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ARTIFACTS OF TIN-BASED SURFACE FLOW MODELING

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ABSTRACT

Information about terrain is basic to nearly any type of environmental research and is especially useful in hydrological and geomorphological modeling. A useful criterion for determining terrain accuracy for the purpose of hydrological modeling is aspect, since it alone determines flow direction on a surface. The paper reviews the three conventional models of terrain: DEM, contour and TIN. Arguments for the efficiency, accuracy and consistency of the TIN model are summarized. Formal concepts important in modeling hydrology using TINs are presented, and algorithms are developed for the major functions. These are tested on a model of a test topography in Kansas, and several classes of artifacts are identified. These originate in the methods used to construct the TIN, but have significant effects on the success of hydrological modeling. Measures to reduce their frequency and consequences are discussed.

INTRODUCTION

Information about terrain is basic to nearly any type of environmental research and is especially useful in hydrological and geomorphological studies. An important area of study within theoretical geomorphology is that of the topology and geometry of the ridge and drainage networks (Mark 1983) which are prominent physical features of a landscape. Automated techniques to delineate these networks from digital elevation models (DEMs) have recently been developed (for purposes of this paper we define a DEM as any form of discrete representation of the variation of topographic elevation over an area, and synonymous with digital terrain model (DTM)). Much of the research pertaining to these procedures has focused on data structures and algorithms that were developed for their convenience in computer storage and programming and not on their ability to represent the phenomenon being modeled or the processes which form and affect the phenomenon. Ideally, the partitioning and discretization of geographical variation should be based upon the environmental processes and structure prominent in physical systems (Band 1986).

Many alternative types of DEMs exist, as there are many possible ways of discretizing any complex geographical variable (Burrough 1986) so that it can be represented in the finite, discrete space of a digital store. In addition the spatial resolution of any DEM can be varied. For purposes of deriving drainage networks and modeling surface flow, alternative DEMs can be evaluated against an appropriate set of criteria to determine the optimal type and level of resolution. Aspect is a major criterion because it is the primary determinant of local flow direction, and so a DEM which minimizes error of aspect would provide a sounder basis for hydrological modeling. Spatial autocorrelation of aspect errors is also important, because errors correlated over large areas can produce large distortions in inferred flow. A DEM for hydrologic modeling should also represent accurately the specific topographic features of the surface, i.e. peaks, pits, passes, ridge and channel lines, because of the importance of these features in determining flow. It is also important to distinguish between the two physical processes of overland and channel flow (Goodchild et al, 1985).

The purpose of this paper is to review the usefulness of one particular type of DEM, the triangulated irregular network or TIN model, as a basis for hydrologic modeling. Besides its elegance, the TIN model possesses substantial advantages over other DEMs, but is relatively novel and uncommon. The paper begins with a review of the advantages and disadvantages of five DEMs, and commonly used methods for constructing them. Hydrologic properties of TINs are compared to those of more conventional approaches in a theoretical section. Algorithms for extracting TIN hydrology are reviewed, and applied to a test data set from Kansas. The final section of the paper reviews some of the artifacts that arise in TIN construction and their effects on inferred hydrology, and discusses approaches to reducing their impact.

Common types of DEMs

There are five common types of DEMs - digitized contour lines, regularly spaced sample grids, irregularly spaced sample points, polygons, and TINs. Digitized contour lines are easily generated from contour maps as sequences of coordinate pairs connected by straight line segments. On a topographic map, contours are an efficient way of providing readily understood information on the general form of the terrain, and are easily drawn with a pen (see Goodchild 1988 for a discussion of the role of technological constraints in mapping practice). But if the purpose of a digital representation of a surface is to provide an accurate estimate z' of the true elevation z at some arbitrarily chosen location (x,y), or its derivatives, then contours are highly inefficient. The variance of estimate $\Sigma(z'-z)^2$ varies with geographical proximity to the nearest contour line, and also with proximity of z to a contoured elevation. Moreover in order for a DEM of digitized contours to return an estimate of the elevation of a point not located on a contour line it is necessary to define a method of spatial interpolation.

For clarity (Goodchild 1990), we define an object DEM as one that provides estimates of elevation only at the locations of objects, e.g. contour lines, and relies on an additional and often unspecified method of spatial variation to provide estimates elsewhere in the plane. We define a layer DEM as one that provides estimates of elevation everywhere in the plane (within some outer boundary). Digitized contour lines are an object DEM.

There are several drawbacks to using contours as a basis for hydrological modeling. Point surface features known to be important in basin characterization and readily interpreted on a topographic map (i.e. peaks, pits and passes), cannot be represented by this method unless they occur at contoured elevations, in which case they will reduce to points. Warntz (1975) argues that topographic mapping practices have not kept up with our understanding of the topology and geometry of surfaces, and calls for the inclusion of points at peaks and pits, and additional self-crossing contour lines at passes. Relative to other DEMs, digitized contour lines require large volumes of storage to store the coordinate pairs. Moore et al (1988) describe an interesting method of defining finite surface elements for hydrologic modeling based on contours. Each contour line is divided into segments, and pairs of segments on adjacent contour lines are then connected to form irregular quadrilaterals. Further work is needed to make the algorithm sufficiently robust to handle any surface, and to compare this approach to others.

The grid DEM is based on a regularly spaced sample of elevation points and is frequently used due to abundant data sources (see O'Callaghan and Mark 1984 for a review) and the computational efficiency associated with its structure. This object DEM also requires an interpolation procedure to estimate elevations at arbitrarily located points. For example, elevation at a point (x,y) can be estimated by centering a 3x3 window on the closest grid point to (x,y), and fitting a plane $z = \alpha x + \beta x + c$ by ordinary least squares to the 9 grid points in the window. Slope and aspect can then be estimated from a and b. Skidmore (1989) compares six different interpolation methods. The uniform spacing of a grid fails to make use of prior knowledge of the form of the surface, or the processes that formed it. Mark (1979, p.34), for example, concludes that "regular square grids are not an appropriate data structure for DTMs, since they do not correspond with the 'structure of the phenomenon'."

A specific problem in surface flow modeling is that errors in slope and aspect estimation are most likely to occur in areas where there is rapid elevation change or where the slope is not continuous. This is the case at the hydrologically-important surface features: channels, ridges, peaks, pits, and passes. Many interpolation procedures, including the linear form described above, produce discontinuities of elevation in the interpolated surface.

However flows are usually modeled as discrete moves between cells, and resolved to either four or eight directions (Rook's or Queen's case moves respectively). This provides a poor approximation to true flow direction, and has particularly significant effects in areas of constant aspect, where inferred flow direction can deviate from the true direction by 45 or 22.5 degrees (Rook's and Queen's cases respectively: see Goodchild 1977 for an analysis of errors in paths in cellular geometries). To distinguish between overland and channelized flow, it is common to assume that channels occur when contributing upstream area, measured in numbers of cells, exceeds a certain threshold (see Morris and Heerdegen, 1988 who explore drainage patterns produced by varying threshold values). Also, ambiguities in flow direction result when neighboring cells have the same elevation. This is especially prevalent in areas of low relief, where the signal to noise ratio is low, and is also the result of the relatively low precision of elevation data in many sources (e.g. 1m in USGS DEMs).

A common feature in gridded data are pits, points of local minimum where all four or eight neighboring cells have higher elevations than the central point they surround. Pits are particularly troublesome in drainage network analysis, for besides being a fairly uncommon feature in nature (Goodchild and Mark, 1987) (except in karst terrain), they create discontinuities in the flow pattern and often in channel networks. These can either be the result of erroneous data (Mark, 1983), or an artifact of the sampling process (Morris and Heerdegen, 1988). Pits are commonly located in or close to stream channels. Since higher order streams tend to occur in areas of low relief, the stoppage of a drainage path by a pit has a disproportionate impact on the channel network. A number of algorithms have been developed to flood pits (O'Callaghan and Mark 1984; Morris and Heerdegen 1988), create depressionless DEMs (Jenson and Domingue, 1988), or create hydrologically-sound DEMs (Hutchinson, 1989; Ehlschlaeger, 1989) in an attempt to resolve these problems.

The third type of DEM uses an irregularly spaced sample of points. The density of sampling can be increased in areas of high variance, increasing the sample's efficiency. Sample points can also be located at peaks and pits, and along channels and ridges. However an explicit interpolation process is again lacking, and the process chosen will affect this object DEM's ultimate performance.

A polygon DEM represents a topographic surface using a piecewise approximation. The plane is partitioned into irregular polygons, and elevation assumed constant within each polygon. The error variance of this DEM tends to be high, except in certain plateaux-dominated topographies. However it is sometimes used in those spatial data handling systems that support piecewise approximations as the only means of representing continuous geographic variation (so-called 'polygon' systems). It can also be generated readily from digitized contours: the contours form the polygon boundaries, and the constant values are taken to be the midpoints of each contour interval.

The final type of DEM is the central focus of this paper. An irregularly spaced sample of points is minimally connected by a set of straight lines to form a network of triangles with the points as the vertices, forming a complete tesselation of the surface, commonly called a triangulated irregular network (TIN). In this paper we follow normal practice by assuming that the surface within each triangle is linear, passing through the three vertices, with elevation continuity but slope discontinuity across every edge, although higher order polynomial surfaces can be fitted with slope continuity (e.g. the quintic polynomials described by Akima 1978). The TIN is a layer DEM and its error variance can be evaluated given known elevations at additional points not located at triangle vertices. A TIN has been defined as a network of contiguous, planar triangles that vary in size, shape, elevation, slope, and aspect in response to local surface geometry (Peucker et al, 1978). The TIN DEM fits best to terrains dominated by areas of constant slope and linear slope breaks (Heil and Brych 1978), and we conjecture that such terrains are most closely associated with fluvial erosion.

A common approach to TIN construction is to select a sample of points, and then connect them using a standard triangulation, the Delaunay being the most widely adopted (three points form a triangle in a Delaunay triangulation if and only if the circle passing through them contains no other point). However recent work has led to the availability of algorithms for forcing linear features, such as known ridge or channel lines, into the set of triangle edges (Chen, 1988). The addition or subtraction of points in a network is fairly easily achieved, either by simply re-triangulating the new set of points, or by changing the connectivity among the triangles. This allows for easy editing and enhancement of a TIN DEM to provide a more realistic hydrological simulation.

From a hydrologic and geomorphic modeling context, a TIN-based DEM has several attractive characteristics. The continuous nature of the DEM, its explicit representation of surface specific punctiform and linear features, its ability to vary sampling density in relation to relief and to model separate hydrologic processes are chief among these. The different physical processes of hillslope and channel routing can be handled separately in a TIN model (Bennet and Armstrong, 1989; see below). Methodologies for surface flow routing on a TIN have been the subject of previous research (Heil, 1974; Palmer, 1984; Frank et al, 1986, and Silfer et al, 1987) but these have not been tested using real data sets or have used TINs which were created manually, hindering replication (Palacios-Velez and Cuevas-Renaud, 1986). The later sections of this paper investigate how various data sources and methods used to produce a TIN create subsequent artifacts in surface flow modeling. These artifacts frequently result in discontinuities in the ridge and channel networks, limiting their usefulness in modeling.

TIN DATA SOURCES

Until recently, a TIN was built using manual methods by selecting information rich points such as peaks, ridges, and streams directly from a contour map (Heil, 1974). However, algorithms now exist which automate the derivation of a TIN model from a regular grid of points, digitized contour lines, and photogrammetry. The combination of the data source and the methodology used to produce a TIN can greatly impact realistic hydrological depiction.

Digitized contour lines can be treated as irregularly distributed points and triangulated directly, but the result is usually unsatisfactory because of the relatively high density of sample points along contours. Generalization and thinning routines (McMaster 1987) can be used to reduce both the artifacts of digitization, such as operator induced loops, and the number of points needed to represent a line, while maintaining the shape of the line. Points along a sharply bending contour, such as occur near a channel, are selected by the generalizing process because they are located in areas of maximum curvature of the surface. There is some literature on methods to convert contour lines to TINs (Christensen, 1987; Scarlatos, 1989) but these do not specifically look at how hydrological flow is affected.

This is one of the commonest sources of data for TINs, and simple, elegant algorithms are available to select grid points as TIN vertices. The Fowler and Little algorithm uses a 3x3 window to search the grid for surface specific points and connects them to form inferred channel and ridge lines (Fowler and Little, 1979). This approach works well in areas of terrain with sharp breaks of slope along ridges and where channels are sharply incised. The Very Important Points (VIP) algorithm (Chen and Guevara, 1987) orders each point based on an estimate of its significance, given by how well each point's elevation is approximated by a plane drawn through its eight neighbors. Starting with the least significant, points are deleted until either a predetermined number of points or a level of error is reached. This method is particularly poor in terrain with smoothly curving surfaces. A third method, the Drop Heuristic, establishes the importance of a point as the difference between its real elevation and an elevation interpolated from the approximated TIN surface (Lee, 1989). Finally, Bennet and Armstrong (1989) find the four transects which bisect a nine point (3x3) window, classifying each center cell into one of six hydrologic categories: divide points, drainage points, pits, passes, slope breaks, and plains. Neighborhood relationships among the cells are stored and allow a reorganization of the data into an intermediary data structure. A topographic threshold value (the difference in elevation between a transect's end points and the center point) provides a filtering mechanism to control the number of important points used as TIN vertices.

Spatially independent errors in grid DEMs create large abundances of spurious peaks and pits, particularly in relatively flat areas of low signal to noise ratio. These errors are likely to be exacerbated by algorithms that select peaks and pits preferentially as triangle vertices. Carter (1989) provides a review of the common types of errors in readily available grid DEMs.

The most obvious source of irregularly spaced points would be manual digitizing from a topographic map. Besides being fairly time consuming, (Palacios-Velez and Cuevas-Renaud 1986 estimate 5 minutes per point), the TIN is subject to individual error and repetition problems. A set of surface-specific points produced directly from a stereo aerial-photograph and selected for use in a TIN might be a useful data source (Theobald, 1989), as this data would be derived directly from photography, instead of from a product which has already undergone

generalization. Peucker et al (1978) mention that technology exists to automate the selection of irregularly distributed points from a stereo plotter. Other sources of this type of data would be from field or survey data.

DEMs can be produced directly from a stereo-pair of imagery. More recently, automated procedures have been used to produce grid DEMs from stereo SPOT imagery (Day and Muller, 1988) and stereo radar images (Leberl et al, 1986). These generally produce DEMs of lower elevation accuracy, though they may provide data on a regional scale and in areas where other approaches are limited (i.e. because of high frequency of cloud cover).

Some combination of the sources might be the best approach. A particularly important addition to both contour lines and a grid DEM would be hydrographic or stream lines. Clarke et al (1982), in a study of algorithms which interpolate grid points from contour lines, find that the inclusion of supplementary data, such as spot heights and breaklines, provide a clear improvement in the grid DEM fidelity. This data can be used to remove sinks which would not otherwise be filled by flooding routines and is the recommended way to correct these remaining drainage anomalies (Hutchinson, 1989). Additionally, selected points from a contour map such as peaks, pits, and possibly stream junctions would improve the triangulation of a surface.

SURFACE FLOW MODELING ON A TIN

Definitions

In a TIN model the elevations of each vertex provide an ordering, and allow us to regard the network of triangle edges as a directed graph. To allow for ties, we define an edge incident at a vertex as either I (in), if it descends to the vertex, O (out) if it descends away from the vertex, or F (flat) if the edge is horizontal. At a peak all edges must be O (but some can be F if the peak is composed of more than one vertex) and at a pit all edges must similarly be I (or F). An edge must either have I at one end (adjacent vertex) and O at the other, or F at both ends. In any circuit (a triangle is a circuit of three edges) the numbers of Is and Os encountered must be equal, and the number of Fs must be even.

Each triangle edge is formed from the intersection of the two adjacent planes. We can classify each edge in one of three ways: cofluent (C) if both planes slope towards it, difluent (D) if both slope away, and transfluent (T) if one slopes towards and the other away. If the edge is F, the lines of steepest slope in both planes are perpendicular to the edge (see Figure 1 showing D, C, T, I, O, and F edges).

Pfaltz (1976) has described many of the geometrical properties of surfaces and related them to hydrologic flows. A topographic surface is assumed everywhere differentiable, leading to rigorous definitions of peaks, pits and passes. A ridgeline is defined by Pfalz as a line of steepest slope joining a peak and a pass, and a courseline similarly as a line of steepest slope joining a pass and a pit. Ridgelines and courselines form a connected, tripartite graph and partition the surface.

In this paper we follow normal practice in the DEM literature by defining a ridgeline as an upwardly convex break of slope: all difluent edges on a TIN are ridgelines and vice versa. Similarly all cofluent edges are channel lines. The TIN surface is not everywhere differentiable. However if we ignore F edges, we can define a peak as having incident O edges and a pit as having incident I edges; if a circuit is made around a pass intersecting all of its incident edges, then the sequence of intersections must include I, O, I, O. Also, we follow practice in defining an IIO triangle where the third vertex lies upslope of this edge, and an IOO triangle where the third vertex lies downslope (Figure 2 illustrates these definitions, and shows certain special computational cases discussed below). In an IIO ('in-in-out') triangle, flow enters the triangle across two edges and exits across the third, and vice versa for an IOO ('in-out- out') triangle.

Previous Research

On a TIN, flow is generally dispersed in analogy to overland flow except where concentrated by C edges, where it resembles channel flow. One of the first approaches in the literature to model surface flow on a TIN is the ADAPT model (Heil, 1974). The data values which comprise the vertices of the TIN are manually digitized data points, interpreted from a topographic map. No algorithms were given for the delineation of the drainage network. Palmer (1984) used a TIN DEM to represent a hypothetical watershed, illustrating unambiguous definitions of common geomorphological features and providing some introductory concepts of modeling flow on a TIN. Frank et al (1986) extend Palmer's earlier research in the formal definition of physical landscape features. They introduce the definitions of cofluent, difluent, and transfluent edges and ridge and channel lines used here.

Palacios-Velez and Cuevas-Renaud (1986) employ an algorithm that tracks the path of steepest slope in both an upstream and downstream direction from the centroid of each facet. This algorithm is used to determine cofluent and difluent edges which may intersect with the slope path. The values which comprise the TIN vertices in their study site are also manually selected, taking an average of 5 minutes to find and digitize each point. The authors have produced a "dynamic Delaunay triangulation procedure" (Palacios-Velez, 1989, personal communication) which allows interactive editing of the TIN to resolve discontinuities in the cofluent network. Silfer et al (1987) use a TIN-based GIS (TINFLOW) as a basis for hydrological modeling. Their methodology is based on finding IIO and IOO facets (also see Palmer, 1984). In the case of IOO facets, the lowest node is projected back uphill along the line of steepest slope, bisecting the facet to calculate the proportion of flow received by each outflow edge. The simplistic waterbasin used as an illustration in the paper is not suitable for a reliable test of the model, and the authors conclude that the model should be tested using a real surface.

Algorithm

We now describe an algorithm for computing flow on a TIN surface, based on classification of edges (C, D or T) and triangles. Each triangle is first identified as one of six possible types (see Figure 5). Special cases of the basic IIO and IOO types exist where the third vertex (see previous definitions) has the second highest elevation, rather than the highest elevation in the IIO case, and the lowest elevation in the IOO case. Two additional types are the flat triangle (all edges are TF), and the case where the line of steepest slope is parallel to an edge (in effect an IO triangle). The type of facet is determined by finding which edge of the triangle is intersected by a line drawn from a vertex down the line of steepest slope (or which edge is intersected by a line drawn up the direction of steepest slope). Each edge is also flagged according to whether flow crosses it or not. The locations of intersection, or pseudo nodes, are stored for later computations.

Next, the fluency of each edge is found. For each pair of facets forming an edge, the flags are checked to see if they both receive flow and thus are cofluent, or if both do not receive flow and are difluent. All other cases are transfluent or undefined (in cases of flat facets). Critical point surface features (peaks, pits, passes) are found on the TIN using the I, O, and F properties as defined above.

For each cofluent edge, the parent facets which contribute flow to a given edge must be found. This is done by tracing up the line of steepest slope, crossing transfluent edges, until a difluent edge is intersected. A recursive algorithm is used because an IIO triangle has two upstream triangles (a left and right) and this upstream bifurcation must be traced appropriately.

The determination of the ordering and topology of the set of cofluent edges whose pairs of vertices are not equal comes next. A list of nodes is sorted in ascending order and beginning with the lowest node, a recursive algorithm examines all edges (in a clockwise order) emanating from this node. When a cofluent edge is found, the edge number is written to a list and the routine is recursively called, finding all cofluent edges which emanate from the node connected to the original node by the cofluent edge. At each call of the routine, the node is marked as "visited". Each non-recursive invocation of the routine completely exhausts the cofluent edges that are connected and uphill of the node (at original invocation). The routine is called until all nodes are marked as visited.

EMPIRICAL TEST

Data set

Although no attempt at generalization is made here, a sample study site was chosen to investigate and illustrate the possible artifacts that are generated in the process of modeling surface flow on an automatically generated TIN. Data were acquired for a small watershed (about 8000 hectares) in the Konza Prairie Natural Area, about 10 km south of Manhattan, Kansas. The data is in the form of a DEM produced by the U.S. Army Corps of Engineers by digitizing the contours from the USGS Swede Creek 7.5' Topographic map (1:24000 scale) and interpolated to form a 25 m grid, then resampled to a 30 m grid. Elevations of sample points range from 306 to 466 m with a mean of 395 m, and slopes (calculated by the directional derivative of elevation) range from 0 to 22 degrees with an average slope of 6.0 degrees (Dubayah et al 1989). Figure 6 shows the study area on the Swede Creek Quadrangle.

Methodology

Five different approaches were used to create TINs from the grid DEM. All select a subset of sample points as vertices, and although the numbers of selected points varied between the five methods, the objective in each case was to create a TIN of roughly the same storage volume as the grid (using ARC/INFO's TIN data structure (ESRI 1987), a 6% sample creates a TIN of about the same volume in storage). We were thus able to explore the effects of different vertex selection methods, but no attempt is made in this paper to generalize about the effects of different sampling densities.

A TIN (identified as TINVIP6) was created from the 30 m grid DEM data using the VIP algorithm (Chen and Guevara, 1987) using a sampling percentage of 6%, resulting in 1352 vertices. Two further TINs were created from the grid data using the LatticeTIN algorithm, which uses the Drop Heuristic, by specifying maximum elevation errors (from the grid) of 30 feet (TINLT30) (809 vertices) and 25 feet (TINLT25) (1126 vertices).

The next approach taken was to produce TINs directly from the contour data, requiring generalization. The Douglas-Peucker generalizing algorithm (Douglas and Peucker, 1973) was applied to reduce the number of points from 5584 to 810 points. Then the ARCTIN routine was used to create a TIN (TINCONT), with no additional weeding of points. Channel information in the form of 230 manually selected and digitized points were added to the contour-derived TIN to investigate the impact of this type of ancillarly information, creating a TIN (TINCONTCHAN) with 1040 vertices. Since there is currently no available software which can model surface flow over a TIN, a set of computer programs, written in C, was developed to implement the surface flow routing algorithm described above.

RESULTS

Problems occur in modeling flow over TIN models in three particularly significant ways: spurious pits, which tend to occur in areas of low relief and interrupt inferred channels; flat facets, triangles with zero slope and hence undefined aspect; and flat cofluent edges. All of the drainage networks delineated from the TINs show numerous discontinuities. Table 1 summarizes the results of the surface flow modeling. The numbers of facets (F), edges (E) and vertices (V) of each TIN obey Euler's theorem that F-E+V=1. Since TIN surfaces are not 'normal' in the sense of Pfaltz (1976), the numbers of peaks (P2), passes (P1), and pits (P0) do not generally obey the relation P0-P1+P2=1 (Morse 1925). While the VIP procedure is computationally efficient, the resulting surface is plagued with large numbers of local extrema: 134 peaks and 150 pits.

Compared to VIP, the TINs produced by the Drop Heuristic showed a reduced rate of peaks and pits (pits dropped from 11.0% to 2.1% and 1.8%) and reduced rate of flat facets (from 2.3% to .8% and .6%). The TINs produced from the contour data had a much higher percentage of both flat facets and flat cofluent edges compared to the other TINs. By introducing 23% additional vertices to contour data in the form of channel points, TINCONTCHAN has a reduced percentage of both flat facets and flat cofluent edges as compared to TINCONT. TINCONT and TINLT30 have nearly the same number of vertices and facets, but the size of the facets and the lengths of the edges in TINCONT are more uniform over the study area, while in TINLT30 the upper reaches where relief changes more rapidly have smaller facets than the lower relief area of the lower valley. Thus, the upper reaches of TINLT30 are modeled better than the lower area where large facets and long edges result in gross errors.

Figure 7 shows the cofluent edge network interrupted by two flat facets and two flat cofluent edges in the TIN TINCONT. Flat facets are common occurrences on contour-derived TINs, and are located in areas where the contour line doubles back on itself in channel and ridge areas (see Christensen (1987) and Ebner and Tang (1989)). In the grid-derived TINs, flat cofluent edges seldomly occur in areas of rapid relief change and are more prevalant in low relief areas. Channel dams (Christensen, 1987) occur where a facet edge crosses several contour lines not only disrupting the flow but also creating a pit on the upstream side. Ridge divots are complementary features to channel dams, and occur in ridge areas where a facet edge cuts through the original surface underneath adjacent contour lines. Another artifact which affects the inferred network is the case of an IOO facet where both the out edges are cofluent. This case allows two channels to come together without an intermediary ridge line (two CI edges adjacent at a vertex) and thus causes problems in the definition of channel junctions and watershed boundaries.

In general, the TIN DEMs used in this study do not provide a good depiction of the surface for surface flow modeling. One of the difficulties in using TINs that were automatically created from source data is that the majority of the algorithms used to select vertices and triangulate them use elevation as the basis of their objective function. Another important problem which needs to be addressed is the relationship between the sampling density and the scale of the land forms, and sampling density's effects on the delineation of drainage networks.

POSSIBLE SOLUTIONS

Bennet and Armstrong's (1989) approach of choosing points from a grid DEM to become TIN vertices (their algorithm was not implemented in this study) may provide a better drainage delineation, though the topographic filter would still cause problems in low relief areas and at ridge and channel junctions. Chen (1988) introduces break lines, or lines or high information content, forcing ridge and channel lines to be edges of triangles (note that the resulting triangle network is no longer Delaunay). Requiring at least one edge of a triangle to lie along a contour line between points of common elevation keeps the integrity of the contour lines intact (Scarlatos, 1989), thus reducing the number of triangles with edges which cross under or over a contour line (channel dams and ridge divots). Ebner and Tang (1989) find the medial axis transform (MAT) of contour lines to automate the production of ridge and channel lines. The introduction of this additional information significantly reduces the number of flat facets created in areas with strong contour curvature (Ebner and Tang, 1989) and the number of flat cofluent edges. Using a three-dimensional Delaunay triangulation may provide a better method of triangulation, particularly in areas of steep terrain where distances on the surface may be longer than their 2-dimensional counterparts (see Watson, 1981).

A possible approach would be a rule-based triangulation algorithm which can interpolate new points to subdivide triangles, creating edges which connect topologically. These rules would prohibit, for instance, the creation of flat triangles by not allowing 3 vertices of the same elevation. If this situation occurred, a new point would be interpolated to subdivide the triangle and/or change the connecting edges. Another method might be to find triangles which minimize aspect errors rather than elevational errors, by comparing the aspect of each facet to estimates of aspect from the grid (e.g. using 3x3 windows).

CONCLUSIONS

Modeling surface flow on a TIN-based DEM has several advantages (e.g. distinction of flow types and completion of the data model) which make it an attractive data structure for hydrological modeling. Current automated methods create TINs which may be optimized to represent elevation. In principle, it is possible to compute the pattern of water flow over a TIN. TINs have a major advantage over grid DEMs as a source of inferred hydrology as flow direction need not be resolved to four or eight directions. However the resulting networks have many discontinuities. In this paper we have also investigated artifacts created by the process of TIN generation, and found that many of these also interfere with inferred hydrology. Specific problems which plague these surfaces are spurious pits, flat facets, flat cofluent edges, channel dams, and ridge divots. Spurious pits are the result of low signal to noise ratio in TINs developed from grid DEMS, and tend to be selected preferentially by common vertex selection algorithms. Flat facets and flat cofluent edges are commonest on TINs developed from digitized contour lines.

The most effective answer to these problems is clearly the use of ancillary data, as no DEM is able to provide accurate information on hydrology on its own. In general, our results show that the grid DEM creates fewer artifacts, and the spurious pits generated by this method can be dealt with either by flooding or by using a more appropriate procedure for vertex selection. The artifacts found when TINs are built from digitized contours are generally more difficult to deal with. Despite the ready availability of this form of data, our results echo the earlier discussion which argued that contours were a poor form of DEM. Ancillary information may be used to guide the selection of TIN vertices, e.g. by including points on ridges or in channels, or to guide the process of triangulation, e.g. by forcing known break lines into the network.

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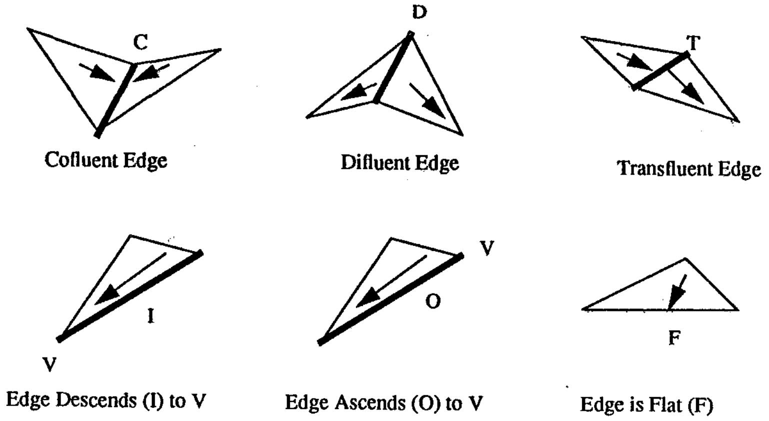

Figure 1: Definitions of Six Edge Types

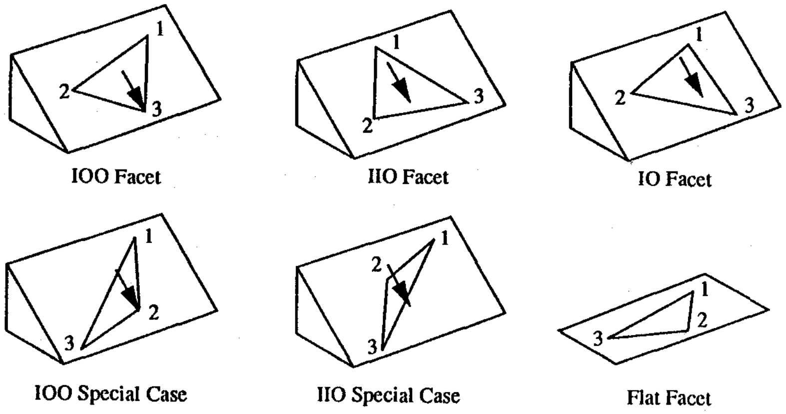

Figure 2: Six possible facet types

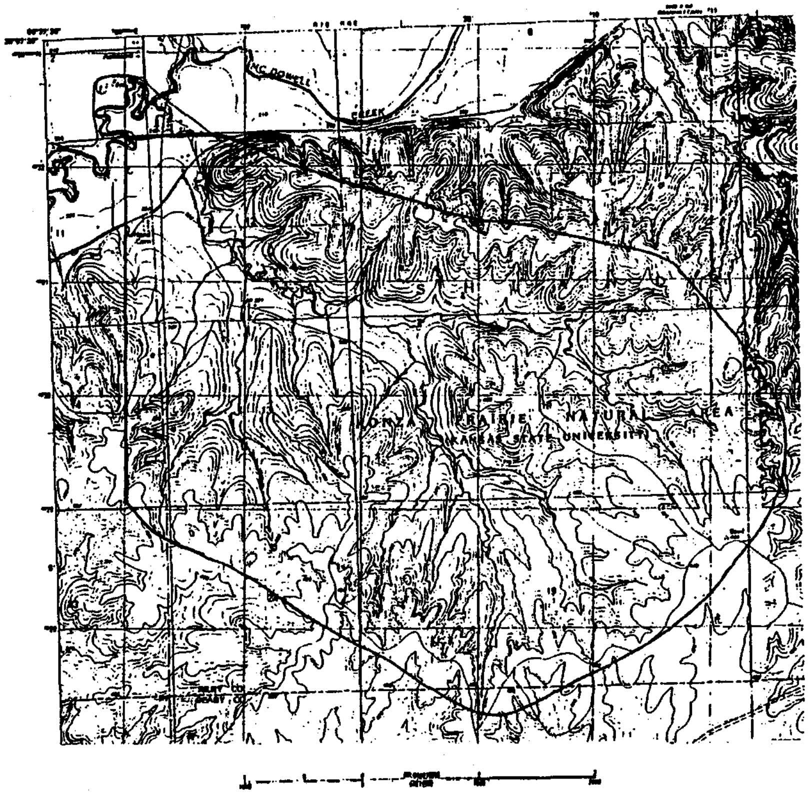

Figure 3: Topographic map of Konza Prairie Natural Area showing waterbasin used as the study site.

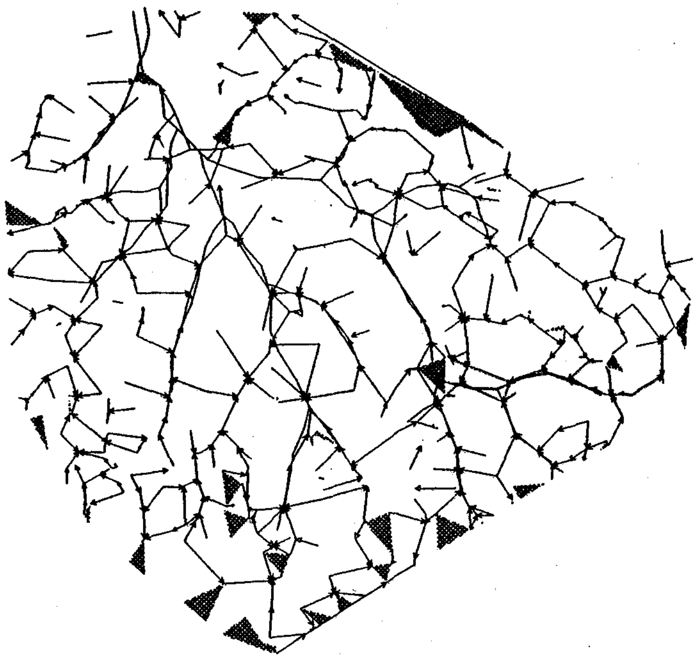

Figure 4: Cofluent network of TINCONT (TIN derived from contour DEM using ARCTIN comprised of 810 vertices). Cofluent edges are drawn as arrows, while flat cofluent edges are straight lines. Flat facets are shown as cross-hatched areas. The digitized blue line network is shown for comparison purposes.

RESULTS OF SURFACE MODELING

TIN	vertices	edges	facets	peaks	pits	passes	flat-co edges	cofluent edges	flat facets
TINCONT as percentage	810	2378	1569	27 3.3%	22 2.7%	16 1.9%	74 3.1%	508 21.3%	54 3.4%
TINCONCHAN as percentage	1040	3069	2030	34 3.2%	13 1.2%	25 2.4%	52 1.6%	679 22.1%	47 2.3%
TINVIP6 as percentage	1352	4019	2668	134 9.9%	150 11.0%	199 14.7%	38 .9%	927 23.0%	62 2.3%
TINLT25 as percentage	1126	3358	2233	43 3.8%	21 1.8%	87 7.7%	15 .4%	509 15.1%	19 .8%
TINLT30 as percentage	809	2408	1600	34 4.2%	17 2.1%	53 6.5%	19 .7%	413 17.1%	11 .6%

Table 1: Results of various TIN methodologies and surface flow modeling.