a mixed second derivative that describes the rate of change of the x derivative in the y direction, or the twisting

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Figure 3.1a shows the arrangement and numbering of the nine grid points that enter into the finite-difference equations, and h is the grid spacing of the DEM. The y axis, which points north, is up in Figure 3.1: Note that this is the opposite sense to the notation sometimes used in image processing where the origin is at the top left (northwest) corner and y points south. The conventions for numbering the nodes vary through the literature, and the notation for the finite difference formulae varies accordingly.

At the edges of the DEM or adjacent to no-data areas where some of the nine points are undefined, forward and backward finite differences are used to avoid reference to nonexistent data. For example, at the left edge where z_6 is not defined the x derivative is calculated as

$$z_x = \frac{z_2 - z_9}{h} \tag{3.8}$$

3.1.2 Slope

Slope S measures the rate of change of elevation in the direction of steepest descent. Slope is the means by which gravity induces flow of water and other materials, so it is of great significance in hydrology and geomorphology. It affects the velocity of both surface and subsurface flow and hence soil water content, erosion potential, soil formation, and many other important processes.

Slope is normally calculated using finite differences:

$$S_{\mathrm{FD}} = \sqrt{p} \tag{3.9}$$

This formula depends only on the elevations in the four cardinal directions. Some other finite difference formulae for slope are also used: For example, the ARC/INFO GIS uses a formula that depends on all eight adjacent cells. There is little difference between the results from these two formulae, although there is some evidence (Jones 1996) that Equation 3.9 is slightly more accurate.

Slope can also be computed using the steepest downhill slope to one of the eight nearest neighbors, the D8 method:

$$S_{\mathrm{D8}} = \max_{i=1,8} \frac{z_9 - z_i}{h\phi(i)} \tag{3.10}$$

where $\phi(i) = 1$ for cardinal (north, south, east, and west) neighbors ($i = 2, 4, 6$, and 8) and $\phi(i) = \sqrt{2}$ for diagonal neighbors to account for the extra distance to those cells (Figure 3.1a).

The D8 method gives slightly smaller average slopes than the finite difference method, because the direction in which the elevation difference is calculated is not always that of the steepest descent. An earlier report in Moore et al. (1993d) that the D8 approach predicted slightly larger average slopes was due to the use of a different formula that gave the steepest slope in any direction, not the downslope direction.

The finite difference method (Equation 3.9) is preferred because of its greater accuracy. The D8 slope estimate is useful when the slope of channels is required, because the finite difference estimate of channel cell slope may be affected by steep slopes adjacent to the channel. Using the D8 slope option guarantees that the slope calculated at a cell corresponds to the slope in the primary flow direction.

Regardless of which estimation method is used, TAPES-G reports slope in percent, or $S \times 100$. Note that slopes greater than 100% are possible in steep areas and signify slope angles greater than 45°. Slope angle β can be calculated from slope using

$$\beta = \arctan(S) \tag{3.11}$$

after dividing the TAPES-G slope value by 100. Figure 3.2 shows slope in percent computed using the finite difference method for the Cottonwood Creek 15-m DEM introduced in Chapter 2. The low slopes along valley bottoms and ridge tops are clearly visible, as are the steep slopes on the hillsides.

3.1.3 Aspect and Primary Flow Direction

Aspect ψ is the orientation of the line of steepest descent and is usually measured in degrees clockwise from north. Aspect is frequently recorded as a site attribute in eco-

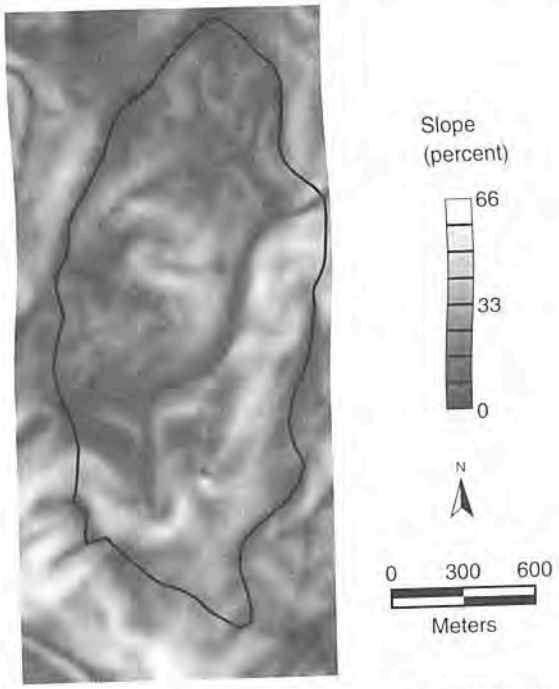

Figure 3.2. Percent slope derived from the Cottonwood Creek DEM using the finite difference formula, with the catchment boundary overlaid.

logical surveys and together with slope can be used to estimate solar radiation (although more sophisticated tools are available for this, such as SRAD described in Chapter 4). Aspect is useful for visualizing landscapes, especially when using a well-chosen color scale (Kimerling and Moellering 1989), although proper hill shading works better. The frequency distribution of aspect can also be used as a diagnostic tool to detect poor quality interpolation with a bias toward multiples of 45° or 90°. Aspect in degrees is calculated using finite differences as

$$\psi_{FD} = 180 - \arctan\left(\frac{z_y}{z_x}\right) + 90\left(\frac{z_x}{|z_x|}\right) \tag{3.12}$$

which is the angle determined by the x and y derivatives via arctan, modified to give degrees clockwise from north.

Aspect becomes rather meaningless when the slope is very small (and mathematically undefined when the slope is zero) so cells with slope less than some minimum value S_{min} may be considered to have undefined aspect (Mitasova and Hofierka 1993). TAPES-G does not currently do this, but it does give undefined aspect (NODATA value) when the slope is exactly zero.

The primary flow direction, FLOWD, is an approximate surrogate for aspect. This is essentially the primary flow direction for water moving over the land surface and identifies the direction to the nearest neighbor with maximum gradient, exactly as in Equation 3.10:

$$\text{FLOWD} = 2^{j-1} \qquad \text{where } j = \arg\max_{i=1,8} \frac{z_9 - z_i}{h\phi(i)} \tag{3.13}$$

or, in words, j is the i that gives the largest slope value and hence is the direction of steepest descent. The approximate aspect corresponding to this flow direction is

$$\psi_{D8} = 45j \tag{3.14}$$

FLOWD is encoded using a binary notation (Figure 3.1b), which permits identification of flow to multiple nearest neighbors (although this capability is not actually used in TAPES-G). Note that this encoding is arbitrary and different software packages use different encoding schemes: ARC/INFO, for example, uses the same power-of-two encoding but with 1 representing flow to the east rather than northeast as in TAPES-G.

If none of the surrounding elevations z_1 to z_8 is higher than the central node z_9 then the node is a sink or in a flat area and has undefined aspect and flow direction. Section 3.1.5.1 describes how depressions are filled and flow directions assigned in flat areas using Jenson and Domingue's (1988) algorithm.

Figure 3.3 shows aspect computed from the Cottonwood Creek 15-m DEM using the finite difference method. The image is dominated by the abrupt changes where aspect switches from near maximum (360°) to near minimum (0°); this is an artifact of the linear gray scale and can be avoided with a scale having the same color for the minimum and maximum values. Some of the abrupt changes occur along the catch-

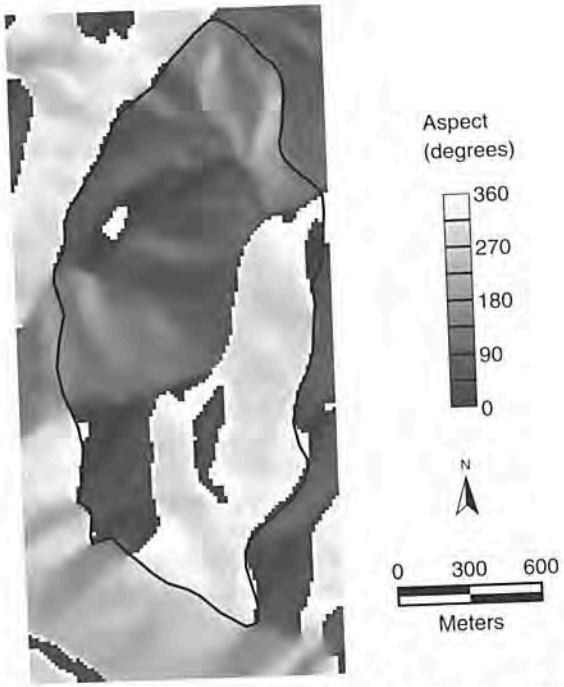

Figure 3.3. Aspect in degrees from north derived from the Cottonwood Creek DEM using the finite difference formula, with the catchment boundary overlaid.

ment boundary. The more subtle variations within the hillslopes show the changes in orientation across the surface.

3.1.4 Curvature

Curvature attributes are based on second derivatives: the rate of change of a first derivative such as slope or aspect, usually in a particular direction. The two curvatures most frequently computed are plan (or contour) curvature, K_c, the rate of change of aspect along a contour, and profile curvature, K_p, the rate of change of slope down a flow line. Profile curvature measures the rate of change of potential gradient so is important for characterizing changes in flow velocity and sediment transport processes. Plan curvature measures topographic convergence and divergence and hence the propensity of water to converge as it flows across the land. Mitasova and Hofierka (1993) have suggested that tangential curvature, K_t (plan curvature multiplied by the sine of the slope angle), is more appropriate than plan curvature for studying flow convergence and divergence because it does not take on extremely large values when slope is small. The distribution of convex and concave areas is the same for both plan and tangential curvature.

Surface curvatures can be thought of as the curvature of a line formed by the intersection of a plane and the topographic surface. The curvature of a line is the reciprocal of the radius of curvature, so a gentle curve has a small curvature value and a tight curve has a large curvature value. Plan curvature is the curvature in the horizontal plane of a contour line, while profile curvature is the curvature in the vertical plane of a flow line. Tangential curvature is curvature in an inclined plane perpendicular to both the direction of flow and the surface.

The units of curvature are radians per meter, the change in orientation resulting from traveling 1 meter along the respective line. Curvature values are typically small (nearly always less than 1), so TAPES-G reports curvature values multiplied by 100 for easier interpretation. The formulae used in TAPES-G are

$$K_p = \frac{z_{xx}z_x^2 + 2z_{xy}z_xz_y + z_{yy}z_y^2}{pq^{3/2}} \tag{3.15}$$

$$K_c = \frac{z_{xx}z_y^2 - 2z_{xy}z_xz_y + z_{yy}z_x^2}{p^{3/2}} \tag{3.16}$$

$$K_t = \frac{z_{xx}z_y^2 - 2z_{xy}z_xz_y + z_{yy}z_x^2}{pq^{1/2}} \tag{3.17}$$

Using these formulae, profile curvature is negative for slope increasing downhill (convex flow profile, typically on upper slopes) and positive for slope decreasing downhill (concave, typically on lower slopes). Plan curvature is negative for diverging flow (on ridges) and positive for converging flow (in valleys). TAPES-G can optionally reverse these sign conventions to give positive values for convex curvatures, which is the more frequently used sign convention.

Total curvature is sometimes used as a measure of surface curvature. This curvature measures the curvature of the surface itself, not the curvature of a line across the surface in some direction. It can be positive or negative, with zero curvature indicating that the surface is either flat or the convexity in one direction is balanced by the concavity in another direction, as at a saddle. Total curvature is computed as

$$K = z_{xx}^2 + 2z_{xy}^2 + z_{yy}^2 \tag{3.18}$$

Apart from their use in modeling flow characteristics, curvatures can be used to delineate geomorphic units (Dikau 1989). Plan curvature can be used to differentiate between ridges, valleys, and hillslopes, whereas profile curvature can differentiate between upper (convex) slopes and lower (concave) slopes.

Any errors in a DEM will be enhanced in the computed values of the curvature parameters because these parameters are based on second derivatives, which accentuate local irregularities. Furthermore, DEMs that have been interpolated primarily from contour data often display biases toward the elevations of the contour data, as discussed in Chapter 2, and profile curvature can alternate in sign systematically down a hillslope giving a "wavy" appearance. This result occurs because the density of data is high along the contours, but there are no data between contours. The inter-

polation methods give more variation in shape (curvature) where the elevation data are densest. In some landscapes this "waviness" is a real phenomenon (Moore et al. 1993d).

Figures 3.4 and 3.5 show plan and profile curvature for the Cottonwood Creek 15-m DEM using the normal sign convention of positive values for convex curves. Plan curvature clearly shows the locations of valleys and ridges with their large negative and positive plan curvatures, and the more gently curved hillslope regions between. Saddles are also visible in some places along the catchment boundary where strongly convex cells are immediately adjacent to strongly concave cells. Profile curvature clearly identifies the convex areas around hilltops and the concave areas in valley bottoms, but there is a considerable amount of pattern in the hillslope areas that is due to irregularities in the contour positions in the source data.

3.1.5 Upslope Contributing Area and Specific Catchment Area

Upslope contributing area, A, is the area above a certain length of contour that contributes flow across the contour, as shown in Figure 3.6. Specific catchment area, A_s (or a), is the ratio of the contributing area to the contour length, A/l. When calculating these areas from gridded DEMs, the contour length is approximately the size of

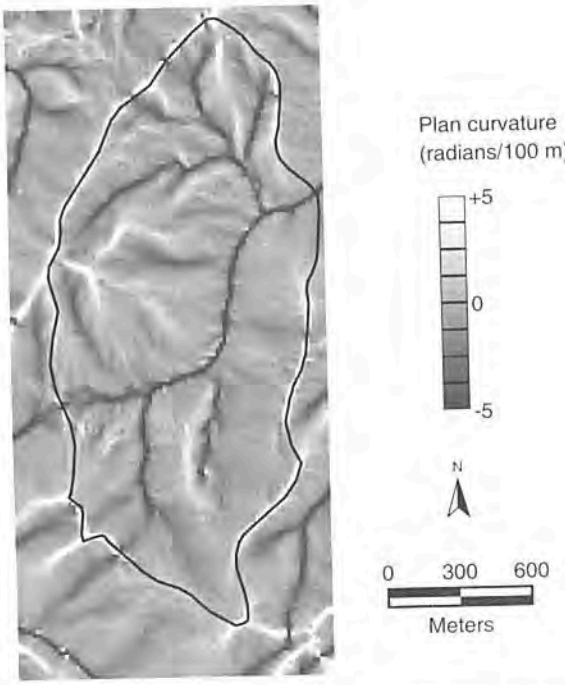

Figure 3.4. Plan curvature (radians per 100 m; convex curvatures are positive) for the Cottonwood Creek DEM, with the catchment boundary overlaid.

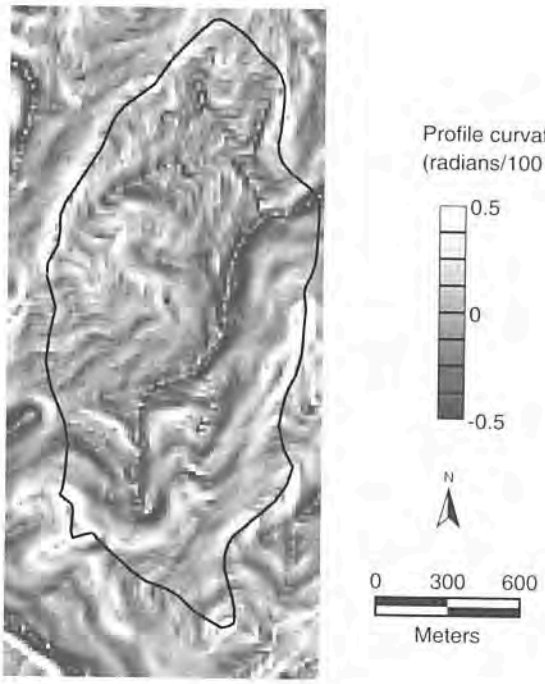

Figure 3.5. Profile curvature (radians per 100 m; convex curvatures are positive) for the Cottonwood Creek DEM, with the catchment boundary overlaid.

a grid cell, and in the simplest case the contributing area is determined by the number of cells contributing flow to a cell. The determination of contour length (or flow width) is described in the following subsection.

The estimation of both upslope contributing area and specific catchment area (i.e., the drainage area per unit width orthogonal to a flow line) is dependent on the estimation of flow direction(s) from a given node (node 9 in Figure 3.1a). Upslope contributing area is often referred to as drainage area or catchment area. TAPES-G reports contributing area in either number of cells or meters squared (m^2). Four different approaches are available in TAPES-G for calculating contributing areas: D8, Rho8, FD8/FRho8, and DEMON. Before any of these methods are applied, depressions and flat areas must be dealt with.

3.1.5.1 Depressions and Flat Areas All contributing area algorithms follow paths of descending elevation to route flow across the surface. Any grid cells that do not have a lower neighbor represent a barrier to these algorithms and in most cases some special handling is required to allow flow accumulation to continue across the surface. There are some cases where this is not appropriate and the flow should terminate, for example, at sink holes in karst landscapes. In depressional landscapes water accumulates as ponds and lakes in depressions but routing of flow out of these

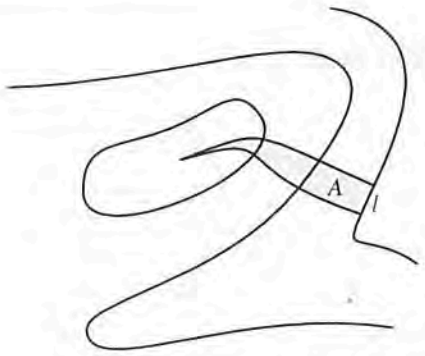

Figure 3.6. Upslope contributing area A is the area of land upslope of a length of contour l. Specific catchment area A_s is A/l.

areas is usually still required to properly represent the source areas of the streams flowing out of the lakes.

TAPES-G uses the method described in Jenson and Domingue (1988) to handle depressions and flat areas. First, depressions are filled by increasing elevations within depressions to their lowest outflow point. Care is taken to ensure that linked depressions do not drain into each other. Flow is then routed across flat areas (including filled depressions) by working backward from the drain points around the edge of each flat area. Where there is a lower point adjacent to the flat area, the flow direction is set to point to this outflow cell. Adjacent cells in the flat area then have their flow directions set to point to this drained cell and this continues across the flat area until flow directions have been assigned to all grid cells. These flow directions are used directly by the D8/Rho8 single-flow-direction, flow-accumulation algorithms and are converted to aspect for use by the DEMON algorithm in flat areas and depressions. The FD8/FRho8 multiple-flow-direction algorithm reverts to single flow directions in flat areas.

Note that in TAPES-G, slope, aspect, and curvatures are calculated from the original DEM and not the filled DEM. The filled DEM can also be saved to avoid refilling the depressions in subsequent runs. TAPES-G also reports the elevation residual between the original elevation and the elevation as modified to fill depressions, which is useful for checking whether the depressions found are substantial enough to warrant a revision of the DEM.

This depression-filling procedure completely ignores the shape of the landscape within a depression, which can be undesirable when the depressions cover many cells. Most depressions occur in valley bottoms, where the interpolation has caused a "dam" to appear across the valley. Filling the depression and then routing across the flat area backward from the outlet can cause the path of the inferred stream to deviate significantly from the lowest part of the topography in the depression. Apart from locational errors, these deviations can cause problems in secondary attributes where, for example, contributing area and slope are combined: The slope at the

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3.1.5.2 Single-Flow

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location of the inferred stream can be much higher than the stream gradient in these instances.

If these artifacts occur and undesirably influence the results, a revision of the DEM should be considered to remove the depressions and restore the connectivity of the drainage network. If the original source data are not available this may require manual modification of the DEM, which is only feasible when there are few sinks requiring correction. One method of restoring drainage to a DEM is "burning in" the streams: reducing by a fixed amount the elevations of cells along mapped stream lines so that the streams are at a lower elevation than the surrounding landscape. When depressions in the stream are filled the raised elevations are still below the surrounding areas so the flow accumulation remains confined to the imposed stream line. This method of restoring drainage is not recommended, because it dramatically alters the slopes around the stream line and can produce multiple stream lines. If the drainage line implicit in the DEM is more than one cell away from the imposed stream it will continue to collect flow from upslope and there will be two streams flowing across the landscape in close proximity: the imposed stream line and the DEM's drainage line. Proper incorporation of stream lines into the construction of the DEM as described in Chapter 2 gives much better results.

3.1.5.2 Single-Flow-Direction D8 Method The D8 (deterministic eight-node) algorithm developed by O'Callaghan and Mark (1984) allows flow from a cell to only one of eight nearest neighbors based on the primary flow direction. Because flow can accumulate into a cell from several upslope cells but only flow out into a single cell, this method can model flow convergence in valleys but not flow divergence in ridge areas. Another defect of this algorithm is that it tends to produce flow in parallel lines along preferred directions that will agree with the aspect only when the aspect is a multiple of 45°. For example, on a surface with aspects ranging from 0 to 22.5°, the D8 algorithm will predict a constant flow direction FLOWD = 128 (due north) (Figure 3.1b). Even with these significant limitations, the D8 algorithm is still frequently used for determining contributing areas, primarily because of its simplicity. In spite of its inability to model flow divergence, it is adequate for delineating catchment boundaries. For calculating the distribution of contributing area and specific catchment area across hillslopes, the more sophisticated FD8 or DEMON methods are recommended.

Figure 3.7 shows upslope contributing area computed using the D8 method on the 15-m resolution Cottonwood Creek DEM. The valley bottoms are clearly defined as a line of white high contributing area cells, and the ridges both within the catchment and at the divide are visible as dark cells with low contributing area. Many obvious straight-line artifacts are visible, due to the absence of dispersion and the inability to respond to subtle changes in surface orientation.

Note that cells of lowest contributing area do not necessarily correspond to the catchment boundary, which is determined by the connections of the flow lines. For example, at several places around the catchment divide, but particularly in the middle of the western edge, the cells of lowest contributing area do not coincide with the catchment boundary determined from the contours. Figure 3.8 shows details of the

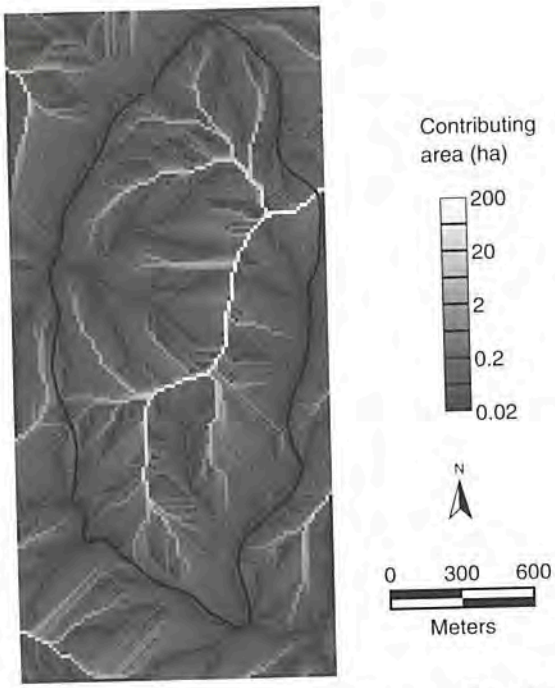

Figure 3.7. Contributing area (ha) derived from the Cottonwood Creek DEM using the D8 single flow direction algorithm, with the catchment boundary overlaid.

flow directions in this area. By following the flow lines downstream it is apparent that the line of dark cells (lowest contributing area) is not the catchment divide, since the flow lines immediately to the west of the dark cells drain eastward into the catchment. The catchment divide as determined by the D8 flow lines is within one cell of the catchment divide line derived from the contours.

The dark, low contributing area cells mark the line where the aspect shifts sufficiently east from south to change the flow direction from south to southeast: The line of dark cells is an artifact of the single-flow-direction method rather than a significant topographic feature. Another artifact of the D8 method can be seen in the valley head in the southeast corner of Figure 3.8. Three flow lines run in parallel along a valley bottom because the convergence of the valley is insufficient to force the lines together.

The effect of these artifacts is to significantly distort the spatial pattern of contributing area. The weakly divergent ridge along the catchment divide is assigned a contributing area of 20 cells or 4500 m^2 while the center of the valley bottom area immediately before the convergence of the three lines is assigned a contributing area of 32 cells or 7200 m^2. These two locations should have contributing areas differing by much more than a factor of 1.6.

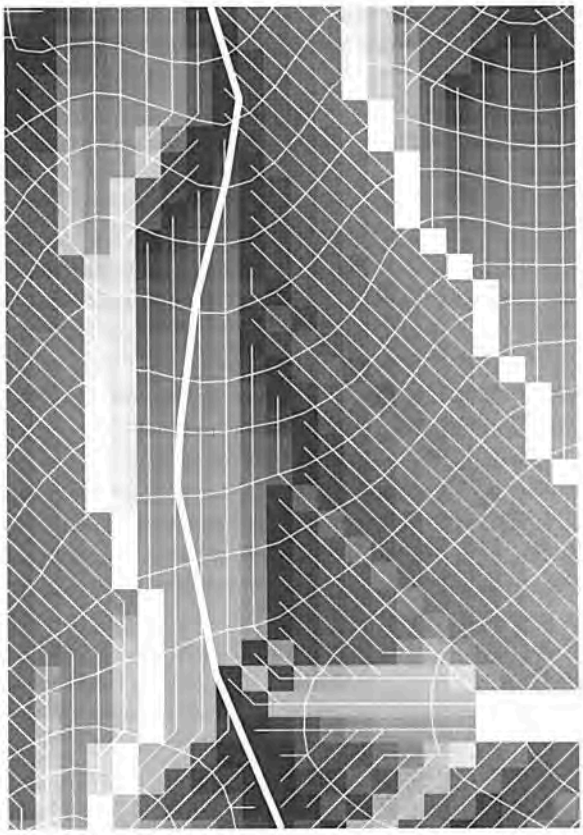

Figure 3.8. Detail of the D8 flow lines, contributing area and catchment boundary on the western edge of the Cottonwood Creek catchment. The narrow white lines are flow lines and contours; the thick white line is the mapped catchment boundary.

3.1.5.3 Randomized Single-Flow-Direction (Rho8) Method The Rho8 (random eight-node) algorithm developed by Fairfield and Leymarie (1991) is a stochastic version of the D8 algorithm in which a degree of randomness is introduced into the flow-direction computations. This algorithm aims to break up parallel flow paths and produces a mean flow direction equal to the aspect. This is achieved by replacing $\phi(i)$, the distance factor of 1 or $\sqrt{2}$ in Equation 3.10, by $2 - r$ for the diagonal neighbors ($i = 1, 3, 5$, or 7 in Figure 3.1a), where r is a uniformly distributed random variable between 0 and 1. The effect of this change will be most noticeable where the slopes are similar, such as on hillslopes, and will have little effect where one direction is clearly the steepest, such as in confined valley bottoms. Like the D8 algorithm, the Rho8 algorithm cannot model flow dispersion, but it does simulate more realistic-looking flow networks. The breakup of long, parallel flow paths

comes at the cost of introducing many more cells that have no upslope connection. The randomizing of flow directions also results in different flow networks each time the program is run (as illustrated in Chapter 5). These characteristics are undesirable, and the Rho8 algorithm is no longer considered a useful alternative to D8. The FD8 and DEMON algorithms provide better solutions to the problem Rho8 was designed to address.

Figure 3.9 shows contributing area computed on the same 15-m Cottonwood Creek DEM using the Rho8 algorithm. Note that the straight-line artifacts produced by D8 have largely disappeared and are replaced by a more dendritic structure. However, the Rho8 surface has many more cells on the hillslopes with no upslope contributing area.

3.1.5.4 Multiple-Flow-Direction Methods (FD8 and FRho8) The FD8 and FRho8 algorithms are modifications of D8 and Rho8 that allow flow divergence to be represented (Moore et al. 1993d). This pair of algorithms allows flow to be distributed to multiple nearest-neighbor nodes in upland areas above defined channels and uses the D8 or Rho8 algorithms below points of presumed channel initiation. On the hillslopes above channels the proportion of flow or upslope contributing area assigned to each downslope neighbor is determined on a slope-weighted basis as pro-

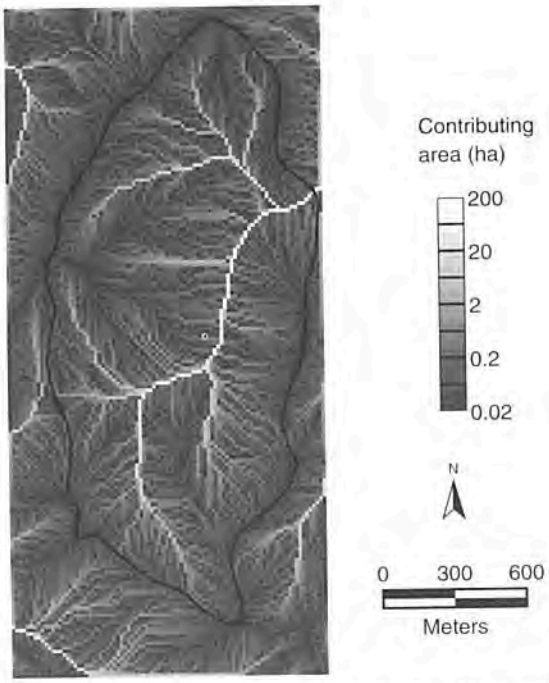

Figure 3.9. Contributing area (ha) derived from the Cottonwood Creek DEM using the Rho8 randomized single flow direction algorithm, with the catchment boundary overlaid.

posed by Freeman (1991) and Quinn et al. (1991). The fraction of contributing area passed from a cell to neighbor i is given by

$$F_i = \frac{\max(0, S_i^v)}{\sum_{i=1}^{8} \max(0, S_i^v)} \tag{3.19}$$

where S_i is the slope from the central node to neighbor i (the same term used in Equation 3.10) and v is a positive constant. Freeman (1991) found that $v = 1.1$ produced the most accurate results for artificial conical surfaces, and TAPES-G uses that value. Larger values of v concentrate the flow more to the direction of steepest slope, giving results more similar to the single-flow-direction (D8) algorithm. Holmgren (1994) reported that much higher values of v in the range 6–8 might be more appropriate. The algorithm of Quinn et al. (1991) is similar to Equation 3.19 but uses a contour-length (flow-width) term in addition to slope to derive the flow fractions.

The FD8 and FRho8 algorithms give more realistic distributions of contributing area in upslope areas, while also eliminating D8's parallel flow paths. This algorithm tends to cause considerable dispersion of flow in valleys, which is considered undesirable because stream lines usually are well defined in valleys. To overcome this, the flow-dispersion algorithm is disabled and replaced by D8 (or Rho8) wherever the contributing area exceeds a user-specified threshold, called the "maximum cross-grading area" in TAPES-G. The dispersion in valleys can be considered as representing a floodplain or riparian area, which might be desirable in some applications; in this case the maximum cross-grading area can be set to a very large value. The transition from multiple- to single-flow-direction algorithm can cause an irregularity in the frequency distribution of the contributing area, particularly if the maximum cross-grading area is set to too small a value. Depending on the landscape, a maximum cross-grading area of about 10 ha or 100,000 m^2 is a reasonable starting point. The optimum value depends on the valley density as represented in the DEM: Finer textured landscapes with high valley density would require a smaller value of cross-grading area to reflect the smaller hillslopes, and coarser landscapes with larger hillslopes would require a higher value.

Quinn et al. (1995) described a variant of the multiple-flow-direction algorithm where the exponent v was changed continuously from 1 (full dispersion) to a large value (single flow direction) as contributing area increased, giving a smooth change from multiple flow direction to single flow direction. This modification has not been implemented in TAPES-G.

The TAPES-G implementation of FD8/FRho8 takes considerably longer to run than D8 or Rho8 because of the greater density of flow connections. Figure 3.10 shows the contributing area for the Cottonwood DEM computed using the FD8 algorithm with a large maximum cross-grading area so flow dispersion is applied everywhere. Note the smooth variation of contributing area in the upland areas in contrast to the D8 and Rho8 results, and the considerable flow dispersion in the valley areas.

3.1.5.5 DEMON Stream-Tube Method The fourth and final algorithm provides a completely different approach for modeling flow accumulation and disper-

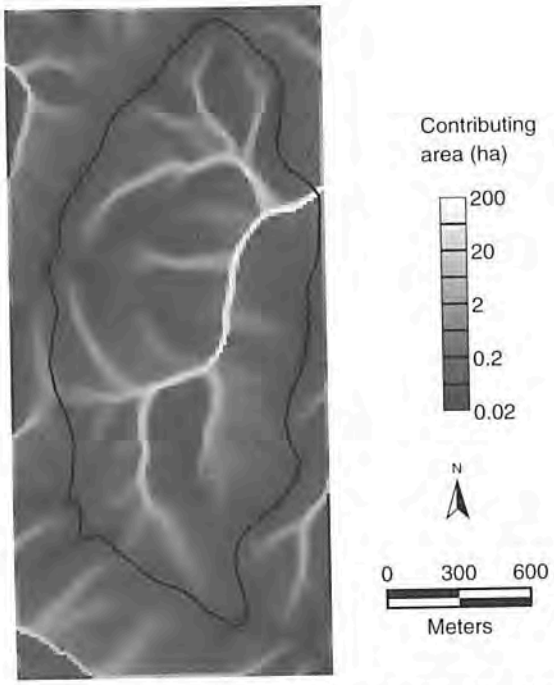

Figure 3.10. Contributing area (ha) derived from the Cottonwood Creek DEM using the FD8 multiple flow direction algorithm with a large maximum cross-grading area, with the catchment boundary overlaid.

sion. This method, which is similar conceptually to the stream-tube approach used with contour-based DEMs by Moore and Grayson (1991), was proposed first by Lea (1992) and Costa-Cabral and Burges (1994). Costa-Cabral and Burges's program is called DEMON (digital elevation model network extraction). In DEMON, flow is generated at each pixel (source pixel) and is routed down a stream tube until the edge of the DEM or a pit is encountered. The stream tubes are not constrained to coincide with the edges of cells and can expand and contract as they traverse divergent and convergent regions of the DEM surface. The stream tubes are constructed from the points of intersections of a line drawn in the gradient direction (aspect) and a grid cell edge. The amount of flow, expressed as a fraction of the area of the source pixel, entering each pixel downstream of the source pixel is added to the flow accumulation value of that pixel. After flow has been generated on all pixels and its impact on each of the pixels has been added, the final flow accumulation value is the total upslope area contributing runoff to each pixel.

The DEMON algorithm has been incorporated into TAPES-G with three modifications. First, DEMON can be applied to either the original DEM or a derived depressionless DEM. Second, the nodes of the DEM define the centroid of the pixels rather than the vertices. Finally, the flow direction of a stream tube for each pixel is

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3.1.5.6 Frequency D

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Figure 3.11. Contributing
DEMON stream tube algori

defined by the aspect (as calculated using Equation 3.12). DEMON takes a similar amount of processing time to FD8/FRho8 and gives results of similar or better quality. DEMON produces few artifacts, although a slight preference for flow in the cardinal north, south, east, and west directions is sometimes apparent.

Figure 3.11 shows the contributing area computed using the DEMON algorithm. Note the smooth variation of contributing area in the upland areas, similar to FD8, contrasted with well-defined channels in the lowlands that are more similar to D8. Minor artifacts of north–south linear features are just noticeable in this image.

3.1.5.6 Frequency Distributions of Contributing Area The cumulative frequency distributions of contributing area calculated by the four different methods are shown in Figure 3.12. The most obvious feature of the plot is the difference at small contributing areas between D8 and Rho8 on the one hand and FD8 and DEMON on the other. The nondispersive single-flow-direction algorithms produce a much higher proportion of low contributing areas because there are many more cells that do not have any inflow. Compared to the DEMON method, which is considered the most accurate of the four, D8 has too high a proportion of low contributing areas by a factor of at least 2 up to about 0.1 ha (4 grid cells), and the effect persists up to contributing areas of about 2.2 ha (about 100 cells). Note that the Rho8 distribution is

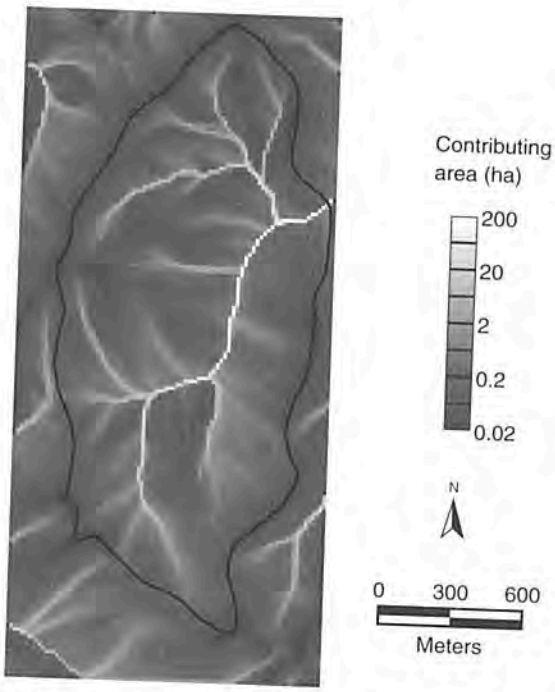


Figure 3.11. Contributing area (ha) derived from the Cottonwood Creek DEM using the DEMON stream tube algorithm, with the catchment boundary overlaid.

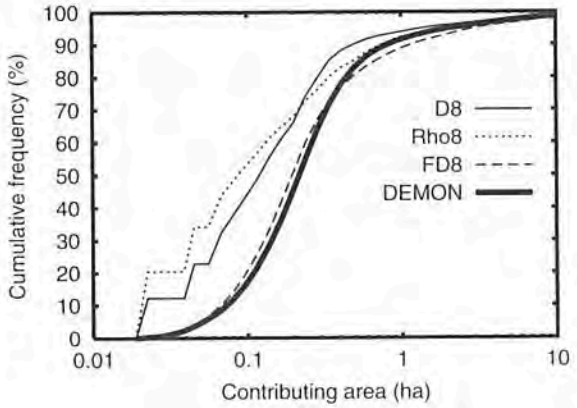


Figure 3.12. Cumulative frequency distributions of contributing area for the Cottonwood DEM computed by the four contributing area algorithms.

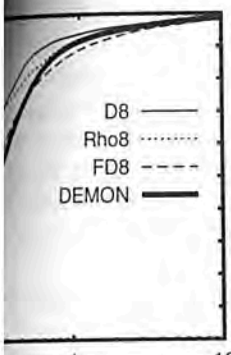
better than D8 for contributing areas larger than about 0.2 ha (10 cells), due to the breakup of linear flow paths and improved flow concentration on mildly convergent hillslopes, which is the effect the algorithm was designed to achieve. However, this improvement comes at the cost of a substantial increase in the number of low contributing area cells, significantly worsening the errors in this part of the distribution.

The other obvious defect of the D8 and Rho8 algorithms is the stepped nature of the distribution that is a consequence of using single flow directions. Without dispersion of flow, the contributing area can only be an integer multiple of the grid cell area, so there are steps at 0.0225, 0.045, and 0.0675 ha, and so on.

The DEMON and FD8 algorithms produce very similar results for small contributing areas, with an absence of steps due to their ability to distribute fractions of cell areas to downslope cells. The FD8 algorithm produces a slightly higher proportion of contributing areas up to about 0.4 ha (18 cells) but a lower proportion of contributing areas above that. Both these effects are due to the higher dispersion of the FD8 algorithm: The extra dispersion in strongly divergent areas produces a higher frequency of small contributing areas, while the dispersion in the valley bottoms results in a lower frequency of high contributing areas.

The frequency distributions are very similar at high contributing areas, due to the convergence of flow into the small number of valley bottom cells. The FD8 algorithm has the lowest proportion of high contributing area cells due to its dispersion of flow across valley bottom areas.

3.1.5.7 Rate of Change of Specific Catchment Area TAPES-G computes the rate of change of specific catchment area along the flow path, dA_s/ds. It is computed as specific catchment area of flow leaving the cell less the average of the specific catchment areas entering the cell, divided by the flow length across the cell. This attribute has application in some erosion models, where erosion is a function of slope, profile curvature, and dA_s/ds (Moore 1996).



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3.1.5.8 Edge Effects and Catchments Contributing area values can be inaccurate where the edge of the DEM does not coincide with the edge of a catchment unless the flow direction is outward across the border of the DEM. TAPES-G does not identify cells that are contaminated with edge effects. However, it does allow the user to interactively choose drainage basins for analysis instead of analyzing the whole DEM. If requested, TAPES-G will display a flow network highlighting drainage lines with contributing area greater than a user-specified amount, and the user can select (using a point-and-click graphical interface) outlet points that define drainage basins to be analyzed. Drainage boundaries can alternatively be specified using a file containing x and y coordinates of a bounding polygon defining the region to be analyzed.

3.1.6 Flow Width

TAPES-G computes a flow-width attribute, w, that is used to compute specific catchment area, A_s, from contributing area, A:

$$A_s = \frac{A}{w} \tag{3.20}$$

Flow width is reported in terms of cell width and is computed in different ways for different flow algorithms. For the D8 and Rho8 algorithms, flow width is equal to cell width for flow in cardinal directions and cell diagonal for flow in diagonal directions:

$$w = \begin{cases} h & i = 2, 4, 6, 8 \\ \sqrt{2h} & i = 1, 3, 5, 7 \end{cases} \tag{3.21}$$

The flow width for the FD8/FRho8 algorithm is difficult to model well since the flow is dispersed in different fractions to multiple downslope cells. Quinn et al. (1995) used a geometrical construction to determine that flow widths in the cardinal directions should be $0.5h$ and those in diagonal directions $0.354h$. The total flow width for a cell is the sum of the flow widths in the directions of downslope cells, and ranges from $0.354h$ to $3.416h$. TAPES-G originally used the D8 flow width for FD8/FRho8, but as a result of recent work (Gallant and Hutchinson in preparation) this was changed to account for the amount of dispersion of flow. Initially, the effective number of flow directions is calculated from the weights:

$$n_{\text{flow}} = \frac{1}{\sum_{i=1}^{8} F_i^2} \tag{3.22}$$

This n_{flow} varies from a minimum of 1 when all flow is in a single direction to a maximum of 8 when flow is dispersed equally in all eight directions. The flow width is then estimated as

$$w = \begin{cases} h & n_{\text{flow}} < 3 \\ h\left[1 + 3\left(\dfrac{n_{\text{flow}} - 3}{5}\right)\right] & n_{\text{flow}} \geq 3 \end{cases} \tag{3.23}$$

This width is h for flow on convergent and planar areas when n_{flow} is small, but increases to a maximum of $4h$ when n_{flow} is large. This method takes no account of whether the flow is in a cardinal or diagonal direction.

For the DEMON algorithm the flow width is the distance across the cell at right angles to the flow direction, which, in turn, is a function of aspect:

$$w = |\sin \psi| + |\cos \psi| \tag{3.24}$$

where $|x|$ denotes the absolute value of x.

3.1.7 Maximum Flow-Path Length

The maximum flow-path length is the maximum length of all flow paths from the catchment boundary to a given point in the DEM. It can be computed using the D8 or Rho8 algorithms described above, but rather than accumulate areas the algorithm accumulates flow distances across cells, and only the largest flow-path length of all upslope cells is passed on to the downslope cell, instead of the sum. For flow in a cardinal direction ($i = 2, 4, 6,$ or 8) the cell flow distance is h (the grid spacing), whereas for diagonal flow ($i = 1, 3, 5,$ or 7) the cell flow distance is $\sqrt{2}\,h$. However, flow paths calculated by these methods tend to have a zigzag appearance because the flow-path directions are restricted to the four cardinal and four diagonal directions. Flow paths calculated using the stream tubes constructed by the DEMON algorithm avoid this problem; however, the calculation of flow-path length using this method has not been implemented in TAPES-G.

3.1.8 Downslope Attributes

In some applications it is the shape of the landscape downslope of each point, rather than upslope, that is of particular interest (Table 1.1). For example, Speight (1980) described how soil-water content was influenced by specific dispersal area in combination with specific catchment area. Specific dispersal area is the area downslope of a unit length of contour to a stream line, and represents the available area into which soil water can drain. Downslope path length is another attribute that can be used where proximity to a stream is considered a useful attribute.

The algorithms for contributing area and flow-path length can be adapted to compute downslope attributes by looking uphill rather than downhill and working from the lowest to highest elevations. However, the existing algorithms can be used without modification simply by inverting the DEM. There are two points to be aware of when using this approach. First, some terrain-analysis programs, including TAPES-G, use negative elevations internally for special purposes, so the elevations of the inverted DEM should be positive. This is easily achieved by subtracting the DEM from a constant value larger than the highest elevation of the DEM. Second, the peaks in the surface become sinks when it is inverted, and in this case these sinks are genuine termination points and must not be filled.

3.1.9 Upslope Averages of Terrain Attributes

For processes connected with the accumulation and dispersal of materials across the surface, such as soil development, the average characteristics of the landscape in a site's contributing area may be more significant than the terrain attributes at the site itself (see Chapters 10–12 for additional applications of this type). The mean slope or curvature upslope of the site can be a useful index of processes linked to the sorting and transport of material to the site.

Program UPSUM-G provided with the TAPES-G package performs this type of analysis. It calculates the area-weighted mean value of several of the TAPES-G primary terrain attributes within the contributing area of each cell. For each cell, the area-weighted mean is the sum of the value at that cell plus the values of the inflowing cells multiplied by the contributing areas, divided by the sum of the weights:

$$\bar{v}_j = \frac{\sum_{i \in U_j} wivi}{\sum_{i \in U_j} wi} \tag{3.25}$$

where v is the value being averaged, U_j is the set of adjacent cells flowing into cell j (including cell j), and v_i and w_i are the value and the weight for cell i. The weights for the inflowing cells are equal to the contributing areas of these cells, and the weight for cell j, the cell under consideration, is 1.

3.1.10 Other Terrain Attributes

While the attributes discussed here are the most frequently used, a number of other attributes can be derived from DEMs to describe the spatial patterns of landscape geometry and processes. These include the identification of streams and ridges and calculations of distance to nearest stream or ridge; stream ordering; statistical measures of the distribution of elevation within regions or catchments, such as skew and kurtosis; and hypsometric analysis.

3.1.11 TAPES-G Inputs

TAPES-G can accept DEM files in several different formats. The DEM can be either x, y, z triplets or just z (elevation) values. An x, y, z file can have points in any order, while a z-only file may be in either row or column order with the first point in either the northwest or southwest corner. Elevation values may be integer or floating point; if they are integer values a scaling factor can be applied, which is often used to increase the vertical resolution. Finally, the file may be in either ASCII or binary form.

ASCII files have one record per line. Unformatted binary files (integer or floating point) also are record oriented, with each record preceded and followed by a four-byte integer specifying the number of bytes in the record (standard FORTRAN unformatted records). Files containing x, y, z triplets must have one triplet per record,

while files containing only z values may have any number of z values per record, so long as each new column or row starts in a new record. Direct access two-byte integer files containing only z values are also accepted. TAPES-G can read ARC/INFO grids exported using the GRIDFLOAT command, which produces a binary floating point file and a separate header file containing metadata such as the size, resolution, and location of the grid.

An input elevation value of 0 indicates a missing value or point outside the analysis region. TAPES-G will not compute attributes for points with 0 elevation, and all elevations for the region to be analyzed should be positive (negative elevations have a special meaning internally). TAPES-G also assumes that coordinates and elevation values are in meters, but other units may be used provided that elevation is in the same units as the x and y coordinates.

The current implementation of TAPES-G requires that the DEM fits into the size limits set when the program is compiled. The arrays are set to 1000 rows and 1000 columns, although these settings can be changed to suit the available memory and size of the DEM. The numbers of rows and columns do not have to be equal. The memory requirements are approximately 80 bytes per grid cell (thus requiring 80 Mbytes of virtual memory in the standard configuration) or 40 bytes per grid cell if the program is compiled without the DEMON module.

3.1.12 TAPES-G Outputs

TAPES-G produces an output attribute file in either binary or ASCII format. The 14 primary topographic attributes that are written to this file are summarized in Table 3.1. Each DEM grid point with all its attributes is written to a single record as either one line in an ASCII file or one unformatted record in a binary file. Cells with missing data can either be omitted from the output file or written with no-data values for all attributes. The no-data value is also used where an attribute is undefined, such as for aspect when the surface is perfectly flat. Other programs using the output of TAPES-G must be aware of the no-data value and take appropriate action when it is encountered.

In addition to the computed terrain attributes, metadata are written to the beginning of the file, describing the contents of the file, the resolution and coordinates of the data, and the options and parameters used by TAPES-G to produce the file. These metadata are used by other programs in the TAPES package to locate the attributes they require, and by TAPESTOARC, which reformats the output data to the form required by ARC/INFO's ASCIIGRID or FLOATGRID command, permitting visualization and further analysis within the ARC/INFO Geographic Information System (GIS).

Two utility programs are provided in the TAPES-G package for simple viewing and analysis of the results. The program ATTRIBUTES provides color visualization of the attributes contained in the TAPES-G output file, with interactive control of the rendering of the data. The program FREQ computes histograms and performs simple statistical analysis of the results. ATTRIBUTES is written in C and uses the X Window system while FREQ is written in FORTRAN.

TABLE 3.1 Terrain Attr

Attributes	
1, 2	x, y
3	Flow direction
4	z
5	Contributing area
6	Flow width
7	Slope
8	Aspect
9	Profile curvature
10	Plan curvature
11	Tangent curvature
12	Elevation residual
13	Flow-path length
14	$d(A_s)/ds$

3.2 ELEVATION RES

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TABLE 3.1 Terrain Attributes in TAPES-G Output File

	Attributes	Units	Definition	Section
1, 2	x, y	Usually meters	x and y coordinates as determined from the DEM	
3	Flow direction	None	Computed using D8 or Rho8 algorithm	3.1.3
4	z	Usually meters	Elevation as read from the DEM	
5	Contributing area	Square meters or number of cells	Area draining out of each cell	3.1.5
6	Flow width	Multiple of cell width	Width associated with flow leaving the cell	3.1.6
7	Slope	Percent	Slope in the steepest downslope direction	3.1.2
8	Aspect	Degrees clockwise from north	The direction of the steepest downslope slope	3.1.3
9	Profile curvature	Radians per 100 meters	Curvature of the surface in the direction of steepest descent	3.1.4
10	Plan curvature	Radians per 100 meters	Curvature of contour drawn through the grid point	3.1.4
11	Tangent curvature	Radians per 100 meters	Plan curvature multiplied by sine of slope angle	3.1.4
12	Elevation residual	Usually meters	Difference between original DEM and depressionless DEM	3.1.5
13	Flow-path length	Usually meters	The longest flow path from the catchment divide or edge of DEM to the cell	3.1.7
14	$d(A_s)/ds$	None	Rate of change of specific catchment area along the flow path	3.1.5

3.2 ELEVATION RESIDUAL ANALYSIS

The terrain attributes computed by TAPES-G are all controlled by local variations in topography (i.e., the change in elevation from one cell to the next). In some instances it can be useful to consider the nature of each point with reference to a wider context (e.g., Blaszczynski 1997). One application of this type of analysis is where subsurface water flow does not follow surface shape but responds to relative elevations within a region. In this situation, a small rise in the bottom of a valley might be nearly as wet as its surroundings, even though it has no contributing area for surface flow. Another application is identifying ridges and valleys by comparing their elevations with those in a surrounding area comparable in size to the length of the hillslopes.

The program ELEVRESIDGRID computes several terrain attributes by comparing the elevation at each point with the elevations in a circular window of a specified

size. The analysis ignores hydrological connectivity of the surface topography, considering instead the relationship of a point to the surrounding landscape. This analysis is similar to the functions provided in some GIS packages, such as the FOCAL operators in the ARC/INFO GRID module.

A key issue with this type of analysis is the choice of a suitable analysis window size. Ideally, the window size should be comparable to the length scale of the process under study. This size is often the hillslope length.

In the following equations, the set of cells included in the circle about the point being considered is denoted by C, and the number of cells in the circle is n_C.

3.2.1 Mean Elevation

Mean elevation in the circular window is primarily used as a reference against which to compare the elevation at the central point of the window. However, the mean elevation can be useful when a smoothed DEM is required:

$$\bar{z} = \frac{1}{n_C} \sum_{i \in C} z_i \tag{3.26}$$

3.2.2 Difference from Mean Elevation

The difference between the elevation at the center of the window and the mean elevation in the window is a measure of the relative topographic position of the central point. Its range depends on the range in elevation within the size of the window:

$$\text{diff} = z_0 - \bar{z} \tag{3.27}$$

This terrain attribute can be useful in connection with processes that are sensitive to local differences from regional elevations, such as groundwater flow (Roberts et al. 1997) and susceptibility to lightning strikes (Cary 1998).

3.2.3 Standard Deviation of Elevation

The standard deviation of elevation is a measure of the variability of elevation within the circular window. It is useful as a measure of local relief at the scale specified by the radius of the window:

$$\text{SD} = \text{sqrt}\left(\frac{1}{n_C - 1} \sum_{i \in C} (z_i - \bar{z})^2 \right) \tag{3.28}$$

Standard deviation is a measure of elevation variability within the window. When the window size is similar to the hillslope length, standard deviation provides a measure of local relief. For much larger window sizes, this attribute measures the roughness of the landscape at that coarser scale.

3.2.4 Elevation Range

Elevation range measures the full range of elevations within the circular window:

$$\text{range} = \max_{i \in C} z_i - \min_{i \in C} z_i \tag{3.29}$$

It is similar to standard deviation in that it measures local relief, but has the disadvantage of sometimes changing abruptly from place to place as individual high and low points enter and leave the window. This can result in visible overlapping circular regions in the results.

3.2.5 Deviation from Mean Elevation

The deviation from the mean is the difference from the mean divided by the standard deviation:

$$\text{dev} = \frac{z_0 - \bar{z}}{\text{SD}} \tag{3.30}$$

This attribute measures the relative topographic position as a fraction of local relief, and so is normalized to the local surface roughness. The deviation mostly ranges between −1 and +1, but values outside this range are possible; large values may indicate irregularities in the DEM, where the elevation is significantly outside the typical range in that region.

3.2.6 Percentile

Percentile is a ranking of the point at the center of the window relative to all the points in the window. It is calculated simply by counting the number of points lower than the central point:

$$\text{pctl} = \frac{100}{n_C} \operatorname*{count}_{i \in C}(z_i < z_0) \tag{3.31}$$

Percentile ranges from 0 to 100, with a value of 0 indicating that the point is the lowest in the circle, 100 indicating that it is the highest, and 50 indicating that half the points in the circle are lower. Percentile is similar to deviation, but its well-defined range makes its application simple and robust. It has been used as an index of local topographic position, which, as Chapter 16 shows, can be a useful explanatory variable for the spatial patterns of vegetation species.

3.2.7 Other Attributes

A number of other attributes can be computed using this type of analysis for various purposes. An alternative to percentile ranking that is easier to implement in the ARC/INFO GIS is the elevation as a percentage of the elevation range:

$$\text{pctg} = 100\,\frac{z_i - z_{\min}}{z_{\max} - z_{\min}} \tag{3.32}$$

Like percentile, this variable always ranges from 0 to 100; unlike percentile it does not account for the distribution of values within the circle so it is not as sensitive to the shape of the surface. It also suffers from the same circular artifacts as elevation range due to the use of minimum and maximum elevations.

3.2.8 ELEVRESIDGRID Examples

Figures 3.13–3.15 show the difference from mean elevation, percentile, and standard deviation calculated for the Cottonwood Creek DEM using a window radius of 200 m. The attributes calculated at this scale are much more generalized than the local attributes computed by TAPES-G and show the variations of topography at a broader scale, roughly matching the length of the hillslopes.

Figure 3.13, difference from mean elevation, shows the generalized structure of ridges and valleys within the catchment. The brightness or darkness indicates the intensity of highness or lowness: for example, there are some low hilltops along the western catchment boundary that are barely noticeable in this image indicating that they do not protrude much above the surrounding landscape. Conversely, the valley of the main

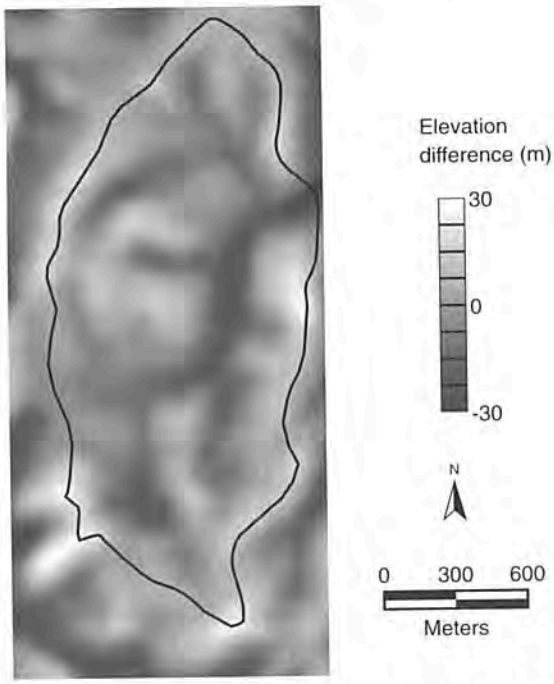

Figure 3.13. Difference from mean elevation for the Cottonwood Creek DEM using a radius of 200 m, with the catchment boundary overlaid.

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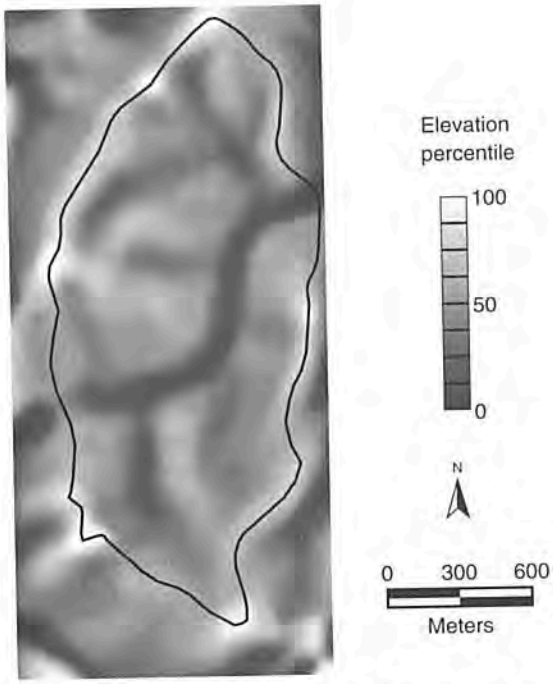

Figure 3.14. Percentile for the Cottonwood Creek DEM using a radius of 200 m, with the catchment boundary overlaid.

drainage line is seen to be deeply incised in its middle portion where its difference from mean elevation becomes more negative than either upstream or downstream.

Figure 3.14, elevation percentile, shows the structure of the catchment in a similar manner to Figure 3.13 but picks out different features of the surface. Being based on a ranking rather than an elevation difference, percentile is insensitive to relief, and so shows all significant hilltops as bright spots regardless of how high they are relative to their surroundings. Similarly, the valleys are more uniformly identified as the lowest part of the landscape without indicating their relative depths.

Figure 3.15, standard deviation, shows the pattern of local relief across the catchment. The valley bottoms and, to a lesser extent, the catchment boundary are areas of lower relief, while the steep hillslopes to the east of the main channel are areas of high relief. The highest standard deviation is found on areas with long, steep slopes, such as on the hill south of the catchment outlet and at the south end of the DEM outside the catchment.

3.3 TAPES-C: TERRAIN ANALYSIS ON CONTOUR DEMS

The contour DEM structure is an alternative representation to the gridded DEM that uses contours and flow lines to delineate elements aligned with the flow direction of

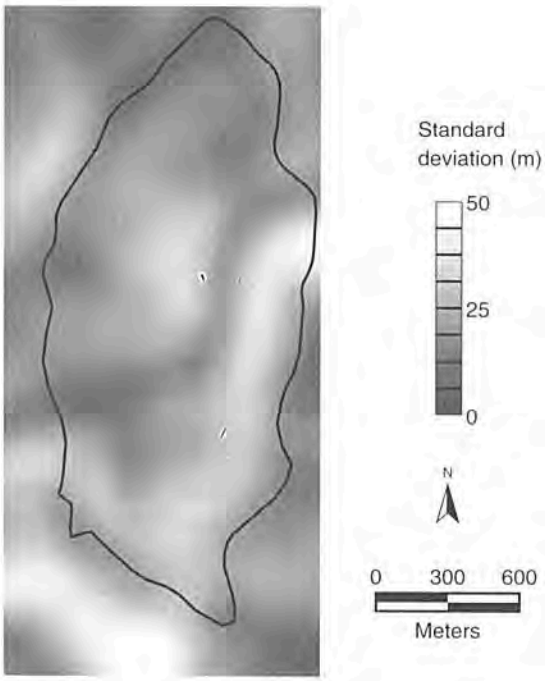

Figure 3.15. Standard deviation of elevation for the Cottonwood Creek DEM using a radius of 200 m, with the catchment boundary overlaid.

the surface, as shown in Figure 3.16. Elements are bounded above and below by contour lines and to the sides by flow lines. Each element is considered to be a unit of landscape, in the same way as the cell of a DEM, but the elements are of variable size and shape. The advantage of this representation is that the flow connectivity is always from one element to its downslope neighbors so the determination of contributing area is trivial. Dynamic hydrologic modeling within this geometric framework is also simpler than grid or triangular geometries because the connectivity of flows is encapsulated in the network geometry; this is the primary use of these terrain representations. The main disadvantage of this approach is that the element network is relatively difficult to construct in the first place.

The method of partitioning catchments into flow elements was pioneered by Onstad and Brakensiek (1968). They referred to it as the "stream-path" or "stream-tube" analogy and implemented the method manually. Speight (1974, 1980) also used manual methods to produce a series of flow lines from which specific catchment and dispersal areas could be estimated.

The automated creation of the network of elements from contour data is not a trivial process and requires well-organized input data and careful handling of critical points in the landscape: peaks, saddles, channel confluences, and ridge junctions.

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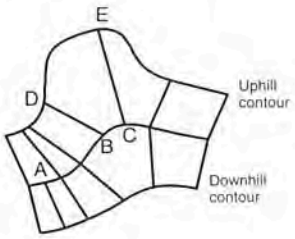

Figure 3.16. A set of elements formed by contours and flow lines. Proceeding uphill, flow lines are terminated (*A*) and added (*B*, *C*) to maintain even spacing. Lines are constructed using either a minimum distance (*BD*) or orthogonal (*CE*) criterion.

Dawes and Short (1994) discuss in detail the use of the topology of the network of lines and critical points to assist the construction of element networks.

There are currently two software implementations of this technique, TAPES-C and TOPOG, which were both developed from the slope line algorithm of O'Loughlin (1986). TAPES-C is described in Moore et al. (1988b) and Moore and Grayson (1991); TOPOG's implementation is described in Vertessy et al. (1993) and Dawes and Short (1994). The five subsections that follow describe the algorithms used by TAPES-C; the topographic attributes TAPES-C calculates; the differences between TAPES-C and TOPOG; and TAPES-C's inputs and outputs.

3.3.1 Element Construction

Creating a network of elements from contour data is fundamentally the construction of regularly spaced flow lines between adjacent contours. These lines are constructed for each pair of adjacent contour lines working from the lowest to highest contour, and the main challenge for the automated algorithms is to select well-chosen lines that provide a uniform and error-free tessellation of the surface.

A user-specified distance controls the spacing of the flow lines, and on the first (lowest) contour, flow lines are placed at that specified distance apart or as close to that distance as the spacing of points along the contour permits. On subsequent higher contours the upper ends of the flow lines from the lower contour are used as the start points of the next set of flow lines provided they are neither too close nor too far apart. This approach results in continuous lines across the surface with each element connecting directly to the element below. The connections from an element to its downslope neighbors are recorded as the elements are constructed.

If a starting point is too close to the previous start point, it is skipped to prevent cluttered lines and narrow elements (although this is optional), as shown at *A* in Figure 3.16. If the points are too far apart, one or more new lines are started between the existing lines to prevent very wide elements as shown at *B* and *C* in Figure 3.16. In TAPES-C a new line is inserted if the distance between the existing start points is more than 1.3 times the user-defined spacing; a line is terminated if the start points are less than half the specified spacing.

Once a start point is chosen for a flow line, its end point on the next highest contour must be found. There are two criteria for choosing this end point:

1. *Minimum distance:* the end point is the point on the next highest contour closest to the start point.
2. *Orthogonal:* the end point is chosen so that the flow line is at right angles to the lower contour.

TAPES-C uses the minimum distance method in divergent (ridge) areas and the orthogonal method in convergent (valley) areas. A user-defined threshold of contour curvature is used to identify convergent areas. This combination of techniques helps overcome the errors introduced by using straight flow lines and always working uphill. The line *CE* in Figure 3.16 is an orthogonal line, while the remaining lines are constructed using the minimum distance criterion.

Peaks and saddles introduce special cases into this construction. Peaks must be explicitly defined within any closed contour that does not have another contour within it, and must be given an elevation higher than the surrounding contour. Flow lines up from the innermost contour all connect to the enclosed peak. Peak points may also be located in flat ridge areas to facilitate the construction of well-shaped elements. Unlike peaks in closed contours, these ridge points connect to a higher contour and multiple ridge points may be strung together, as shown in Figure 3.17.

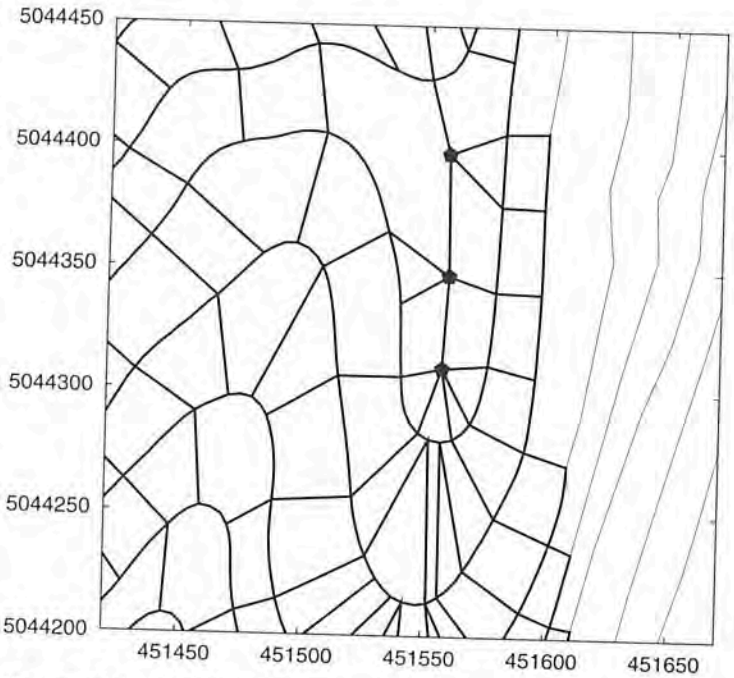

Figure 3.17. Part of the TAPES-C element network constructed from the Cottonwood Creek DEM showing a ridge and valley. Connected high points form a ridge line to facilitate element construction.

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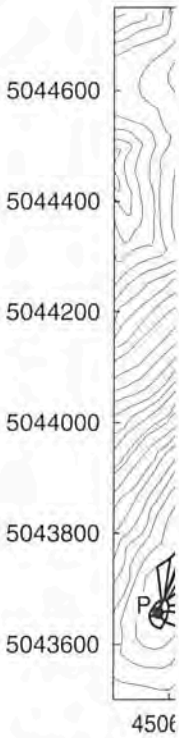

Figure 3.18. The TAP
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ridge (R) points.

Saddle points are required between adjacent contours of the same elevation. These saddles must be given the elevation corresponding to the upslope contour to which they connect. The saddle then forms the connection between the two separate segments of contour at this elevation. TAPES-C constructs lines from the saddle to the closest points on both contour segments before commencing element construction. When one of these points is reached while scanning along the upper contour for a candidate upper end point, the scan switches to the other contour segment.

Figure 3.18 shows the element network constructed for a tributary of the Cottonwood Creek catchment, including the high points, saddle points, and ridge points, and the inferred channel network. Figure 3.19 shows contributing area computed from the element network. The same gray-scale legend has been used here as in the grid-based contributing area images in Figures 3.7–3.11 to allow comparison. One of the deficiencies of the contour-based element network is the large valley bottom elements resulting from the construction of flow lines in an upslope direction. This results in high contributing areas spread across relatively wide valley bottoms, in a similar manner to the FD8 grid algorithm (see Section 3.1.5.4 and Figure 3.10). This

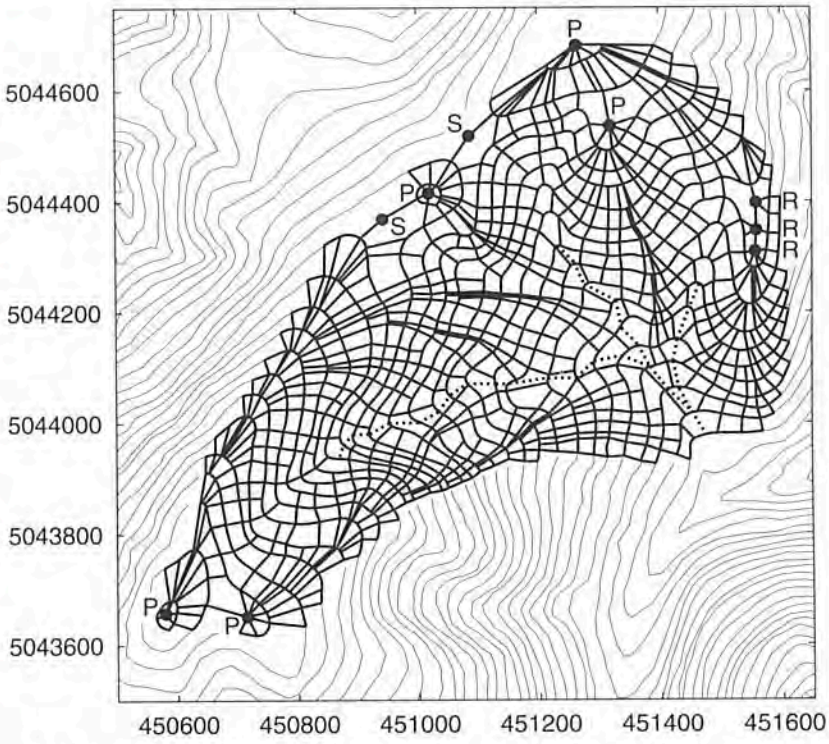

Figure 3.18. The TAPES-C element network for a tributary of the Cottonwood Creek DEM at the northern end of the catchment. The dashed line is the inferred channel based on a contributing area threshold of 5 ha. The labels indicate user-supplied peak (P), saddle (S), and ridge (R) points.

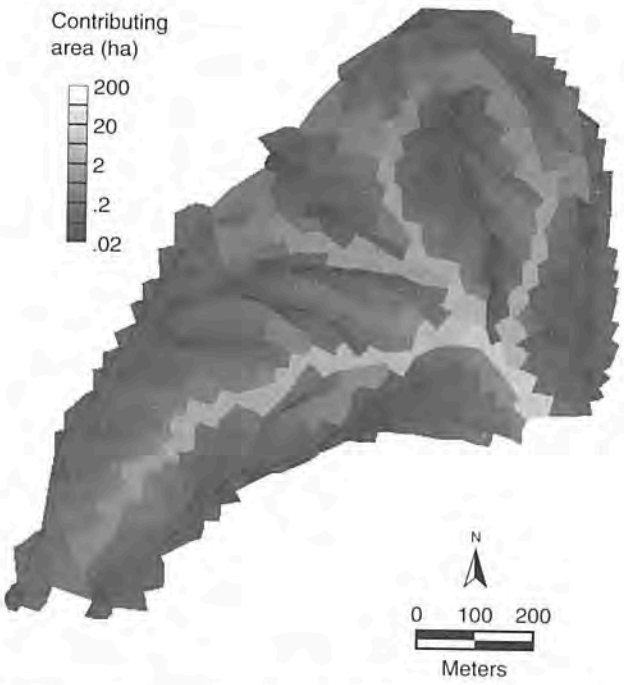

Figure 3.19. Contributing area computed from the TAPES-C element network of Figure 3.18.

can be a particular problem when used for hydrologic modeling, but the inclusion of channels within high contributing area cells allows the model to represent the convergence of flow to a narrow channel in those cells, rather than spread across the whole element.

Note that because TAPES-C and TOPOG are designed primarily for dynamic hydrological modeling they expect to produce element networks for whole catchments. These programs are not designed to construct element networks on arbitrary pieces of topography. The programs can also fail if provided with improper input data such as contours oriented in different directions and mislocated peaks or saddles. Excessive contour spacing also causes difficulties and can be remedied by providing additional contours.

3.3.2 Computed Terrain Attributes

After constructing all the elements, TAPES-C computes the attributes of each element. The area of the element, A_e, and its width at the upper and lower ends, W_u and W_l, are calculated from the coordinates of the element boundary. The effective length of the element, reported as overland flow distance, is the area divided by the average width:

$$l = \frac{A_e}{0.5(W_u + W_l)} \tag{3.33}$$

Two slopes are calculated for each element: the average slope across the element and the slope down the center of the element. Average slope is the elevation change (contour interval) divided by the element length:

$$S = \frac{z_u - z_l}{l} \tag{3.34}$$

Slope down the center of the element is useful as an estimate of the slope of the channel in valley bottom elements. The center line of the element is defined as the line from the point of maximum curvature on the upper contour to the point of maximum curvature on the lower contour, and its length is l_c, the channel flow distance. The channel slope is

$$S_c = \frac{z_u - z_l}{l_c} \tag{3.35}$$

Aspect is computed as the orthogonal direction to a straight line drawn across the lower end of the element (the line *BC* in Figure 3.16). Plan curvature is not calculated explicitly, but convergence and divergence is represented by the change in width from upper to lower contour. Plan curvature at the center of the element can be approximated by

$$K_c = \frac{2(W_l - W_u)}{l(W_l + W_u)} \tag{3.36}$$

with the sign convention of positive curvatures being convex.

Contributing area is determined by accumulating element areas from highest to lowest elevations using the previously recorded links between elements. Where the contributing area is greater than a user-specified threshold, TAPES-C constructs a channel line down the center of the element joining the points of maximum contour curvature on the upper and lower contour segments.

3.3.3 Differences Between TAPES-C and TOPOG Element Networks

While using similar principles of element construction, TAPES-C and TOPOG differ in their implementation of the methods. TOPOG always uses minimum distance to select the upper end of each flow line. This avoids some problems that occur with the orthogonal lines but sometimes causes problems, such as crossing over valley bottoms where the contours are quite asymmetric. TOPOG constructs drainage lines down from prespecified channel heads before constructing elements, which both increases efficiency and gives better control of elements in valley bottoms, reducing the need for the orthogonal method. As a result of this construction, channels in TOPOG are located between valley bottom cells, rather than in the center of valley bottom cells as in TAPES-C. TOPOG does not handle connected peaks, and it con-

TABLE 3.2 Terrain Attributes in TAPES-C Output File

	Attributes	Units	Definition
1	Contour number	None	Index of contour starting from 1 at lowest contour
2	Element number	None	Index of element on each contour
3	Downslope connection	None	Index of downslope element number to which the element connects
4	Contributing area	Usually square meters	Area draining across lower contour of the element
5–7	Bottom center x, y, and z	Usually meters	Location and elevation of the center of the lower contour
8	Element area	Usually square meters	Area of the element, not including inflowing elements
9	Element slope	Percent	Average slope across the element
10	Downhill width	Usually meters	Length of lower contour segment
11	Uphill width	Usually meters	Length of upper contour segment
12	Overland flow distance	Usually meters	Average length of cell
13	Channel flow distance	Usually meters	Length of channel line
14–16	Centroid x, y, and z	Usually meters	Location and elevation of element centroid
17	Channel slope	Percent	Slope of channel line
18	Aspect	Degrees clockwise from north	Orientation of element as determined from lower contour
19, 20	Max curvature x and y	Usually meters	Location of maximum curvature point on lower contour

structs lines from saddles up and down to adjacent contours before constructing elements. TOPOG is a more robust software product than TAPES-C, having benefited from a more sustained software development effort. TOPOG can be obtained from CSIRO Land and Water through *http://www.clw.csiro.au/topog*. The program is free but registration is required before the software can be downloaded.

3.3.4 Inputs

The input data for TAPES-C consists of contour data supplemented by high points and saddle points. These data must be collected into a particular format readable by TAPES-C, with the contour data ordered from lowest to highest elevations, oriented consistently (with uphill on either the left or right of all contours), and with evenly spaced samples. These resampling, reordering, and reformatting tasks are performed by two support programs, PLOTCON and PREPROC, provided with the TAPES-C package. An interactive contour-editing program, EDITCON, is also provided with the package. TAPES-C also requires some user intervention during running to identify whether particular peak points connect to an uphill contour.

3.3.5 Outputs

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3.3.5 Outputs

TAPES-C produces an output file in the same format as TAPES-G, with a list of attributes for each element (Table 3.2). Metadata have not been implemented in TAPES-C output files at this time. A separate vertex file provides the shapes of each element, in the same order as the attribute file.

3.4 CONCLUSIONS

This chapter described the commonly used primary terrain attributes that are calculated directly from elevation data. The most commonly used are slope, aspect, contributing area, specific catchment area, plan curvature, and profile curvature. These attributes and others are calculated by the TAPES-G program from regular grid DEMs and by the TAPES-C program from contour DEMs. The following chapter describes various secondary terrain attributes, combinations of two or more primary topographic attributes, that are frequently used as surrogates of physical processes.