A GEOGRAPHIC INFORMATION SYSTEM UTILIZING THE TRIANGULATED IRREGULAR NETWORK AS A BASIS FOR HYDROLOGIC MODELING

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ABSTRACT

The TINFLOW system is a PC-based Geographic Information System (GIS) that utilizes the Triangulated Irregular Network (TIN) and associated data structures, together with a deterministic, finite difference approach, to model rainfall-runoff processes via overland flow and interflow. The Triangulated Irregular Network is used to accurately model a watershed as a series of triangular facets. The TIN methodology and data structure allows the user to conveniently store or directly calculate the necessary physical information of the basin required by the hydrologic model. In addition to these parameters, attributes such as soil type or cover type may be specified and stored directly in the data structure. These attributes allow the user to specify, on a facet-by-facet basis, the physical parameters that drive the hydrologic model. This type of analysis is particularly well suited to modeling of urban areas with its alternating areas of pavement and vegetation. It may also offer the capability to predict the results of change within a watershed (for example, a clearcut area's effect on rainfall- runoff, water quality and soil erosion).

TINFLOW SYSTEM DESCRIPTION

TINFLOW is a geographic information system (GIS) written for a personal computer environment in Turbo Pascal. The GIS contains a hydrologic module that can predict a stream's response to storm events. It is useful in predicting flood levels, in maximizing hydroelectric power generation from a given storm, in determining release schedules of reservoir systems to optimize water storage, and in understanding stream characteristics that may influence the design of flood control structures, dams, and habitat improvements.

Over the last fifty years many methods have been developed to predict the outflow hydrograph of a stream. These methods range from the unit hydrograph theory, which is applicable only if measured flow data is available for that stream, to mathematically complex hydrologic models that predict a watershed's outflow hydrograph based on the physical characteristics of the watershed. Examples of these models are the Stormwater Management Model (SWMM) and the Stanford Watershed Model.

The majority of these models discretize the watershed into a small number of subwatersheds. Each subwatershed is then assigned one number, or index, for each physical characteristic of the land such as slope or land cover type. It is logical to assume that the more discretized a watershed, the more accurately physical attributes can be assigned. These attributes are what determine a watershed's response to storm events.

The TINFLOW system also uses a discretized watershed, with physical attributes assigned to each subarea, as a basis for the associated hydrologic model. However, the method used to discretize the watershed is unique. The TINFLOW system employs the Triangulated Irregular Network (TIN) as a digital terrain model to represent the topography of the watershed.

TIN FORMAT VS. MATRIX FORMAT

The primary method for the production and distribution of digital terrain models is the matrix format, a raster of equally spaced elevation posts. The question then arises, what value does the TIN format offer over a matrix format for this particular application? The answer becomes apparent when the modular character of the solution is examined. It is desirable for software solutions to be very modular. This characteristic allows easy modification and makes future development more cost-effective.

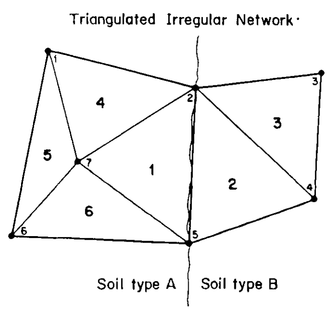
The elemental unit for the terrain matrix is a point. A data point, however, does not allow meaningful analysis of terrain. The elemental cluster in a matrix would consist of four points, or a two-by-two cell. This represents a complex surface because it can be curved between elevation posts. Similiarly, depending on the interpolation schemes, the boundary conditions of this elemental cluster may be quite complex.

The TIN model consists of a collection of triangular planes joined at their boundaries. The spacing and shape of the triangles is determined by the terrain and by the desired degree of fit. Even though the elemental information is a point, the elemental cluster is always a triangle. The interpolation scheme is assumed to be linear, therefore, the few boundary conditions are straight forward to specify.

The development of a hydrologic model for a plane surface is trivial. If a model can be developed to handle the set of all possible boundary conditions to that plane, then the complete solution for a TIN terrain model can be specified. Furthermore, if the software is developed in this way, the individual developing the hydrologic model needs only to be concerned with one routine that describes the flow over a plane. This highly normalized approach lends itself to a modular software solution.

SYSTEM COMPONENTS

The TINFLOW GIS's data requirements are created from two initial data files: a topology file and a node coordinate file. The TIN topology file contains topologic and attribute data for each facet. An example of the structure used in this study is illustrated in figure 1. The second data file contains node coordinate information. In this file each node's location—latitude, longitude, and elevation—are stored. Two preprocessing algorithms, PREPRO and CHECKR are used to perform calculations and place the data into the structure required by the hydrologic model.



TIN Data structure: OPPIJ - Facet opposite IJ node link

TIN facet #	I node #	OPP IJ	J node #	OPP JK	K node #	OPP KI	Soil Attribute
1	2	2	5	6	7	4	A
2	2	3	4		5	1	B
3	3		4	2	2		B
4	1		2	1	7	5	A
5	1	4	7	6	6		A
6	7	1	5		6	5	A

Blank fields denote the edge of the TIN.

Figure 1—An example of a TIN data structure

The hydrologic model is used to simulate the watershed's runoff hydrograph. A postprocessing menu system that immediately follows the model allows the user to graphically view the results of each hydrologic simulation.

ALGORITHM DESCRIPTIONS

PREPRO Algorithm

The PREPRO algorithm performs several important operations.

- It performs a relational join of the topologic and node coordinate files to form a third hybrid data structure.
- It calculates physical parameters of each TIN facet such as slope, area, and aspect, from the TIN geometry.
- It determines how water should be routed across the surface of each TIN facet.

One of the most difficult problems involved in developing a dual digital terrain and hydrologic model is the linking of individual TIN facets hydrologically. During storm events, one of the paths water follows to a stream is over the land's surface; therefore , it is important to understand how water flows across an individual TIN facet surface, and from one facet's surface to another.

All possible flow cases were examined during development of the mode. It was determined that there were two basic conditions that can occur:

- Flow enters two sides of a facet and exits from one side.
- Flow enters one side of a facet and exits from two sides.

To determine which flow case exists for each facet in the watershed, the PREPRO algorithm first calculates the equation of the vector normal to the facet's surface, as shown in Figure 2.

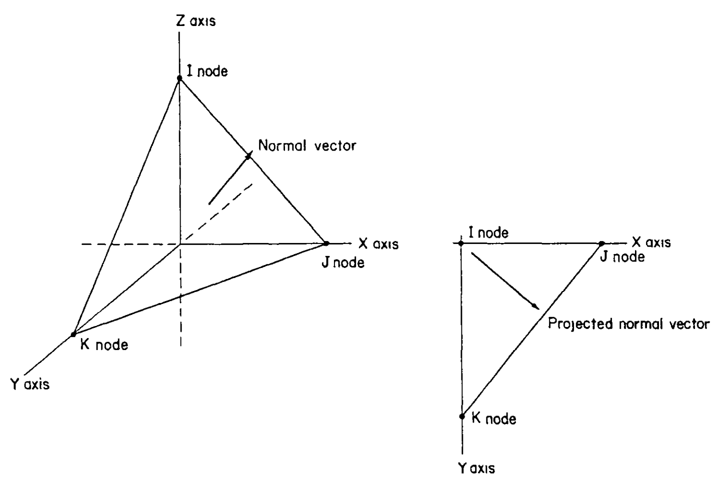


Figure 2—Schematic view of a facet showing the normal vector

This vector, when projected onto the x-y plane, defines the line of maximum slope and thus the direction that water would flow across the facet's surface. The x and y components of the projected vector are used to find the aspect of the fall line or the direction of flow for that facet.

One of the major challenges involved in the design and implementation of this algorithm was devising decision rules that would distinguish between the expected flow cases. Each facet's geometric orientation is evaluated and one of two fundamental flow cases is assigned. Case one has flow entering two sides of a facet and exiting one side, thus called In-In-Out or I-I-O. Case two has flow entering one side and exiting two, and is called I-O-O. Because the chance of encountering a level facet in a natural watershed is very small, this situation was ignored. Cases involving flow entering or exiting three sides of a facet are viewed as null cases in a natural watershed, since sewers and manholes do not exist.

A decision rule was developed to distinguish between the I-O-O and I-I-O cases. During creation of the TIN facets, the I node label is assigned to the one of the facet's three nodes with the highest elevation. From the I node, one moves clockwise around the facet, with the first node encountered being assigned the J node label, and the second node being assigned the K node label. The decision rule involves examining the aspects of the IJ and IK vectors. Conceptually, the facet is placed on a set of cartesian axes, with the I node positioned at the origin. Next, the aspects of the IJ vector, the IK vector, and the facet's slope aspect are drawn on the axes. Then, beginning at the IJ vector, one moves in a clockwise direction across the facet's surface. If the facet's slope aspect is encountered before the IK vector then the facet is oriented as an In-Out-Out case, as illustrated in Figure 3. If this decision rule is not met, the case is ruled an In-In-Out scenario.

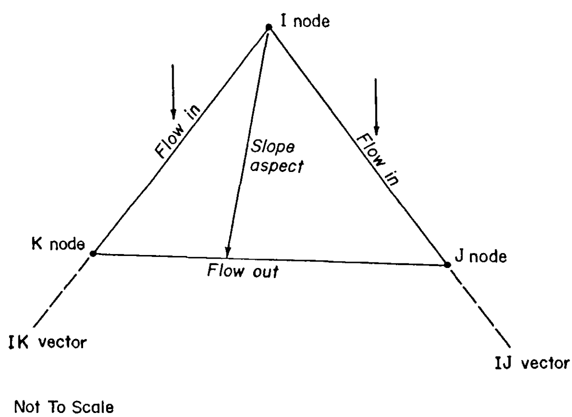


Figure 3—Schematic of typical In-In-Out flow case

To represent the flow of water across a discretized surface, it is important to route the flow accurately between adjacent TIN facets. PREPRO uses the flow case information to calculate the percentage of flow exiting from the current facet of interest to the downhill facets. This problem is simplified for the In-In-Out case since flow exits totally to one TIN facet.

For the In-Out-Out case, the slope aspect line, which defines the direction of runoff for that facet, is placed through the node with the lowest elevation. PREPRO then solves for the coordinates of the intersection point of the slope aspect and the opposite node link. The area to the left of the fall line, divided by the facet's total area, represents the percentage of that facets outflow draining to the facet opposite this JK node link. Likewise, the area on the right of the fall line divided by the total facet area represents the percentage of flow exiting to the facet opposite the KI node link, as shown in Figure 4. These neighbor relationships are easily determined from the TIN topology. Adopting the convention that inflow is positive and outflow is negative, the database is then updated with the outflow percentages so that they may be accessed later by the hydrologic model.

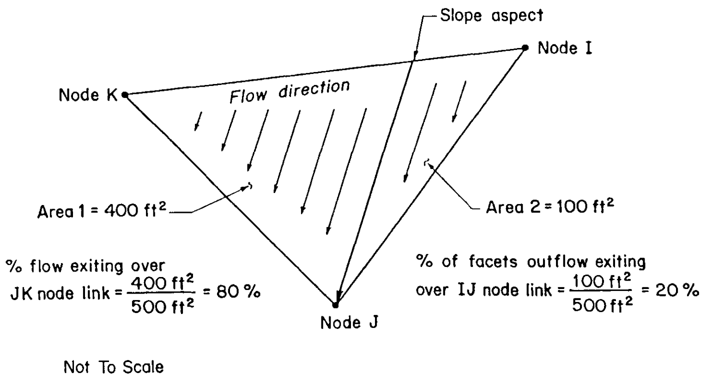


Figure 4—Schematic diagram of the routing of flows

CHECKR Algorithm

It is helpful in hydrologic modeling to know as much information about the watershed as possible. Examples of useful information are locations of stream lengths and ridge lines in the basin, since these influence the watershed's response to storm events. Also, knowing the locations of these entities would aid the user in validating the data set and in contributing to the GIS's completeness. The CHECKR algorithm used after PREPRO, is designed, using decision rules, to locate the ridge and stream lines in the watershed.

Determining the location of the stream and ridge lines in a watershed is facilitated by the nature of the TIN data structure and the information added to the database by the PREPRO algorithm. The rigid triangular structure of the TIN allows the decision rules to be simple and thus more easily coded. If the watershed were represented by a polygon structure, the location of ridge and stream lines would most likely come from another source, rather than an automated process as in the TINFLOW system.

The decision rule used to determine the location of a stream segment in the TIN involves examination of a facet's node link outflow statements. Each node link is examined, in turn, for a given facet. If the outflow statement for a given node link shows that it is not an output side for that facet, then that link is dropped from consideration as a stream segment since an inflow side cannot possibly be a stream segment. However, if that node link is an output side for that facet, then the record for the facet opposite that particular link is found through the TIN topology and brought into memory. Next, the outflow statement of the common node link is examined to determine if, for the new facet, it has also been classified as an outflow side. If the node link on the opposite facet is not an outflow side, then the flow is simply from one facet to another. But if this node link is also an outflow side , then a stream segment has been found, since two adjacent facets with a common outflow side define a stream segment. This node link's comment statement is then updated with this stream information. This process continues for each node link of each facet. After this operation is completed, sequential processing of each facet in the watershed resumes.

The decision rule used to determine the location of ridge lines in the TIN is similiar to the stream segment rule. Instead of searching for two adjacent outflow sides, however, two adjacent inflow sides are needed to classify the node link as a ridge segment. If two adjacent facets both classify the common link as an inflow side, then the flow is divided at this segment and is classified as a ridge line. This node link's comment statement is updated with this ridge information.

Because TINFLOW is a PC-based GIS, accessing random records in the relational database is the most time-consuming operation in the system. To decrease the time required to run the hydrologic model, the records in the database are put into a B-tree structure in the last step of the CHECKR algorithm. This step decreases the running time of the hydrologic model by approximately one half, even though a separate lookup file of TIN facet numbers must be accessed to tell the hydrologic model in which order the facets should be processed.

Hydrologic Processing

After the two preprocessors have prepared the database with the information and structure required by the hydrologic model, the model itself can be used. The hydrologic model component of the GIS simulates a watershed's response to storm events by modeling the two major components that contribute to storm runoff: overland flow and interflow.

Overland flow, as the name implies, is water that flows over the ground surface until it is intercepted by a stream segment. Interflow is water that infiltrates into the ground and then travels through the shallow soil layers to the stream. Ground water flow is not simulated in the model since it is generally considered to recharge the stream during periods of no precipitation, and does not usually contribute to storm runoff.

The TINFLOW system uses a finite difference solution of the St. Venant equations with a kinematic cascade approximation to simulate overland flow (Hong and Eli, 1985). For a finite difference solution to be used on a triangular element, the facet is converted during the simulation process to a rectangle with equal legnth and aspect ratios. The interflow process is modeled with the well-known Darcy's Law. The interflow model uses an expandable interflow zone, so that as the storm progresses, the wetting front of the interflow zone expands downward.

The TIN structure's capability of allowing attributes to be assigned on a facet-by-facet basis is vital to the hydrologic model. The attributes considered to have the greatest influence on simulating storm events are cover type and soil type. The cover type influences the amount of precipitation intercepted by vegetation before it reaches the ground. The soil type affects infiltration rates, roughness coefficients, and hydraulic conductivities.

The hydrologic model simulates, for an individual TIN facet, the hydrologic process for that land parcel. A hydrologic mass balance is calculated to determine if excess water is present and runoff can occur. Inputs to the mass balance are precipitation and water flowing onto the current TIN from uphill neighbor(s) through overland flow and interflow. To determine inputs, a record(s) of an uphill facet(s) is found by examining outflow percentages calculated during PREPRO. If the node link's outflow percentage is negative, flow exits over that node link. However, if the flow percentage is positive, flow enters current facet over that node link, and the uphill facet's outflow is accessed. If the current facet has two uphill neighbors contributing flow to the current facet, then the flow entering the current facet is a percentage of the outflows from the two uphill facets. Outputs include the overland flow and interflow exiting to the TIN facet downhill. The database is updated with these outputs so that they may be accessed by downgradient facets. This routing scheme requires that the processing begin with the most uphill facet in the watershed (i.e., the facet that has no uphill neighbors).

For a given time period, precipitation, if it occurs, is assumed to occur for the entire duration. After one period of precipitation has occurred, the water from that precipitation is routed through the basin by the sequential hydrologic processing of each facet. When a stream segment is encountered, as determined by CHECKR, the flow that would enter the stream is added cumulatively for the time period. The standard time period is one hour. It is assumed that, in a small watershed, any water that enters the stream during a given period will pass by the gage before the period ends.

Menu System

After the completion of a hydrologic simulation, a postprocessing menu of graphic outputs is presented to the user. Possible choices include a stream runoff hydrograph, a precipitation hyetograph or bar chart, a mass balance summary of overland flow, interflow and infiltration volumes, a cover type map, a soil type map, and a diagram of the watershed's stream network. Several of these graphics are illustrated at reduced scale in figures 5 through 7.

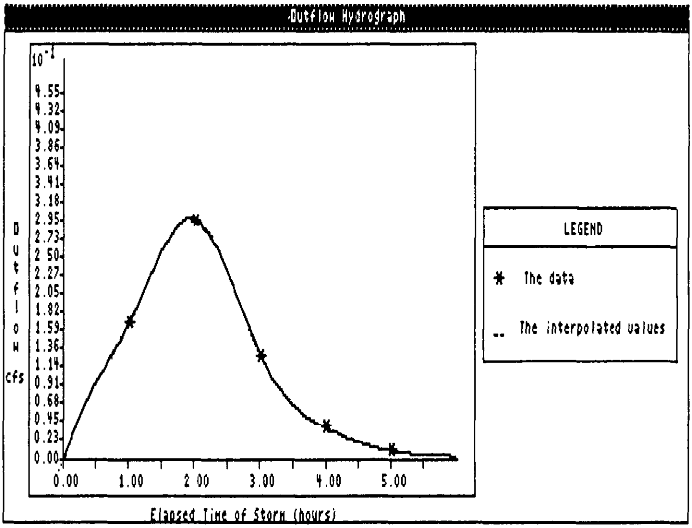


Figure 5—A runoff hydrograph

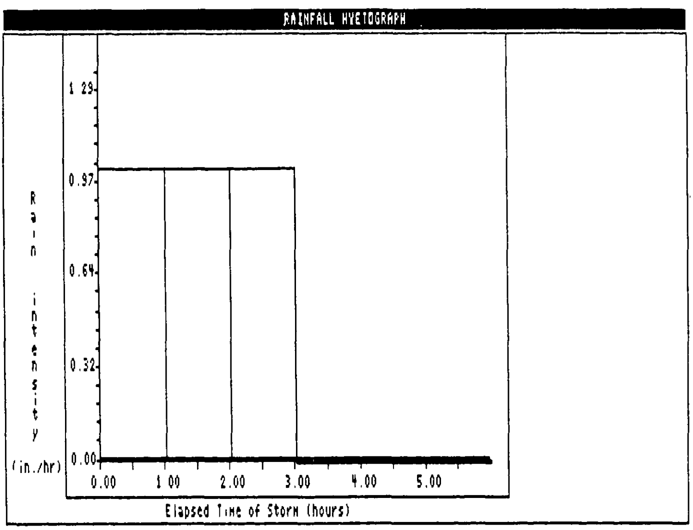


Figure 6—Precipitation hyetograph

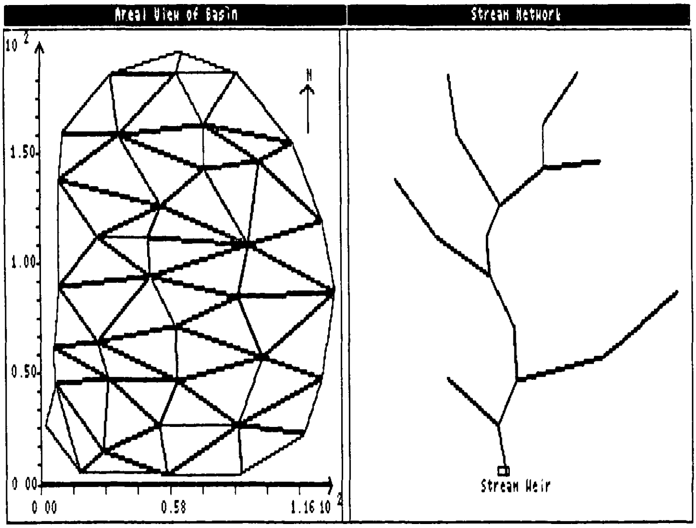


Figure 7—The watershed's stream network

CONCLUSIONS

The TINFLOW system is a functioning GIS that performs hydrologi c simulations on a personal computer. It has been tested on a synthetic watershed has yielded suitable results.

To improve the system, several avenues should be pursued. First, several of the assumptions made on the hydraulics of the hydrologic model should be examined and improved upon. Second, the quality of the outputs are limited primarily by the resolution of the PC graphics. The TURBO Pascal Graphics Toolbox used in the system supports a resolution of 640 x 200 pixels. Converting the system to a mainframe environment would allow faster processing times and provide the user with higher resolution screens on which to display graphic output. Third, the TINFLOW system's method of discretizing a watershed using the TIN should enable hydrologic simulations to be capable of predicting the change in a stream's runoff patterns caused by a change in a watershed. Demonstrating, on a real watershed, that the TINFLOW model could simulate a stream's storm hydrograph under natural conditions would be a large step forward for hydrologic modeling.

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