Algorithm for Precise Drainage-Basin Delineation

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ALGORITHM FOR PRECISE DRAINAGE-BASIN DELINEATION

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ABSTRACT: Computer-based terrain models have become increasingly popular as a tool for automating much of the geometrical data acquisition necessary for hydrologic analyses. An algorithm is presented that uses triangulated irregular networks (TINs) to accurately delineate drainage-basin boundaries. Boundary delineation can be performed for areas that drain to individual points or stream networks defined on the TIN. A special feature of the algorithm is that the segments of the stream network need not correspond to channel edges. This allows greater flexibility in defining stream networks on the TIN and makes it possible to apply the boundary delineation algorithm to urban areas where the stream networks may be dominated by manmade structures such as streets and canals or to rural areas where the terrain exhibits little relief. Once the basin boundaries are established, geometric parameters such as basin areas, slopes, and maximum flow distances are easily computed. These tools can be combined with hydrologic modeling software such as HEC-1 to create a comprehensive hydrologic modeling environment.

INTRODUCTION

To perform a hydrologic analysis using computer programs such as HEC-1, a significant amount of information must be gathered before the actual computer analysis can be done. Much of this information is related to geometric characteristics of the watershed. Acquisition of these data typically requires that engineers spend many hours studying contour maps to delineate basin boundaries. Once the boundaries are delineated, subbasin areas and slopes, stream lengths and slopes, basin centroids, maximum flow distances within basins, and other geometric parameters can be extracted. This process of basin delineation and extracting geometric parameters is often the most time-consuming and costly part of a hydrologic analysis.

Several researchers have investigated techniques for automating hydrologic analysis using digital terrain models. Terrain models are typically constructed from gridded data, from points organized along contour strings, or from triangulated sets of scattered data points [triangulated irregular network (TIN) models]. Models derived from gridded data have frequently been used for terrain model generation and analysis because of their widespread availability. Several researchers have presented algorithms for computing subbasin boundaries using gridded data. Peucker and Douglas (1975) were among the first to develop and present such algorithms. O'Callaghan and Mark (1984), Band (1986), and Jenson and Domingue (1988), among others, contributed to the refinement of the process for extracting drainage networks from gridded data. Moore et al. (1988) showed that data organized in the form of contour strings can be useful in defining drainage because

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flow across the model is always orthogonal to the contours. Several previous investigators have studied drainage on a TIN model. Grayman et al. (1975, 1979, 1982) and Heil (1979) showed that TINs are not only suitable for terrain modeling, but also make a good data structure for geographic information systems, particularly when hydrologic data needs to be extracted. Silfer et al. (1987) and Gandoy-Bernasconi and Palacios-Velez (1990) developed a kinematic wave model for flow hydrographs based on partitioning the flow across the triangles. Palacios-Velez and Cuevas-Renaud (1986) showed how streams and ridges could be inferred from a TIN model. They also presented a technique for computing the approximate contributing area for selected points on a stream. Jones et al. (1990) presented an algorithm for automatic stream network and subbasin delineation, which featured a triangle subdivision process to improve the accuracy of subbasin boundaries.

While the boundary delineation procedure described by Jones et al. (1990) works well in many cases, there are three important limitations to the procedure. First, to delineate subbasins the presence of a stream network, automatically inferred from the TIN, was required. Representing a stream network is difficult in cases where the terrain is flat, because the TIN must be edited to ensure that the stream channel is accurately represented in the TIN. Also, when combining basin delineation results with geographic information systems (GISs), situations often arise in which it is useful to delineate the boundary of the contributing area to an individual point without first delineating a stream network.

The second shortcoming of the original algorithm is that the resulting subbasin boundaries were not always exact. While Jones et al. (1990) implemented the capability to smooth basin boundaries by splitting triangles so that they conformed precisely to boundary edges, the automating process was not complete. This method worked well when the TIN boundary conformed to a watershed boundary, but it did not guarantee that the triangles along all boundaries between adjacent subbasins would be subdivided.

A third problem with the original algorithm was that it required the stream segments in a stream network to conform to channel edges (edges where both adjacent triangles slope towards the edge). Ensuring that a continuous set of channel edges exists where a stream is to be defined sometimes requires a significant amount of interactive editing especially in urban areas where storm drains and streets make up a large part of the stream network.

A new algorithm is presented in this paper that can be used to precisely delineate watershed boundaries using a TIN model for individual points or arbitrarily defined stream networks.

TIN MODELING

A TIN is constructed by connecting a set of data points with edges to form a network of triangles. If the surface is assumed to vary linearly across each triangle, the TIN represents a piecewise linear interpolation of the data points. Many different algorithms for triangulating a set of *xyz* data points have been presented (Lawson 1977; Watson 1981; Watson and Philip 1984; Lee and Schacter 1980; and Jones 1990). Most of these algorithms use the Delauney criterion to guide the triangulation process. The Delauney criterion is satisfied when the circumcircle (the circle defined by the triangle vertices) of the three vertices forming a triangle encompasses no other vertices (Fig. 1). During the triangulation process, the shared edges of pairs of adjacent triangles are swapped as necessary to ensure that this criterion is satisfied. The result of the Delauney criterion is that the possibility of

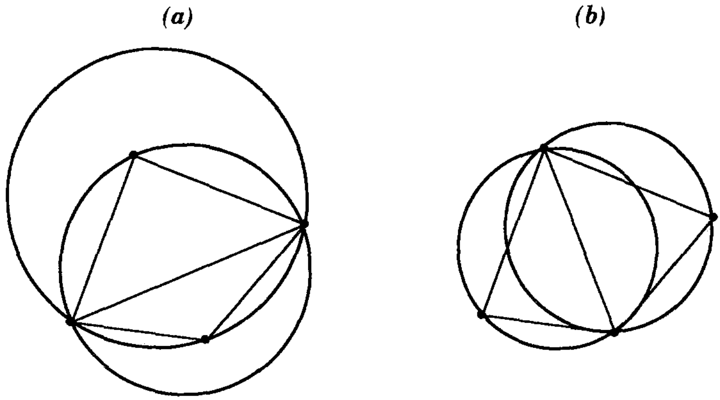

FIG. 1. Two Possible Triangle Configurations for Same Four Points: (*a*) That Violate Delauney Criterion; (*b*) That Satisfy Delauney Criterion

long, thin triangles has been minimized, and triangles are as equiangular as possible. Data points used to construct a TIN may originate from gridded data sets such as those provided by the U.S. Geological Survey. Data points may also originate from digitizing an existing contour map, or as the result of on-site surveying. As a result, a TIN can be constructed from almost any type of *xyz* data set. Another important advantage of TINs is that they are easily modified or refined by sampling extra data points in regions of high relief. In other words, fewer points are required using a TIN to produce the same amount of terrain accuracy.

FLOW PATHS

A fundamental part of the basin boundary delineation process involves tracing flow paths on a TIN. As water begins to flow across a surface it will tend to follow the path of steepest descent (assuming that local roughness variations and momentum are negligible). Flow paths can be constructed from any arbitrary point on a TIN by following the path of maximum downward gradient from triangle to triangle (Jones et al. 1990). A sample flow path computed from triangles is shown in Fig. 2.

As expected, the flow paths are perpendicular to the contour segments across triangles. Flow where the path is traced from edge to edge across the face of adjacent triangles is termed "overland flow." Whenever the flow path encounters an edge whose two adjacent triangles both slope towards it, the flow path follows the triangle edge. This flow along an edge is termed "channel flow." An entire flow path is determined by following a series of overland and channel flow paths until a pit on the interior of the TIN or a boundary on the exterior is reached.

By initiating a flow path at the centroid of each triangle in a TIN, and following its flow along the path of steepest descent, the drainage patterns of a TIN can effectively be displayed. Fig. 3 shows the contours and resulting flow paths for a sample TIN.

TERMINUS POINTS

The first step in the drainage-basin boundary delineation process is to determine points on the TIN for which drainage basins should be computed.

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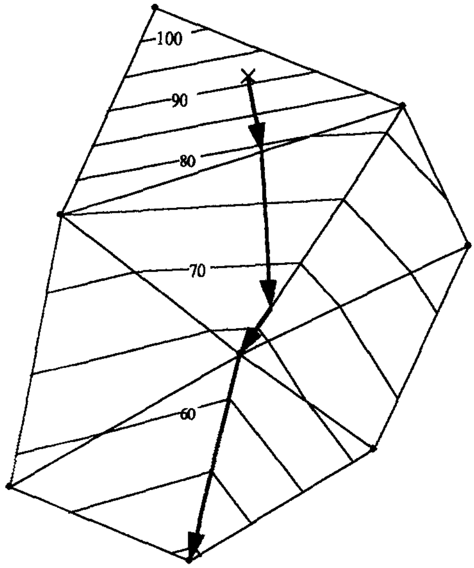

FIG. 2. Sample Path of Maximum Downward Gradient

Fig. 3(*b*) shows that flow tends to converge or congregate at certain points. These points are referred to as "terminus points" since flow terminates there. A set of terminus points for a TIN can be determined automatically by locating points on the perimeter where flow exits along a channel edge, and by finding all interior points that are local minima, or pits (Jones et al. 1990). In most applications, the points on the TIN whose drainage basins are of interest correspond to one or more of these default terminus points. However, since drainage-basin delineation is not restricted to this default set of points, any point on the TIN can be explicitly designated as a terminus point.

BASIN DELINEATION

Drainage basins for the specified terminus points can be created by determining the subset of triangles in the TIN that contribute flow to each terminus point. This is accomplished by initiating a flow path at the centroid of each of the triangles in the TIN and tracing the path until it encounters one of the specified terminus points. The triangle where the flow path was initiated is then assigned the basin ID of the terminus point encountered. The perimeter of the group of triangles associated with a terminus point defines the boundary of that point's drainage basin. If the flow path of a triangle reaches the TIN boundary without passing through a terminus point it is assigned to the "null" drainage basin. In other words, all triangles not associated with a terminus point are grouped together. A set of basin boundaries delineated in this manner is shown in Fig. 4(*a*).

The basin boundaries found using the process just described are only the approximate boundaries. The boundaries are not precise because each triangle is assigned to a drainage basin based solely upon flow from its centroid. Many triangles actually straddle basin boundaries and contribute flow to more than one basin. To accurately delineate basin boundaries, triangles

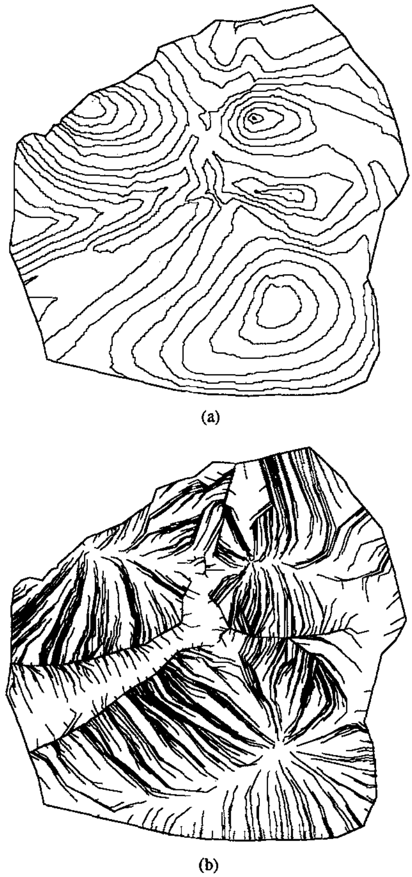

FIG. 3. Sample Triangulated Irregular Network (TIN): (*a*) Contours; (*b*) Drainage Pattern

that straddle boundaries need to be subdivided into smaller triangles that lie completely within a single drainage basin. This subdivision process is composed of three major steps: (1) A set of critical vertices corresponding to local minima on drainage basin boundaries is determined; (2) paths of maximum upward gradient (uphill flow paths) are traced from each of these vertices and the triangles encountered by the paths are subdivided. These uphill flow paths follow the precise boundaries between adjacent drainage basins; (3) the drainage basin ID associated with each of the subdivided triangles is updated.

IDENTIFYING BOUNDARY MINIMA

To accurately subdivide all triangles that straddle basin boundaries, a set of critical vertices must be located and used to initiate paths of maximum upward gradient for triangle subdivision. These vertices correspond to local minima on the boundaries of subbasins and consist of: (1) Terminus points on the perimeter of the TIN; (2) saddle points or spill points where ridges

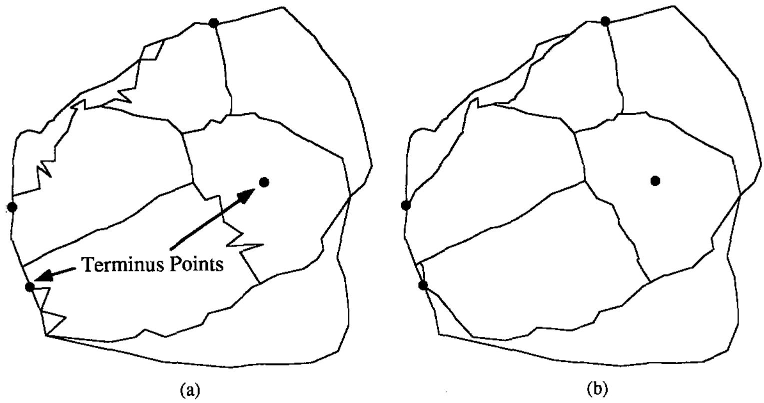

FIG. 4. Basin Boundaries: (*a*) Approximate; (*b*) Precise

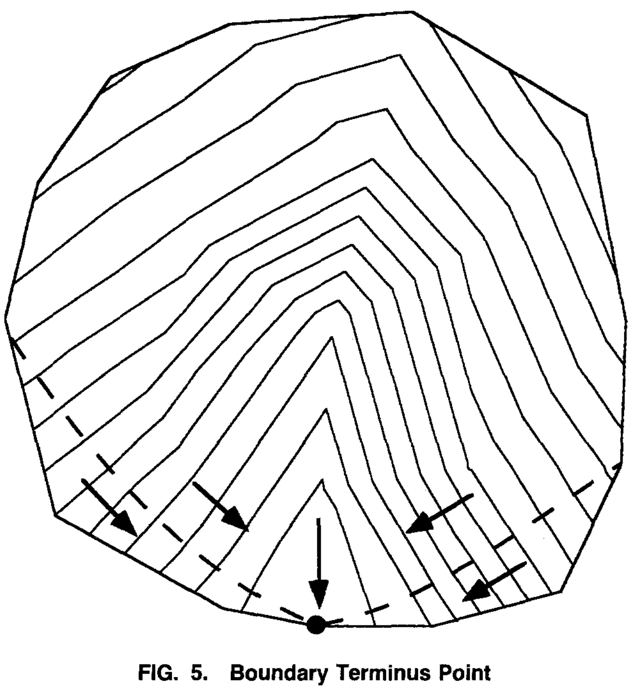

FIG. 5. Boundary Terminus Point

that divide basins converge; and (3) points where basin boundaries meet the perimeter of the TIN.

The subdivision process must be initiated from terminus points on the perimeter of the TIN to accurately separate the area that flows off the perimeter of the TIN prior to encountering a terminus point, from the area which contributes flow to the terminus point (Fig. 5).

A saddle point is a local minima on the boundary of two adjacent sub-basins and can be thought of as the point where water would spill from one basin into the next if the water level were sufficiently high. Using the following algorithm, each vertex on the interior of the TIN is checked to see

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if it is a saddle point. For each vertex, all paths of both maximum upward and downward gradient are computed. These paths are then sorted by angle, so that as a 360° sweep around the vertex is made, a determination of alternating upward and downward paths can be made. If two upward paths are separated by two alternating downward paths [Fig. 6(*a*)], then the vertex can be classified as a saddle point. Occasionally, a vertex lies on the boundary of three basins. This type of saddle point is identified by three upward paths separated by three alternating downward paths. In general, a saddle point is identified by two or more uphill paths separated by two or more downhill paths. Once a saddle point has been identified in this manner, a final check is made to see if in fact the saddle vertex lies on a basin boundary. This check is made by tracing the flow along each of the downward flow paths until a terminus point or the perimeter of the TIN is encountered. If all flow paths end at the same terminus point, the vertex is a local minima or saddle within a basin and it does not lie on a basin boundary.

The third type of boundary minima corresponds to points where basin boundaries meet the perimeter of the TIN, and includes points where a ridge dividing two adjacent drainage basins meets the perimeter of the TIN. They also include points where the boundary between a drainage basin and an area that drains off the perimeter of the TIN meets the perimeter of the TIN. This type of minima is found using a very simple test. An attempt is made to initiate paths of maximum upward and downward gradient from each perimeter vertex. The vertex is classified as a boundary minima if one or more upward and one or more downward paths are discovered and one of the downward paths eventually encounters a terminus point [Fig. 6(*b*)].

TRIANGLE SUBDIVISION

Once all of the boundary minima are determined, the next step in the boundary refinement process is to trace paths of maximum upward gradient from each of these points and subdivide the triangles encountered by the paths. These paths trace along the precise drainage-basin boundaries. The paths stop when they encounter local maxima on basin boundaries. Local maxima correspond to peaks where ridges dividing basins converge, and points where ridges dividing basin boundaries intersect the perimeter of the TIN. If all of the boundary minima are found as such, the complete basin boundaries will be traced by the uphill flow paths (with the exception of

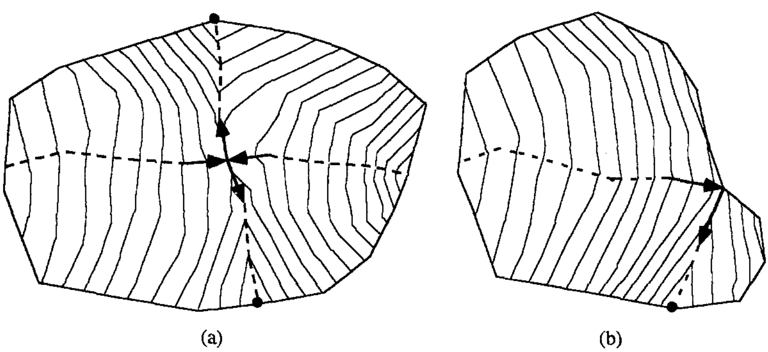

FIG. 6. Boundary Minima at: (*a*) Saddle Points; (*b*) Triangulated Irregular Network (TIN) Perimeter

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basin boundaries coinciding with the perimeter of the TIN, which do not need to be subdivided).

The triangle subdivision process is illustrated in Fig. 7. Vertex *a* has been identified as a boundary minima, and the paths of maximum upward gradient from *a* are displayed. With vertex *a* as the active vertex, a path of maximum upward gradient is initiated and found to follow the path from *a* to *b* (edge *ab* corresponds to a ridge). Since this path moves along an existing triangle edge, no subdivision is necessary and the active vertex becomes *b*. The path of maximum upward gradient from *b* is defined along the line between *b* and *c*. Since this path moves across a triangle face, the triangle is subdivided. First, the triangle crossed by edge *bc* is split by inserting a new vertex at *c* and subdividing the triangle. Then, to maintain a valid TIN topology, the other triangle adjacent to the edge containing the new point *c* is split by inserting an edge from vertex *c* to vertex *d*. Finally, *c* becomes the active vertex and a new upward path is computed. This process is repeated until the flow path encounters the perimeter of the TIN (point *g*).

UPDATING SUBDIVIDED TRIANGLES

The final step in the boundary refinement process is to update the basin ID associated with the triangles that were subdivided by the upward flow paths initiated from the boundary minima. A downhill flow path from the centroid of each modified triangle is traced until it encounters a terminus point or the perimeter of the TIN. The basin ID of the terminus point encountered is then assigned to the triangle. At this point the precise basin boundaries for the TIN are completely delineated. Fig. 4(*b*) shows the precise boundaries for the TIN of Fig. 4(*a*) using the methods described previously.

AUTOMATIC STREAM NETWORK CREATION

While the algorithms described previously herein do not require stream networks to be present, it is often useful to subdivide a watershed into

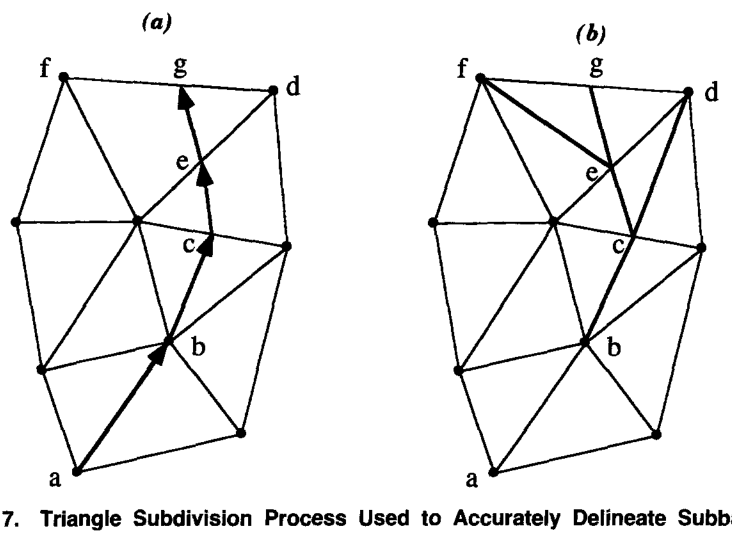

FIG. 7. Triangle Subdivision Process Used to Accurately Delineate Subbasin Boundaries

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subbasins using a stream network. Without incorporating them into the TIN model, it is possible to delineate and subdivide watersheds using individual points, however streams provide a logical placement of terminus points necessary for subdividing basins.

A stream network for a TIN can be automatically delineated by starting at terminus points and recursively tracing uphill along channel edges until all branches of the stream are found (Jones et al. 1990). The TIN vertices defining the stream segments are stored in a tree-type data structure. With the stream network in place, the subbasin for any point on the stream may be computed by designating the point as a terminus point. Branching nodes in the stream are typically designated as terminus points, but any point on the stream can be selected. By tracing flow paths from the centroid of each triangle, as described before, a drainage basin can be computed for each terminus point in the TIN. If a terminus point happens to correspond to a branching node on a stream, a separate drainage basin is computed for each upstream branch leading out of the point.

As before, approximate basin boundaries are defined by initiating flow paths from the centroid of each triangle and tracing the paths until the first terminus point is encountered. If the terminus point corresponds to a branching node of a stream with multiple drainage basins, the basin ID assigned to the triangle where the flow path originated depends upon which branch of the stream the flow path enters the terminus. The boundary refinement process is the same as described previously, except that all the terminus points on the stream network are added to the set of boundary minima from which uphill flow paths are traced to subdivide triangles. The results of this type of basin delineation for a stream network where terminus points have been designated at all branching nodes on the stream are shown in Fig. 8.

LIMITATIONS OF AUTOMATICALLY DELINEATING STREAM NETWORKS

Automatically delineating stream networks by tracing upstream along contiguous channel edges can prove difficult for several reasons. First of all, this process presupposes that a contiguous set of channel edges exists

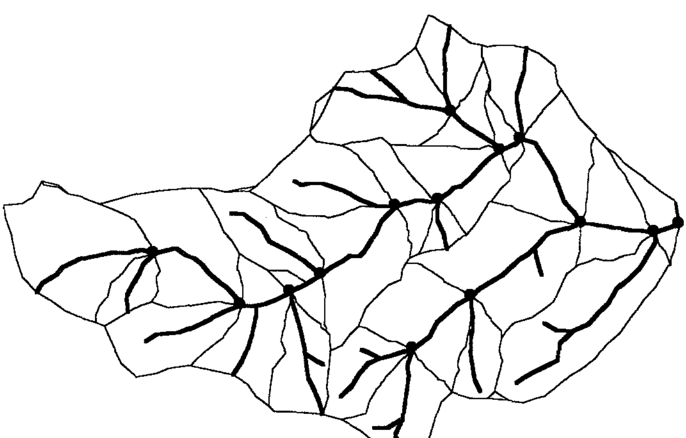

FIG. 8. Sample Triangulated Irregular Network (TIN) with Streams and Subbasins

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in the TIN. However, it is the writers' experience that such a set of channel edges is difficult to obtain when triangulating an arbitrary set of *xyz* data points. While a Delauney tesselation provides a good starting triangulation, it does not ensure that important hydrologic features such as streams and ridges are accurately modeled. In their original paper, Jones et al. (1990) addressed a number of TIN anomalies such as false dams, pits, and flat triangles that obstruct continuous channel segments. They described interactive techniques such as breakline insertion, edge swapping, and point insertion that can be used to adjust the TIN topology of a Delauney triangulation so that a set of continuous channel edges could be formed. In most rural areas where erosion processes naturally cause the terrain to slope towards streams, these types of TIN editing techniques can be effective. However, even in rural areas, the relief in the terrain may be minimal and several hours of editing may be required to ensure that a continuous sequence of channels exist where streams are to be defined. In urban areas, storm drains and streets form a large part of the stream network. Since they typically do not correspond to natural channels, it is very difficult and time consuming to add supplemental data points and refine the TIN until each storm drain and street is represented by contiguous channel edges.

Another problem exists where stream edges extend all the way to basin boundaries such as can be seen in Fig. 8. This occurs because stream edges are classified as such strictly on the basis of the connectivity and slope of adjacent triangles. Many algorithms for automatic basin delineation incorporate some type of threshold drainage area to further identify actual streams. Such a threshold drainage area could be incorporated into the automatic stream network generation technique so that streams do not artificially extend too far upstream. This threshold value is somewhat subjective and a better method for creating streams, which overcomes this as well as the need for extensive editing is described in the following.

These problems can be overcome if stream networks, where stream segments conform to triangle edges but not necessarily to explicit channel edges, can be entered interactively. Creating a stream in this fashion avoids the need of removing pits where small local variations in the TIN exist, and eliminates much of the need for TIN editing. Contours, which are easily constructed for a TIN, can be displayed to guide logical placement of stream networks in rural areas. In addition, individual channel edges may be displayed separately so that where possible continuous channel edges may be followed. In urban areas, maps of streets and drainage systems can be used to guide the placement of the stream network.

Streams are always entered from downstream to upstream for the purpose of defining the flow direction, and a splitting stream (creation of a stream with more than one downstream vertex) is not allowed. As before, additional terminus points may be added at any vertex of the stream to further subdivide basins defined by stream networks. The flow-path algorithm can be modified to ensure that once a flow path encounters a stream, the flow is then traced downstream along stream segments regardless of the surrounding TIN geometry.

BASIN DELINEATION FOR ARBITRARY STREAM NETWORKS

Arbitrary streams (streams that do not necessarily correspond to channels) can be thought of as polylines that intercept flow across a terrain model as is the case with canals, streets, and other drainage structures. Basin boundaries can still be defined with such a stream network by flowing down

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from the triangles' centroids until a stream segment is encountered that routes the flow to a terminus point. However, the boundary-refinement process described previously for stream networks must be modified. If the stream network is composed entirely of channel edges, the only points on the stream from which the triangle subdivision process is initiated are the terminus points. This is because these are the only points where drainage basin boundaries are in contact with the stream network (other than saddle points found separately). However, by allowing for arbitrary stream segments it is possible for flow to be tangent to several points in the stream network, and the triangle subdivision process must be initiated from each of these vertices in addition to the terminus points.

Consider the sample TIN shown in Fig. 9(*a*). The stream network in this case is a street system, and flow across the TIN is represented by the small arrows. It can be seen that the basin boundary intersects the stream at points *q*, *r*, *s*, and *w* and to accurately define the subbasin for this stream network the subdivision process must be initiated from these points in addition to the terminus point [Fig. 9(*b*)]. In general, it may be observed that if a boundary is in contact with a stream vertex, a downstream flow path coincident with the boundary intersects the vertex and then continues downhill without intersecting the associated stream. This can be visualized as points where a downstream flow path is tangent to the stream network. This observation can be formulated into an algorithm for identifying these critical points along the stream from which boundary subdivision must be initiated.

For each vertex in a stream segment defining a subbasin, the following determines whether or not splitting must be initiated from it: (1) A set of vectors associated with the vertex is found which represent the first segment of all downhill flow paths from the vertex which do not intersect the associated stream network, the first segment of all uphill flow paths from the vertex, and the vectors defined by all upstream and downstream vertices connected to the vertex via stream segments; (2) the vectors obtained in the first step are sorted by angle; and (3) the set of sorted vectors is traversed and each uphill flow vector adjacent to a downhill vector is an upstream flow path from which triangle subdivision should be initiated. Since downhill vectors that intersect the associated stream are eliminated from this set, an

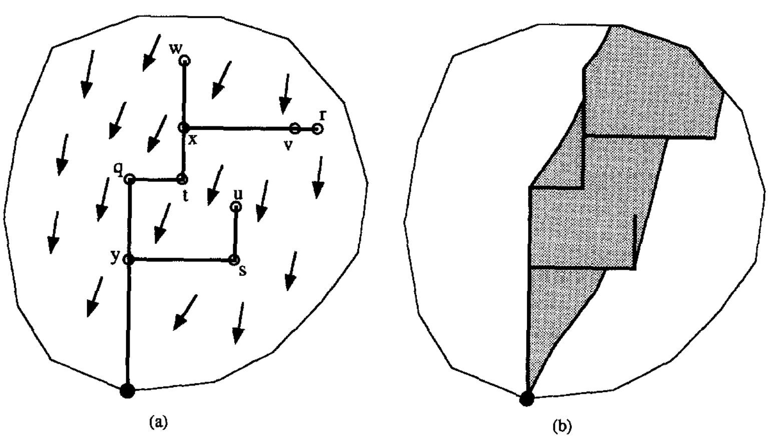

FIG. 9. Sample Triangulated Irregular Network (TIN): (*a*) with Stream Network and Arrows Indicating Flow Directions; (*b*) Drainage Basin for Stream Network

uphill vector adjacent to a downhill vector signifies the presence of a downstream flow path just tangent to the vertex as just described. Fig. 10 shows the sorted vectors for several points from the sample TIN of Fig. 9(*a*). Points *q*, *r*, and *s* are examples of points that pass the tangency test and hence the triangles are subdivided along the uphill flow paths from these points. Points *t* and *u* are rejected because the downhill flow paths encounter the stream network the points are located on. Point *v* is rejected because the uphill and downhill flow paths are not adjacent.

ALTERING SUBBASIN CONFIGURATION

Once a stream network is in place and basin boundaries are delineated, there are a variety of options for manipulating subbasin configurations. In the case of the TIN shown in Fig. 8, a subbasin is defined for several branches in the stream network. Subdividing in this fashion is not always optimal since an engineer typically wants to establish basins where similar hydrology exists and/or where data such as precipitation have been gathered. Once the subbasins for a watershed have been computed, it is possible to modify the subbasin configuration without recomputing all of the basin boundaries for the entire watershed. For example, if a terminus point is removed from a stream node, then all of the triangles that belonged to any basins of that terminus are grouped with the appropriate basin of the next downstream terminus point. In addition, two or more adjacent subbasins associated with a given terminus on a stream branch may be merged to form a single basin. Basins previously merged may be split once again if desired. Finally, further subdivision may also be accomplished by adding new terminus points and redefining basin boundaries. In this case, only the triangles in the basins where the new terminus points are added need to be subdivided during the boundary-refinement process.

CALCULATING BASIN PARAMETERS

Once subbasins have been defined, the TIN model makes an ideal base for automatically calculating many important geometric parameters associated with the streams and basins. Basin areas are computed by summing

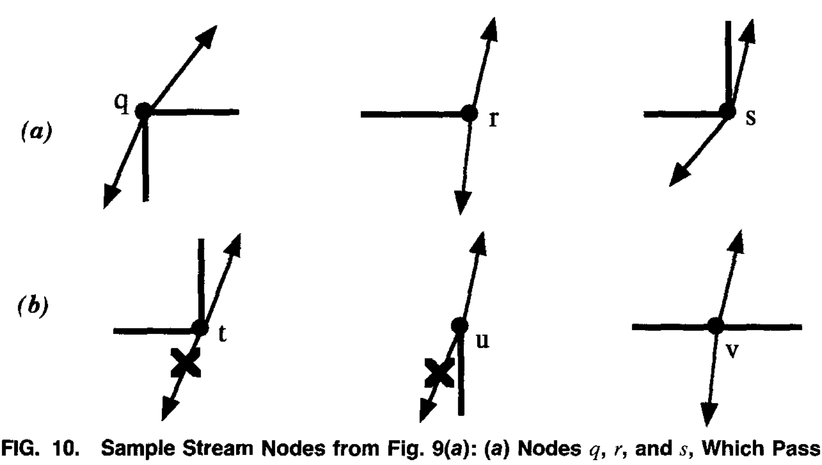

FIG. 10. Sample Stream Nodes from Fig. 9(*a*): (*a*) Nodes *q*, *r*, and *s*, Which Pass Tangency Test; (*b*) Nodes *t*, *u*, and *v*, Which Do Not Pass Tangency Test

the area of all triangles in a subbasin. Average basin slopes are determined by computing a weighted average of the slope for each triangle in the basin, and stream lengths and slopes for individual segments are easily computed by traversing the tree data structure of the stream network. In addition, basin centroids, maximum flow paths, and other parameters necessary for hydrologic analysis can be automatically calculated. If subbasins are combined or subdivided as described previously, these geometric parameters can be updated almost instantaneously, making it possible to model several basin configurations in a relatively short period of time.

APPLICATIONS

The algorithms described in the present paper have been implemented in a computer program written in the C language on Unix workstations and IBM personal computers and compatibles. The program has been tested with data sets ranging in size from several hundred points to tens of thousands of points. Data sets included terrain from regions of high relief such as the Rocky mountains, as well as flat regions like the Nevada deserts. In a typical case of several thousand data points, the entire triangulation, TIN editing, and stream and subbasin delineation process can be completed in several minutes to a few hours depending mainly on the amount of interactive TIN editing required. The stream- and subbasin-delineation process is very efficient and can be completed in several seconds to several minutes.

As mentioned before, once streams and subbasins have been automatically delineated or arbitrarily entered, all of the geometric parameters necessary for performing a hydrologic analysis can be extracted directly from the TIN. Tools for entering nongeometric hydrologic parameters such as rainfall rates have been implemented in the basin-delineation program and the program has been linked with HEC-1 so that hydrographs can be computed directly from the TIN model.

The algorithms described in the present paper could also be effectively used in conjunction with geographic information systems. Stream networks and polygons representing basin boundaries may be written to a digital line graph file and imported to a GIS as a coverage. These polygons may then be used to perform spatial queries with other coverages representing such things as soil properties, vegetation cover, and rain/snowfall data.

CONCLUSIONS

A TIN-based representation of a terrain surface is very useful for calculating geometric properties of a watershed. By using the fundamental idea of tracing flow paths or paths of maximum downward and upward gradient across piecewise linear triangles, drainage patterns, stream networks, and drainage-basin boundaries can be accurately computed. Techniques for entering a stream network as a series of TIN vertices allows streets or other water conveyance networks to be incorporated into the runoff model without the need to edit the TIN in such a way that continuous channel segments are explicitly represented.

Once boundaries have been defined, geometric attributes necessary for input to hydrologic programs such as HEC-1 are easily computed. These attributes include basin area, centroid, overland flow distances and slopes, and stream lengths and slopes. The automatic computation of these attributes allows an engineer to perform a hydrologic analysis of a watershed with significant time savings over conventional manual techniques. In addition, polygons representing the drainage basin boundaries may be used in conjunction with GIS software.

The algorithm described in the present paper assumes that no flat triangles or flat channel edges exist in the TIN since the direction of maximum downward gradient is not defined on such objects. Techniques for automatically editing such objects are being researched. In addition, algorithms for intelligent preprocessing of data extracted from gridded digital elevation models and contour data are being developed.

ACKNOWLEDGMENTS

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