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16. Abstract

The design of highway drainage facilities involves a hydrologic analysis to determine the design discharge, as well as a hydraulic analysis of the conveyance capacity of the facility. In this report, we present a geographic information system (GIS) for the development of hydrologic data for the design of highway drainage structures. This GIS has been developed to reduce the analysis time and to improve its accuracy by integrating spatial data describing the watershed through hydrologic theory.

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GEOGRAPHIC INFORMATION SYSTEM FOR HYDROLOGIC DATA DEVELOPMENT FOR DESIGN OF HIGHWAY DRAINAGE FACILITIES

by
Francisco Olivera, Juling Bao, and David Maidment

Research Report Number 1738-3

Research Project 0-1738
System of GIS-Based Hydrologic and Hydraulic
Applications for Highway Engineering

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION
in cooperation with
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SUMMARY

The design of highway drainage facilities involves a hydrologic analysis to determine the design discharge, as well as a hydraulic analysis of the conveyance capacity of the facility. In this report, a geographic information system (GIS) for the development of hydrologic data for the design of highway drainage structures is presented. This GIS has been developed to reduce the analysis time and to improve its accuracy by integrating spatial data describing the watershed through hydrologic theory.

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David Maidment, P.E. (Texas No. 53819)
Research Supervisor

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GEOGRAPHIC INFORMATION SYSTEM FOR HYDROLOGIC DATA DEVELOPMENT FOR DESIGN OF HIGHWAY DRAINAGE FACILITIES

1. INTRODUCTION

The design and construction of highway drainage facilities — storm drains, highway culverts, bridges, and water quality and quantity control structures — represent between 25% and 50% of the total cost of most highway projects. The design of these facilities involves a hydrologic analysis to determine the design discharge, as well as a hydraulic analysis of the conveyance capacity of the facility. In this report, we present a geographic information system (GIS) for the design of drainage facilities, developed to reduce the analysis time and to improve its accuracy by integrating spatial data describing the watershed with hydrologic theory. At present, the Texas Department of Transportation (TxDOT) has existing procedures for hydrologic and hydraulic analysis in the Texas Hydraulic System (THYSYS), with each application requiring the computerization of the description of the watershed and the stream channel using data extracted manually from maps and cross sections contained in paper drawings. By building a hydrologic spatial database of Texas, and by then developing a GIS that operates off this database, TxDOT could more efficiently extract data relevant to the design and construction of drainage facilities.

In a relatively short time, geographic information systems have gained fairly widespread use in a variety of engineering applications. Originally envisioned (and used) as a geographic mapper with integrated spatial database, these systems are increasingly being used in modeling applications, where geographic data can be readily accessed, processed, and displayed. Even though GIS has been implemented mostly by large entities (e.g., federal, state, and local government agencies) predominantly for mapping and managing spatial data, there is increasing interest in the potential application of GIS in engineering design and analysis, especially in hydrology and hydraulics.

This report describes a grid-based GIS developed to estimate potential extreme peak discharges (Asquith and Slade 1995), watershed parameters, peak discharges for different frequencies (Asquith and Slade 1997), isochrone lines, and runoff curve numbers.

2. PREVIOUS WORK

Because GIS is not yet widely used for hydrologic modeling, the practicing engineering community has had only limited exposure to this technology. This fact was verified by a survey, developed as part of Smith's master project (1995), sent out to the fifty state highway agencies to assess the current use (state of the practice) and expected use of GIS for hydraulics-related highway work. From the thirty-two responses received, it became evident that those state highway agencies that have implemented GIS (ten states) are using it for mapping and data management only. Most of them recognize the potential of GIS for engineering analysis, but only the state of Maryland has implemented a system (i.e., GISHYDRO) that supports hydrologic analysis (Ragan 1991).

Raster-based GIS appears to be a suitable tool for hydrologic modeling, mainly because "raster systems have been used for digital image processing for decades and a mature understanding and technology has been created for that task" (Maidment 1992). Grid systems have proven to be ideal for modeling topographically driven flow, given that a characteristic of this type of flow is that flow directions do not depend on any time-dependent variables (e.g., flow or water depth). This characteristic is what makes topographically driven flow so suitable for modeling in a raster environment; consequently, grid systems include hydrologic functions as part of their capabilities. At present, hydrologic functions, available in raster GIS software, allow one to determine flow direction and drainage area at any location, stream networks, watershed delineation, etc. (Maidment 1992). Jensen and Domingue (1988) and Jensen (1991) outlined a grid scheme to delineate watershed boundaries to previously defined outfalls (pour points) and stream networks. The scheme uses digital elevation data to determine the hypothetical direction of flow from each cell in a grid to one of its eight neighboring cells according to the path of the steepest descent (i.e., each cell of the watershed is connected to the lowest of its neighbor cells). The cells contributing flow to the pour point can be counted, representing area, and the cells having no contributing flow define drainage boundaries. Cells having a flow accumulation in excess of a threshold establish stream network cells.

Although most hydrologic and hydraulic calculation procedures are now available in computer programs, the use of which has significantly reduced the mathematical effort involved, a substantial effort is still necessary to establish and manipulate the data required for input into those programs. In trying to simplify the process of determining these input data, the departments of transportation in Maryland and Texas have developed a GIS that calculates spatial hydrologic parameters that can then be used by standard hydrologic software packages.

GISHYDRO, a GIS structured for hydrologic analysis, was developed and installed in the Maryland State Highway Administration's (MSHA) Division of Bridge Design in Baltimore in 1991 (Ragan 1991). The objective of GISHYDRO is to improve the efficiency and quality of hydraulic design by allowing the user to quickly assemble the land use, soil, and slope data for any watershed in the state, and then create the necessary interfaces to define the required input parameters and run the SCS TR-20 hydrologic model for existing or proposed watershed conditions. A digitizer is used to delineate watershed and subwatershed boundaries, define details of the stream, swale and overland flow paths, and enter areas proposed for land-use change. GISHYDRO then sets up the files for entry into the Soil Conservation Service's TR-20 computer program, so the model can be run for existing or proposed conditions. The same files are used to run a nonpoint-source pollution model that estimates BOD, nitrate, phosphate, and other loadings in terms of the watershed land use and soil types.

The Hydrologic Data Development System (HDDS), developed by Smith (1995), is a prototype system intended to demonstrate the potential for using GIS for highway-based hydrologic data development and analysis. Smith's system employs data that are now widely available or will become more prevalent. The focus of HDDS is on the development of an integrated set of Arc/Info programs and associated data. Although the HDDS programming is specific to Arc/Info, the data are transferable and the general methodology should be applicable to any GIS package that has similar capabilities. The system provides the user with the capability of establishing some of the most important hydrologic parameters used in hydrologic analysis methods, including the drainage basin boundaries, areas and subareas, the maximum flow-path length, the estimated travel time, the watershed average slope, the hydrologic soil group, the design rainfall, the weighted runoff coefficients, and other hydrologic parameters of a catchment defined by a highway/stream crossing. The resulting data may be passed automatically from HDDS to the TxDOT Hydrologic and Hydraulic System (THYSYS) to calculate the relationships between design floods and their frequency, and then be manipulated to create drainage area maps, tables, and other documentation.

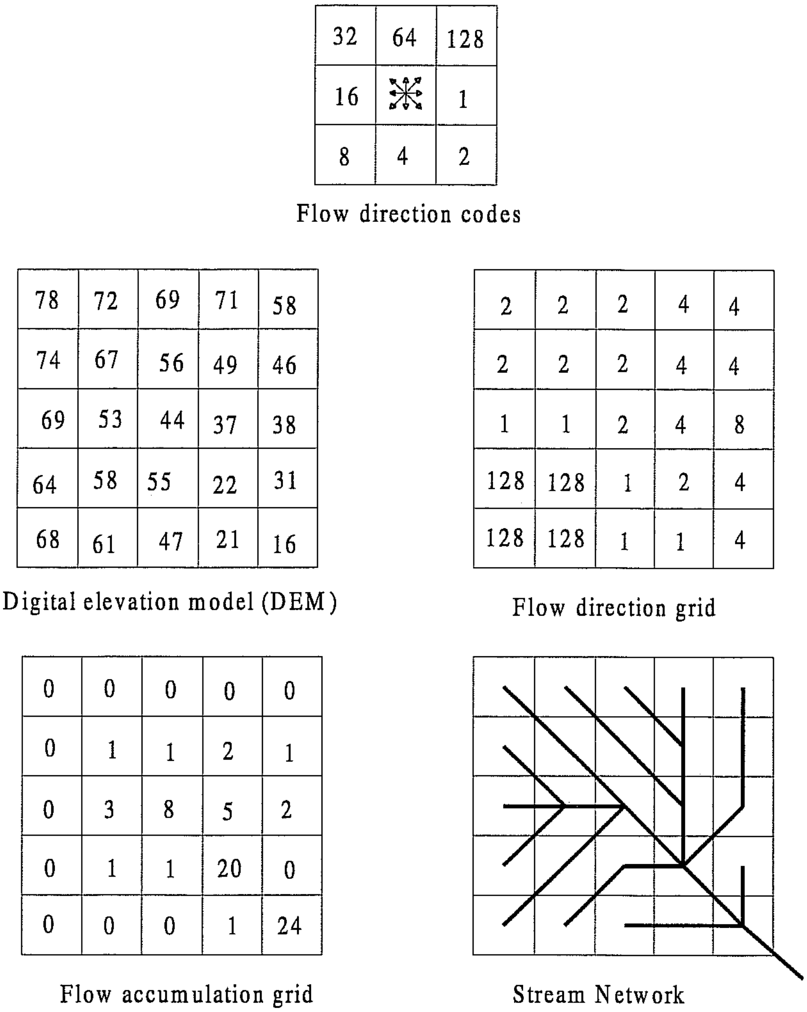
3. METHODOLOGY

The GIS presented in this report is a raster-based model that analyzes the watershed and calculates some of the necessary hydrologic data for designing highway drainage facilities, considering the spatial variability of the terrain. A raster data structure, also called a *grid,* is a discrete representation of the terrain based on identical square cells arranged in rows and columns. Grids are used to describe spatially distributed terrain parameters (i.e., elevation, land use, impervious cover, etc.), and one grid is necessary for representing each parameter. The density of the grid cells should be such as to render a continuous character of the terrain.

3.1 Spatial Data of Texas Used for Developing and Testing the GIS

Studying the hydrology of the state of Texas requires consideration of the entire drainage area of the Gulf of Mexico from the Sabine River on the Texas-Louisiana border to the Rio Grande on the Texas-Mexico border. Spatial data of Texas were obtained from different sources and processed in different forms, as explained below. To assemble a consistent data set, all spatial data were projected into Albers Projection and raster data were defined with a cell size equal to 500 m (547 yds).

Starting from the digital elevation model (DEM), hydrologic features of the terrain (i.e., flow direction, flow accumulation, flow length, stream network, and drainage areas) can be determined using standard functions included in commercially available GIS software that operates on raster terrain data (see Figure 1). The topography of the study area is described by the U.S. 15-minute DEM, and by the North America 30-minute DEM for the northern part of Mexico. In order to delineate accurate streams, the DEM was modified by *burning in* the digitized streams, a process that uses an algorithm to add a constant number to the DEM value in all cells except those that coincide with the observed streams. Instead of forcing the water to flow toward the streams, this process forces the water to remain in the streams once it gets there. The burning in of the streams has proved to be an efficient way to alter the DEM in such a way that produces delineated streams that match the digitized ones. The digitized stream network used for burning in was taken from the EPA's River Reach File RF1. Next, the DEM was filled to eliminate spurious terrain pits, the flow direction of each cell was determined, and, finally, the drainage area of each cell (in units of grid cells) was calculated.



32	64	128
16	✳	1
8	4	2

Flow direction codes

78	72	69	71	58
74	67	56	49	46
69	53	44	37	38
64	58	55	22	31
68	61	47	21	16

Digital elevation model (DEM)

2	2	2	4	4
2	2	2	4	4
1	1	2	4	8
128	128	1	2	4
128	128	1	1	4

Flow direction grid

0	0	0	0	0
0	1	1	2	1
0	3	8	5	2
0	1	1	20	0
0	0	0	1	24

Flow accumulation grid

Stream Network

Figure 1: Hydrologic functions available in raster GIS software.

The grid of hydrologic regions was produced by rasterizing the polygon coverage of hydrologic regions developed by the USGS. The runoff curve number grid was obtained using the USGS land-use/land-cover coverage, STATSGO soil data, and a look-up table developed by Smith (1995) that relates land use and percentage of hydrologic soil type to curve number. Scanned USGS maps of Texas, at a scale of 1:2,000,000, were used as background.

3.2 GIS for Determining Potential Extreme Peak Discharges

The *potential extreme peak discharge* is an estimate of the highest peak discharge expected to occur at a certain location. Following the methodology presented by Asquith and Slade (1995), a grid of potential extreme peak discharges in Texas, with a resolution of 500 m by 500 m (547 yds by 547 yds), has been prepared. According to Asquith and Slade, documented extreme peak discharges better correlate with the contributing drainage area and hydrologic region than with any other watershed characteristic, such as channel length or slope; therefore, the other characteristics were not used for estimating potential extreme peak discharges. The authors, though, do not mention in their report other physical characteristics of the watershed, such as land use, soil type, or geology that might affect how storm runoff is routed through the terrain. Potential extreme peak discharges are greater than the 100-year peak discharges, already available from other USGS studies and — as an average — are 74% of the probable maximum flood peak discharge, calculated based on probable maximum precipitation (PMP).

Developing a grid of potential extreme peak discharges requires three processes: (1) determining the mathematical equations that relate potential extreme peak discharge with drainage area for each hydrologic region, (2) developing a drainage area grid and a flood region grid, and (3) calculating a grid of potential extreme peak discharges by applying the equations of (1) to the grids of (2). A brief discussion of each part of the methodology is included below.

Documented extreme peak discharges for a total of 619 sites with streamflow-gauging stations and 213 sites without streamflow-gauging stations in natural basins were collected. For each site, the following information was provided: USGS station number and name or stream name and approximate location, hydrologic region number, latitude, longitude, drainage area, documented extreme peak discharge, and date of occurrence.

Estimating the potential extreme peak discharge as a function of drainage area and hydrologic region consists of plotting in a chart documented peak discharges vs. drainage area for all the stations of a hydrologic region, and drawing an envelope curve above all the observed values. Stations as far away as 40 km (24.85 miles) from the region border were also considered in the plot. One envelope curve was developed for each hydrologic region and a set of mathematical equations was defined to describe each curve.

The equations determined with this methodology apply to natural basins for which the peak discharges are not effected by regulation, reservoirs, diversions, urbanization, or other human-related activities; they should not, therefore, be applied downstream of nearby reservoirs and cities.

Finally, the drainage area grid (in units of grid cells) mentioned above was multiplied by the grid cell area (0.25 sq. km [0.0965 sq. miles]) to produce a drainage area grid in square miles. This methodology to calculate the drainage area better suits large watersheds in which the absolute errors tend to offset each other and where the relative errors tend to be small. As a rule of thumb, a minimum drainage area of 100 cells is recommended. This implies that drainage areas of 25.9 sq. km (10 sq. miles) or less would be considered inaccurate.

The grid of potential extreme peak discharges was created with a set of condition statements that, for each grid cell, evaluated the drainage area number and the hydrologic region, and then applied the corresponding equation to calculate the potential extreme peak discharge.

The resulting product of this work is a grid of potential extreme peak discharges that can be displayed and queried with commercially available raster GIS software. To determine the discharge at any specific point, the user clicks on the point of the display (map) and reads the discharge value in the query window.

3.3 GIS for Determining Watershed Parameters, Peak Discharges, Isochrone Lines, and Runoff Curve Numbers

A GIS has been developed to calculate watershed parameters, peak discharges, isochrone lines, and runoff curve numbers. The watershed parameters calculated are area, length of longest flow path, slope of longest flow path, shape factor, and average curve number. Peak discharges are calculated for different return periods (2, 5, 10, 25, 50, and 100 years) according to Asquith and Slade (1997) and the TxDOT Statewide Regional Rural Regression Equations. Isochrone lines are determined as the contour lines of a 3-D surface of flow times to the watershed outlet, according to a velocity field defined by the user. Runoff curve numbers are calculated from user-defined land-use data, STATSGO soil data, and a look-up table that relates land use and percentage of hydrologic soil type with curve number.

The GIS has been developed independent of specific spatial data sets; consequently, it can be applied to other regions — provided that the required spatial database is prepared. However, changes in some of the programs (associated with the horizontal and vertical units [meters or feet] of the spatial data and with the cell size of the raster data) might be necessary. Likewise, redefinition of the peak discharge equations according to the study site should be applied. All these changes are minor modifications and should by no means be interpreted as a limitation in the applicability of the system.

Determining Watershed Parameters

For determining the watershed parameters, the GIS requires the following input data: DEM, (burned-in and) filled DEM, flow-direction grid, flow-accumulation grid, upstream flow-length grid, downstream flow-length grid, and runoff curve number grid. All these data, with the exception of the runoff curve number grid, can be computed from the DEM. The runoff curve number grid, in turn, can be computed by the GIS, if not available from a different source.

For a location selected by the user clicking the mouse, the GIS delineates the watershed and creates that watershed's polygon coverage. The watershed area is calculated as the flow-accumulation value at the outlet (selected point) multiplied by the cell area. The longest flow path, identified as the set of cells of the watershed for which the sum of the upstream flow length plus the downstream flow length is a maximum (Smith 1995), is stored by the system as a separate grid. The length of the longest flow path is equal to the maximum value of the sum of the upstream flow length plus the downstream flow length (used before to identify the longest flow path). The slope of the longest flow path is determined as the elevation drop between two points of the longest flow path, divided by the flow distance between those two points. Because the channel slope is defined as the slope of an arbitrarily bound channel segment, the points can be located at any user-defined distance from the watershed outlet, expressed as a percentage of the length of the longest flow path. For instance, percentages of 10% and 85% refer to that 75% portion of the channel located 10% of the channel length upstream of the watershed outlet. The watershed shape factor is calculated as the square of the length of the longest flow path divided by the watershed area. The shape factor is an indirect way of measuring the length/width ratio of the watershed. Long and narrow watersheds tend to have high shape factors, while short and wide ones have low shape factors. The average curve number of the watershed is calculated as the average of the curve numbers within the watershed polygon.

Determining Peak Discharges

Asquith and Slade (1997), in cooperation with TxDOT, have prepared regional equations to calculate peak discharges in natural basins in Texas in terms of drainage area, shape factor, and channel slope. Similar equations, for the entire U.S., were proposed by Asquith and Slade (1994) in cooperation with the Federal Highway Administration and the Federal Emergency Management Agency. As mentioned above, minor changes in the programs would be necessary before applying the system to other regions of the country.

According to Asquith and Slade (1997), peak discharges are expressed as:

$$Q = a\, A^{b}\, SH^{c}\, SL^{d}$$

where Q is the peak discharge, A is the drainage area, SH is the shape factor, SL is the channel slope, and a, b, c, and d are parameters that depend on the return period and hydrologic region.

The drainage area, shape factor, and channel slope are calculated as part of the watershed parameter determination explained above. The parameters a, b, c, and d are taken from the USGS (1997) regional equations.

Determining Isochrone Lines

Isochrone lines are a basic concept for modeling watershed responses when the spatial variability of the hydrologic system matters. Isochrone lines are the contour lines of a 3-D surface that represent the flow time to the watershed outlet as a function of location. Flow time to the outlet is the sum of the time spent by a water particle in the cells of the flow path, and is calculated as a weighted flow length. The weighted flow-length function — available in raster GIS software — multiplies the flow length in each cell by a weight, so that, if the weight is the inverse of the flow velocity, the flow-length function results in flow time. Therefore, before determining isochrone lines, a velocity field must be defined. According to Maidment et al. (1996), the flow velocity is equal to:

$$v = p\, A^{q}\, S^{r}$$

where v is the flow velocity, A is the drainage area, S is the terrain slope, and p, q, and r are parameters that depend on the watershed. It has been observed that values of q and r of 0.5 give reasonable results, provided that maximum and minimum velocities are established.

After prompting the user to input the parameters p, q, and r, and the minimum and maximum flow velocities, the GIS calculates a flow-velocity grid and, next, a flow-time grid from which the isochrone lines can be determined.

Determining Runoff Curve Numbers

The Soil Conservation Service's (1972) method for calculating abstractions is based on the runoff curve number CN, a parameter that represents the capacity of the terrain to produce runoff. Although a simple model, the curve number method has become widely used, for it allows one to estimate abstractions with relatively few data. Runoff curve numbers depend on land use and soil properties.

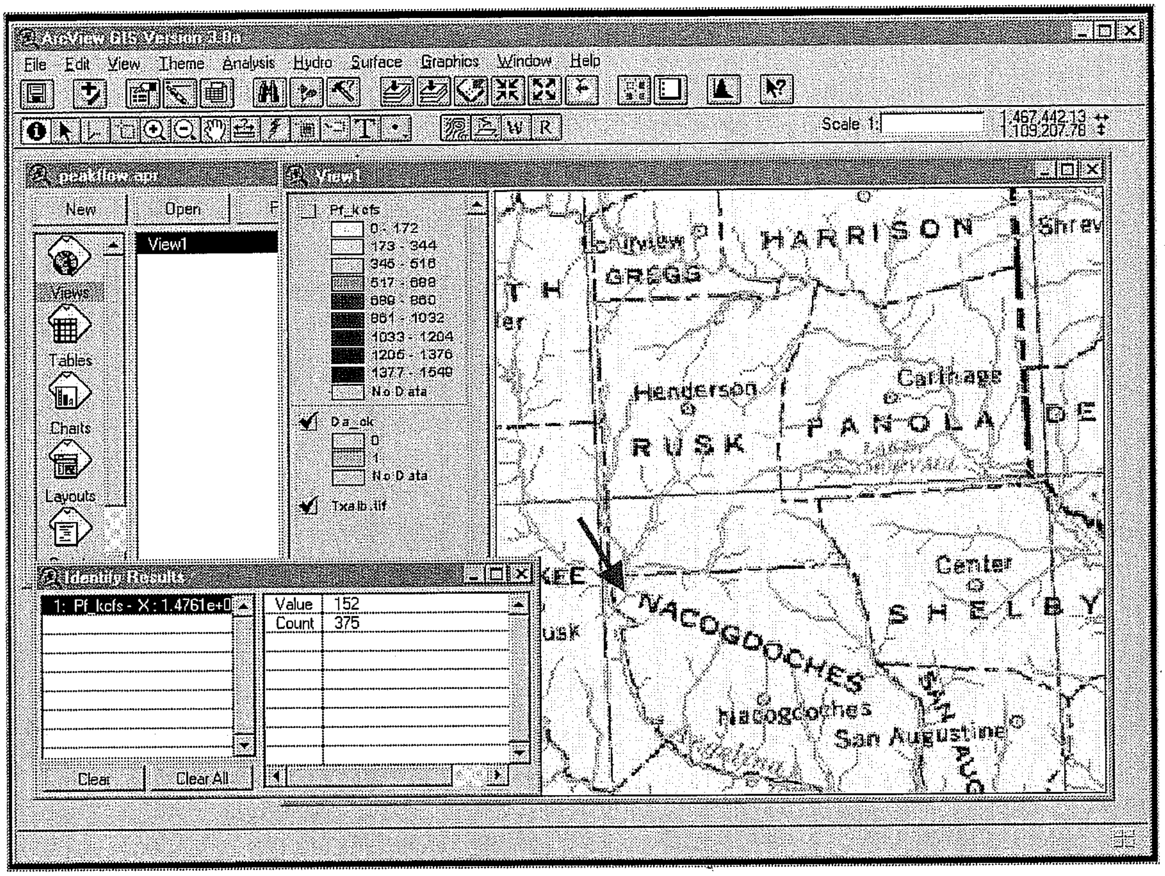
A script to calculate runoff curve numbers using land-use data, hydrologic soil type data, and a look-up table that relates curve number with land use and hydrologic soil type (Smith 1995) as inputs, was developed. This script produces a grid of curve numbers for an area, and with a resolution, defined by the user.

4. APPLICATION

Computation of hydrologic parameters of the watershed becomes much faster and accurate when using a GIS developed for that specific purpose.

4.1 GIS for Determining Potential Extreme Peak Discharges

Without using a GIS, determination of potential extreme peak discharges would require manually delineating the watershed from topographic maps before applying the corresponding peak discharge equations. Because the watershed delineation has been automated, peak discharges can be calculated by clicking the point of interest in the screen (map). Figure 2 shows the resulting screen after applying the GIS to a tributary of the Angelina River in Nacogdoches County, Texas. The arrow in the map points to the location at which the peak discharge has been calculated, while the "Identify Results" window indicates a value of 152 (in thousands of cubic feet per second) for the potential extreme peak discharge. Results can be obtained almost instantaneously because, as explained above, the discharges have all been precomputed.



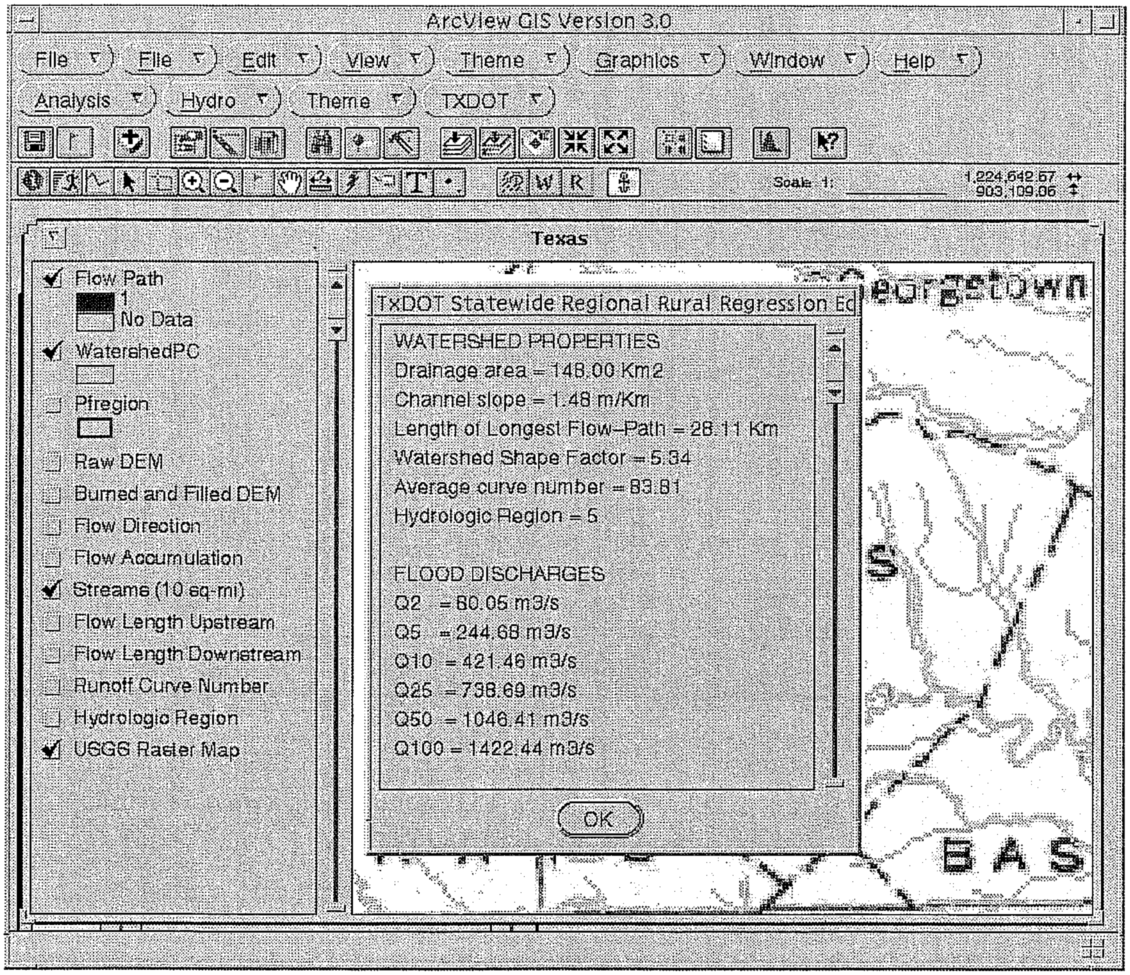
1: Pf_kcfs - X: 1.4761e+0

Value	152
Count	375

Figure 2: Potential extreme peak discharge for a tributary of the Angelina River in Nacogdoches County, Texas. The value 152 in the *Identify Results* window stands for a discharge of 152,000 cfs.

4.2 GIS for Determining Watershed Parameters, Peak Discharges, Isochrone Lines, and Runoff Curve Numbers

Determination of the watershed parameters and peak discharges with the GIS consists of clicking the point on the screen corresponding to the watershed outlet. Figure 3 presents the message box prepared by the program after applying the GIS to Walnut Creek, a tributary of the Colorado River in Travis County, Texas. For this case a drainage area of 148 km^2, channel slope of 1.48 m/km, length of longest flow path of 28.11 km, and shape factor of 5.34 was calculated. An average curve number value of 84, according to the precomputed curve number grid, was also determined. This curve number is a very conservative value used for a worst-case scenario. Additionally, Figure 4 shows the delineated watershed and the longest flow path, such that not only are the watershed parameters calculated but also the watershed's shape and location.

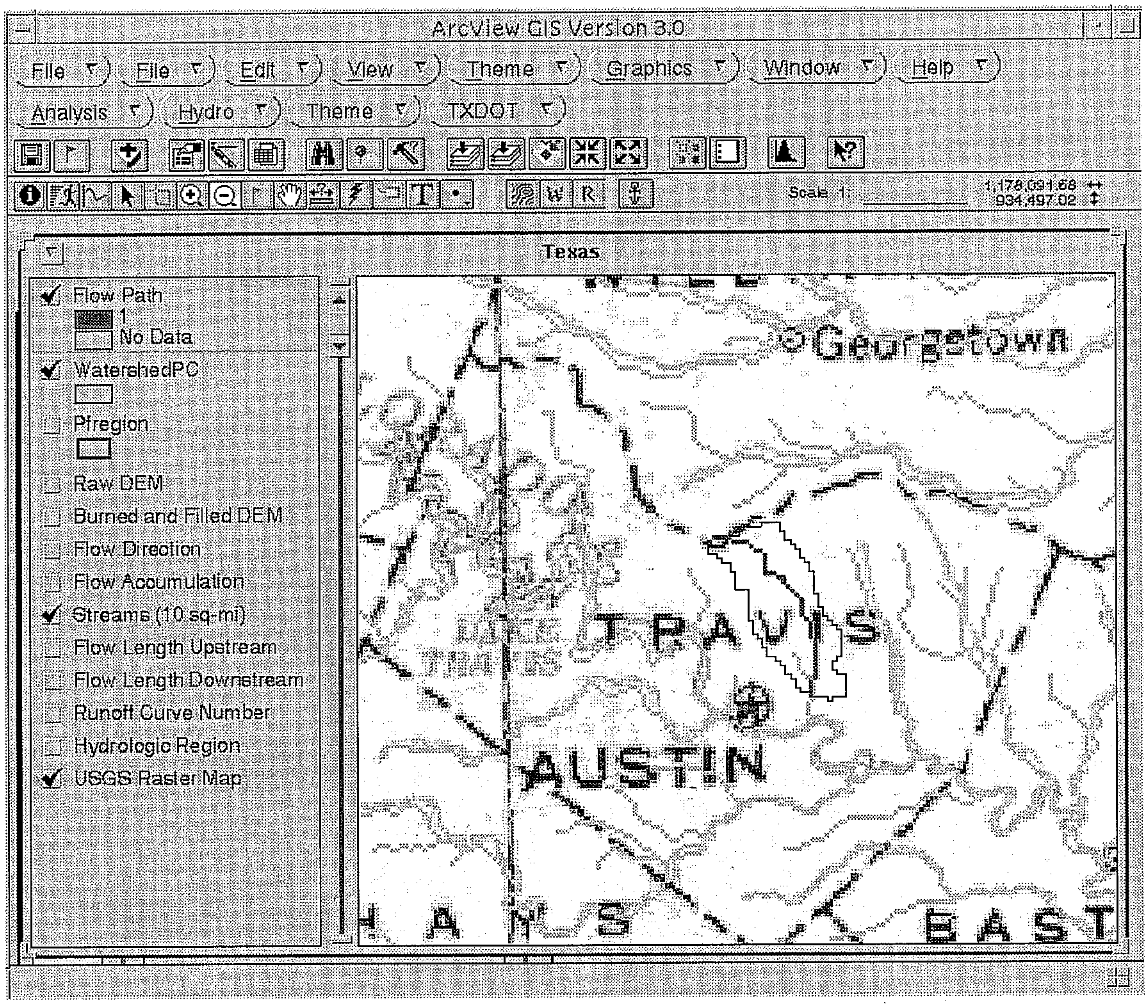


```
WATERSHED PROPERTIES
Drainage area = 148.00 Km2
Channel slope = 1.48 m/Km
Length of Longest Flow-Path = 28.11 Km
Watershed Shape Factor = 5.34
Average curve number = 83.81
Hydrologic Region = 5

FLOOD DISCHARGES
Q2   = 80.05 m3/s
Q5   = 244.68 m3/s
Q10  = 421.46 m3/s
Q25  = 738.69 m3/s
Q50  = 1046.41 m3/s
Q100 = 1422.44 m3/s
```

Figure 3: Watershed parameters and peak discharges for the Walnut Creek drainage area in Travis County, Texas

Calculation of the isochrone lines consists of defining a velocity field and, next, a flow-time grid. Figure 5 presents the velocity field for Barton Creek, a tributary of the Colorado River in Travis County, Texas. The flow velocity was defined as v = 2 $S^{0.5}$ $A^{0.5}$ (v in m/s and A in km^2) with maximum and minimum values of 10 m/s and 0.1 m/s, though further calibration of the model is necessary. It can be seen that, as expected, the main channel has higher velocity, while sheet flow is relatively slow compared even with small creeks. Figure 6 shows the distribution of the flow time to the outlet, in which changes in color represent isochrone lines. It can be seen that those cells that are close to the outlet or to the streams have shorter flow time, while those areas that undergo sheet flow for a long distance tend to have longer flow time.



☑ Flow Path
▨ 1
☐ No Data
☑ WatershedPC
☐ Pfregion
☐ Raw DEM
☐ Burned and Filled DEM
☐ Flow Direction
☐ Flow Accumulation
☑ Streams (10 sq-mi)
☐ Flow Length Upstream
☐ Flow Length Downstream
☐ Runoff Curve Number
☐ Hydrologic Region
☑ USGS Raster Map

Figure 4: Watershed and longest flow path for the Walnut Creek drainage area in Travis County, Texas.

Figure 7 presents the runoff curve number grid calculated for the Barton Creek area. This option of the GIS allows the user to define a curve number grid different from the precomputed one (i.e., when the user has detailed land use and soils data for the specific area of interest).

5. CONCLUSIONS

Because of the possibility of developing GIS tools for automated hydrologic analysis, and of the availability of digital elevation data at different scales for different parts of the country, GIS appears to be an excellent environment for developing hydrologic planning and management.

The GIS presented in this paper consists of two components: a spatial database of the state of Texas, and a set of consistent programs for hydrologic analysis. Although the programs operate off the database, they are not bound to it and can be applied to any other spatial database. Such capability suggests that an effort should made to develop data-independent tools that can be applied nationwide and that can operate with the more precise spatial data that will be developed in the future.

The GIS for determining watershed parameters, peak discharges, isochrone lines, and runoff curve numbers is a data developer for hydrologic analysis using standard hydrologic software (HEC1, TR20, and others). It is intended to facilitate the always time-consuming operation of obtaining watershed parameters from paper maps. An automated connection between the GIS and the already-available hydrologic software could be a topic for further research, but steps have been taken toward a fully computer-based hydrologic analysis of the watershed.

The GIS for determining potential extreme peak discharges is a powerful tool for estimating worst-case scenario design flows for highway hydraulic structures. This grid tends to overestimate flows, since some watershed characteristics, such as land use, soil type, or geology, have been ignored. Also not considered is the effect of reservoirs and cities on the downstream water bodies.

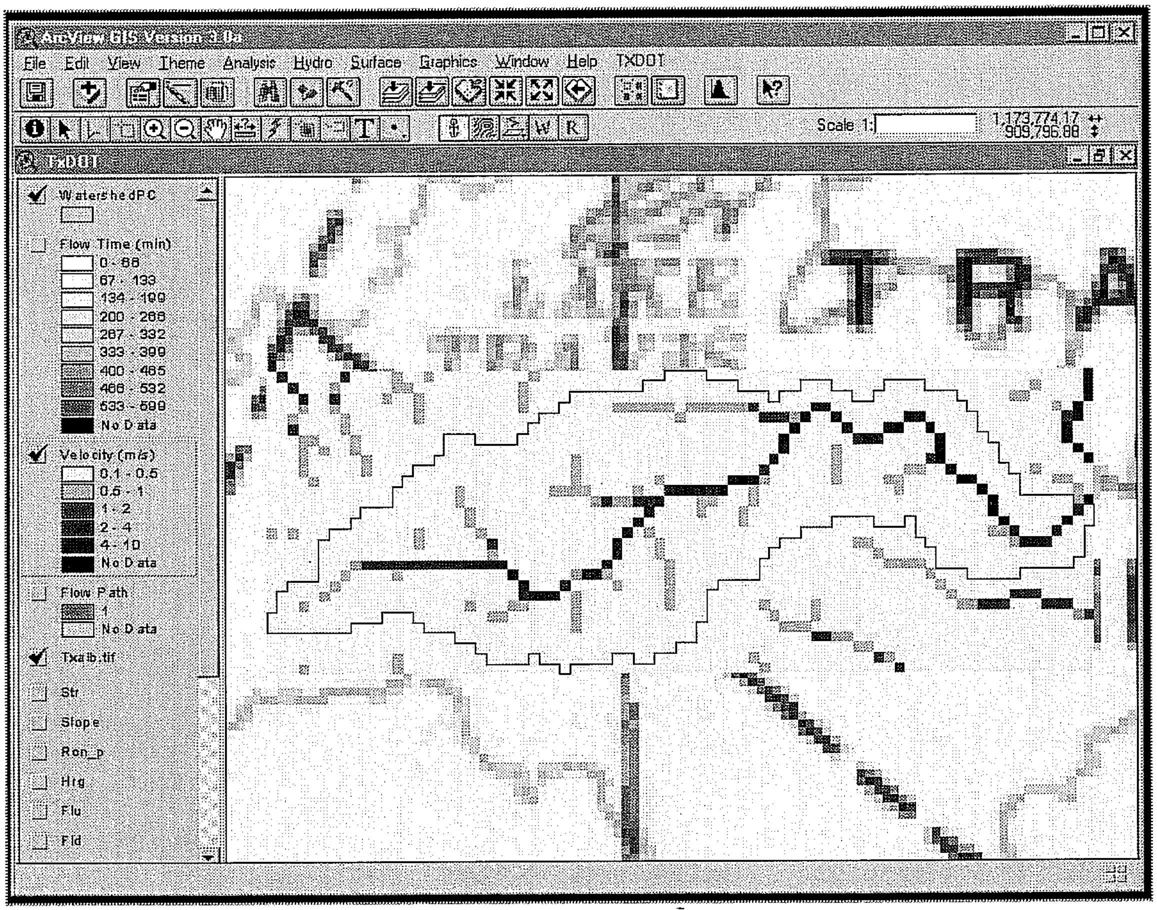


Figure 5: Flow velocity grid for the Barton Creek drainage area in Travis County, Texas. Note that the velocity is higher in the main channel than in the small creeks, and that sheet flow is relatively slow.

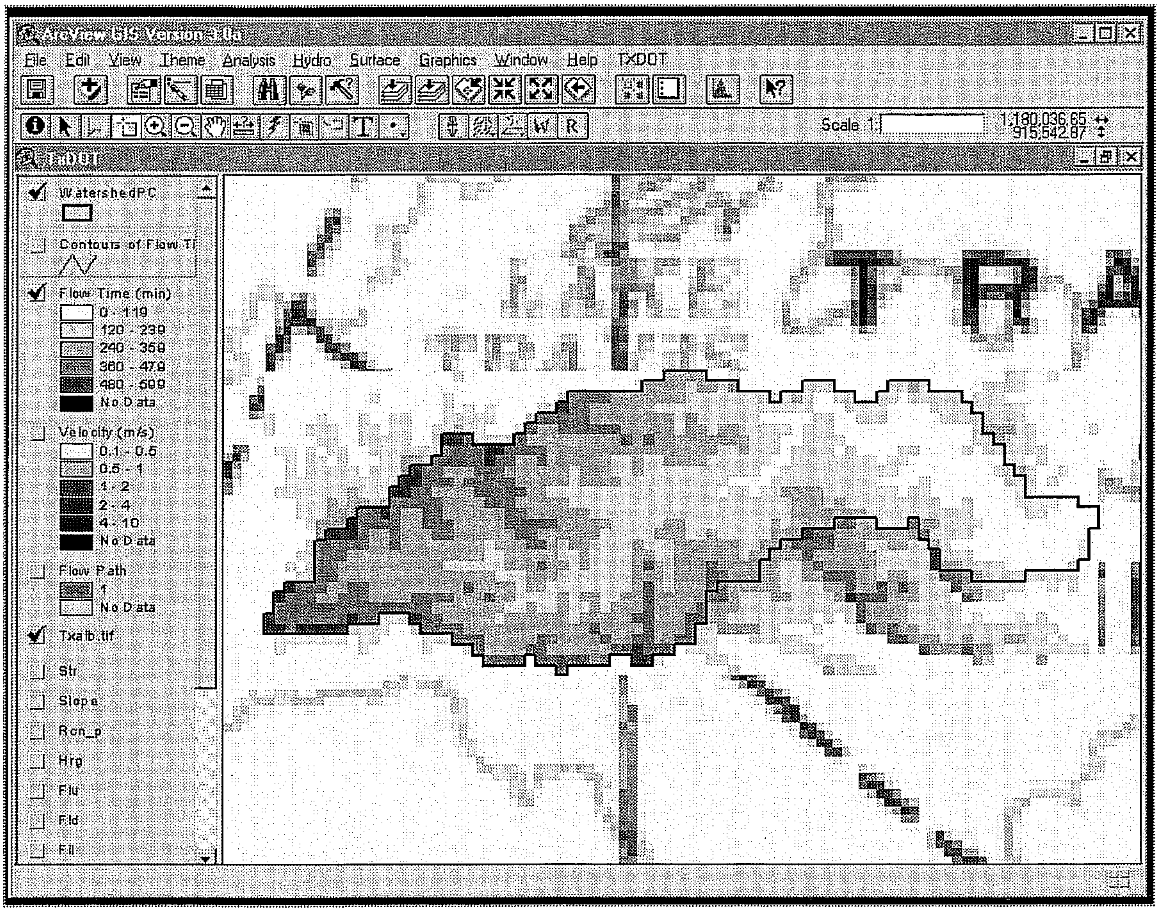


Figure 6: Flow-time grid for the Barton Creek drainage area in Travis County, Texas. Changes in color within the watershed correspond to isochrone lines.

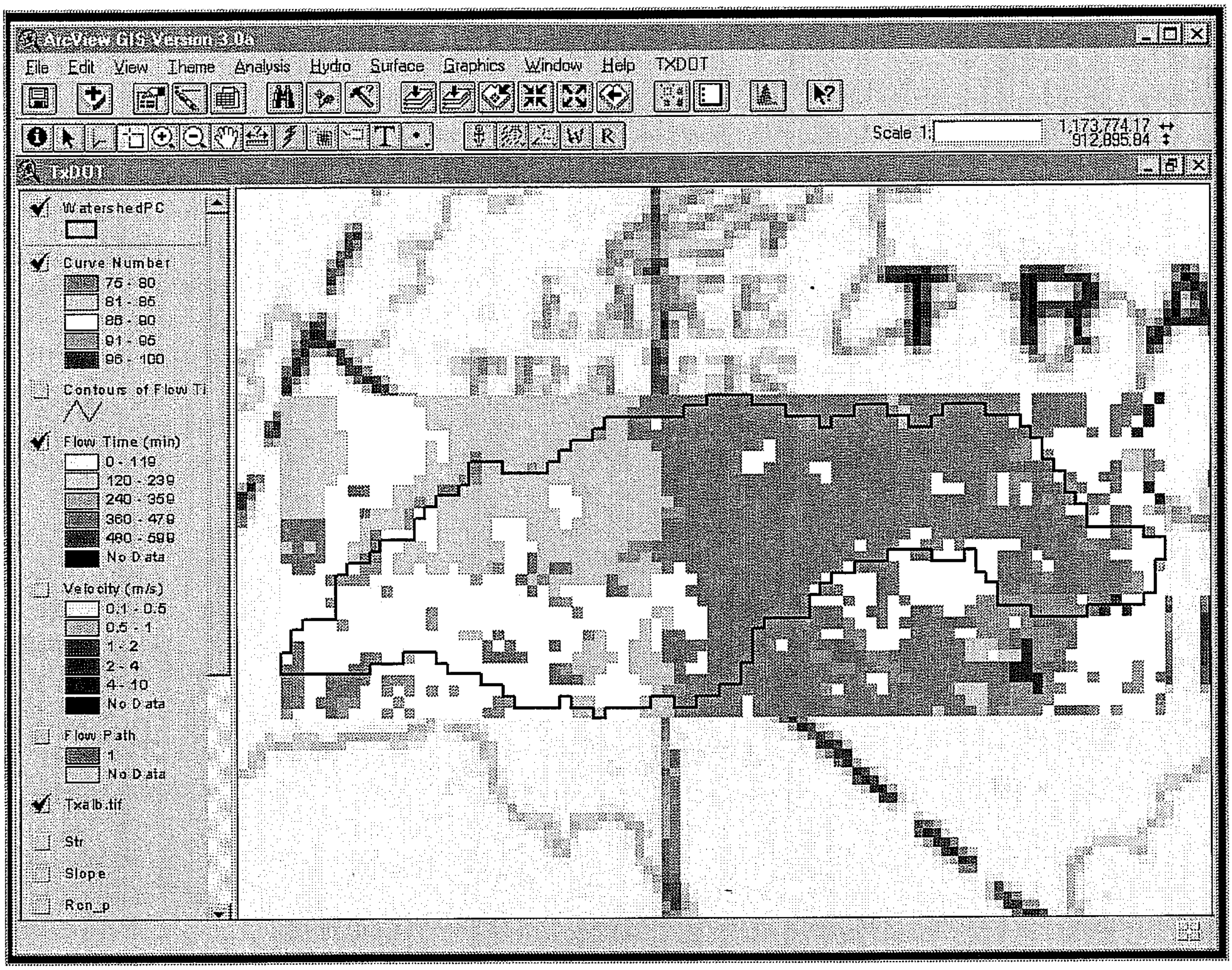


Figure 7: Runoff curve number grid for the Barton Creek drainage area in Travis County, Texas.

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