Slope-Line Detection in a Vector-Based GIS

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ABSTRACT: Previous methods for detecting slope lines from digital topographic data are all raster-based due to the dominating raster data structures. The recent developments in geographic information systems (GISs) make it necessary for vector-based methods to be constructed in order to handle vector-structured data more effectively. This paper presents a vector method of slope-line detection for terrain analysis. Topographic data coded in digitized contours are organized in two relational files, a Contour Attribute Table (CAT) and a Point Location File (PLF). Given any location as the origin of gravity flow in a surface, the method identifies consecutive segments of steepest descent according to the Cauchy-Schwarz theorem. An empirical study using the topographic database of Idyllwild, California demonstrates the operation of the method. On average, it takes less than two seconds of CPU time for the method to identify a slope line from the generalized contour coverage of a 15-minute quadrangle.

INTRODUCTION

A SLOPE LINE IS THE LINE OF GREATEST INCLINATION through any point on a slope (Douglas, 1986). It represents the path of gravity flow along which objects move downslope from any given location on a surface. Different terms are used in the literature, including slope direction, flow path, overland path, and flow direction (Speight, 1968; Marks *et al.*, 1984; Wadge, 1988; Jenson and Domingue, 1988). Slope lines describe certain topographic characteristics of a surface, such as the direction, length, and gradient of downslope movement. The capability of detecting slope lines from digital topographic data makes geographic information systems (GISs) an effective tool for a variety of terrain analyses, e.g., the delineation of drainage networks and the extraction of topographic structure (Mark, 1984; Band and Robinson, 1986). Wadge (1988) points out the potential of using a GIS to model gravity flows and slope instabilities.

Existing methods for detecting slope lines from digital elevation data are raster-based and characterized by neighborhood operations and grid cell manipulations. There are two reasons for the dominance of raster methods. First, the digital elevation models (DEMs) of the U.S. Geological Survey, the most common source of digital topographic data, are organized in a grid format (U.S. Geological Survey, 1987). Second, raster-based mapping packages and GISs were developed earlier than, and still outnumber, vector-based systems (Peucker and Chrisman, 1975; Tomlinson *et al.*, 1976; Monmonier, 1982; Burrough, 1986; Douglas, 1986; Tomlinson, 1988).

Recent progress in vector-based GIS technology has enhanced the efficiency in handling topographical information and facilitated high-accuracy mathematical computations in surface modeling (Burrough, 1986; Carter, 1988). Although functions for converting digital data between raster and vector modes are furnished in major GISs, full utilization of vector-based GISs requires that spatial analyses employ methods that are designed specifically for vector-based data structures. This paper discusses different methods for slope-line detection and presents a vector method based on digitized contours. The operation of the method is demonstrated using the DEM of the 15-minute quadrangle of Idyllwild, California.

RASTER METHODS FOR SLOPE-LINE DETECTION

Raster methods for slope-line detection and related surface analyses are characterized by grid cell manipulation and neighborhood operation. Grid cell manipulation means that a slope line consists of a number of straight-line segments each of which is defined in a grid cell. In the neighborhood operation, the direction of a segment is determined by the steepest descent between the cell and its neighboring cells selected according to some predetermined rules.

Figure 1 gives a hypothetical example for illustrating the general principles of raster methods. If the slope line to be identified starts at the central cell, its eight neighboring cells are compared and the one giving the steepest descent determines the direction of downslope flow. In this example, the slope line direction is to the central cell's right-hand side (east) neighbor and an arrow is assigned (Figure 1b). The east cell becomes the central cell for the next segment. The procedure continues until a local depression or a flat surface is reached.

In the above example, the direction of each segment of a slope line is determined by the data values of eight adjacent cells. The number of searched neighbors may vary, e.g., four (Peucker and Douglas, 1975; Kikuchi *et al.*, 1982) or eight (Speight, 1968; Evans, 1980; Horn, 1981; Jenson and Domingue, 1988). Nonimmediate neighbors may also be considered, e.g., 20 cells are compared in Douglas (1986). In fact, this number can be extended to any specified R-value defined by Huber and Church (1985).

The gradient between each pair of grid cells is their difference in elevation divided by distance. A distance weight may be used to reflect the varying distances between different types of neighbors. For instance, the distance between diagonal neighboring cells is $\sqrt{2}$ of that between orthogonal neighboring cells (Burrough, 1986; Jenson and Domingue, 1988).

As the principal advantage of raster data structures is their simplicity (Clarke, 1990), the principal advantage of raster methods is that they are easier to conceptualize and their procedures easier to program. Another practical advantage of raster methods is that they can be processed directly on large amounts of available elevation data sets acquired in grid formats, e.g., satellite and scanned air photo data. Because remote sensing has become a major source of cartographic data, raster methods will remain advantageous over alternative vector methods in terms of direct applicability since no raster-vector conversions are needed. Another advantage of raster methods is that most

129	128	126
130	127	124
129	127	126

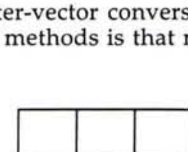

FIG. 1. A hypothetical example illustrating the raster principles of slope-line detection. The left shows the elevation data of a 3 by 3 kernel. An arrow indicating the direction of steepest descent is assigned to the central cell as shown on the right.

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raster-based GISs are more affordable than their vector-based counterparts. Because raster-based GISs favor methods that operate on their databases directly, raster methods will continue to be implemented in such systems.

The advantage of a raster-base GIS owing to data availability has become less prominent since the 1970s (Peucker and Chrisman, 1975). Recently the number of vector-based GIS users has been growing rapidly. The implementation of the TIGER database for the 1990 Census in the United States (Marx, 1986), along with the release of the 100K Digital Line Graph database (DLG) by the U.S. Geological Survey (Batten, 1988), indicates a trend toward greater use of vector-based geographic data and GIS's.

For detecting slope lines from digital elevation data, raster data structures and raster methods possess certain disadvantages. A common drawback is the requirement of large memory space due to data redundancy (Monmonier, 1982; Burrough, 1986; Ibbs and Stevens, 1988; Clarke, 1990). Consequently, processing the redundant data consumes a great deal of CPU time and thus hampers the efficiency of raster methods. This problem becomes severe when the study area contains numerous small flat surfaces or areas of constant slope.

Data redundancy in raster methods also reduces the efficiency in downslope tracing. In vector data structures, a long slope line on a surface of constant slope is coded by a starting node and an end node; thus, downslope tracing is merely a two-step procedure. The same line must be coded in raster methods by as many grid cells as necessary to maintain the same level of resolution, which drastically increases the number of steps required to trace the slope line downward.

A common problem with raster data is the existence of single pixel pits resulting from noise (Mark, 1984; Jenson and Domingue, 1988). The undesired local depressions must be eliminated prior to the processing or slope lines may be erroneously directed. Although remedial methods such as data-filtering or depression-filling are available, each corrective procedure costs additional CPU time. It is not unusual to have many single-cell depressions in a database. In such cases, it is laborious to distinguish those caused by noise from the correct features.

In order to improve the efficiency of data storage, compact forms of data structure like quadtrees have been adopted in raster-based GISs (Ibbs and Stevens, 1988, Goodchild, 1988; Mark *et al.*, 1989). Because neighborhood processing for detecting slope lines is applicable only to the original row-column format, detecting slope lines with raster methods requires conversions of elevation data between the compact and the grid formats until more sophisticated and effective procedures become available.

A theoretical shortcoming with raster methods is their limited number of search directions. No matter how many directions are searched, it is always possible to omit the true steepest descent. Searching through the four adjacent cells covers only the immediate orthogonal neighbors and is hardly satisfactory. It is desirable to refine the method by increasing the number of search directions; however, computational cost increases exponentially with the increasing number of search directions because both the required number of logical operations is increased and the varying distance weights must be incorporated.

A VECTOR METHOD FOR SLOPE-LINE DETECTION

Vector data are organized in points, lines, and polygons (Peucker and Chrisman, 1975; Estes, 1986; Dangermond, 1988; 1989). The vector structure is efficient in storing spatial data because data points can be irregularly located, allowing for varying density of coding in response to the variation of local relief. For large areas of flat surfaces or constant slope, a few well-selected data points are sufficient to represent the entire surface. The density of data points can be increased locally for areas of greater relief. Figure 2 shows a hypothetical example of point data of elevation in a vector-based GIS. Table 1 lists part of the data file for this coverage, in which each record (data point) contains an ID code, *X*- and *Y*-coordinates, and elevation.

The point coverage of elevation is not the ideal form for presenting topographic information because it is hard to discern any spatial pattern of the terrain. Besides, its data file possesses no topological information required for extracting topographic structures. From the point coverage, slope lines can be detected using a radial-search method (Oshima *et al.*, 1986).

The radial-search method begins at any given location and searches for all nearest data points within a specified radius at a pre-determined constant increment of search angle (e.g., 10 degrees). The point with steepest descent from the origin gives the direction of the slope line and becomes the next starting point. Severe shortcomings of this approach exist: First, the results depend on the search radius and angular interval; second, it has the same problem of limited search directions as the raster methods; and third, this method is less efficient than raster methods because, in order to maintain the same level of precision as that of a raster method, both the initial search radius and the angular interval of search must be set equivalent to the resolution in the raster method. Such settings make the radial-search method less efficient than the raster method due to the required efforts in altering search directions and angular increments.

Alternatively, the point data of elevation can be reorganized into either digitized contours or triangulated irregular networks (TIN) (Peucker *et al.*, 1978; Carter, 1988). Figures 3 and 4 show the contour coverage and the TIN coverage, respectively, generated from the point coverage.

In developing vector methods for GIS applications, a compact data structure is preferred. In most terrain analyses, large volumes of topographic and topological data must be processed; therefore, a more compact data structure makes empirical testing more cost-effective and more feasible. Also, a compact data structure for terrain analysis requires that only the elements

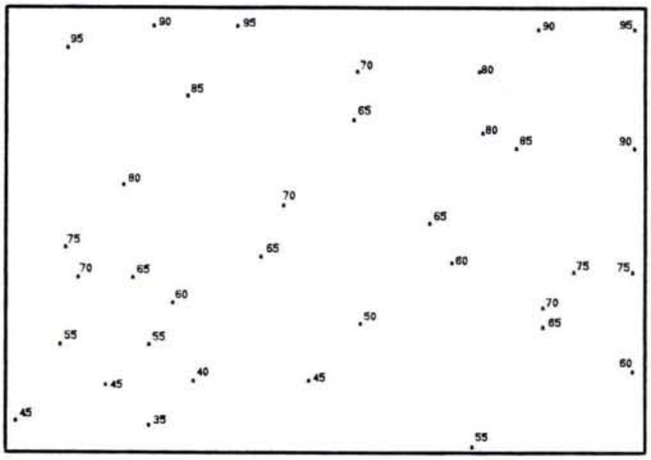

FIG. 2. A hypothetical point coverage of elevation data.

TABLE 1. DATA STRUCTURE OF THE POINT COVERAGE IN FIGURE 2.

Point-ID	X-coordinate	Y-coordinate	Elevation
1	2.79	6.76	95
2	10.67	7.02	95
–	–	–	–
–	–	–	–
34	9.40	2.89	65
35	3.93	1.51	45

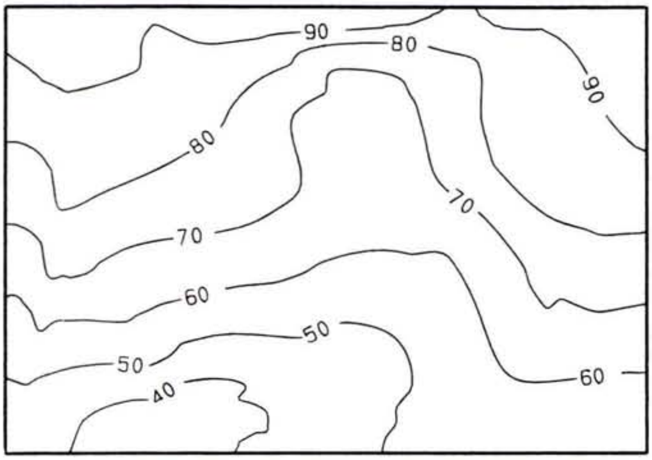

FIG. 3. The contour coverage generated from the point coverage of Figure 2.

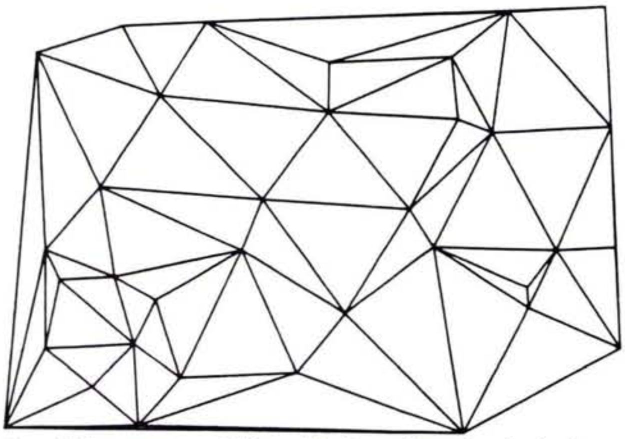

FIG. 4. The coverage of triangulated irregular networks (TIN) generated from the point coverage of Figure 2.

necessary in data processing be incorporated; thus, it tends to reduce both processing time and computing cost. For these reasons, the method developed here is based on digitized contours because contour recording minimizes storage requirement (Douglas, 1986).

Figure 5 shows the point coverage generated from the DEM of the 7.5-minute quadrangle of Palmview Peak, California. The contour coverage and TIN coverage derived from the point coverage are shown, respectively, in Figures 6 and 7. The data volumes for these coverages are listed in the first column of Table 2.

It is important to mention that comparing the lattice file generated from the DEM with other data structures is inappropriate because the lattice file records the unprocessed elevation data while other data files have been processed through a filtering procedure (Chen and Guevara, 1987). The second column of this table lists the data volumes for the 15-minute quadrangle of Idyllwild, California. This table illustrates that data storage of contour coverages is more compact than that of TIN coverages. The CAT-PLF format of contour coverage is designed for effective terrain analysis and will be explained later.

Detecting slope lines from digitized contours is based on the Cauchy-Schwarz theorem, such that, for any given point on a contour, the steepest descent is perpendicular to the curve at that point (e.g., see Cheney and Kincaid (1985)]. This principle

FIG. 5. The point coverage of the 7.5-minute quadrangle of Palmview Peak, California.

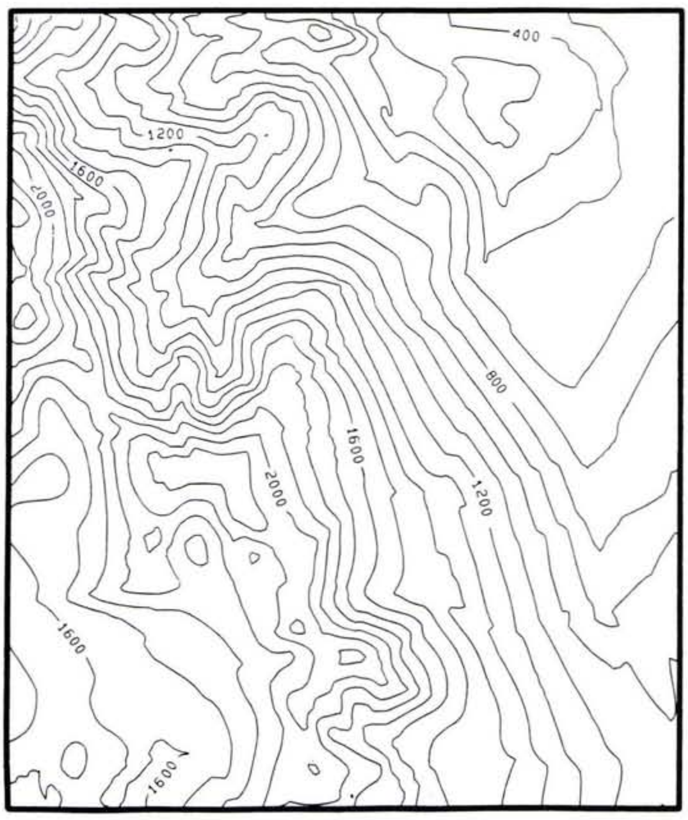

FIG. 6. The contour coverage of the Palmview Peak quadrangle.

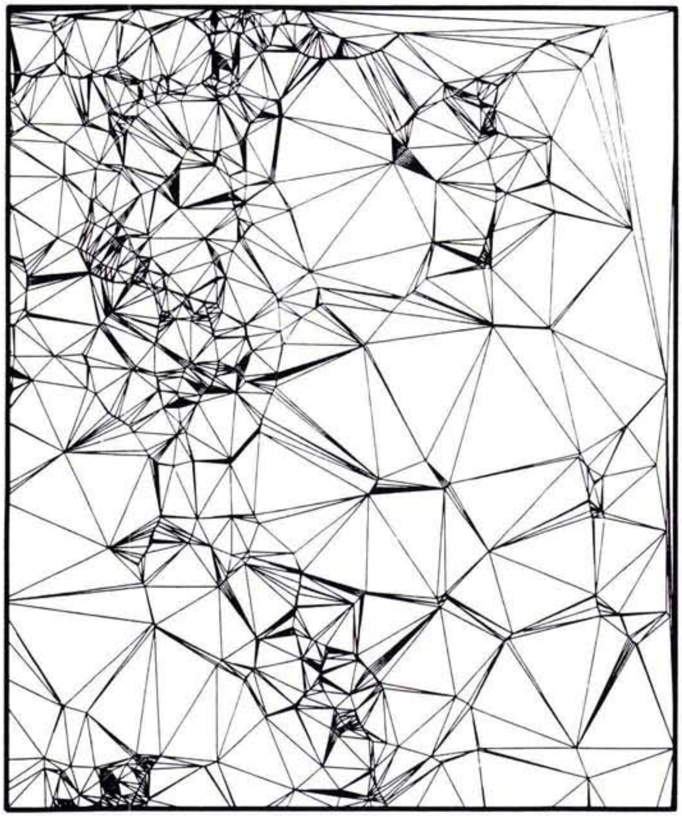

FIG. 7. The TIN coverage of the Palmview Peak quadrangle.

TABLE 2. DATA VOLUMES OF BASIC DATA STRUCTURES.

Coverage Type	Data volume (k bytes)	
	Palmview Peak	Idyllwild
Lattice (from DEM)	720	2,877
Point	68	128
TIN	606	1,108
Contour (ARC/INFO)	124	214
Contour (CAT-PLF)	83	201

TABLE 3. THE CONTOUR ATTRIBUTE TABLE (CAT) OF THE CONTOUR COVERAGE IN FIGURE 3.

ID	ELEV	STAD	PNT	NLC	LC	NHC	HC
1	90	1	19	1	3	0	0
2	90	20	7	1	3	0	0
3	80	27	32	1	4	2	1,2
4	70	59	44	1	5	1	3
5	60	103	36	1	6	1	4
6	50	139	25	1	7	1	5
7	40	164	12	0	0	1	6

ID: arc-ID
ELEV: elevation
STAD: starting address of the arc
PNT: number of points defining the arc
NLC: number of adjacent contour arcs of lower elevation
LC: list of adjacent contour arcs of lower elevation
NHC: number of adjacent contour arcs of higher elevation
HC: list of adjacent contour arcs of higher elevation

TABLE 4. A PARTIAL LIST OF THE POINT LOCATION FILE (PLF) OF THE CONTOUR COVERAGE IN FIGURE 3.

Address	*X*	*Y*	Address	*X*	*Y*
1	7.17	7.03	–	–	–
2	6.93	7.01	–	–	–
3	6.69	7.00	170	4.41	2.12
4	6.39	6.98	171	4.69	2.16
5	6.16	6.97	172	4.97	2.16
6	5.88	6.95	173	5.23	2.10
–	–	–	174	5.19	1.87
–	–	–	175	5.42	1.80

is adopted in Speight's (1968) raster method in which a grid is laid over the contour map for identifying a line segment in each cell which is perpendicular to the contour.

In vector-based GISs, each contour is coded by one or more arcs and each arc is defined by a sequence of points termed nodes or vertices. For detecting slope lines, the topographic data are reorganized into two relational files, a Contour Attribute Table (CAT) and a Point Location File (PLF). The CAT of the contour coverage in Figure 3 is given in Table 3. For simplicity, Table 4 gives only a partial list of the PLF. This data structure is system independent, i.e., both files are coded in ASCII format and can be used by any GIS capable of converting ASCII files into its own database. In this study, a FORTRAN program is employed to construct the CAT and PLF files directly from the Arc Attribute Table (AAT) and the Polygon Attribute Table (PAT) automated in ARC/INFO, a commonly used GIS.

Given any location in the surface, a slope line is identified from the CAT and the PLF using the following six-step iterative procedure. In this method, a segment is defined as a straight line coded by a starting node and an end node; an arc contains one or more segments and is assigned a unique code of arc ID; a contour contains one or more arcs.

THE OPERATIONAL PROCEDURE

Step 1: Initial Search

According to the exogenously given location of any starting point or origin (*OR*), identify the point in the PLF which is closest to *OR* and define this point as *Q*. Identify the contour that contains *Q* and define this contour as *QARC*. This step ensures that the data to be evaluated in the following search be limited to the adjacent contours.

Step 2: Intersection Check

For *QARC*, identify the neighboring contours of higher elevation and lower elevation from the CAT table. If any of the neighboring contours intersects the segment connecting *OR* and *Q*, redefine *Q* by the intersection location and redefine *QARC* by that intersecting contour. Continue the intersection check until no other contour intersects the segment linking *OR* and *Q*. This step ensures that the identified *QARC* is the contour closest to *OR*. The procedure of intersection check is described in Monmonier (1982, pp. 118–120).

Step 3: Direction Check

Based on (1) the segment *OR* and *Q*, (2) the contour labeled *QARC*, (3) the neighboring lower contour, *LC*, identified from the CAT, and (4) the neighboring higher contour, *HC*, determine if the elevation of *OR* is higher or lower than *QARC*. If higher, the first segment of the slope line is the one connecting *OR* and *QARC*; otherwise, the first segment connects *OR* and *LC*. Once the first segment is found, redefine *QARC* by the contour containing the end node of this segment. This step ensures that the direction of the first segment is correct.

Step 4: Visibility Check

This step ensures that the next choice set of contour arcs be limited to the segments of *QARC* that are visible to *OR*. A segment is visible to a specific point if no other arc exists between them. The purpose of this procedure is to eliminate the possibility of crossing contour segments when constructing the slope line. From the limited choice set, identify the visible segment which is closest to *OR*.

Step 5: Downslope Extension

In the first iteration, this step constructs the first segment of the slope line by connecting *OR* and *QARC*. In each of the following iterations, this step adds an additional segment to the slope line by extending *OR* to the closest visible segment on *QARC*. In any case, the segment represents the shortest point-to-arc distance. The *X*- and *Y*-coordinates of the end node of the segment are then saved in the output file. Define the end node as the new *OR* for the next iteration.

Step 6: Termination Check

From the contour containing the new *OR*, determine if a neighboring contour of lower elevation exists. If so, define that contour as the new *QARC* and return to step four to identify the next segment. Otherwise, extend the last segment by an arbitrarily defined length and terminate the procedure.

The Experiment

The method was programmed in FORTRAN and tested on both hypothetical and empirical data. The entire procedure is automated without the need of manual operations. Figure 8 shows the slope lines identified by the proposed method for three arbitrarily located origins, O_1, O_2, and O_3. Their destinations are labeled D_1, D_2, and D_3, respectively. All three slope lines are as accurate as can be defined from the data, except that edge effect appears in the line $O_1 - D_1$.

The empirical test of the method is based on the digital elevation data of the 15-minute quadrangle of Idyllwild, California. The DEMs covering this quadrangle are converted into a contour coverage in ARC/INFO. For simplicity, the contours are smoothed by the GENERALIZE procedure in ARC/INFO. The Arc Attribute Table and the Polygon Attribute Table of the contour coverage provide the source data. In the generalized coverage, there are 39 contours coded by 1,876 points. Contours range from 200 metres to 2200 metres at an interval of 200 metres. For illustrative purposes, ten arbitrarily selected locations are assigned as origins. The method detected all ten slope lines in 16.23 seconds of CPU time on a VAX 8820 computer. On average, it takes less than two seconds of CPU time for the method to identify a slope line from a generalized contour coverage of the 15-minute quadrangle.

The contours and identified slope lines are depicted in Figure 9. The accuracy of the slope lines must, of course, be assessed according to the digital data in the generalized contour coverage rather than from the original topographic sheet. Draped onto the three-dimensional perspective diagram of the surface, the five slope lines on the eastern slope are shown in Figure 10 as the surface is viewed from east of the area.

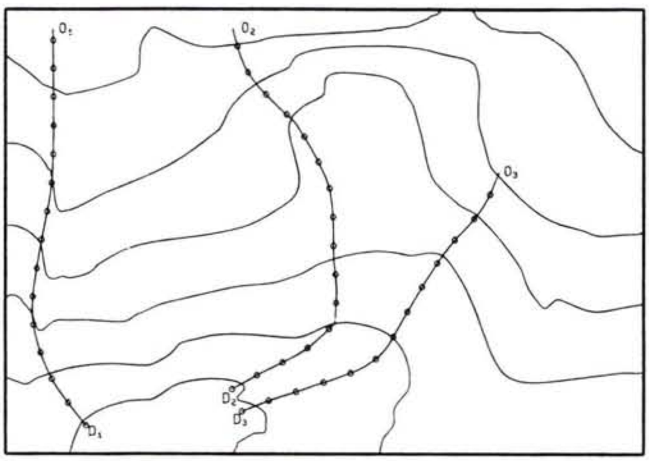

FIG. 8. Three slope lines identified from the contour coverage of Figure 3.

DISCUSSION

The proposed method is characterized as follows. First, because its data structure is compact and data redundancy is minimized, the processing speed is enhanced as unnecessary processing of redundant data is eliminated. Second, the vector codes of slope-line segments provide easy access to topographic attributes for terrain analysis. For instance, the gradient of each segment of a slope line, which is the ratio of contour interval to segment length, can be derived directly from the output file.

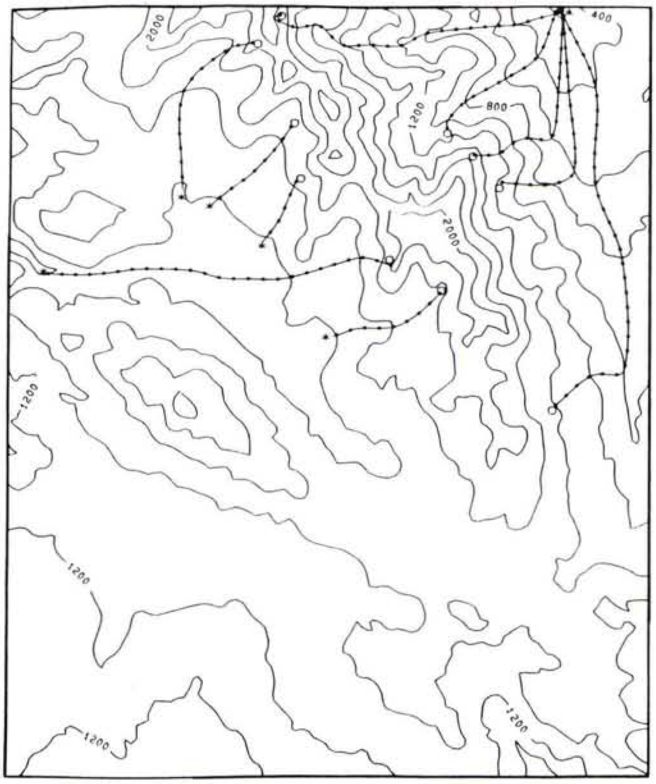

FIG. 9. Ten slope lines identified from the contour coverage of the 15-minute quadrangle of Idyllwild, California. The locations of origins are arbitrarily assigned.

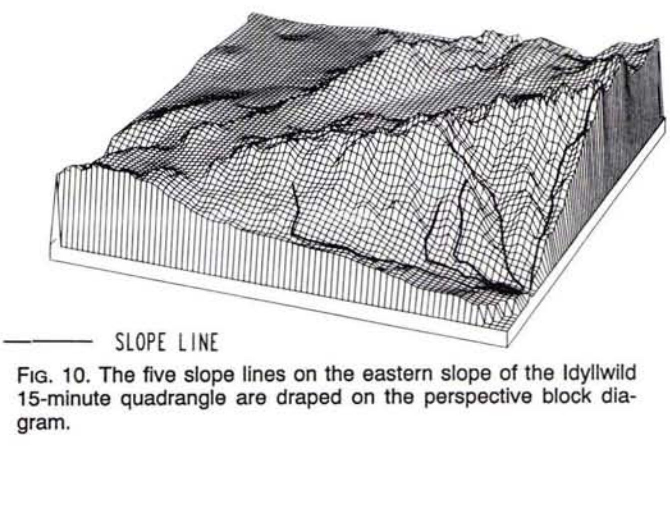

FIG. 10. The five slope lines on the eastern slope of the Idyllwild 15-minute quadrangle are draped on the perspective block diagram.

The same gradient in raster codes requires more steps to calculate unless raster codes are converted into vector codes prior to processing. Third, while the precision level of the slope lines detected from the proposed method depends on data resolution, the consistency is ensured. This property is not maintained in raster methods where a different number of neighboring cells to be searched may result in a different slope line.

Another important contributing factor to the efficiency of the proposed method is the design of the Contour Attribute Table (CAT) in which lower and higher adjacent contours are listed. This structure reduces processing time significantly because the contour search in each iteration applies to a relatively small choice set in the database and the termination of a slope line is determined by a simple logical operation.

In digital topographic data, the chance for two line segments to be of equal distance from a point is extremely slim. In this unusual situation, the method arbitrarily connects the point to the segment which has an end node closest to the point. Unless additional local data are provided, this is the only feasible criterion to be implemented in a vector method.

One must be aware of the limitation of the proposed method due to the visibility check in the fourth step. Under normal conditions, a slope line is terminated when its lower end node has reached a contour which has no more lower neighboring contours. Even when the last contour is enclosed as a local depression, the slope line will be accurately terminated inside the depression. The termination procedure, however, is limited by the visibility check which may create a potential problem for areas with many long, narrow, curving gullies where the actual lower neighboring contour may not be visible. To solve this problem, one has to either reduce the local contour interval, if detailed topographic data are available, or enhance visibility by implementing a subprogram for automated generation of intermediate contours such as the method proposed by Paled *et al.* (1989).

Edge effect presents an inevitable problem for the application of the proposed method. Unless additional topographic data beyond the map coverage are available, correction procedures do not guarantee more accurate results. The only suggestion is to extend the boundary of the map coverage and avoid assigning origins from areas near map borders.

As mentioned before, the elevation data can be systematically organized into either digitized contours or TIN. The method presented here is based on digitized contours to take advantage of compact storage. It is important that, in a further study, a vector method based on the TIN structure be developed and compared with this method in order to construct the most effective vector method for terrain analysis.

The current TIN coverage contains the topographic and topological information needed for detecting slope lines, including the locational characteristics, slope gradient, and aspect (compass direction of slope) of each triangular facet. In general, the TIN method of slope-line detection may be constructed in the following procedure. For any location specified as the origin of a slope line, the triangle in which the point is located is identified. A straight line starting at the origin, parallel to the slope aspect of the triangle, and ending either at the intersection between the parallel line and the edge of lower elevation, or the lowest vertex of the triangle, defines the segment of the slope line in that triangle. The end point is then treated as the next starting point. The procedure continues until a flat triangular facet or a depression at a vertex is reached. To develop such a TIN method, two stumbling blocks must be removed first.

First, triangular facets have been considered unnatural in representing the Earth's surface (e.g., see Figure 7). Segments of slope lines defined on the triangular facets tend to reflect the same unnatural pattern and often produce disturbingly sharp angles between segments. Even when the segments are modified by a spline function, the smoothed lines still meander unnaturally on the surface.

Second, the operational procedure of the TIN approach is complicated by the fact that a TIN coverage consists of several relational data files. For instance, in ARC/INFO, seven relational files are used to carry the topological and topographic information of a TIN coverage, including the TIN environment file (ENV), the file of convex hull (HUL), the file of edges (EDG), the file of vertices (NOD), the file of *X*- and *Y*-coordinates (NXY), the file of elevation data (NZ), and the polygon attribute table (PAT) which contains the slope gradient and slope aspect (Environmental Systems Research Institute, 1987). Basic inquiries in slope-line detection, such as whether the downslope segment reaches an edge or a vertex, or which adjacent triangle will be considered in the next iteration, require additional logical operations in searching through these files. Clearly, the development of a TIN method of slope-line detection requires that the current data structure be reconstructed for efficient processing.

CONCLUSIONS

The capability of detecting slope lines in vector-based GISs is useful for a variety of surface analyses. This study was conducted for the U.S. Forest Service in an effort to develop efficient methods for identifying most likely paths of landslides and deposition sites. Given potential locations of slope failure, the method can be used to identify the paths and deposition sites in seconds, thereby allowing for quick implementation of protective measures. Even at the planning stage, zones of merging paths may be delineated by assigning multiple spots of origin, which may pinpoint areas of highest priority for slope conservation. In another possible application, a hydrologist may overlay a contour coverage with a lattice of points in order to generate slope lines from all sites on the surface. The slope lines identify the pattern of overland flow and potential areas of excessive runoff during a major storm.

The proposed method requires that topographic data be organized in digitized contours. At present, the contour method utilizes a more compact data structure and thus is more effective than the alternative TIN approach. A recommended further study is one that reconstructs the TIN data structure and develops an effective TIN method of slope-line detection. A careful comparison between the contour method and the TIN method should determine which approach is more effective for terrain analysis in vector-based GISs.

It is also important to carry out a comprehensive comparison between vector methods and raster methods. The result of such a comparison has important implications to GIS developers. Because slope-line detection represents a basic problem in a wide range of spatial analyses, if vector methods are proven to be more efficient, the future development in vector GIS must emphasize the implementation of the most effective vector methods for specific research problems in surface analysis. Otherwise, the strategy in developing GIS technology must be focused on building efficient algorithms for raster-vector data conversions.

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REFERENCES

Band, L. E., and V. B. Robinson, 1986. Automated construction of a hydrological information system from digital elevation data, *Geo-*

graphic Information Systems for Environmental Protection, Workshop Proceedings, University of Nevada, Las Vegas, pp. 99–112.

Batten, L. G., 1988. Geographic information systems research utilizing 1:100,000 digital line graph data, *Technical Papers, 1988 ACSM-ASPRS Convention*. St. Louis, Missouri.

Burrough, P. A., 1986. *Principles of Geographical Information Systems for Land Resources Assessment*, Clarendon Press, Oxford. Chapter 3.

Carter, J. R., 1988. Digital representations of topographic surfaces: an overview, *Technical Papers, 1988 ACSM-ASPRS Annual Convention*, pp. 54–60.

Chen, Z., and J. A. Guevara, 1987. Systematic selection of very important points (VIP) from digital terrain model for constructing triangulated irregular networks, *AUTO-CARTO 8 Proceedings*, ASPRS-ACSM. pp. 50–56.

Cheney, W., and D. Kincaid. 1985. *Numerical Mathematics and Computing*, 2nd ed., Brooks/Cole Publishing Co., Monterey, California, pp. 473–476.

Clarke, K. C., 1990. *Analytical and Computer Cartography*, Prentice Hall.

Dangermond, J., 1988. A review of digital data commonly available and some of the practical problems of entering them into a GIS, *ACSM-ASPRS Technical Papers*, 5, 1–10.

———, 1989. Entering digital data into a GIS, *Proceedings, AM/FM Conference XII*, New Orleans, Louisiana. 1, 130–137.

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

Dulaney, R. A., 1987. A geographic information system for large area environmental analysis, *GIS'87-San Francisco*. ASPRS-ACSM, pp. 206–215.

Environmental Systems Research Institute (ESRI), 1987. *ARC/INFO TIN User Manual*, Ch. 2, Fundamentals of TIN. Redlands, California.

Estes, J. E., 1986. A perspective on the use of geographic information systems for environmental protection, *Workshop Proceedings, Geographic Information Systems for Environmental Protection*, University of Nevada, Las Vegas, Nevada, pp. 3–23.

Evans, I. S., 1980. An integrated system of terrain analysis and slope mapping, *Zeitschrift für Geomorphology*, 36, 274–295.

Goodchild, M. F., 1988. Stepping over the line: technological constraints and the new cartography, *The American Cartographer*, 15, 311–319.

Horn, B. K. P., 1981. Hill shading and the reflectance map, *Proceedings, IEEE*, 69(1), 14–47.

Huber, D. L., and R. L. Church, 1985. Transmission corridor location modelng, *Journal of Transportation Engineering*, 111, 114–130.

Hutchinson, M. F., 1988. Calculation of hydrologically sound digital elevation models, *Proceedings, Third International Symposium on Spatial Data Handling*, Sydney, Australia, pp. 117–133.

Ibbs, T. J., and A. Stevens, 1988. Quadtree storage of vector data, *International Journal of Geographical Information Systems*, 2, 43–56.

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

Kikuchi, L., J. A. Guevara, D. Mark, and D. F. Marble, 1982. Rapid display of digital elevation data in a mini-computer environment, *Proceedings, ISPRS Commission IV Symposium*.

Mark, D.M., 1984. Automated detection of drainage networks from digital elevation models, *Cartographica*, 21, 168–178.

Mark, D. M., J. P. Lauzon, and J. A. Cebrian, 1989. A review of quadtree-based strategies for interfacing coverage data with digital elevation models in grid form, *International Journal of Geographical Information Systems*, 3, 3–14.

Marks, D., J. Dozier, and J. Frew, 1984. Automated basin delineation from digital elevation data, *Geo-Processing*, 2, 299–311.

Marx, R. W., 1986. The Tiger system: automating the geographic structure of the United States Census, *Government Publications Review*, 13, 181–201.

Monmonier, M. S., 1982. *Computer-Assisted Cartography: Principles and Prospects*, Prentice Hall, Englewood Cliffs, New Jersey.

O'Callaghan, J. F., and D. M. Mark, 1984. The extraction of drainage networks from digital elevation data, *Computer Vision, Graphics and Image Processing*, 28, 323–344.

Oshima, T., Y. Yasuda, and Y. Emori, 1986. Computer aided route selection on the base of GIS by a micro-computer, *Technical Papers, 1986 ACSM-ASPRS Convention*, 3, 31–37.

Paled, A., J. C. Loon, and J. D. Bossler, 1989. Producing intermediate contours from digitized contours, *The American Cartographer*, 16: 191–200.

Peucker, T. K., and N. Chrisman, 1975. Cartographic data structures, *The American Cartographer*, 2, 55.

Peucker, T. K., and D. H. Douglas, 1975. Detection of surface-specific points by local parallel processing of discrete terrain elevation data, *Computer Graphics and Image Processing*, 4, 375–387.

Peucker, T. K., R. J. Little, and D. M. Mark, 1978. The triangulated irregular network. *Proceedings of the DTM symposium*, ASPRS-ACSM, 24–31. St Louis, Missouri.

Speight, J. G., 1968. Parametric description of land form, *Land Evaluation*, (G. A. Stewart, editor), Papers of a CSIRO Symposium in Cooperation with UNESCO, pp. 239–250.

Tomlinson, R. F., 1988. The impact of the transition from analogue to digital cartographic representation, *The American Cartographer*, 15, 249–261.

Tomlinson, R. F., H. W. Calkins, and D. F. Marble, 1976. *Computer Handling of Geographical Data*, The Unesco Press.

U. S. Geological Survey, 1987. *Digital Elevation Models*, U.S.G.S. Data User's Guide 5, 38.

Wadge, G., 1988. The potential of GIS modelling of gravity flows and slope instabilities, *International Journal of Geographical Information Systems*, 2, 143–152.

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