# AUTOMATED DETECTION OF DRAINAGE NETWORKS FROM DIGITAL ELEVATION MODELS

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THE TOPOLOGY and geometry of drainage networks has been an important area of study within theoretical geomorphology for almost four decades. Furthermore, the drainage network is very important in models of landscape development, as well as in drainage basin hydrology. Drainage networks can also form a vital element in geographic information systems for land systems analysis and resource management.

One problem in drainage networks studies is the amount of effort which is needed to identify the drainage net and to measure basic properties. First, the drainage network must be delimited on maps or aerial photographs, or surveyed in the field; then, link lengths, junction angles, and other properties of interest must be measured. During the last two decades, the measurement phase has been simplified and its time demands reduced through the use of coordinate digitizers (see Jarvis 1977). Once the drainage net has been identified on the source documents, the drainage network can be traced and the coordinates encoded. From these coordinate files, link properties can readily be computed. While this represents an improvement over manual measurements, the digitization phase can still be very tedious, and furthermore, the channel network must still be identified.

Recently, there has been a great increase in the quantity of topographic and hydrographic data available in machine-readable form. Notable in North America are the Digital Elevation Models (DEMS) and Digital Line Graphs (DLGS) currently being produced and distributed by the United States Geological Survey (Elassel 1978; Allder and others 1982). If these data resources can be used to quantify drainage network measures atuomatically, research on drainage network topology and geometry would be aided considerably. This paper addresses the problem of automated detection of drainage networks from digital elevation models. Two algorithms for drainage network identification are discussed and illustrated. One is based on the detection of local surface concavity (after Peucker and Douglas 1975), while the other simulates runoff concentration, with those cells receiving simulated surface runoff above some pre-determined threshold being declared to be the drainage network (after Speight 1968). The important roles of data acquisition methods and of data filtering are discussed, and the results of the two algorithms are compared with 'traditional' manual methods of characterizing the drainage network from maps.

## DEFINITION OF THE DRAINAGE NETWORK

The drainage network which is of interest to most geomorphologists is simply a map of all those points at which fluvial processes are sufficiently dominant over slope processes that a channel is maintained. It is generally recognized among geomorphologists that the 'blue line' stream networks printed on most North American topographic maps at scales of around 1:24,000 and smaller are very conservative representations of the actual drainage network as defined above (see Mark, 1983). Blue lines are draughted on the maps at publication scale only where permanently flowing streams, or major intermittent or ephemeral streams, are present. Many minor channels which even in a humid area carry water only during precipitation or snowmelt events are omitted from the maps, even though they usually comprise the majority of the total length of channels in a region. Thus it has become a standard procedure for workers to extend the drainage network up any small valleys whose presence is indicated by aligned, concave-downhill cusps or crenulations in the contours.

When compiling a contour map, USGS topographers are instructed to first sketch in all channels, and then to draw the contours so as to show these channels (Mark 1983). The channels themselves, however, are generally omitted from the blue lines printed on the map unless they are permanent or major features. Thus, when the geomorphologist extends the drainage network to include small crenulation valleys, he or she is in effect restoring valleys detected by the topographer and which, in most cases, probably appeared on the compilation sheet.

There have been a few attempts to employ quantitative rules governing the inclusion or exclusion of concavities indicated by contour crenulations (for example, see Lubowe 1964). By and large, however, most workers have relied upon subjective judgement to identify 'definite' valleys. Krumbein and Shreve (1970) found that there was a very high degree of correspondence between the networks identified independently by experienced researchers. While there was much more variance among inexperienced operators, such individuals could be trained relatively quickly. Nevertheless, this subjective element in drainage network research seems undesirable. The acknowledged inadequacy of the printed blue line networks on topographic maps clearly implies that the USGS Digital Line Graphs do not represent a viable data resource for drainage network studies, since they are obtained by digitizing the blue line networks on maps. Thus attempts to automate the data collection phase of drainage network studies must turn to Digital Elevation Models (DEMS) as a data source.

## USGS DIGITAL ELEVATION MODELS

Several years ago, the U.S. Geological Survey began to distribute gridded elevation data sets which had been collected from 1:250,000 scale topographic maps by the Defense Mapping Agency. These sets, termed Digital Terrain

Models by the survey, cover 1 by 1 degree areas, and have a grid cell size or spacing of 63.5 metres (208 feet) on the ground; however, since the elevations were obtained by interpolation from digitized contours, the effective resolution is not this good. More recently, the USGS has begun to distribute a new series of elevation grids which they term Digital Elevation Models (DEMS). These cover quadrangle areas 7½ by 7½ minutes (the same size as the USGS 1:24,000 scale topographic map series) and have a 30 metre grid size. Unlike the earlier series, these models have not been obtained from maps, but are a by-product of an orthophotomapping program. In orthophotomapping, elevations must be generated in order to compute and remove parallax effects; the elevation data can, of course, be stored and used for further processing.

Some of the USGS DEMS have been obtained using the Gestalt Photomapper II, or GPM II (Swan and others 1978; Allam 1978; Allder and others 1982). This image correlation device produces grids of elevations at a spacing of 0.182 mm at the scale of the aerial photographs; these grids are then re-sampled to produce a 30 metre (ground scale) grid aligned with the axes of the Universal Transverse Mercator (UTM) coordinate system. The USGS also produces orthophotos using semi-automatic profiling devices; these yield elevations along profiles. Generally, the spacing of points along the profiles is considerably less than 30 m, while the distance between profiles is considerably greater than this value. When these heights are re-sampled to a 30-metre square grid, the interpolation technique produces estimated elevations which have a much stronger spatial autocorrelation along the direction parallel to the profiles than in the orthogonal direction. Many images produced from these models have clearly visible 'stripes' parallel with the scanning direction of the profiler. Nevertheless, the over-all root mean square error in these models is considered to be less than the error in models produced using the GPM II. The re-gridded data are reported as integers in metres above the sea level datum, regardless of the data collection method.

The data tapes distributed by the USGS include file headers containing information on the geographical location of the area covered by the DEM, the method used to collect the data, the date and place that this was done, the minimum and maximum elevations, and other characteristics of the models; these data are followed by the elevations, reported as north-south profiles. Kikuchi and others (1982) discussed the analysis and display of these models in a mini-computer environment. They found that pre-processing the data and saving the elevations using system-specific block read and write commands produces a considerable improvement in the time required to analyze and display these data sets.

These USGS DEM data sets have been used for all testing of algorithms reported in this paper; however, similar results should be obtained for any DEMS collected and re-sampled in the same manner as these.

## AUTOMATED DETECTION OF DRAINAGE BASINS: LOCAL SURFACE CONCAVITY

Any portion of a topographic surface which is locally concave-upward will be a place where surface runoff will tend to be concentrated. Thus a map of the concave-upward portions of a digital elevation model could be considered to be an approximation of the drainage network. David H. Douglas developed an algorithm for identifying such concave-upward portions of a DEM (Peucker and Douglas 1975). This algorithm simply flags the highest point among each square of four mutually-adjacent points in the grid. Once this flagging phase has been completed, all those points which have not been flagged are the estimated channel network. Note that, except for points along the boundary of the DEM, each point is involved in exactly four comparisons.

One of the programs in the Digital Elevation Models Graphic System (Kikuchi and others 1982) was modified to produce program HILO, so named because it detects local high and low points. This FORTRAN program reads two north-south profiles from the DEM into core, and then applies the algorithm to all sets of four mutually-adjacent points. Profiles are processed from west (left) to east (right), and so at each stage, the unflagged points in the left (westernmost) profile can be plotted, before a new profile is read. The program can also detect ridges simultaneously; in this case, the lowest point in each set of four is flagged, and the unflagged points are the ridges. The program can display the ridges only, the channels only, or both.

Program HILO was used to process the DEM representing the topography of the Keating Summit, Pennsylvania, quadrangle. The study area is located in the well-dissected Appalachian Plateau region in north-western Pennsylvania, and has relatively high local relief and coarse topographic texture. The algorithms should perform well for such an area. Figure 1 shows the results, which are far from ideal. The drainage network has clearly been identified, but there are also numerous isolated pixels, most of which represent pits or closed depressions. These pits are concentrated in the relatively flat areas, the valley floors and the undissected plateau remnants. Since pits detectable at a resolution of 30 metres are essentially absent in fluvially eroded topography (except for limestone areas), these pits presumably represent 'errors' in the models. The pits appear only in the flatter areas because of what is essentially a signal-to-noise ratio effect; while the pits are numerous, most are only one or two metres deep. Where slopes are gentle, a 1-metre negative error may be sufficient to produce a closed depression, while on steeper slopes, a pit does not result.

The Keating Summit DEM was produced using a GPM II. It is clear from a visual inspection of analytical hill shading images of this and other DEMs for forested areas which have been produced using the GPM II that the elevations are generally those of a tree-top surface rather than of the ground surface itself. The evidence is that road, power-line, and pipe-line cuts are clearly visible as 'grooves' in the surface. Thus, the errors referred to above may be correct representations of the surface which was sensed by the GPM II. Whether the pits represent clearings or low areas in the forest cover, or are simply measurement errors, is hardly relevant in the present context: they clearly are not part of the drainage net.

Two approaches can be taken to solve this problem. One approach would begin with the image depicted in Figure 1, and use image processing techniques to detect connected components, and then to eliminate isolated points or connected components below some size threshold. Alternatively, the DEM could be filtered or smoothed to remove or reduce the errors before program HILO is applied. Only the latter approach has been explored thus far.

A simple binomial smoothing operator (Tobler 1966) was applied once and

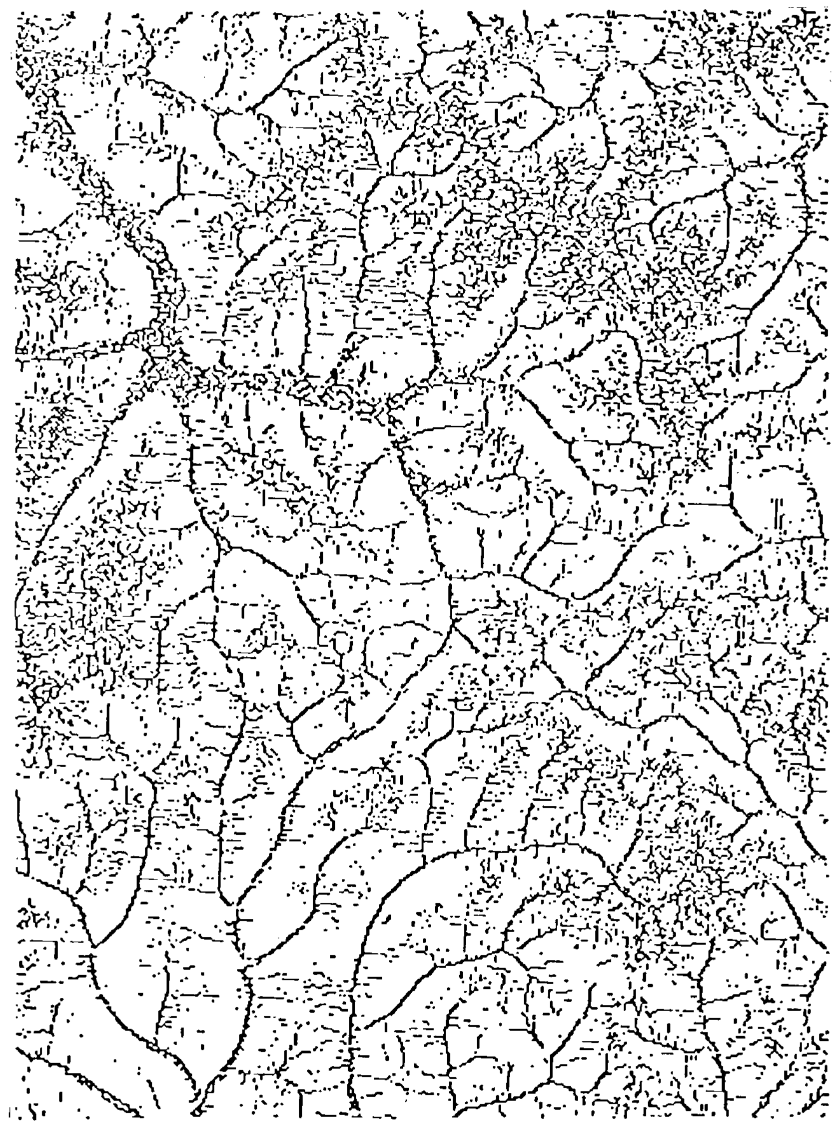

FIGURE 1. *Channel network for the Keating Summit, Pa quadrangle, based on original (unsmoothed)* USGS DEM *data (program* HILO*).*

then a second time to the Keating Summit DEM. Program HILO was then used to estimate the drainage network from these once- and twice-smoothed elevation models; the results are shown in Figures 2 and 3, respectively. The smoothing clearly improves the performance of the algorithm. One pass of the filter eliminates most of the isolated dots, while a second pass removes most of the rest. However, the second smoothing also begins to break up some of the

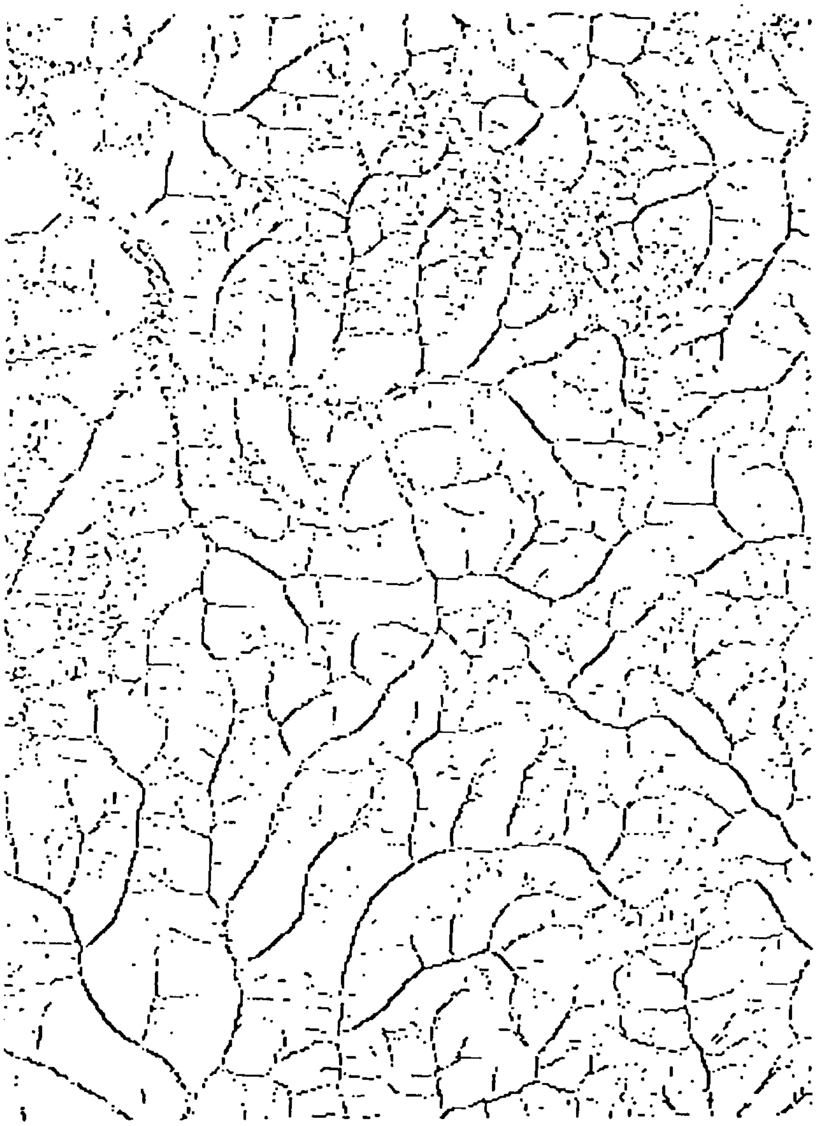

FIGURE 2. *The same as in Figure 1, but with* DEM *data smoothed once before processing by program* HILO.

well-defined channels; for the Keating Summit area, a single pass of the smoothing operator seems to produce the best results.

## AUTOMATED DETECTION OF DRAINAGE NETWORKS: A HYDROLOGIC APPROACH

Hydrophysically, the drainage network represents those points at which runoff is sufficiently concentrated that fluvial processes dominate over slope processes.

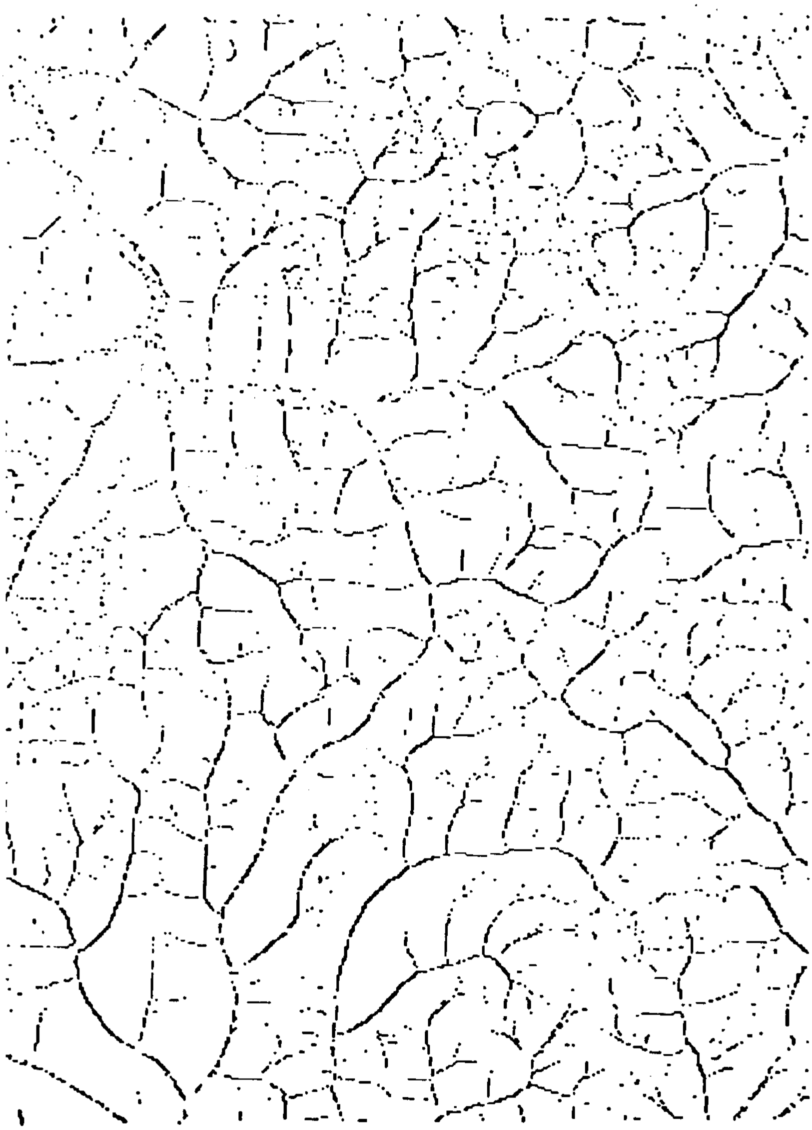

FIGURE 3. *The same as in Figure 1, but with DEM data smoothed twice before processing by program HILO.*

If the spatial concentration of surface runoff is simulated, then those points at which this runoff exceeds some threshold can be considered to be the drainage network. This approach has considerable appeal to the geomorphologist, since it is based on physical conditions related to processes. Furthermore, the effects of the chosen threshold on the geometry and topology of channel networks would represent an interesting and as yet unexplored area in network research.

Speight (1968) applied this approach manually. First, a square grid of points spaced 100 feet (30.5 m) apart (ground scale) was drawn on a contour map. Next, a slope line perpendicular to the contours was traced downslope from each grid point. Finally, a line segment the same 100 feet (30.5 m) in length was successively centred, parallel to the contours, on each grid point, and the number of slope lines crossing it was determined. If this count exceeded 100 lines, or if the line had a density over a 'narrow zone of flow concentration' of more than one slope line per foot of sampling line, the point was declared to lie on a 'watercourse' (Speight 1968, p. 244).

Speight's approach can be automated rather directly for gridded elevation data. Each cell is considered to drain to whichever of its eight neighbours has the steepest downslope toward it. This is not always the lowest neighbour, since the height differences for the four diagonal half-neighbours of a point must be divided by the grid spacing multiplied by the square root of two. Initially, each cell may be considered to produce a unit quantity of runoff; this runoff is then carried downslope in accordance with the drainage directions of the grid cells. Any imported runoff is exported by a cell, together with the locally produced runoff. Then, whenever the runoff in a cell exceeds some threshold, the cell is considered to be part of the drainage network.

Three distinct algorithms for runoff simulation are possible. One requires random access to the elevation data, or at least to the slope directions, and also requires a runoff counter for every cell in the DEM. Each cell is visited, and the runoff unit produced in that cell is followed downslope to the edge of the DEM or to a pit. All cells along the way have one unit of runoff added to the runoff already present. Since runoff from any cell could potentially flow entirely across the data area, the elevations and the runoff counters for the entire model must be available at all times.

A second approach to runoff simulation is local, and each cell is visited only once; however, this algorithm requires that the points be processed in order of decreasing elevation. If cells are processed from highest to lowest, then by the time a cell is processed, all possible inputs to that cell will have been defined (since a cell cannot receive input from one which is lower). In this approach, a sequential file is first written which contains the elevation of each point, together with the cell to which it drains; this file must then be sorted in decreasing order by elevation. A runoff vector with a length equal to the number of elevation points must be initialized to 1, and then the points are processed in order. The runoff present in each cell is simply added to the runoff present in the cell toward which it drains; the runoff need not be carried farther at each step, since all the inputs of any cell are determined before that cell is processed.

A third approach, which as been adopted by O'Callaghan and Mark (unpublished) determines the number of inputs to each cell in the matrix. On each pass through the matrix, the contents of any cell with no undefined inputs is exported to the cell toward which it slopes, and the number of inputs of the receiving cell is decremented by one. On the first pass through the matrix, only cells along ridges would be processed. While the worst-case number of iterations for this process is proportional to the total number of cells in the elevation matrix ($o(n)$), the expected average case will be proprotional to the diameter of the matrix ($o(n^{1/2})$).

The current research was conducted using an Eclipse S/130 mini-computer, and the sorting of a file containing some 160,000 records was considered to be impractical. Therefore, the second approach was adopted. The FORTRAN program DRAIN achieves random access to the elevation data through the use of a Full Morton contiguous data file (Lauzon and others, unpublished manuscript) in conjunction with a virtual array emulator. Briefly, the row and column of a cell are combined to produce a Morton number (Morton 1966; Lauzon and others, unpublished manuscript); this is then used as an address in the virtual array. Points are brought into core in blocks of 256 elevations. Morton addressing maximizes the probability that the next point required will already be in core, assuming that it is a spatial neighbour. Because of limited core space, the image buffer of a Ramtek color monitor was used to count accumulated runoff. The unit runoff initially placed in each cell was followed downhill to a pit or the map boundary, each pixel along the path was examined, and if its runoff value ('colour') was less than 15, 1 was added to this 'colour'. Because the image buffer has only four bit-planes, the maximum runoff which could be distinguished was 15; for the present test, then, 15 cells, or 13,500 square metres, was used as the critical drainage area threshold.

Again, pits in the data, which are present due to errors, cause serious problems. Since pits do not have any lower neighbours to which they would drain, runoff accumulation stops at these points, and would begin again from 1 just down-slope. While the runoff of a pit could be exported to its lowest neighbour, this could easily lead to an infinite loop, since the lowest neighbour could simply drain back toward the pit again. Again, smoothing reduces the difficulties, but it is also possible to, in a sense, 'fill' pits with water until they overflow (see O'Callaghan and Mark, unpublished).

## EVALUATION

The local concavity approach (program HILO) is much more space- and time-efficient. The method is strictly local, and the single pass through the DEM requires less than 3 minutes on the Eclipse. On the other hand, the runoff simulation approach (program DRAIN), as currently implemented, is extremely slow, requiring more than an hour of processing time for a single DEM. This is in part because a peripheral device, the Ramtek image buffer, is used to keep track of the runoff, and there is a great deal of costly I/O. Each of the approximately 160,000 cells in a DEM is visited from 1 to 16 times, and at each visit, a 'read image', a 'move', and a 'draw' instruction must be executed. In the present hardware environment, the principal appeal of the DRAIN approach, the possibility of choosing a physically-meaningful threshold for stream sources, is severely restricted; coupled with the extreme slowness of the algorithm, this indicates that at present the HILO approach is to be preferred. However, the DRAIN method still has the potential to make a greater contribution to our understanding of the relations among topography, runoff, stream sources, and drainage network structure. Recent results by O'Callaghan and Mark (unpublished) using the third method for drainage accummulation outlined above are very promising for small (50 by 50) matrices, but have not yet been adapted to mini-computers, nor tested for larger data sets.

Critical and quantitative comparisons must be made, not only with networks obtained from maps using 'traditional' methods, but also with channel networks mapped in the field. The stream patterns identified using either of the algorithms discussed in this paper must also be converted from raster to vector form, in order that link lengths, junction angles, and other properties of interest can be determined. If that result is achieved, data collection should become much less of a limiting factor in drainage network research.

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## REFERENCES

ALLAM, M.M., 1978. DTM's application in topographic mapping. *Proceedings*, Digital Terrain Models (DTM) Symposium, ASP/ACSM, St. Louis, Missouri, May 9–11, 1978, pp. 1–15.

ALLDER, W.R., CARUSO, V.M., PEARSALL, R.A., and TROUP, M.I., 1982. An overview of digital elevation model production at the United States Geological Survey. *Proceedings*, Auto Carto 5, (Fifth International Symposium on Computer-Assisted Cartography and ISPRS IV *Proceedings*, 1982), pp. 23–32.

ELASSAL, A.A., 1978. USGS digital cartographic file management system. *Proceedings*, Digital Terrain Models (DTM) Symposium, ASP/ACSM, St. Louis, Missouri, May 9–11, 1978, pp. 16–23.

JARVIS, R.S., 1977. Drainage network analysis. *Progress in Physical Geography*, v. 1, pp. 271–295.

KIKUCHI, L,, GUEVARA, J.A., MARK, D., and MARBLE, D.F., 1982. Rapid display of digital elevation data in a mini-computer environment. *Proceedings*, ISPRS Commission IV Symposium 1982, (Fifth International Symposium on Computer-Assisted Cartography and ISPRS IV *Proceedings*, 1982), pp. 297–307.

KRUMBEIN, W.C., and SHREVE, R.L., 1970. Some statistical properties of dendritic channel networks. Technical Report No. 13, U.S. Office of Naval Research, Contract Nonr-1228(36), Task No. 389–150, Department of Geological Sciences, Northwestern University, and Special Project Report, National Science Foundation Grant GA–1137, Department of Geology, University of California, Los Angeles.

LAUZON, J.P., MARK, D.M., KIKUCHI, L., and GUEVARA, J.A. Two-dimensional run-encoding for quadtree representation. Submitted to: Computer Vision, Graphics, and Image Processing.

LUBOWE, J.R. 1964. Stream junction angles in the dendritic drainage pattern. *American Journal of Science*, v. 262, pp. 325–339.

MARK, D.M. 1983. Relations between field-surveyed channel networks and map-based geomorphometric measures, Inez, Kentucky. *Annals*, Association of American Geographers, v. 73, no. 3, in press.

MORTON, G.M., 1966. A computer oriented geodetic data base, and a new technique in file sequencing. Manuscript, IBM Canada Limited, March 1, 1966.

O'CALLAGHAN, J.F., and MARK, D.M. The extraction of drainage networks from digital elevation data. Submitted to: *Computer Vision, Graphics, and Image Processing*.

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

SPEIGHT, J.G., 1968. Parametric description of land form. In Stewart, G.A., editor, *Land Evaluation,* Papers of a CSIRO Symposium in Co-operation with UNESCO, 26–31 August, 1968, pp. 239–250.

SWAN, R., THOMPSON, J., and DAYKIN, S.E., 1978. Applications of low cost dense digital elevation models. *Proceedings,* Digital Terrain Models (DTM) Symposium, ASP/ACSM, St. Louis, Missouri, May 9–11, 1978, pp. 141–155.

TOBLER, W.R., 1966. Numerical map generalization and notes on the analysis of geographical distributions. Michigan Inter-University Community of Mathematical Geographers (MICMOG), Discussion Paper 8, University of Michigan, January, 1966.