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GIS-BASED SYSTEM OF HYDROLOGIC AND HYDRAULIC APPLICATIONS FOR HIGHWAY ENGINEERING

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16. Abstract

A significant portion of the cost of most highway projects can be attributed to the design and construction of such drainage facilities as bridges, highway culverts, storm drains, and water quality and quantity control structures. At the minimum, the design of these facilities involves hydrologic analyses to determine the design discharge and hydraulic analyses to determine the conveyance capacity of the facility. Although most hydrologic and hydraulic calculation procedures are now available as computer programs — programs that can significantly reduce the mathematical effort involved — substantial effort is still necessary to establish and manipulate the data required for input into those programs. To simplify the process of determining the input data, several state departments of transportation are developing geographic information systems (GIS) to calculate spatial hydrologic parameters that can then be used as input values to standard hydrologic software packages.

The hydrologic software package currently utilized by the Texas Department of Transportation (TxDOT) is the Texas Hydraulic System (THYSYS). This program is comprised of applications that perform hydrologic and hydraulic analyses based on descriptions of the watershed and/or the stream channel of interest. Traditionally, the data generated to support these programs have been extracted manually from maps and cross sections presented on paper drawings. However, by building a digital spatial database of the hydrologic features of Texas, and developing a GIS that operates in conjunction with this database, the extraction of data and application of the design procedures becomes automated and more efficient.

In this research project, a GIS has been developed to assist in the design of highway drainage facilities by utilizing hydrologic spatial data to calculate the input parameters for standard hydrologic software packages. This GIS reduces the analysis time and improves the analysis accuracy by integrating digital spatial data that describe the watershed of interest with hydrologic theory.

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CHAPTER 1. INTRODUCTION

A significant portion of the cost of most highway projects can be attributed to the design and construction of drainage facilities, with such facilities including bridges, highway culverts, storm drains, and water quality and quantity control structures. At the minimum, the design of these facilities involves hydrologic analyses to determine the design discharge and hydraulic analyses to determine the conveyance capacity of the facility. Although most hydrologic and hydraulic calculation procedures are now available as computer programs, which can significantly reduce the mathematical effort involved, substantial effort is still necessary to establish and manipulate the data required for input into those programs. To simplify the process of determining the input data, several state departments of transportation are developing geographic information systems (GIS) to calculate spatial hydrologic parameters that can then be used as input values to standard hydrologic software packages.

The hydrologic software package currently utilized by the Texas Department of Transportation (TxDOT) is the Texas Hydraulic System (THYSYS). This program is comprised of applications that perform hydrologic and hydraulic analyses based on descriptions of the watershed and/or the stream channel of interest. Traditionally, the data generated to support these programs have been extracted manually from maps and cross-sections presented on paper drawings. However, by building a digital spatial database of the hydrologic features of Texas, and developing a GIS that operates in conjunction with this database, the extraction of data and application of the design procedures becomes automated and more efficient.

1.1 PURPOSE

In this research project, a GIS has been developed to assist in the design of highway drainage facilities by utilizing hydrologic spatial data to calculate the input parameters for standard hydrologic software packages. This GIS reduces the analysis time and improves the analysis accuracy by integrating digital spatial data that describes the watershed of interest

with hydrologic theory. This Final Report presents a summary of the results obtained throughout the duration of this three-year project.

1.2 ORGANIZATION

This report consists of one main document and three CD-ROMs. The main document is subdivided into the following nine chapters:

Chapter 1 – Introduction: This chapter presents a brief summary of the background of the project, the purpose of the report, and the organization of the document.

Chapter 2 – Literature Review: This chapter has been subdivided into the following two sections: (1) flow hydrographs and peak discharges, and (2) computer-based hydrologic and hydraulic modeling. The first section deals with flow estimation, and special attention has been given to flood peak discharges because they are a key design parameter for highway drainage structures. The second section addresses the use of computers for hydrologic/hydraulic analysis, the use of GIS to account for the spatial variability of the terrain, and the use of GIS-based hydrologic models for designing highway drainage structures.

Chapter 3 – Use of GIS for Hydrologic and Hydraulic Modeling: General concepts related to the use of digital spatial data and GIS tools for hydrologic and hydraulic modeling are presented in this chapter. It specifically addresses the extraction of hydrologic information (i.e., stream and watershed delineation) from topographic data in raster format. It also explains the different methodologies that can be implemented to combine terrain data of different types into a single data set.

Chapter 4 – Digital Spatial Data of Texas: In this chapter, the geographic information (in digital format) that has been, or is being, developed by several federal, state, and local agencies, as well as private organizations, is discussed. For this project, there is particular interest in the hydrologic spatial data (data related to the design of highway drainage facilities) of the drainage area of the Gulf of Mexico that spans from the Sabine River at the Texas-Louisiana border to the Rio Grande at the Texas-Mexico border.

Chapter 5 – Raster Map of Potential Extreme Peak Discharges: Potential extreme peak discharges are estimates of the highest peak discharge expected to occur at a certain location. This chapter explains the process of generating a raster map (i.e., grid) of the precomputed values of potential extreme peak discharges in GIS for a particular watershed.

Chapter 6 – Flood Flow Calculator: Chapter 6 documents the development of an ArcView extension that calculates watershed parameters, peak discharges, isochrone lines, and runoff curve numbers using GIS. Using available hydrologic spatial data, the watershed parameters calculated are area, length of longest flowpath, slope of longest flowpath, shape factor, and average curve number. Peak discharges are calculated for different return periods (2, 5, 10, 25, 50, and 100 years); isochrone lines are determined as the contour lines of a 3-D surface of flow times to the watershed outlet; and runoff curve numbers are calculated from land use data, soil data, and a look-up table that relates land use and percentage of hydrologic soil group with curve number.

Chapter 7 – Rainfall Runoff Model: This chapter deals with the development of CRWR-PrePro, a system of ArcView scripts and associated controls that extract topographic, topologic, and hydrologic information from digital spatial data of a hydrologic system, and prepare ASCII files for the basin and precipitation components of HEC-HMS. These files, when opened by HEC-HMS, automatically create: (1) a topologically correct schematic network of sub-basins and reaches attributed with hydrologic parameters, and (2) a protocol to relate gage to sub-basin precipitation time series.

Chapter 8 – Floodplain Mapping: A discussion of an automated approach to floodplain mapping using GIS, developed to aid in the design of drainage facilities, is presented in this chapter. The approach establishes a connection between ArcView and HEC-RAS by taking computed water surface profiles generated in HEC-RAS and displaying them three-dimensionally in ArcView, significantly improving the visualization and analysis of floodplain data. It also permits a GIS to function as an effective planning tool by making

hydraulic data easily transferable to floodplain management, flood insurance rate determination, economic impact analysis, and flood warning systems.

Chapter 9 – Conclusions: This chapter summarizes the findings of the project as a whole and comments on the focus of the research. The successes and limitations of using GIS to: (1) determine flood peak discharges and hydrographs, and (2) map floodplains, are discussed in detail. The chapter also presents the advantages of using a GIS to process large quantities of spatially variable hydrologic data, and the impact of GIS on the engineering community.

The three CD-ROMs that form part of this *Final Report* include *README.txt* files that explain the contents of each disk:

CD-ROM 1 – Hydrologic Modeling in Texas Using GIS: This disk includes three directories, the first of which, TXDATA, stores the digital spatial data of Texas presented in Chapter 4. The PEAKFLOW directory stores the grid of potential extreme peak discharges presented in Chapter 5 and some related GIS maps (raster, vector, and images) to aid in the retrieving of flow values. The NFF directory stores the ***Flood Flow Calculator*** ArcView extension presented in Chapter 6 and all necessary digital spatial data required by the extension.

CD-ROM 2 – CRWR-PrePro – An ArcView Pre-Processor for HEC-HMS: This disk includes an HTML file that constitutes a cover page, from which hyperlinks connect the user to working files (i.e., ArcView projects and tables), papers, conference presentations, and tutorial movies and exercises that provide instructions on the use of CRWR-PrePro. All of the working files are also contained on the disc.

CD-ROM 3 – Floodplain Mapping: This disk also includes an HTML file that constitutes a cover page. From this cover page, links connect the user to Avenue scripts, tutorial exercises, and demonstration movies that describe the use of ArcView in floodplain mapping activities. The entire set of Avenue scripts, exercises, and movies are also contained on the disk.

Additional documentation related to this project can be found on the project web page, located at www.ce.utexas.edu/prof/olivera/txdot/txdot.htm, and on the CRWR-PrePro web page, at http://civil.ce.utexas.edu/prof/olivera/prepro/prepro.htm. These web pages will not necessarily be updated in the future.

CHAPTER 2. LITERATURE REVIEW

This literature review has been divided into the following two sections: (1) flow hydrographs and peak discharges, and (2) computer-based hydrologic and hydraulic modeling. The first section deals with flow estimation, and special attention has been given to flood peak discharges because they are a key design parameter for highway drainage structures. The second section addresses the use of computers for hydrologic/hydraulic analysis, the use of geographic information systems (GIS) to account for the spatial variability of the terrain, and the use of GIS-based hydrologic models for designing highway drainage structures.

2.1 FLOW HYDROGRAPHS AND PEAK DISCHARGES

Because of the importance of estimating flow hydrographs and peak discharges for design purposes, an extensive discussion of the published work in this field has been included.

2.1.1 Evolution of Runoff Hydrograph Models

The unit hydrograph, a method for estimating storm runoff, was first proposed by L.K. Sherman in 1932 (Chow et al., 1988), and since then has been used as a key concept. The unit hydrograph is defined as the watershed response to a unit depth of excess rainfall, uniformly distributed over the entire watershed, and applied at a constant rate for a given period. In 1938, after studying watersheds in the Appalachian mountains of the United States, Snyder proposed relationships between individual characteristics of the unit hydrograph, such as peak flow, lag time, base time, and width (in units of time) at 50% and 75% of the peak flow (Chow et al., 1988). Snyder's method was enhanced with the regionalization of the watershed parameters developed in 1977 by Espey, Altman, and Graves (Chow et al., 1988). Clark (1945) proposed that a unit hydrograph is the result of a combination of a pure translation routing process followed by a pure storage routing process. Although Clark does

not develop a spatially distributed analysis, the translation component of the routing is based on the time-area diagram of the watershed. The storage component consists of routing the response of the translation through a single linear reservoir located at the watershed outlet. The detention time of the reservoir is selected in order to reproduce the falling limb of observed hydrographs. Note that the actual travel time of a water particle, according to this approach, is the travel time given by the time-area diagram plus the detention time of the reservoir, which is somewhat inconsistent. Some years later, a unit hydrograph equation was proposed that is the response of a cascade of identical linear reservoirs to a unit impulse, i.e., a gamma distribution (Nash, 1957). It is important to notice that the method proposed by Nash does not model the watershed itself, but is just a fitting technique based on the first and second moments of the calculated and observed hydrographs. In 1972, the Soil Conservation Service (SCS) of the United States Department of Agriculture (USDA) proposed a unit hydrograph model based on a single parameter: the lag time between the center of mass of the excess precipitation hyetograph and the peak of the unit hydrograph. The shape of the hydrograph is given by an average precomputed dimensionless unit hydrograph curve or, as a simplification, by a triangular dimensionless unit hydrograph (Chow et al., 1988).

However, studying the relationship between storm rainfall and runoff involves much more than studying only the unit hydrograph. Consequently, in trying to relax the unit hydrograph assumptions of uniform and constant rainfall, and to account for spatial variability of the catchment, considerable research has been done in recent years, and many articles dealing with these topics can be found in the literature.

Pilgrim (1976) carried out an experimental study consisting of tracing flood runoff from specific points of a 0.39 square kilometer (km^2) watershed, near Sydney, Australia, and measuring the travel time of the labeled particles to the outlet. He concludes that "at medium to high flows the travel times and average velocities become almost constant, indicating that linearity is approximated at this range of flows. "Pilgrim also states that time-variations of the tracer activity time curves "make an additional contribution to the non-linearity of the runoff process."

An attempt to link the geomorphologic characteristics of a watershed with the hydrologic response of that watershed is given by Rodriguez-Iturbe and Valdes (1979). In their paper, Horton's empirical laws (i.e., laws of stream numbers, lengths, and areas) are used to describe the geomorphology of the system. The instantaneous unit hydrograph is defined as the probability density function of the time it takes a randomly chosen rainfall drop to reach the outlet of the watershed. This time is given by the sum of the times spent in each state (the order of the stream in which the drop is located) on its way to the outlet. The time spent in each state is taken as a random variable with an exponential probability density function whose parameter depends on Horton's length ratio, the mean velocity of the stream flow (dynamic parameter), and a scale factor.

Mesa and Mifflin (1986), Naden (1992), and Troch et al. (1994) present similar methodologies to account for spatial variability when determining the watershed response. The catchment response is calculated as the convolution of a network response and a hillslope response.

To calculate the network response, Mesa and Mifflin (1986) use the solution of the advection-dispersion equation, weighted according to the normalized width function of the network. In their paper, the normalized width function is defined as the number of channels at a given distance to the outlet, divided by the total length of all channels in the network. For the hillslope response, Mesa and Mifflin suggest a double travel time function, related to fast and slow flow, in the form of two isosceles triangles. The two functions are weighted, according to the probability that a water drop would take either path to the channel system, and added to give the final hillslope response. From the physical viewpoint, fast and slow hillslope responses are related to surface and subsurface flow respectively. Their model was tested in a 1.24 km^2 sub-basin of the Goodwin Creek watershed in Mississippi. For the stream network, an average velocity of 1 meter per second (m/s) and a dispersion coefficient of 9.06 square meters per second (m^2/s) were found. For the hillslope response, the average velocities of the fast and slow components were 0.25 m/s and 0.0046 m/s respectively, and the fraction of the slow flow was taken equal to 90% of the total hillslope response.

For the network response, Naden (1992) also suggests the solution of the advection-dispersion equation, but weighted by a standardized width function of the network. In her paper, the standardized width function is defined as the number of channels at a given distance to the outlet, divided by the total number of channels in the network. She also recommends an additional weighting of the width function by the excess rainfall spatial distribution. Naden does not give a specific methodology to determine the hillslope response, and the one used in her paper "was selected by eye" as a single peak, reflecting the quick response, followed by an exponentially decaying curve for the slow component. For the case of the River Thames at Cookham in the United Kingdom, a stream flow velocity of 0.6 m/s and dispersion coefficient of 1 m^2/s were found. Additionally, because of the slow component of the hillslope response, which yields about 80% of the flow volume, the rainfall spatial variability is smoothed out resulting in almost identical watershed responses for different rainfall spatial patterns. The ratio of the average velocities of the fast and slow components was found to be around 20.

Troch et al. (1994) propose the same stream network response as Mesa and Mifflin (1986). However, for the hillslope response they suggest a function given by the solution to the advection-dispersion equation, applied this time to the overland flow, and weighted according to a normalized hillslope function. The normalized hillslope function is interpreted as the probability density function of runoff generated at a given overland flow distance from the channel network. Contrary to Mesa and Mifflin's and Naden's hillslope response functions, Troch et al.'s does not account for the slow component.

An interesting approach to model the fast and slow responses of a catchment is presented by Littlewood and Jakeman (1992, 1994). In their model, the watershed is idealized as two linear storage systems in parallel, representing the surface and the subsurface water systems. The surface system is faster and affects mainly the rising limb of the resulting hydrograph, while the subsurface system is slow and determines the recession part of the response.

Although the linear unit hydrograph model has been used for more than 60 years, it is well known that flow, especially in streams, exhibits a non-linear behavior. Flow velocity, as modeled by Manning's or Chezy's equations for example, is a function of the water depth, which implies that the duration of the watershed response depends on the volume of water flowing. Therefore, the principle of superposition, a well-known property of linear systems, does not apply to flow systems.

Many distributed flow-routing methods can be found in the literature (Chow et al. 1988, Lettenmaier and Wood, 1993). Based on the Saint Venant continuity and momentum equations, the dynamic wave model, diffusion wave model, and kinematic wave model can be derived. The simplest among them, the kinematic wave model, neglects pressure and inertial forces in the flow and leaves friction equal to gravity forces. The diffusion wave model considers, additionally, pressure force terms, whereas the dynamic wave model includes also inertial terms. These models can be defined as linear or non-linear, depending on the way the original equations are set.

In non-linear systems, the terrain should be analyzed continuously because its hydrologic behavior changes with time and superposition cannot be used. Not using superposition, though, implies the ability to determine the continuously changing response of the watershed, which might be complicated for uniform systems and eventually inapplicable for spatially variable systems.

2.1.2 Flood Peak Discharges

Estimates of the magnitude and frequency of flood peak discharges and flood hydrographs are used for a variety of purposes, such as the design of bridges and culverts, flood control structures, and floodplain management. These estimates are often needed at ungauged sites where no observed flood data are available for frequency analysis.

Available at-site systematic gauged records are the traditional and most obvious source of information on the frequency of floods, but they are of limited length. Flood flows are predicted using plotting positions and curve fitting based on a graphical representation of

systematic and historical flood peaks. Lognormal, Pearson type III, and generalized extreme value distributions are reasonable choices for describing flood flows. However, as pointed out by Stedinger et al. (1993), it is advisable to use regional experience to select a distribution for a region and to reduce the number of parameters estimated for an individual site.

Recommended procedures for flood frequency analyses developed cooperatively by several federal agencies are described in Bulletin 17B (Interagency Advisory Committee, 1982). This bulletin describes a methodology for computing flood flow frequency curves using annual flood series with at least 10 years of data, and recommends special procedures for zero flows, low outliers, historic peaks, regional information, confidence intervals, and expected probabilities for estimated quantities. The recommended technique assumes that the decimal logarithms of the peak discharges have a Pearson type III distribution, and therefore the flood flow associated with a specific exceedance probability is a function of the sample mean, standard deviation, skew coefficient, and the exceedance probability itself.

For many years, the United States Geological Survey (USGS) has been involved in the development of regional regression equations for estimating flood magnitude and frequency at ungauged sites. Since 1973, regression equations for estimating flood peak discharges for rural, unregulated watersheds have been published at least once for every state, as well as for the Commonwealth of Puerto Rico. For some areas of the nation, however, data are still inadequate to define flood frequency characteristics. Regression equations for estimating urban flood-peak discharges for several metropolitan areas in at least 13 states are also available. These regression equations are used to transfer flood characteristics from gauged to ungauged sites by using watershed and climatic characteristics as explanatory or predictor variables. Generally, these equations have been developed on a statewide or metropolitan area basis as part of cooperative study programs with specific state transportation departments or specific cities.

In 1994 the USGS, in cooperation with the Federal Highway Administration (FHA) and the Federal Emergency Management Agency (FEMA), compiled all of the statewide and

metropolitan area regression equations as of September 1993 into a microcomputer program known as the *National Flood Frequency Program* (M.E. Jennings, W.O. Thomas, Jr. and H.C. Riggs, 1994). The program includes equations -- developed based on the statistical (regression) analysis of data collected at gauging stations -- for estimating flood-peak discharges and techniques for estimating a typical flood hydrograph for a given recurrence interval for unregulated rural and urban watersheds.

The evolution of flood peak discharge regionalization procedures within USGS is described by discussing the following three procedures: (1) the index-flood procedure used from the late 1940s to the 1960s, (2) the ordinary-least-squares regression procedure used in the 1970s and 1980s, and (3) the generalized-least-squares regression procedure that is being used today (in the 1990s).

The index-flood procedure consisted of two major parts. The first was the development of basic, dimensionless frequency curves representing the ratio of flood discharges at selected recurrence intervals to an index flood (mean annual flood). The second part was the development of a relation between watershed and climatic characteristics and the mean annual flood, to enable the mean annual flood to be predicted at any point in the region. The combination of the mean annual flood with the basic frequency curve provided a frequency curve for any location.

In the following years, the use of ordinary-least-squares regression methods addressed some of the limitations of the index-flood procedure. Direct estimation of T-year flood peak discharges, using ordinary-least-squares regression methods, avoided the following deficiencies in the index-flood procedure: (1) the flood ratios for comparable streams may differ because of large differences in the index flood; (2) homogeneity of frequency curve slope can be established at the 10-year level, but individual frequency curves commonly show wide and sometimes systematic differences at the higher recurrence levels; and (3) the slopes of the frequency curves generally vary inversely with drainage area. Additionally, it was observed that the flood ratios also vary with channel slope and climatic characteristics. T-year flood peak discharges for each gauging station were estimated by

fitting the Pearson type III distribution to the logarithms of the annual peak discharges. The regression equations that related the T-year flood peak discharges to watershed and climatic characteristics were computed using ordinary least-squares techniques. In ordinary-least-squares regression, equal weight is given to all stations in the analysis regardless of record length and the possible correlation of flood estimates among stations. Additionally, in most statewide flood frequency reports that used this method, the analysts divided their states into separate hydrologic regions.

Recent developments in the regionalization of flood characteristics have centered on accounting for the deficiencies in the assumptions of ordinary-least-squares regression and on more accurate and objective tests of regional homogeneity. Ordinary-least-squares regression procedures do not account for variable errors in flood characteristics that exist due to unequal record lengths at gauging stations, and both ordinary- and record-length weighted-least-squares regression methods do not account for the possible correlation of annual peak flow records between sites. A new procedure, the generalized-least-squares regression, was developed that accounts for both the unequal reliability and the correlation of flood characteristics between sites. It was shown, in a Monte Carlo simulation, that generalized-least-squares regression procedures provided more accurate estimates of regression coefficients, better estimates of the accuracy of the regression coefficients, and better estimates of the model error than did ordinary-least-squares procedures.

For the case of the state of Texas, regional regression equations for calculating peak flood flows for different frequencies and potential extreme peak discharges have been developed. The peak flood flow is the maximum expected flow at a certain location for a given frequency. According to Asquith and Slade (1997), peak flood flows depend on the catchment area, the slope of the main channel, the basin shape factor, the hydrologic region, and the return period. Potential extreme peak discharges are estimates of the highest peak discharges expected to occur at a certain location and, according to Asquith and Slade (1995), are explained mostly by the area of the corresponding catchment and by the hydrologic region where the catchment is located.

2.2 COMPUTER-BASED HYDROLOGIC AND HYDRAULIC MODELING

The use of computers for hydrologic and hydraulic modeling is not new for the engineering community. However, taking full advantage of their capabilities has always been delayed by the availability of models and software that can represent complex processes. From lumped-model software packages to GIS-based models, a significant step forward has been taken, but further development is still necessary when accounting for spatially distributed terrain parameters. A brief discussion on the available software packages and model development trends is presented in the following sections.

2.2.1 Hydrologic and Hydraulic Software

Many computer programs for hydrologic and hydraulic modeling are available to the engineering community. Some of these programs have been developed by the government and are in the public domain. DeVries and Hromadka (1993) have prepared a comprehensive summary of available software, in which programs are grouped in the following categories: (1) single-event rainfall-runoff and routing models, (2) continuous-stream flow simulation models, (3) flood-hydraulics models, and (4) water-quality models. Because of the widespread use of HEC-1, HEC-2 (and its Windows version HEC-RAS), and TR-20, overviews of these programs are included in this review; however, the reader is referred to the software manuals for detailed information about each program.

2.2.1.1 HEC-1 and HEC-HMS

HEC-1 is a computer model for rainfall-runoff analysis developed by the Hydrologic Engineering Center (HEC) of the United States Army Corps of Engineers. The program develops discharge hydrographs for either historical or hypothetical storm events for one or more locations in a basin. To account (to a certain extent) for spatial variability of the system, the basin can be divided into sub-basins with specific hydrologic parameters.

The program options include: (1) calibration of unit hydrograph and loss-rate parameters, (2) calibration of routing parameters, (3) generation of hypothetical storm data,

(4) simulation of snowpack processes and snowmelt runoff, (5) dam safety applications, (6) multi-plan/multi-flood analysis, (7) flood damage analysis, and (8) optimization of flood control system components. Uncontrolled reservoirs and diversions can also be accommodated.

Precipitation excess is transformed into direct runoff using either unit hydrograph or kinematic wave techniques. The unit hydrograph can be entirely supplied by the user or defined based on hydrologic parameters of the watershed, for which several built-in unit hydrograph options are available in the program (i.e., Clark, Snyder, or Soil Conservation Service unit hydrographs). The kinematic wave option permits depiction of sub-basin runoff with elements representing one or two overland flow planes, one or two collector channels, and a main channel.

HEC-HMS (Hydrologic Modeling System) is software for precipitation-runoff simulation that supercedes HEC-1 and runs on Windows-based operating systems as well as on Unix workstations. HEC-HMS is a significant advancement over HEC-1 in terms of both computer science and hydrologic engineering. Although a product under development, it contains most of the watershed-runoff and routing capabilities of its predecessor HEC-1, while providing new capabilities, such as continuous hydrograph simulations over long periods and spatially distributed runoff computation using a grid-cell depiction of the watershed. HEC-HMS is comprised of a graphical user interface (GUI), integrated hydrologic analysis components, data storage and management capabilities, and graphics and reporting facilities.

2.2.1.2 HEC-2 and HEC-RAS

HEC-2 was developed by the HEC of the Army Corps of Engineers to compute steady-state water surface elevation profiles in natural and constructed channels. Its primary use is for natural channels with complex geometry such as rivers and natural streams. The program requires that three flow-path distances be used between cross sections: a channel

length, and left and right overbank lengths. The program also analyzes flow through bridges, culverts, weirs, and other types of structures.

The encroachment computation option, widely used in the analysis of floodplain encroachments for the FEMA flood insurance program, allows the user to specify encroachments with fixed dimensions or to designate target values for water surface increases associated with floodplain encroachments.

HEC-2 uses the standard direct step method for water surface profile calculations, assuming that flow is one-dimensional, gradually varied, and steady. The program computes water surfaces as either a subcritical profile or a supercritical flow profile. Mixed subcritical and supercritical profiles are not computed simultaneously. If the computations indicate that the profile should cross the critical depth, the water surface elevation used for continuing the computations to the next cross section is the critical water surface elevation.

HEC-2 computes up to 14 individual water surface elevation profiles in a given run. Usually a different discharge is used for each profile, although when the encroachment or channel improvement options are used, the section dimensions are changed rather than the discharge. The discharge can be changed at each cross section to reflect tributaries, lateral inflows, or diversions.

Recently, HEC has developed HEC-RAS (River Analysis System), which has the same features as HEC-2 but with a Windows interface. Besides the user interface, no major differences between the programs have been observed.

2.2.1.3 Soil Conservation Service TR-20

The SCS TR-20 computer model is a single-event rainfall-runoff model that is normally used with a design storm as rainfall input. The program computes runoff hydrographs, routes flows through channel reaches and reservoirs, and combines hydrographs at confluences of the watershed stream system. Runoff hydrographs are computed by using the SCS curve number method, based on land use information and soil maps indicating soil type, and the SCS dimensionless unit hydrograph defined by a single

parameter, the watershed lag. TR-20 utilizes the SCS methods given in the Hydrology section of the National Engineering Handbook (Soil Conservation Service, 1972).

Watersheds are usually divided into sub-basins, which have similar hydrologic characteristics and are based on the location of control points through the watershed. Control points are locations of tributary confluences, a structure, a reservoir, a diversion point, a damage center, or a flood gauge location.

Historical or synthetic storm data are used to compute surface runoff from each sub-basin. Excess rainfall is applied to the unit hydrograph to generate the sub-basin runoff hydrograph. Base flow can be treated as a constant flow or as a triangular hydrograph. A linear routing procedure is used to route flow through stream channels. The modified Puls method (storage-indication routing) is used for reservoir routing. As many as 200 channel reaches, and 99 reservoirs or water-retarding structures, can be used.

TR-20 has been widely used by SCS engineers in the United States for urban and rural watershed planning, flood insurance, flood hazard studies, and for design of reservoirs and channel projects. The SCS methodology is accepted by many local agencies as well. TR-55 is a simplified version of TR-20 that does rainfall-runoff modeling.

2.2.2 GIS for Hydrologic and Hydraulic Modeling

In a relatively short time, GIS has gained widespread use in a variety of engineering applications. Originally envisioned (and used) as a geographic mapper with an integrated spatial database, GIS is increasingly being used in modeling applications, where geographic data can be readily accessed, processed, and displayed. GIS has been implemented mostly by large entities such as federal, state, and local government agencies, with mapping and management of spatial data being the predominant use. However, there is increasing interest in the potential application of GIS to engineering design and analysis, especially in hydrology and hydraulics.

Because the use of GIS for hydrologic modeling is still in its infancy, the practicing engineering community has had only limited exposure to this field. This was verified by a

survey (Smith, 1995) sent out to 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 that were received, it became evident that those state highway agencies that have implemented GIS (ten states) are using it exclusively for mapping and data management. Most of them recognize the potential of GIS for engineering analysis, but only the state of Maryland has implemented a system that supports hydrologic analysis, i.e., GISHYDRO (Ragan, 1991). To some extent, the distinction between GIS and computer aided design (CAD) seems to be blurred. GEOPAK, for example, listed by one responder as a GIS, is a roadway design CAD package that has digital elevation model (DEM) capability.

In the hydrologic environment, GIS is a tool that allows one to move from lumped (pre-GIS) models to spatially distributed (GIS) models. The border between lumped and distributed models is not sharp, and there are pre-GIS attempts to deal with spatially distributed terrain attributes. For example, the Army Corps of Engineers model HEC-1, well known as a lumped model, allows the user to divide the watershed into smaller sub-basins for analysis purposes, and route their corresponding responses to the watershed outlet. In this case, the concept of a purely lumped model does not apply, although the model cannot be considered a fully spatially distributed model either. It is therefore advisable to keep in mind the extent to which a given model is lumped or distributed.

Several pioneers are worthy of note for their foresight and work in the development of hydrology-related engineering applications of GIS. DeVantier and Feldman (1993) present a general review of the connection between GIS and hydrologic modeling, which "summarizes past efforts and current trends in using digital terrain models and GIS to perform hydrologic analysis." The link between GIS and hydrologic modeling becomes more natural as the concern about spatially distributed terrain parameters and the use of computers for hydrologic analysis becomes more widespread. GIS uses digital terrain models (DTM) to describe the spatially distributed attributes of the terrain, which are classified as topologic and topographic data (strictly speaking, however, topographic is part of topologic data). DEMs, in particular, refer to the topographic data, while all other attributes not related to

elevation constitute the topologic data. It can be expected that, because of the large amount of information required to describe the terrain, GIS is a memory and computationally intensive system. However, storing and handling the data is not necessarily the critical point when working with GIS, because the acquisition and compilation of the information can be an even more difficult task.

Terrain data can be handled in different ways, depending on the type of model to be used. The grid approach consists of subdividing the terrain into identical square cells arranged in rows and columns. Triangular irregular networks (TINs) are formed by selecting a set of representative irregularly distributed points and connecting them by straight lines producing triangles. Digital line graphs (DLGs) are formed by digitally representing the elevation contour lines as a set of point-to-point paths. Accordingly, it is expected that grid data, because of its geometric structure, lead to finite difference methods of runoff computation, while TIN data lead to finite element methods of runoff computation. The extra effort required for working with TINs and finite element methods is compensated by the fact that TINs are less memory demanding, because their resolution is not fixed and can be suited to the local terrain characteristics. On the other hand, although modeling with grid and finite difference methods is less complex, because of its fixed geometric structure, it is more memory demanding. DLGs appear mainly as a natural way to store information, and as a data source for analysis with grids or TINs.

2.2.2.1 Hydrologic Analysis using GIS

Much research has focused on stream-watershed delineation and, in general, on watershed analysis based on topographic data, such as DEMs or DLGs. Hutchinson (1989) presents an interpolation algorithm to determine the DEM from elevation data points and streamlines. This algorithm produces DEMs that are consistent with the streamlines and has been proven to produce more accurate DEMs than the ones obtained with previous methodologies. Jensen and Domingue (1988) and Jensen (1991) outlined a grid scheme to delineate watershed boundaries and stream networks to defined outfalls (pour points). 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 neighboring cells). The cells contributing flow to the pour point can be counted, representing drainage area, and are referred to as the flow accumulation. The cells having no contributing flow define the boundaries of the drainage area. Cells having a flow accumulation in excess of a threshold establish stream network cells. Tarboton et al. (1991) computed stream slopes and stream lengths using a similar grid system. In addition, the authors proposed criteria for proper selection of the threshold based on statistical properties of the terrain. Jones et al. (1990) employed a triangulation scheme on digital elevation data to determine watershed boundaries and flow paths. Procedures for delineating streams and watersheds from DEMs, as well as for correcting DEMs depressions produced by data noise, can be found in Maidment (1997), Meijerink et al. (1994), Environmental Systems Research Institute (ESRI) (1992), Garbrecht and Martz (1995a, 1995b) and Martz and Garbrecht (1992).

Maidment et al. (1996b) present the watershed delineation of the Niger River basin based on a 1-km DEM. In this delineation, a stream is identified on the DEM wherever the upstream drainage area exceeds 10,000 km^2, and sub-watershed boundaries are delineated from outlets at each stream junction, which produces a drainage network with a single stream for each sub-watershed. To avoid long reaches between junctions, outlets were also placed on long streams each 250 km. A total of 167 streams with their corresponding drainage areas were determined in this way. Before delineating the watersheds, the DEM had to be corrected to account for the Lake Chad inland catchment, to the northeast of the Niger basin. Since the standard delineation process consists of filling up terrain depressions, a pour point at the lowest point of the Lake Chad basin was defined to avoid filling up the whole catchment and making it overflow toward the Niger basin.

Rinaldo et al. (1992) analyzed the similarities between stream networks derived from DEMs and optimal channel networks (OCN) obtained by minimizing the energy spent in the system. Likewise, Moore et al. (1988) and Moore and Grayson (1991) describe an automated

procedure, fully based on topographic data, for subdividing catchments into smaller elements and for calculating hydrologically relevant attributes of the elements. This catchment partitioning is done in order to apply lumped models that represent particular hydrologic processes, at an element level. The integration of the element responses gives the spatially distributed response of the entire catchment.

Grid-based GIS appears to be a very 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 1992a). The ESRI Arc/Info-GRID system and the Army Corps of Engineers GRASS system use a grid data structure. Grid systems have proven to be ideal for modeling topographically driven flow, because a characteristic of this type of flow is that flow directions do not depend on any time dependent variable, such as flow or water depth. This characteristic is what makes topographically driven flow easily modeled in a grid environment and, 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 1992a).

2.2.2.2 GIS Pollution Modeling

Recently, there have been attempts to take advantage of GIS capabilities for runoff and non-point source pollution modeling. Vieux (1991) presents a review of water quantity and quality modeling with GIS and, as an application example, employs the kinematic wave method to an overland flow problem. GIS is used to process the spatially variable terrain and the finite elements method (FEM) is used to solve the mathematics. Maidment (1992a, 1992b, 1993) presents a grid-based methodology for determining a spatially distributed unit hydrograph that assumes a time-invariant flow velocity field. According to him, the velocity time invariance is a requirement for the existence of a unit hydrograph with a constant time base and relative shape. In Maidment's articles, from a constant velocity grid, a flow-time

grid is obtained and subsequently the isochrone curves and the time-area diagram are determined. The unit hydrograph is obtained as the incremental areas of the time-area diagram, assuming a pure translation flow process. A more elaborate flow process, accounting for both translation and storage effects, is presented by Maidment et al. (1996a). In their paper, the watershed response is calculated as the sum of the responses of each individual grid cell, which is determined as a combined process of channel flow (translation process) followed by a linear reservoir routing (spreading process). Although an approximate method, the model shows a good fit for the unit hydrograph of the Severn watershed at Plynlimon in Wales. Olivera et al. (1995) and Olivera and Maidment (1996) present a grid-based, unsteady-flow, linear approach that uses the diffusion wave method to model storm runoff and constituent transport. According to these papers, the routing from a certain location to the outlet is calculated by convolving the responses of the grid cells of the drainage path.

Sensitivity of model results to the spatial resolution of the data has been addressed by Vieux (1993), who discusses how the grid cell size affects the terrain slope and flow-path length, and accordingly the surface runoff. Vieux and Needham (1993) conclude that increasing the cell size shortens the stream length and increases the sediment yield.

Watershed Modeling System (WMS), developed at the Engineering Computer Graphics Laboratory (ECGL) at Brigham Young University, is a hydrologic software package for runoff modeling in a watershed. WMS is divided logically into six integrated modules (TIN Module, DEM Module, Tree Module, Grid Module, Scatter Point Module, and Map Module), which can be used to address different tasks.

2.2.2.3 Water Balances Using GIS

A water balance of Texas, using GIS, was prepared by Reed et al. (1997), in which a 5 km precipitation grid, a 500 m DEM, gauged stream flow data, and other spatial data sets were used to generate spatially distributed maps of mean annual runoff and evaporation. One hundred sixty-six gauged watersheds were delineated from a 500 m DEM and hydrologic

attributes were compiled for each of them. To estimate the runoff in ungauged locations, plots of watershed average annual rainfall (mm) versus annual runoff per unit watershed area (mm) were analyzed. By eliminating watersheds with a large amount of reservoir evaporation, urbanization, recharge, or spring flow, a clear trend emerged in this rainfall-runoff data, and a runoff coefficient function was derived. Because runoff values were normalized by watershed area, this runoff coefficient function is scale-independent, and represents watersheds with drainage areas ranging from 270 to 50,000 km^2. Next, an expected runoff grid was created by applying the runoff coefficient function to the precipitation grid. Finally, a grid of actual runoff was created on a 500 m grid by combining gauged stream flow data with expected runoff information. By applying a flow accumulation function to the runoff maps, the expected and actual flows were calculated at each 500 m DEM cell. Flow maps created using these results show statewide spatial trends such as the increased density of stream networks in East Texas, and capture localized phenomena such as large spring flows and agricultural diversions. A map of the differences between actual and expected runoff shows where human activities have altered natural runoff.

2.2.2.4 Floodplain Management Using GIS

In the area of floodplain management, the Army Corps of Engineers has developed an integration between HEC-2, a widely used floodplain determination package, and GRASS, a software developed to work with raster data (Walker et al., 1993). The integration package accesses HEC-2 output in tabular form, and converts it into GRASS format. For floodplain determination, Talbot et al. (1993) developed a GIS application that takes water elevations as input. Their approach is intended to be non-specific, accepting stage values from any model that can determine water elevations along a stream channel. HEC-1 and HEC-2 are mentioned as valid sources of stage values. The application involves the intersection of two TINs, one representing the terrain, and the other the channel's water elevations, so that the banks of the floodplain can be established. The authors indicate that the resulting floodplain is locally reasonable and indicative of the overall floodplain. Beavers (1994) has developed

ARC/HEC2, a set of AML (Arc/Info Macro Language) and C programs, which work to extract terrain information from contour coverages, insert user-supplied information (such as roughness coefficients, or location of left and right overbanks), and format the information into HEC-2 readable data. Following HEC-2 execution, ARC/HEC2 is capable of retrieving the HEC-2 output (in the form of water elevations at each cross section) and creating an Arc/Info coverage of the floodplain. This process allows the resulting floodplain to be stored in a coverage format that is readily accessed by users who wish to use the floodplain information in conjunction with other Arc/Info coverages. ARC/HEC2 requires that a terrain surface be generated so that accurate cross-section profiles are provided to HEC-2. These terrain surfaces, in the format of TINs or grids, are created within Arc/Info based on contour lines, survey data, or other means of establishing terrain relief. The accuracy of the surface representation is crucial for accurate floodplain calculations.

2.2.3 Use of GIS for Design of Highway Drainage Structures

For TxDOT, as well as for other highway agencies, a continuing concern is the need to apply current engineering hydrologic and hydraulic design and analysis procedures that balance simplicity with accuracy. Although most hydrologic and hydraulic calculation procedures are now available as computer programs, substantially reducing the mathematical effort involved, significant effort is still necessary to establish and manipulate the data required for input into those programs. To simplify the process of determining the input data, the Texas and Maryland Departments of Transportation have developed GIS systems that calculate spatial hydrologic parameters that can then be used by standard hydrologic software packages.

2.2.3.1 GISHYDRO

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 make 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 sub-watershed 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 SCS computer program TR-20, so the model can be run for existing or proposed conditions. The same files are used to run a non-point source pollution model that estimates BOD, nitrate, phosphate, and other loadings in terms of the watershed land use and soil types.

2.2.3.2 Hydrologic Data Development System

Hydrologic Data Development System (HDDS) (Smith, 1995) is a prototype system intended to demonstrate the potential capabilities of using GIS for highway-based hydrologic data development and analysis. The focus of HDDS is on the development of an integrated set of Arc/Info programs and associated data that are now widely available or will become more prevalent in the future. Though 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, such as the drainage basin boundaries, areas and sub-areas, 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 data may be passed automatically from HDDS to the TxDOT Hydrologic and Hydraulic System (THYSYS) to calculate design flood frequency relationships. The resulting data may then be manipulated to create drainage area maps, tables, and other documentation.

CHAPTER 3. USE OF GIS FOR HYDROLOGIC AND HYDRAULIC MODELING

The shape of a surface determines how water will flow across it. The hydrologic modeling tools in the Spatial Analyst ArcView extension provide a method to describe the physical characteristics of a surface. Using a digital elevation model (DEM) as input, it is possible to delineate a drainage system and then quantify the characteristics of that system. These tools let you determine, for any location in a grid, the upslope area contributing to that point and the downslope path water would follow.

Watersheds and stream networks, created from DEMs using the Spatial Analyst, are the primary inputs to most surface hydrologic models. These models are used for such things as determining the height, timing, and inundation of a flood, locating areas contributing pollutants to a stream, or predicting the effects of altering the landscape. An understanding of the shape of the Earth's surface is useful for many fields such as urban and regional planning, agriculture, and forestry. These fields require an understanding of how water flows across an area, and how changes in that area may affect that flow.

The source and ultimate destination of water must be determined before modeling the behavior of water in a system. This section explains the concepts and key terms regarding drainage systems and surface processes, and how to use the tools in the Spatial Analyst to model the movement of water across a surface and to extract hydrologic information from a DEM. Sections 3.1 to 3.3 have been adapted from ESRI (1992).

3.1 HYDROLOGIC CONCEPTS

The area upon which water falls, and the network through which it travels to an outlet, is referred to as a *drainage system.* The flow of water through a drainage system is only a subset of what is commonly referred to as the *hydrologic cycle,* which also includes precipitation, evapotranspiration, and groundwater flow. This discussion concerns the movement of water across a surface.

A *drainage basin* is an area that drains water and other substances to a common outlet as concentrated drainage (Figure 3.1). Other common terms for a drainage basin are:

watershed, basin, catchment, or *contributing area.* This area is normally defined as the total area flowing to a given outlet, or pour point. An *outlet,* or *pour point,* is the point at which water flows out of an area. This is the lowest point along the boundary of the drainage basin. The boundary between two basins is referred to as a *drainage divide* or *watershed boundary.*

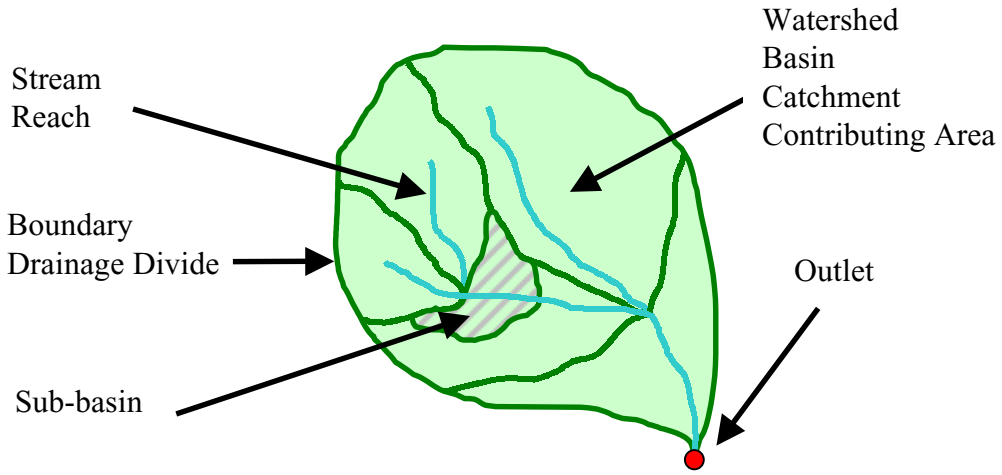


Figure 3.1 Drainage Basin Terminology

The network through which water travels to the outlet can be visualized as a tree, with the base of the tree being the outlet (Figure 3.2). The branches of the tree are stream channels. The intersection of two stream channels is referred to as a *node* or *junction.* The sections of a stream channel connecting two successive junctions, or a junction and the outlet are referred to as *interior links. Exterior links* are the outermost branches of the tree (i.e., they have no tributaries). Links can be either exterior or interior.

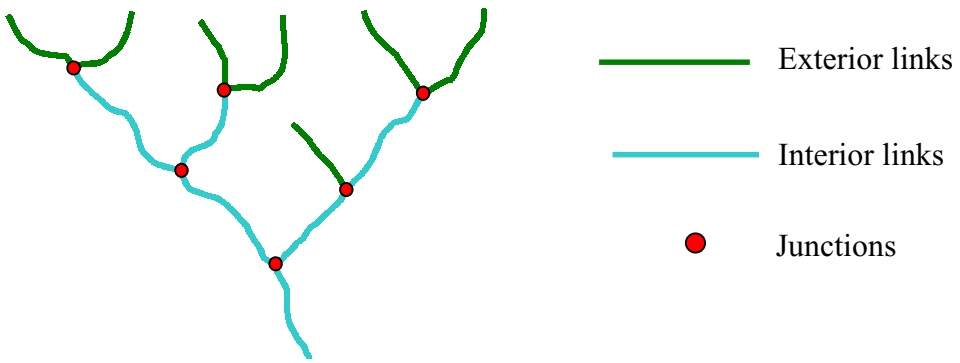


Figure 3.2 Water Network Terminology

The physical characteristics of a surface determine the characteristics of flow across it, and the flow across that surface changes its physical characteristics.

The direction of flow across a surface is determined by the aspect at each location. Aspect is the direction of the maximum rate of change in elevation from each cell. Aspect is also referred to as the slope direction.

The energy of flow is determined by the slope of the surface. Slope is the maximum rate of change in elevation from each cell. A steeper slope results in greater energy. As the energy of a stream increases, its ability to transport more and larger particles also increases. Therefore, steeper slopes result in a greater potential for erosion. *Profile curvature* indicates where the surface is concave or convex, resulting in acceleration or deceleration of flow (Figure 3.3). Where acceleration of flow occurs, the stream gains energy and its ability to transport particles increases. Therefore, areas of convex profile curvature indicate areas of erosion. Conversely, in areas of concave profile curvature, the flow rate decreases, the stream loses energy, and deposition occurs.

The curvature of a surface perpendicular to the direction of slope is referred to as the *planform curvature.* Planform curvature indicates where the surface is concave or convex,

resulting in convergence and divergence of flow respectively. Convergent flow indicates a concentration of runoff and would indicate a valley. Alternatively, divergent flow would indicate a ridge.

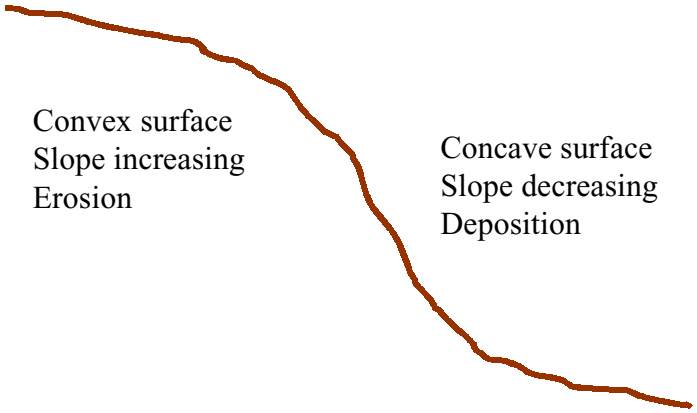


Figure 3.3 Profile Curvature

3.2 DEM-BASED TERRAIN ANALYSIS

The most common digital data of the shape of the earth's surface are cell-based DEMs. These data are used as input to the raster tools to quantify the characteristics of the land surface.

3.2.1 Digital Elevation Data

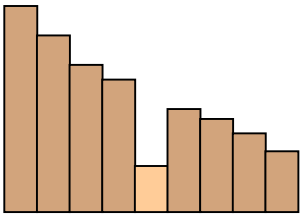
A DEM is a raster representation of a continuous surface, usually referring to the surface of the earth (Figure 3.4). The accuracy of this data is determined primarily by the resolution (distance between sample points). Other factors affecting accuracy are data type (integer or floating point) and the actual sampling of the surface when creating the original DEM.

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

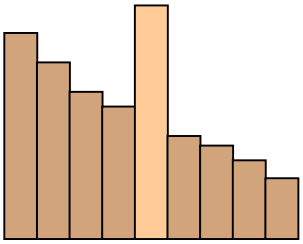
Digital elevation model (DEM)

Figure 3.4 Digital Elevation Model

Errors in DEMs are usually classified as either sinks or peaks (Figure 3.5). A *sink* is an area surrounded by higher elevation values, and can be referred to as a depression or pit. This is an area of internal drainage, which may be natural, particularly in glacial or karat areas (Mark, 1988), although many sinks are imperfections in the DEM. Likewise, a spike, or *peak,* is an area surrounded by cells of lower value. These are more commonly natural features and are less detrimental to the calculation of flow direction.



Profile view of a sink



Profile view of a peak

Figure 3.5 Sinks and Peaks in DEMs

DEMs may also contain noticeable horizontal striping, which results from systematic sampling errors when creating the DEM. This again is most noticeable on integer data in flat areas.

Flow across a surface will always be in the steepest downslope direction. Once the direction of flow out of each cell is known, it is possible to determine which and how many cells flow into any given cell. This information can be used to define watershed boundaries and stream networks. The process of extracting hydrologic information, such as watershed boundaries and stream networks, from a DEM is presented in the following sections.

3.2.2 Flow Direction

One of the keys to deriving hydrologic characteristics about a surface is the ability to determine the direction of flow from every cell in the grid. This is done with the FLOWDIRECTION Avenue request. This request takes a surface as input and outputs a grid showing the direction of flow out of each cell. There are eight valid output directions, relating to the eight adjacent cells into which flow could travel. This model is known as the eight-direction pour point model (Figure 3.6).

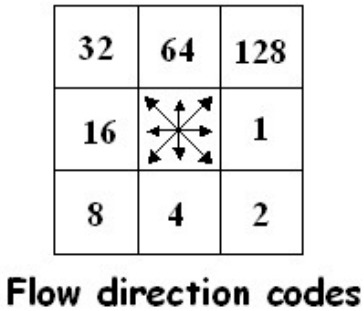


Figure 3.6 Eight-Direction Pour Point Model

The direction of flow is determined by finding the direction of steepest descent, or maximum drop, from each cell. This is calculated as the change in elevation divided by the distance. The distance is determined between cell centers. Therefore, if the cell size is 1, the

distance between two orthogonal cells is 1 and the distance between two diagonal cells 1.414214, the square root of 2. If the descent to all adjacent cells is the same, the neighborhood is enlarged until the steepest descent is found. When the direction of steepest descent is found, the output cell is coded with the value representing that direction. Figure 3.7 represents the flow direction grid generated from the DEM of Figure 3.4.

The Avenue syntax for the FLOWDIRECTION request is:

*flow_dir = elevation.**FLOWDIRECTION(FALSE)***

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

Figure 3.7 Flow Direction Grid

If all neighbors are higher than the processing cell, the processing cell is a sink, and has an undefined flow direction. If two cells flow to each other, they are sinks, and have an undefined flow direction. If a cell has the same change in z value in multiple directions it is also a sink and has an undefined flow direction.

For cells that have an undefined flow direction, the value for that cell in the output flow direction grid will be the sum of those directions. For example, if the change in z value is the same both to the east (flow direction = 1) and south (flow direction = 4), the flow direction for that cell will be 1 + 4 = 5. Cells with an undefined flow direction can be flagged as sinks using the SINK Avenue request. To obtain an accurate representation of flow direction across a surface, the sinks should be filled.

3.2.3 Accumulated Flow

The FLOWACCUMULATION Avenue request calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output grid (Figure 3.8). If no weight grid is provided, a weight of one is applied to each cell, and the value of cells in the output grid will be the number of cells that flow into each cell.

The Avenue syntax for the FLOWACCUMULATION Avenue request is:

*flow_acc = flow_dir.**FLOWACCUMULATION**(weight_grid)*

The {weight_grid} is NIL for the case when no weight grid is defined.

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

Figure 3.8 Flow Accumulation Grid

Cells with a high flow accumulation are areas of concentrated flow and may be used to identify stream channels. Cells with a flow accumulation of zero are local topographic highs and may be used to identify ridges.

An example of using a {weight_grid} with the FLOWACCUMULATION request might determine how much rain has fallen within a given watershed. In such a case, the {weight_grid} may be a continuous grid representing average rainfall during a given storm:

*flow_acc = flow_dir.**FLOWACCUMULATION**(rainfall)*

The output of FLOWACCUMULATION would then represent the amount of rain that would flow into each cell, assuming that all rain became runoff and there was no

interception, evapotranspiration, or loss to groundwater. This could also be viewed as the amount of rain that fell on the surface, upslope from each cell.

3.3 STREAM AND WATERSHED DELINEATION

Stream and watershed delineation is the process of identifying flow elements (streams) and drainage areas (watersheds) of a hydrologic system. In this application, delineation is based on raster topographic data, i.e., DEMs.

3.3.1 Watersheds

A watershed is the upslope area contributing flow to a given location, and can also be referred to as a basin, catchment, sub-watershed, or contributing area. A sub-watershed is simply part of a hierarchy implying that a given watershed is part of a larger watershed. Watersheds can be delineated from a DEM using the output from the FLOWDIRECTION request as input to the WATERSHED Avenue request. This request uses a grid of flow direction and a grid of outlets, or pour points, to determine the contributing area. Technology has come a long way from manually interpreting contours and then edge matching all the pieces.

The Avenue syntax for the WATERSHED request is:

*watersheds = flow_dir.**WATERSHED**(pourpoints)*

Watershed boundaries are a key requirement for nearly all surface hydrologic modeling. These boundaries can then be combined with soil and land use information to create, for example, summary statistics for input to a basin-wide (lumped) model for predicting sediment loss or flood height.

3.3.2 Stream Networks

Stream networks can be delineated from a DEM using the output from the FLOWACCUMULATION request. Flow accumulation in its simplest form is the number of upslope cells that flow into each cell. By applying a threshold value to the results of

FLOWACCUMULATION using a Spatial Analyst algebraic expression, a stream network can be delineated. For example, the expression to create a grid where the value 1 represents a stream network on a background of NODATA would be:

*streamnet=(flow_acc<[threshold].**ASGRID**).**SETNULL**(1.**ASGRID**)*

In the example, all cells with more than the threshold value of cells flowing into them are assigned l, and all other cells are assigned NODATA. For future processing, it is important that the stream network, a set of raster linear features, be represented as values on a background of NODATA. Once created, the stream network can be further analyzed using the STREAMORDER, STREAMLINK, and STREAMTOPOLYLINEFTAB Avenue requests, for ordering (ranking) the streams, assigning unique IDs to stream links, or creating a vector coverage, respectively.

3.3.2.1 Ordering

Stream ordering is a method of assigning a numeric order to links in a stream network. This order is a method for identifying and classifying types of streams based upon their number of tributaries. Some characteristics of streams can be inferred by simply knowing their order.

For example, first-order streams are dominated by overland flow of water; they have no upstream concentrated flow. Because of this, they are most susceptible to non-point source pollution problems and can derive more benefit from wide riparian buffers than other areas of the watershed.

The STREAMORDER request has two methods you can use to assign orders. These are the methods proposed by Strahler (1957) and Shreve (1966).

The Avenue syntax for the STREAMORDER request is:

*stream_order = streamnet.**STREAMORDER**(flow_dir, **TRUE**)*

TRUE stands for the Shreve ordering method and FALSE stands for the Strahler method.

In both methods, exterior links are always assigned an order of one. In the Strahler method, stream order increases when streams of the same order intersect. Therefore the

intersection of two first-order links will create a second-order link, and the intersection of two second-order links will create a third-order link (Figure 3.9). The intersection of two links of different order, however, will not result in an increase in order. For example, the intersection of a first-order and second-order link will not create a third-order link, but will retain the order of the highest ordered link. The Strahler method is the most common stream ordering method. However, this method only increases in order at the intersections of the same order; it does not account for all links and can be very sensitive to addition or removal of links.

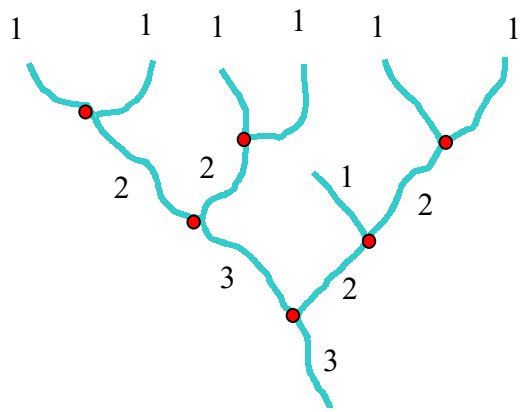


Figure 3.9 Strahler Ordering Method

The Shreve method accounts for all links in the network. Here, as with the Strahler method, all exterior links are assigned an order of one. For all interior links in the Shreve method, however, the orders are additive (Figure 3.10). For example, the intersection of two first-order links creates a second-order link, the intersection of a first- and second-order link creates a third-order link, and the intersection of a second- and third-order link creates a fifth-order link.

Because the orders are additive, the numbers from the Shreve method are sometimes referred to as *magnitudes* instead of orders. The magnitude of a link in the Shreve method is the number of upstream links.

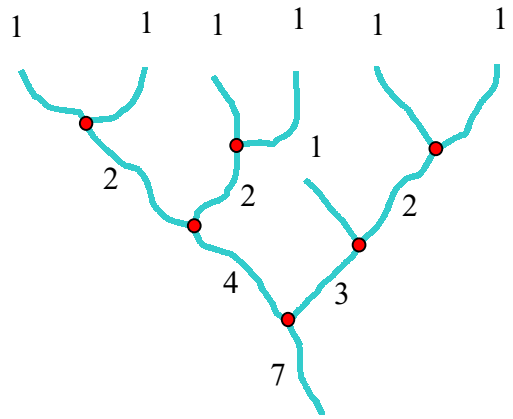


Figure 3.10 Schreve Ordering Method

3.3.2.2 Links

The STREAMLINK Avenue request allows the user to assign unique values to each of the links in a raster linear network. This can be useful for attaching related attribute information to individual segments of a stream.

The Avenue syntax for the STREAMLINK request is:

*stream_links = streamnet.**STREAMLINK**(flow_dir)*

3.3.2.3 Vectorizing

A raster linear network can be accurately converted to an arc coverage using the STREAMTOPOLYLINEFTAB Avenue request. STREAMTOPOLYLINEFTAB is a vectorization program designed primarily for vectorization of stream networks, or any other grid representing a raster linear network for which directionality is known. In the output coverage, all arcs will point downstream.

STREAMTOPOLYLINEFTAB is optimized to use a direction grid to aid in vectorizing intersecting and adjacent cells. Using STREAMTOPOLYLINEFTAB, it is possible for two adjacent linear features of the same value to be vectorized as two parallel lines instead of being lumped into a single line.

3.4 MODIFYING THE TERRAIN DATA FOR MODELING PURPOSES

Terrain data, in the format of DEMs and TINs, can be developed for other purposes beyond water resources modeling. Use of these data for hydrologic and hydraulic modeling, therefore, may present problems because of inconsistencies between the data and well-known hydrologic or hydraulic features of the terrain. To address these problems, terrain data has to be modified in a way that preserves the topographic description of the terrain while facilitating the extraction of the hydrologic and hydraulic parameters of the system.

3.4.1 Creating a Depressionless DEM

DEM errors such as sinks and peaks should be removed before attempting to derive any surface information. In particular, sinks (defined as areas of internal drainage) may cause undesirable results when calculating flow direction.

The number of sinks in a given DEM is normally higher for coarser resolution DEMs. Another common cause of sinks results from storing the elevation data as an integer number. This can be particularly troublesome in areas of low vertical relief. It is common to find about 1% of the cells in a 30-meter-resolution DEM are sinks. This can jump sometimes as high as 5% for 3-arc-second DEMs.

A DEM free of sinks, a *depressionless DEM,* is the desired input to the FLOWDIRECTION Avenue request. The presence of sinks may result in an erroneous flow-direction grid. Since FLOWDIRECTION is the first step in deriving hydrologic information about a surface, its input should be as accurate as possible.

In some cases, there may be legitimate sinks in the data. It is important in this case to understand the morphology of the area to know what features may truly be sinks on the surface of the earth, and which are data errors.

Sinks can be located using the SINK Avenue request. Sinks can be filled in batch mode by running an Avenue script specifically written for this purpose available in the Hydrologic Modeling ArcView extension (included in the Spatial Analyst as a non-supported

module), or interactively by using a series of Avenue requests. Either way, a maximum sink depth {z_limit}, beyond which a sink is not filled, is required as input.

The script for filling the sinks uses a variety of functions, including several of the hydrologic tools previously discussed, to create a depressionless DEM. When a sink is filled, it is filled to its pour point, the minimum elevation along its watershed boundary (Figure 3.11).

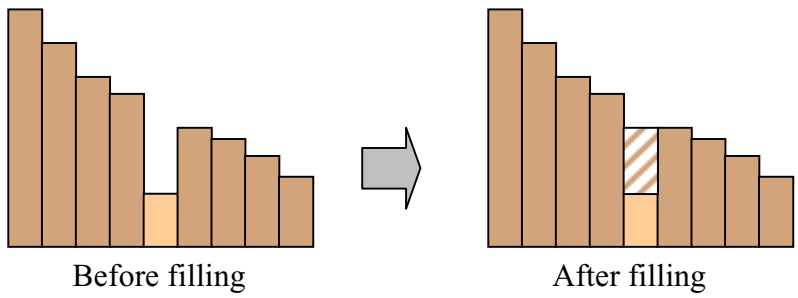


Figure 3.11 Filling a Sink in a DEM

The identification and removal of sinks, when trying to create a depressionless DEM, is an iterative process. When a sink is filled, the boundaries of the filled area may create new sinks, which then need to be filled. Because of this fact, it will often require three iterations of this process to remove all sinks.

The steps used to create a depressionless DEM are listed below. These are the steps used by the Avenue script, and can be used as a guide to filling sinks interactively.

1. Determine flow direction using the FLOWDIRECTION request.
2. Find the sinks using the SINK request.
3. Find the contributing area above each sink using the WATERSHED request.
4. Find the depth of the sinks and, if less than {z_limit}, proceed.
5. Fill the sinks to the value of the lowest boundary cell in the watershed of each sink using the ZONALFILL request.

6. Repeat from step 1 until there are no more sinks found in step 2, or there are no more sinks deeper than {z_limit} in step 4.

It can be useful to know the depth of a sink or group of sinks. This information can be used to determine an appropriate {z_limit}, to understand the type of errors present in the data, or to decide whether some of the sinks are legitimate morphological features. The steps to be followed to create a grid of sinks coded with depth are:

1. Run the SINK request to locate the sinks in the grid
2. Run the WATERSHED request to create a grid of the contributing area for each sink.
3. Calculate a grid of the minimum elevation in the watershed of each sink.
4. Calculate a grid of the maximum elevation in the watershed of each sink.
5. Subtract the minimum value from the maximum values to find the depth.

3.4.2 Burning-in Streams

It has been shown (Saunders and Maidment, 1995; Mizgalewicz and Maidment, 1996) that the use of raster data sets for watershed and stream delineation can produce stream networks that are inconsistent with previously accepted vector representations, such as those depicted on USGS 7.5-minute quadrangle maps, the River Reach files of the Environmental Protection Agency (EPA), or the DLGs of the USGS. These inconsistencies are due mostly to problems of inadequate DEM vertical and horizontal resolution.

One method that can help to resolve the problem of digital stream network replication involves the integration of a vector hydrography data layer into the DEM prior to watershed delineation. This process is referred to as stream "burning" and can be effective in the digital reproduction of a known and generally accepted stream network. The process is not without its drawbacks, though, as the vector hydrography layer chosen for integration must be at a similar scale as the DEM and must undergo some pre-processing prior to stream burning. Other deficiencies with the process have also been noted, such as the erroneous introduction

of artificial parallel streams into the drainage network (Hellweger, 1997) and the distortion of watershed boundaries delineated from the burned DEM (Saunders and Maidment, 1996).

The stream-burning algorithm consists of adding a constant elevation increment to the DEM value in all cells except in those that coincide with the observed streams. This process does not force the water to flow toward the streams, but forces it to remain in them once it gets there. Stream burning has proven to be an efficient way to alter the DEM in such a way that produces delineated streams that match the digitized ones. The DEM is then filled to eliminate spurious terrain pits, and the flow direction of each cell is determined.

The steps to be followed to burn in the streams are:

1. Select the arcs of the polyline feature data set of observed streams that correspond to the study area. Arcs on both sides of drainage divides should be selected even if only one side is to be studied. Small tributaries should be avoided to prevent hydraulic short circuits.
2. Convert the selected arcs into a grid with value 1 on the cells that coincide with the arcs and NODATA elsewhere.
3. Multiply the resulting grid by the DEM. This grid stores the DEM value in the stream cells and NODATA elsewhere.
4. Add a constant value to the DEM grid.
5. Merge the two grids, so that the original elevations are kept in the stream cells and the increased elevations in the off-stream cells.

The resulting grid can be used for stream and watershed delineation. Some properties of the terrain have been lost, however, which precludes the user from calculating, for example, terrain slope.

3.4.3 Merging TIN with DEM Data for Floodplain Mapping

In order to produce floodplain maps, accurate topographic information is required. In that sense, TINs are the optimum data format for floodplain mapping, because they are the best available data for large-scale terrain representation. It is therefore desirable to develop a TIN model of the study area that encompasses the streambed, the floodplain, and the surrounding landscape.

Using three-dimensional cross sections (which can be obtained after a georeferencing process of the cross-section vertices), a TIN model of the stream channel and floodplain can be constructed. Unfortunately, a TIN created solely from these vector data would not include the surrounding landscape. (DEMs, on the other hand, are the standard data format used for small-scale representation of the general land surface.) Therefore, in order to create a comprehensive TIN, a method to integrate relatively low-resolution DEM data with comparatively higher resolution vector floodplain data is required. By combining the vector and raster data to form a TIN, the intended result is a continuous three-dimensional landscape surface that contains additional detail in stream channels. This approach was employed to form the terrain TIN of Figure 3.12.

Application of the approach consists of the following steps. The data inputs for the terrain TIN are presented in Figure 3.13.

1. Clip the 30 m DEM to a manageable size. The Texas Natural Resources Information System (TNRIS) DEM has the same areal extent as a USGS 7.5-minute quadrangle map (approximately 17,000 km^2). Using the script ***Gridclip.ave*****,** the DEM can be clipped to the extent of any given polygon theme. The script requires a DEM and clipping polygon theme as inputs. The output is a clipped DEM.

2. Perform a raster to vector conversion on the clipped DEM to create a point shapefile of terrain elevations. This is performed using the script ***R2Vpoint.ave*****.** In the

conversion process, the DEM cells are converted to a point shapefile, with each point attributed with the elevation of the cell.

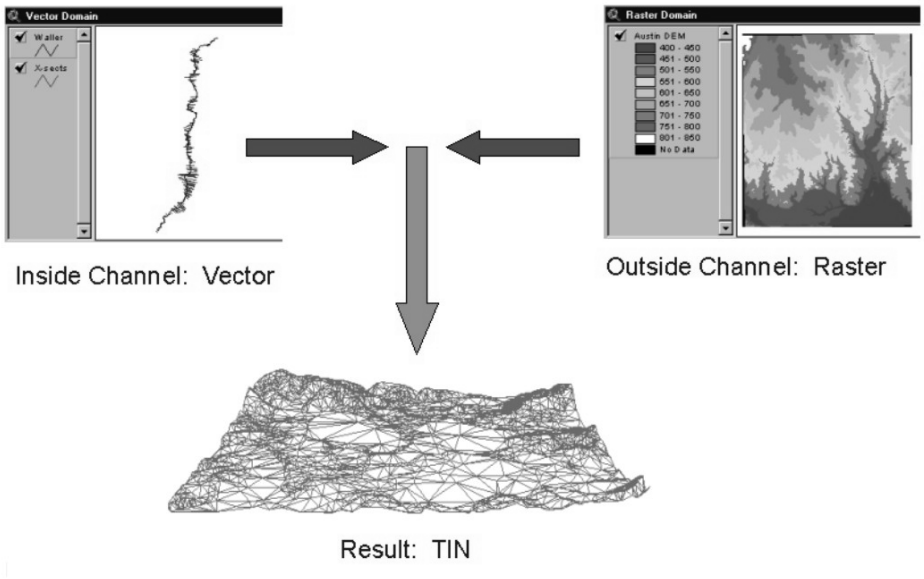


Figure 3.12 Three-Dimensional TIN Terrain Modeling Approach

3. Construct a bounding polygon from the cross-section endpoints. The script ***Boundary.ave*** carries out this task. The script uses the cross-section theme as input to create the bounding polygon theme.
4. Eliminate any points from the DEM point theme that fall within the bounding polygon. First, the DEM point theme is intersected with the bounding polygon theme using the *Theme/Select by Theme* menu option in the ArcView view window. The selected points can then be deleted from the point shapefile using the *Table/Start Editing* menu option in the ArcView table window, followed by *Edit/Delete Records*.
5. From the cross-section theme, extract the center point and bank stations at each cross section in order to create a three-dimensional line theme consisting of the stream centerline and bank lines. The Avenue script ***Banklines.ave*** performs this task.

6. Create a TIN using three input data sources: the DEM point theme, cross-section line theme, and the centerline and banks line theme. TIN nodes are formed from the DEM points and the vertices of the cross-section lines. The stream centerline and bank lines are enforced in the TIN as breaklines. The TIN is created using the *Surface/Create TIN from Features* menu item from the ArcView view window.

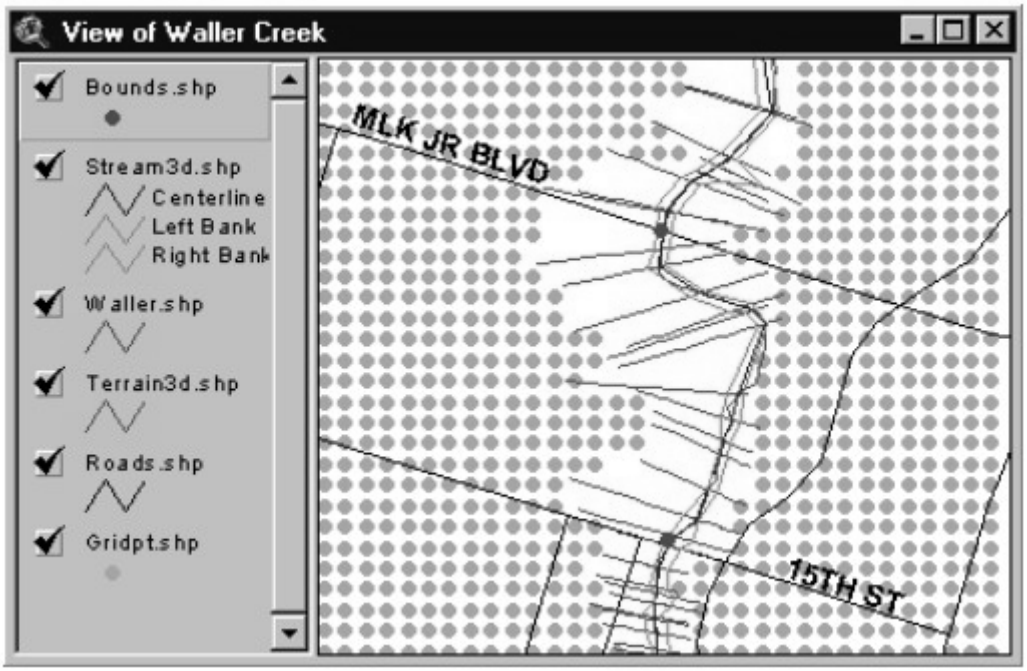


Figure 3.13 Terrain TIN Data Inputs

A three-dimensional terrain TIN can then be constructed such that the stream channel data supersede the terrain data within the area for which they are defined, and the DEM point data prevail elsewhere. The initial concern with this procedure was that it would not produce a smooth zone of transition between the vector and raster data points. A cursory examination of the resulting TIN (Figure 3.14) shows this to indeed be the case. The TIN has quite a rugged surface, especially in the zone of transition, which is not representative of actual terrain conditions.

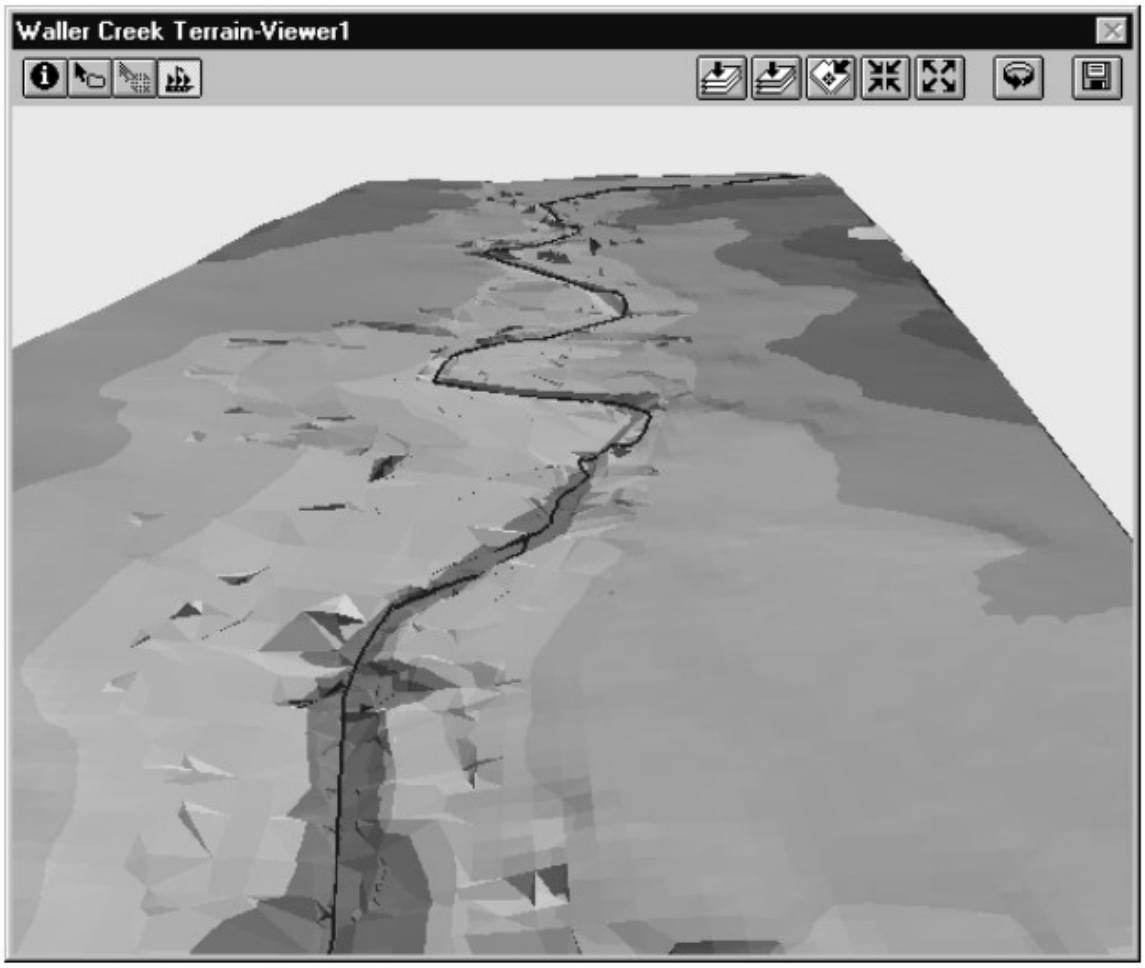


Figure 3.14 Waller Creek Terrain TIN

The majority of stream hydraulic analyses are performed using the River Analysis System (RAS) developed by HEC. Given that the RAS vector data and DEM raster data have different collection times, methods, and resolution, it is not surprising that they are somewhat incompatible. The floodplain elevation data is an amalgam of land surveys and topographic map estimations over a period of 10–15 years in the 1970s and 1980s. In contrast, the DEM is a product of the process used to develop the TNRIS 1995 Digital Orthophoto Quadrangles (DOQs). The zone of transition between the two data sets typically had an elevation gap ranging between 0 and 2 meters. These elevation differences may not be representative of actual terrain conditions. As such, the next task was to develop an approach

with which to smooth the TIN-DEM data transition zone. Development of the Waller Creek HEC-RAS model is presented as an example of an approach to TIN-DEM data transition smoothing.

The cross-section point elevations for the Waller Creek HEC-RAS model were collected during various land surveys. However, elevations in the floodway were often estimated by City of Austin engineers, based on available topographic maps. Hence, the accuracy of the HEC-RAS data was likely greater within the channel than in the floodway. Therefore, in comparison to the HEC-RAS data, the DEM elevations in the floodway were considered the more accurate, albeit lower resolution, data source. In addition, the DEM represents the entire floodway terrain, not only the places where the cross sections exist. In order to smooth the transition zone, elevations in the cross-sections and/or DEM data points needed to be altered. Because the cross-section elevation data in the floodway were considered the least accurate, an interpolation approach was applied to these data. Within each cross section, the elevations of all points between the bank stations (within the channel) were left unchanged. At the end of each cross section, the elevation was assumed equal to that of the DEM. The smoothing approach was applied to all cross-section points in the left and right floodways. The following steps present the approach used to smooth each cross section:

1. Calculate the lateral distance along the cross section between the bank station and the cross-section end, on both the left and right hand side of the cross section.
2. Identify the first cross-section point, outside the bank station, and note its elevation.
3. Query the DEM elevation at that location.
4. Determine the point's location in the floodway as a fraction of the distance calculated in Step 1. The new elevation of the point is calculated as a weighted average of the original elevation and the DEM elevation:

$$z_2 = z_1 \, (1 - \boldsymbol{f}) + \boldsymbol{DEM}_z \; \boldsymbol{f} \qquad \textbf{(3.1)}$$

where z_2 is the new point elevation, z_1 is the original point elevation, $\boldsymbol{DEM_z}$ is the DEM elevation at the point, and $\boldsymbol{f}$ is the point location in the floodway measured as a fraction of the lateral distance between the bank and cross-section end. For example, if the point is located 40% away from the bank station, the new elevation is the sum of 60% of the original elevation and 40% of the DEM elevation.

5. Repeat steps 1 through 4 for all floodway cross-section points.

The Avenue script ***NewXSects.ave*** carries out the approach described above. Akin to the original cross-section line theme, the resampled cross-section theme is attributed with river station number, cross-section length, and the locations of the center point and bank stations. By employing the transition zone smoothing approach, the point elevations in the floodway will gradually trend toward the DEM elevation, moving from the bank station to the end of the cross section. To help illustrate the effect of the cross-section elevation resampling, the Avenue script ***Compare.ave*** is applied. The script determines the coordinates of points along a given cross section as defined by three input data sets: the original HEC-RAS data, the DEM, and the resampled HEC-RAS data. The coordinates are written to a comma delimited text file, which can subsequently be imported into a spreadsheet and plotted (Figure 3.15).

The original and resampled cross-sections are identical within the channel. But in the floodway, the elevation of the resampled cross section falls somewhere between the original and DEM elevation. Using the resampled cross-section theme as input, the terrain TIN is reconstructed. In the reconstructed TIN, the land surface is more fluid and the zone of transition is difficult to discern. The figure also demonstrates how 30 meter DEMs do not provide sufficient detail within the channel for hydraulic modeling applications. However, recent advances in digital photogrammetry have allowed the production of higher resolution DEMs, such as a 10 m DEM (Figure 3.16). The 10 m DEM generates a somewhat better representation of the channel than the 30 m DEM.

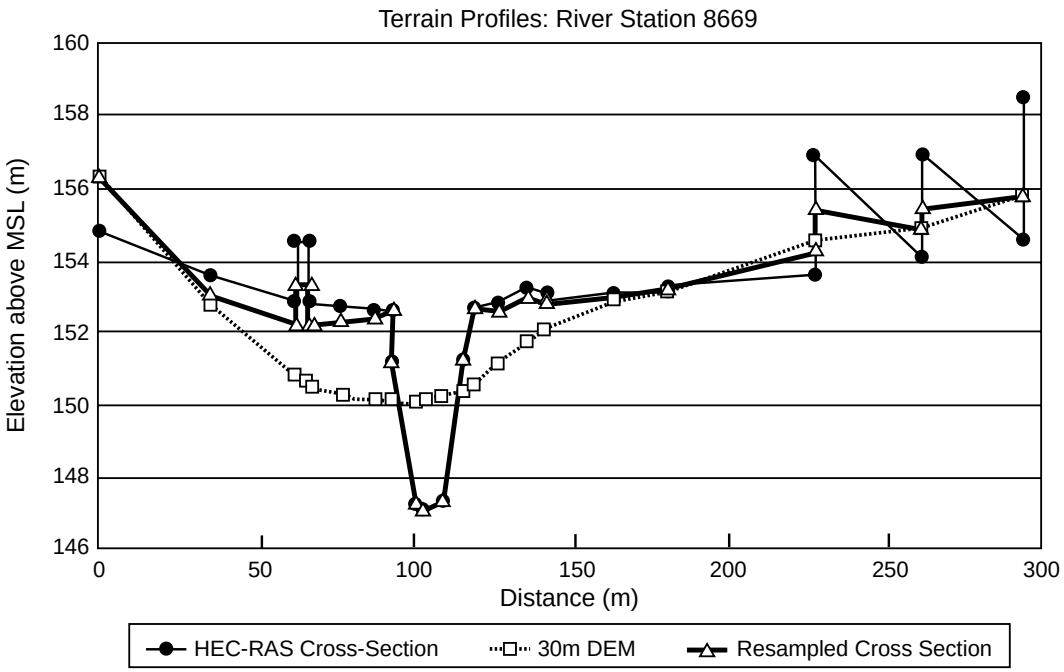


Figure 3.15 Terrain Profiles Based on Vector Cross Sections and a 30m DEM

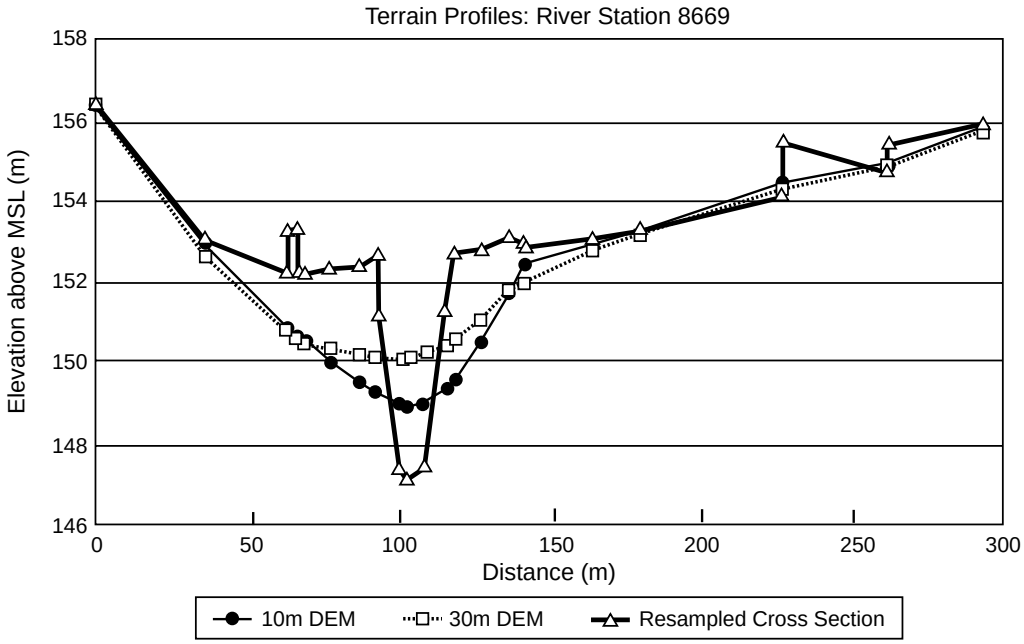


Figure 3.16 Terrain Profile Comparison between HEC-RAS and 10 m and 30 m DEM

CHAPTER 4. DIGITAL SPATIAL DATA OF TEXAS

Owing to the increasing use of GIS, several federal, state, and local agencies, as well as private organizations, have developed and are developing geographic information in digital format. For this project, we are particularly interested in hydrologic spatial data — related to the design of highway drainage facilities — of the drainage area of the Gulf of Mexico, spanning from the Sabine River at the Texas-Louisiana border to the Rio Grande at the Texas-Mexico border.

The following paragraphs present digital spatial data related to Texas and gathered during this project. This digital spatial database is included in the *TXDOT* folder of the *Hydrologic Modeling in Texas Using GIS* CD-ROM, delivered previously.

The map projection used in this database is defined by:

PROJECTION ALBERS
UNITS METERS
PARAMETERS

1ST STANDARD PARALLEL:	*27 25 0.00 (27.4167°)*
2ND STANDARD PARALLEL:	*34 55 0.00 (34.9167°)*
CENTRAL MERIDIAN:	*-100 0 0.00 (-100.0000°)*
LATITUDE OF PROJECTION'S ORIGIN:	*31 10 0.00 (31.1667°)*
FALSE EASTING (METERS):	*1000000*
FALSE NORTHING:	*1000000*

4.1 DIGITAL ELEVATION MODELS

A DEM is a sampled array of elevations for ground positions that are normally at regularly spaced intervals. Texas DEMs can be grouped according to their spatial resolution (cell size).

4.1.1 30-Arc-Second DEM

The Digital Chart of the World (DCW) DEM provides 30-by-30-arc-second — approximately 1 km cell size — digital elevation data. These data have been produced from

the Defense Mapping Agency's (DMA) 1:1,000,000-scale DCW contour and hydrology data. The DCW - DEM project, of the USGS EROS Data Center, includes 30-arc-second data for the entire world, made available on CD-ROM media and downloadable from the USGS EROS Data Center Internet site.

In this project, the 30-arc-second DEM was used for the areas where more detailed elevation data was not available, i.e., the part of the Rio Grande drainage area located in Mexico.

4.1.2 500 m DEM

The 500 m DEM is part of a compilation of geospatial data sets, formatted for use in GIS, prepared by the Global Energy and Water Cycle Experiment (GEWEX) for its Continental-Scale International Project (GCIP) Reference Data Set (GREDS). The data have been consistently integrated and written to a CD-ROM (USGS Open-File Report 94-388). The data sets, source scales, and projection were chosen to support the global change research community, specifically the GCIP, with input from the GCIP Data Committee and the GCIP Hydrometeorology and Atmospheric Subpanels. The 500 m DEM contained in this data set covers the conterminous United States and part of southern Canada, while most of the other data sets cover only the United States.

4.1.3 3-Arc-Second DEM

The 1-degree DEM (3-by-3-arc-second data spacing) provides coverage in 1° by 1° blocks for all of the conterminous United States, Hawaii, and limited portions of Alaska. The basic elevation model was produced by, and for, the DMA, but is distributed by the USGS EROS Data Center in DEM data record format. In reformatting the product, the USGS has not changed the basic elevation information. One-degree DEMs are also referred to as "3-arc-second" or "1:250,000 scale" DEM data.

4.1.4 30 m DEM

The DEM data for 7.5-minute units correspond to the USGS 1:24,000 and 1:25,000 scale topographic quadrangle map series for all of the United States and its territories. Each 7.5-minute DEM is based on 30- by 30-meter data spacing with the Universal Transverse Mercator (UTM) projection. Each 7.5- by 7.5-minute block provides the same coverage as the standard USGS 7.5-minute map series. These DEMs are distributed by the USGS EROS Data Center.

The 7.5-minute DEM data are produced in 7.5- by 7.5-minute blocks either from digitized cartographic map contour overlays or from scanned National Aerial Photography Program (NAPP) photographs. Four processes were used to generate DEM data for 7.5-minute units (the first three have since been discontinued): (1) Gestalt Photo Mapper II (GPM2), an automated photogrammetric system designed to produce orthophotos, digital terrain data, and contours in subunits known as patches; (2) manual profiling from photogrammetric stereomodels, which uses stereoplotters equipped with three-axis electronic digital profile recording modules for scanning stereomodels along successive terrain profiles; (3) recording of elevations by stereomodel digitizing of contours, in which digital contours are acquired on stereoplotters equipped with three-axis digital recording modules; and (4) interpolating hypsographic and hydrographic data from DLGs.

A 500 m DEM for the study area has been included in the *Hydrologic Modeling in Texas Using GIS* CD-ROM (Figure 4.1). This grid is the product of merging the 500 m DEM of the area within the United States (Texas, East New Mexico, South Oklahoma and West Louisiana), with a resampled version of the 30-arc-second DEM of northern Mexico. Most grids that can be derived from the DEM, such as flow direction (flow network), flow accumulation (drainage area), and flow length downstream and upstream, have also been included in the CD-ROM.

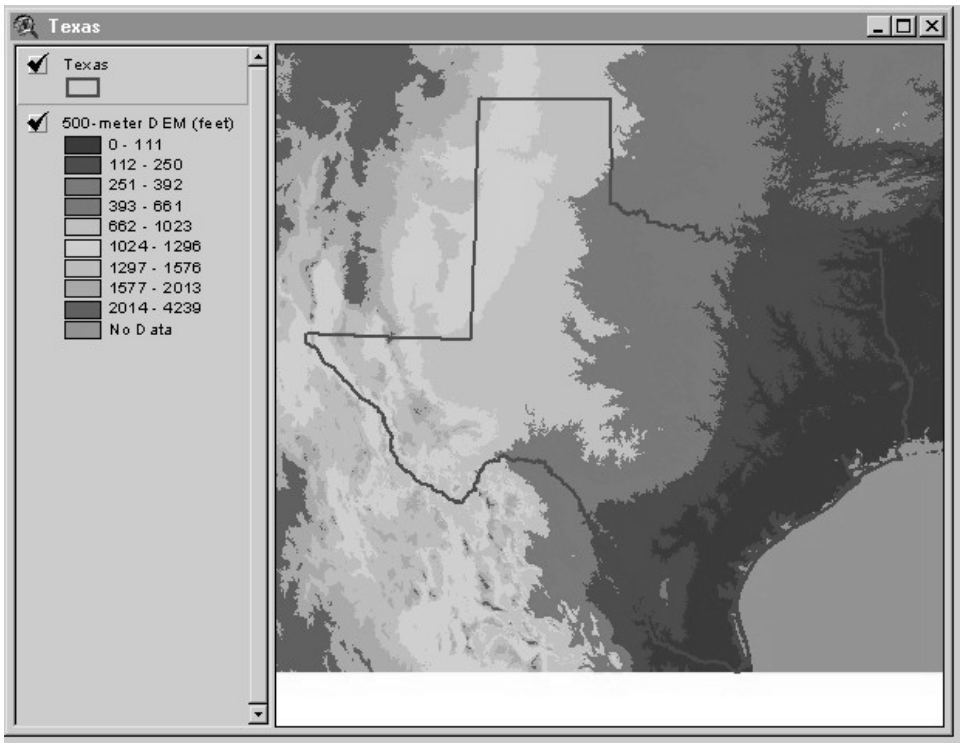


Figure 4.1 500 m DEM Coverage of Study Area

4.2 REACH FILES

The U.S. Environmental Protection Agency's (EPA) Reach Files are a series of hydrographic databases of the surface waters of the continental United States and Hawaii. The structure and content of the Reach File databases were created expressly to establish hydrologic ordering, to perform hydrologic navigation for modeling applications, and to provide a unique identifier for each surface water feature, i.e., reach codes.

An important characteristic of the Reach Files is their attributes that define the connected stream network. These attributes provide connectivity regardless of the presence or absence of topologic continuity in the digital linework. Flow direction is inherent in the connectivity attributes. This attribute-level connectivity enables the Reach Files to provide hydrologic ordering of stream locations using reach codes (what is upstream and downstream

of a given point in the stream network) as well as network navigation proceeding in either the upstream or downstream direction.

The Reach File was first conceived in the 1970s with a proof-of-concept file, known as Reach File Version 1.0 Alpha (RF1A), completed in 1975. The first full implementation, referred to as Reach File Version 1.0 (RF1), was completed in 1982. The source for RF1 was the USGS 1:250,000 scale hydrography maps that had been photo-reduced to a scale of 1:500,000 by the National Oceanic and Atmospheric Administration (NOAA). RF1 consists of approximately 68,000 reach segments comprising 650,000 miles of stream.

While RF1 still supports broad-based national applications, the need to provide a complementary and more detailed hydrologic network motivated the development of Reach File Version 2.0 (RF2) in the late 1980s. RF2 was created by using the Feature File of the USGS Geographic Names Information System (GNIS) to add one new level of reach segments to RF1. RF2 contains 170,000 stream segments. Shortly thereafter, widespread interest in providing a more comprehensive, nationally consistent hydrologic database led to the development of the Reach File Version 3-Alpha (RF3-Alpha).

The Reach File Version 3.0 (RF3) development project was begun in the fall of 1988 when the 1:100,000 scale DLG data became available. RF3 is being developed by EPA's Office of Water to provide a nationally consistent database to promote comparability for national, regional, and state reporting requirements such as those found in 305(b) and other sections of the Clean Water Act. RF3-Alpha includes about 3,500,000 reaches representing streams, wide rivers, reservoirs, lakes, a variety of miscellaneous hydrographic features, and the coastal shorelines for the Atlantic and Pacific Oceans, the Great Lakes, the Gulf of Mexico and the Hawaiian Islands.

The RF1 line coverage for the study area has been included in the *Hydrologic Modeling in Texas Using GIS* CD-ROM (Figure 4.2).

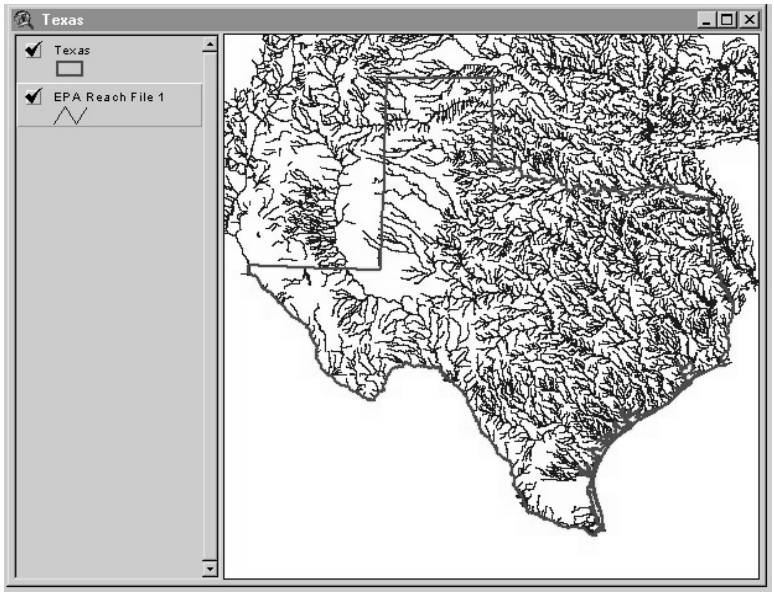


Figure 4.2 EPA RF1 Coverage of Study Area

4.3 HYDROLOGIC UNITS

Hydrologic unit maps of the United States, and of each state, show the hydrographic boundaries of river basins and numeric codes assigned to each of them. The maps were prepared in a cooperative project initiated in 1972 between the USGS and the US Water Resources Council. Boundaries and numeric codes are depicted for 21 regions, 222 sub-regions, 352 accounting units, and 2,100 cataloging units. River basins that have drainage areas greater than 700 square miles are delineated. Also included on the maps are state and county codes that use the Federal Information Processing Standards (FIPS). State maps are published at a scale of 1:500,000, and the US map (out of print) at a scale of 1:2,500,000. *Hydrologic Unit Maps* (USGS Water-Supply Paper 2294) describes the maps and contains the numeric codes for the river basins.

Digital data sets for hydrologic units are available at scales of 1:2,000,000 and 1:250,000. Each is a single coverage for the conterminous United States. Attributes of the 1:2,000,000-scale version include basin names. The digital data sets are available on-line in Spatial Data Transfer Standard (SDTS) format and in Arc/INFO Export format.

Putting the hydrologic-unit maps in digital form (at scale of 1:250,000) is part of the Geographic Information Retrieval and Analysis System (GIRAS) developed in the mid-1970s. The digital data are based on the Hydrologic Unit Maps published by the USGS Office of Water Data Coordination, together with the list descriptions and name of region, sub-region, accounting units, and cataloging unit. The hydrologic units are encoded with an eight-digit number that indicates the hydrologic region (first two digits), hydrologic sub-region (second two digits), accounting unit (third two digits), and cataloging unit (fourth two digits).

The data produced by GIRAS was originally collected at a scale of 1:250,000. Some areas, notably major cities in the west, were recompiled at a scale of 1:100,000. In order to join the data together and use it in a GIS, the data were processed in the Arc/Info GIS software package. Within the GIS, the data were edgematched and the neatline boundaries between maps were removed to create a single data set for the conterminous United States.
The 1:250,000 HUC coverage for the study area is included in the *Hydrologic Modeling in Texas Using GIS* CD-ROM (Figure 4.3).

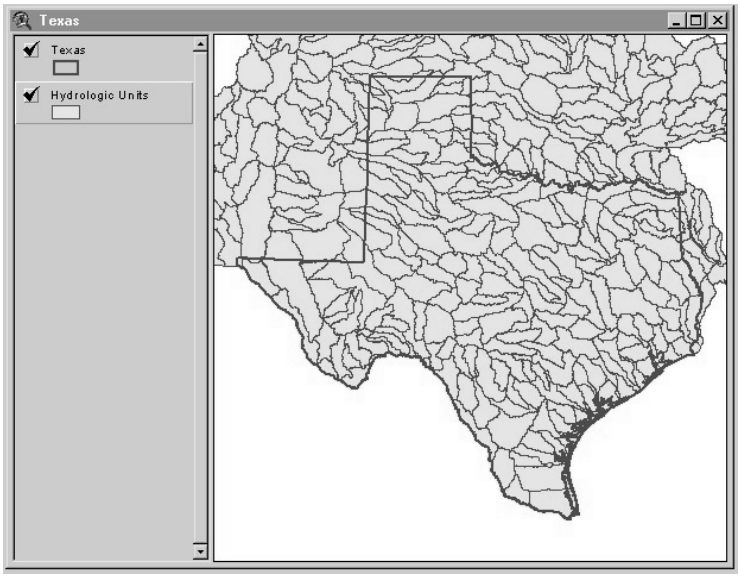


Figure 4.3 Hydrologic Units of Study Area

4.4 PRECIPITATION

Mean monthly precipitation grids for the conterminous United States have been developed by Daly et al. (1994). These grids were originally in Geographic Projection and had a cell size of 2.5' (approximately 4.5 km). The precipitation units are mm/month.

Twelve mean-monthly and one mean-annual 5000 m precipitation grids of the study area are included in the *Hydrologic Modeling in Texas Using GIS* CD-ROM (Figure 4.4). Data from Willmott et al. (1985) have been appended to these grids to cover the northern part of Mexico that drains to the Rio Grande.

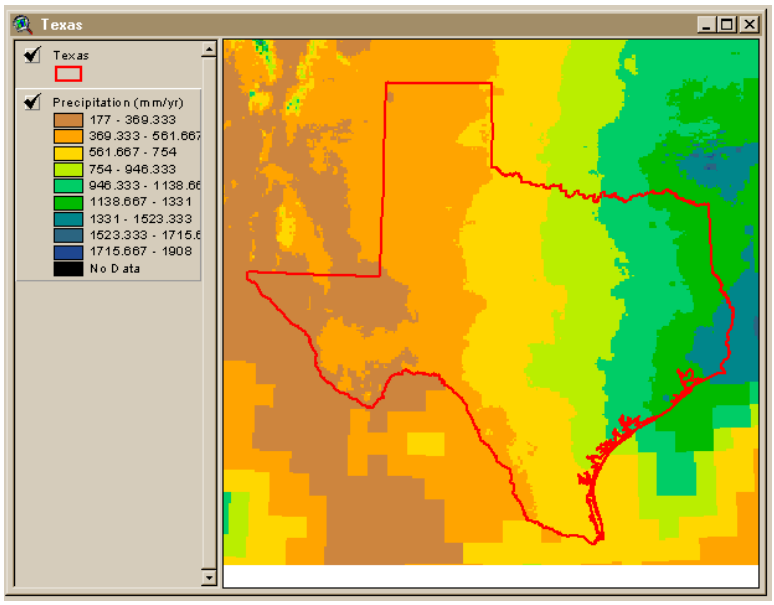


Figure 4.4 Precipitation Grid for Study Area

4.5 SOILS STATSGO

Soil maps for the State Soil Geographic Database (STATSGO) were created by generalizing the detailed soil survey or (SSURGO) geographic database. Since the base used for digitizing was the USGS 1:250,000 topographic quadrangles maps, STATSGO is intended for broad planning and management covering state, regional or multi-county areas. States have been joined as one complete seamless database to form statewide coverages. The

composition of soil map units was coordinated across state boundaries, so that component identities and relative extents would match. The number of soil polygons per 7.5' quadrangle tile is between 100 and 400, and the minimum area mapped is 1,544 acres (6 km^2). STATSGO data are available for most states.

Each STATSGO soil polygon is linked to a Soil Interpretations Record attribute database. This attribute database gives the proportionate extent of the component soils and their properties for each map unit. The STATSGO map units framework consists of 1 to 21 components. The Soil Interpretations Record database includes over 25 soil physical and chemical properties for approximately 18,000 soil series recognized in the United States.

A STATSGO polygon coverage of the study area has been included in the *Hydrologic Modeling in Texas Using GIS* CD-ROMs (Figure 4.5). The percentage of each of the four hydrologic soil groups (A, B, C, and D) in each map unit has been appended as additional attributes.

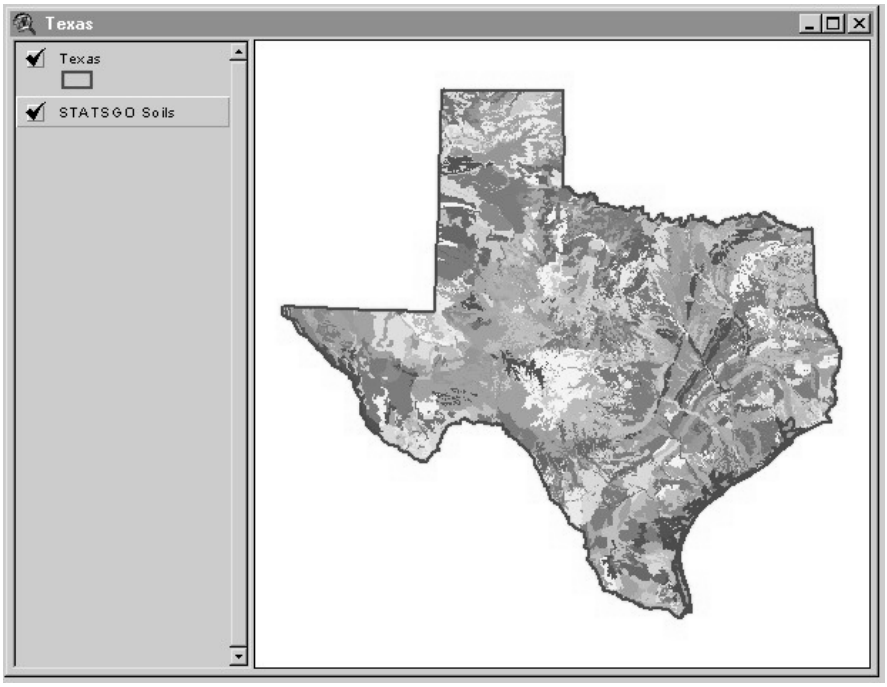


Figure 4.5 STATSGO Soils Coverage for Study Area

4.6 LAND USE

The Land Use and Land Cover (LULC) data files describe the vegetation, water, natural surface, and cultural features on the land surface. The USGS provides these data sets and associated maps as part of its National Mapping Program, which are available for most of the conterminous United States and Hawaii. This mapping program is designed such that standard topographic maps at a scale of 1:250,000 can be used for compilation and organization of the land use and land cover data. In some cases, such as Hawaii, 1:100,000 scale maps are also used.

Manual interpretation of aerial photographs acquired from National Aeronautics and Space Administration (NASA) high-altitude missions and other sources were first used to compile the land use and land cover maps. Secondary sources from earlier land use maps and field surveys were also incorporated into the LULC maps as needed. Later, the LULC maps were digitized to create a national digital LULC database.

The minimum area representing the manmade features of the LULC polygons is 10 acres (4 hectares), which have a minimum width of 660 feet (200 meters). This minimum width precludes the existence of very narrow or long tracts of data classification. Non-urban and non-manmade features may be mapped with polygons with a minimal area of 40 acres (16 hectares), which have a minimum width of 1320 feet (400 meters).

The LULC polygon coverage of Texas has been included in the *Hydrologic Modeling in Texas Using GIS* CD-ROM (Figure 4.6).

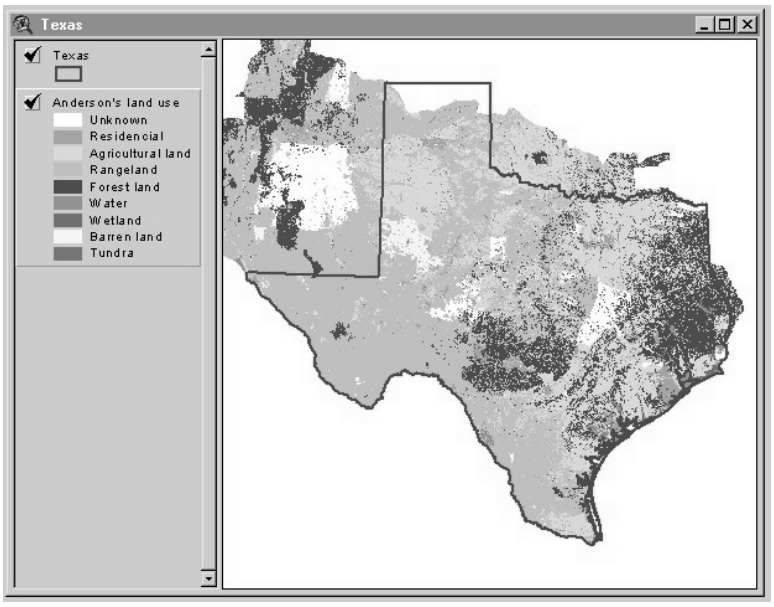


Figure 4.6 Land Use and Land Cover Polygon Coverage of Study Area

4.7 POLITICAL

A coverage of the county boundaries of the conterminous United States (Alaska, Hawaii and Puerto Rico are available separately) has been prepared by the USGS at a scale of 1:100,000.

The part of the county coverage that corresponds to Texas has been isolated, projected, and included in the *Hydrologic Modeling in Texas Using GIS* CD-ROM (Figure 4.7).

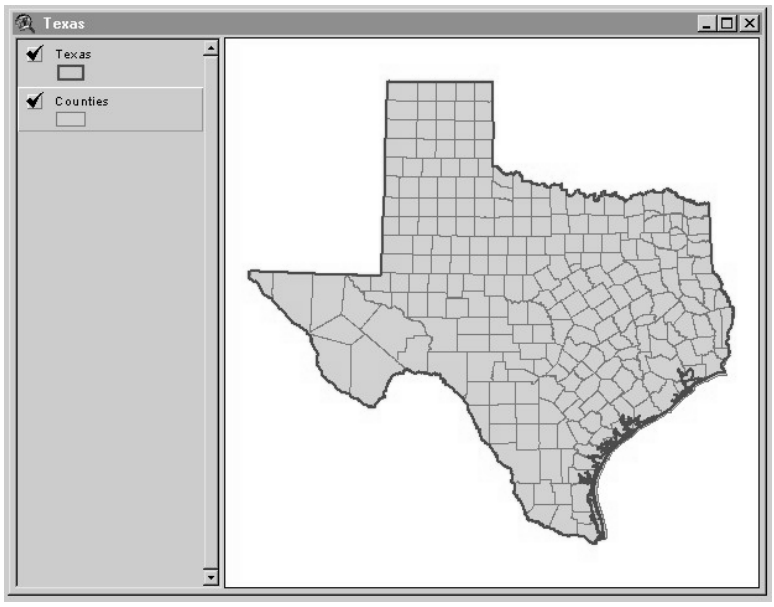


Figure 4.7 County Coverage of Study Area

4.8 RESERVOIRS

A coverage of the reservoirs of Texas was supplied by the Texas Water Development Board (TWDB) and depicted in Figure 4.8. No information about the coverage was obtained, but it was observed that the map projection was Albers equal-area and, by comparison with the EPA River Reach Files 1, the resolution of the data was at a scale of 1:250,000 or finer. The reservoir coverage is included in the *Hydrologic Modeling in Texas Using GIS* CD-ROM (Figure 4.8).

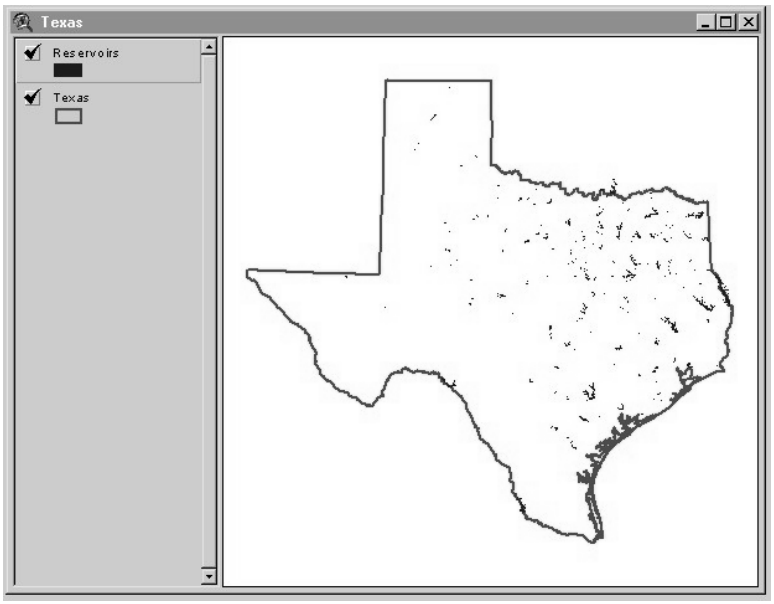


Figure 4.8 Reservoir Map of Study Area

4.9 AQUIFERS

Digital spatial data describing the aquifers of Texas were digitized from 1:250,000 geologic maps by the GIS Planning Division of the TWDB. A coverage of the major aquifers is included in the *Hydrologic Modeling in Texas Using GIS CD-ROM* (Figure 4.9).

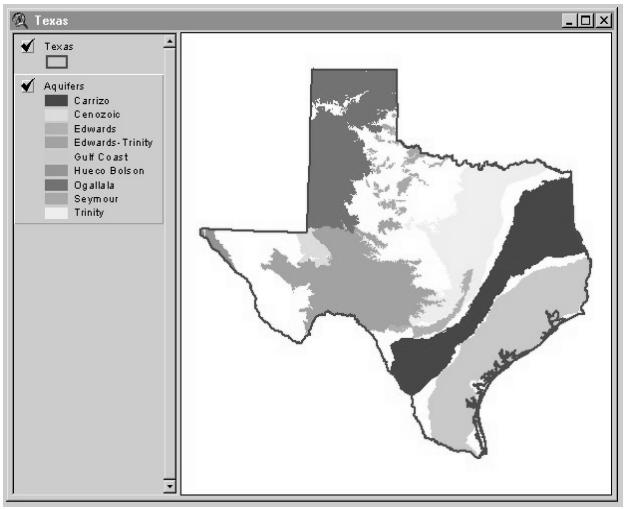


Figure 4.9 Aquifer Map of Study Area

4.10 ROADS

Digital road data for each state has been developed by the United States Department of Transportation (DOT). A highway coverage of Texas is included in the *Hydrologic Modeling in Texas Using GIS* CD-ROM (Figure 4.10).

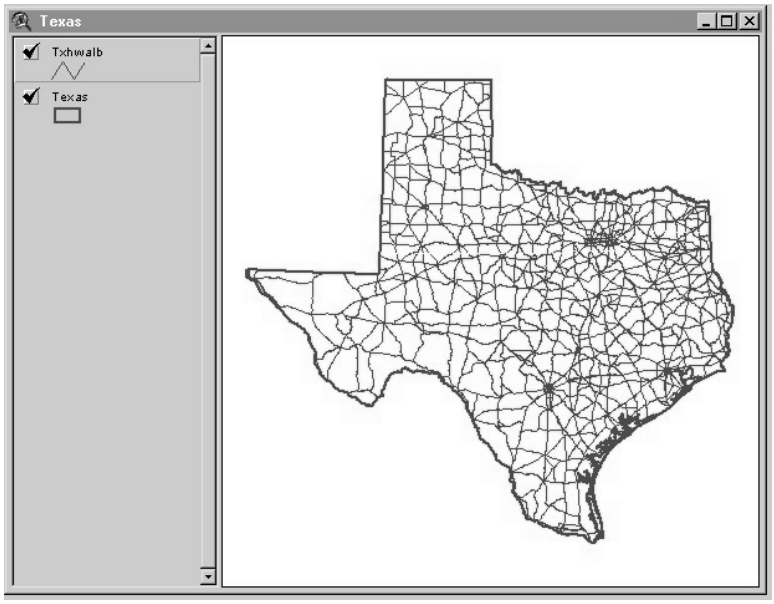


Figure 4.10 Highway Map of Study Area

4.11 RASTER MAPS

Digital raster graphic (DRG) data on CD-ROM were produced from 1995-1998 by the USGS through an Innovative Partnership agreement with The Land Information Technology Company, Ltd., of Aurora, CO. This series includes DRGs of USGS standard series quadrangle maps of the United States, its Trusts, and Territories. DRGs are made by scanning published paper maps on high-resolution scanners. The raster image is georeferenced and fit to the UTM projection. Colors are standardized to remove scanner limitations and artifacts. The average data set size is about 8 megabytes in Tagged Image File Format (TIFF) with PackBits compression. DRGs can be easily combined with other digital cartographic products such as DEMs and digital orthophoto quadrangles (DOQs). DRGs for

Texas have been developed and are being distributed by the USGS. More than 80 quadrangle maps are necessary to cover Texas.

Digital raster maps have been prepared by Horizons Technologies, Inc. by scanning the corresponding USGS topographic paper maps. Digital maps at a scale of 1:24,000 have been prepared for most of the United States. Twenty-one CD-ROMs are needed to cover the entire state of Texas at this resolution. Digital maps at a scale of 1:100,000 have also been prepared for the entire United States. Two CD-ROMs are required to cover the state of Texas: one for North Texas, Kansas and Oklahoma, and the other for South Texas. At this scale, maps show major streets, highways, freeways, parks, hospitals, airports, waterways of all kinds, topographic contour information, selected place names, as well as other cultural information. Contours are at intervals of 5, 10, 20 or 50 m, depending on terrain relief. In addition, digital maps at a scale of 1:250,000 have also been prepared for the entire United States. Five CD-ROMs are required to cover the United States. The *Midwest* CD-ROM includes the states of North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, New Mexico, Colorado, and Wyoming. At this scale, maps show county boundaries as well as state and federal reservations, major built-up areas, highway and water features, and limited topographic contour information.

The digital raster map of Texas at a scale of 1:2,000,000, prepared by Horizons Technologies, Inc., is included in the *Hydrologic Modeling in Texas Using GIS* CD-ROM (Figure 4.11 and 4.12).

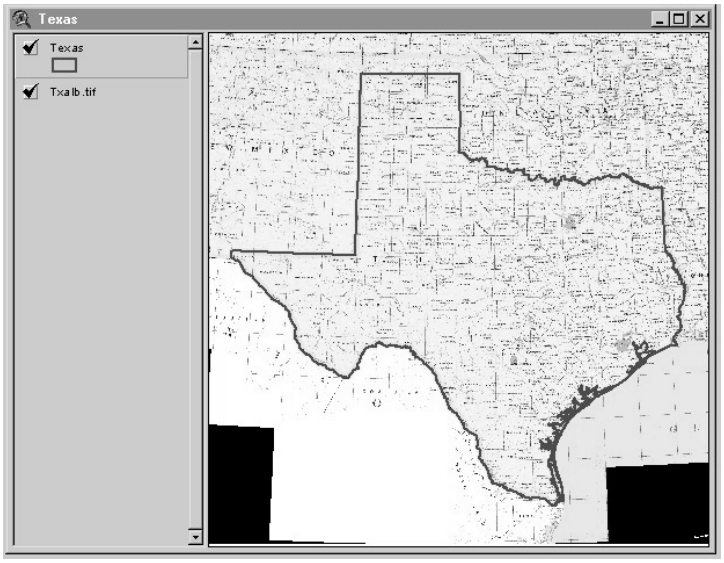


Figure 4.11 Digital Raster Map of Texas at a Scale of 1:2,000,000

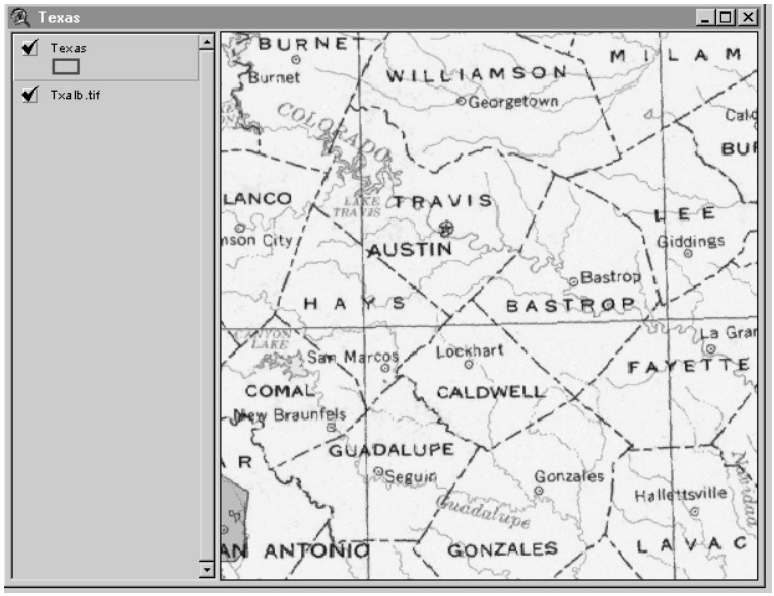


Figure 4.12 Detailed Digital Raster Map of Texas at a Scale of 1:2,000,000

CHAPTER 5. RASTER MAP OF POTENTIAL EXTREME PEAK DISCHARGES

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 has been prepared. According to the authors, 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, and therefore the other characteristics were not used for estimating potential extreme peak discharges. The authors do not mention in their report, however, other physical characteristics of the watershed that might affect how storm runoff is routed through the terrain, such as land use, soil type, or geology. 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).

5.1 METHODOLOGY

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 discussion of each part of the methodology is included below.

Documented extreme peak discharges for 619 sites with streamflow-gaging stations and 213 sites without streamflow-gaging 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 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 as 40 km 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. Peak discharge vs. drainage area plots for the eleven hydrologic regions of Texas are shown in Figures 5.1-5.11. The set of equations for each region is presented below the corresponding figures; Q is the potential extreme peak discharge in cubic feet per second (cfs) and A is the drainage area in square miles.

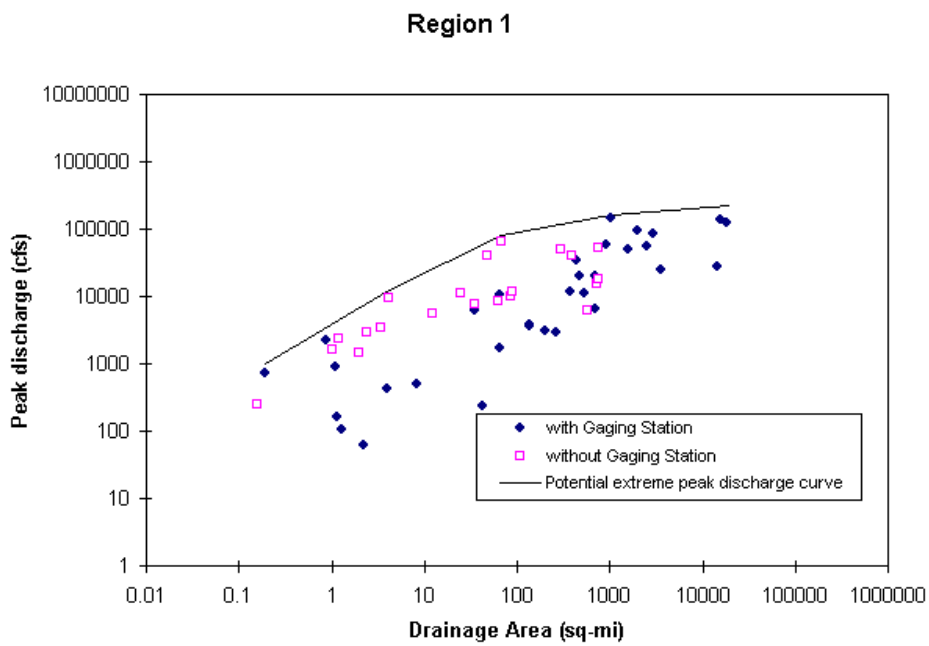


Figure 5.1 Peak Discharge vs. Drainage Area for Hydrologic Region 1 in Texas

Equations for Hydrologic Region 1:

$$\boldsymbol{Q} = 3{,}950\ \boldsymbol{A}^{0.83} \quad \textit{for}\ \boldsymbol{A} = 0 - 5\ \boldsymbol{sq.mi}.$$

$$\boldsymbol{Q} = 5{,}050\ \boldsymbol{A}^{0.65} \quad \textit{for}\ \boldsymbol{A} = 5 - 70\ \boldsymbol{sq.mi}.$$

$$\boldsymbol{Q} = 26{,}871\ \boldsymbol{A}^{0.26} \quad \textit{for}\ \boldsymbol{A} = 70 - 1000\ \boldsymbol{sq.mi}.$$

$$\boldsymbol{Q} = 71{,}072\ \boldsymbol{A}^{0.12} \quad \textit{for}\ \boldsymbol{A} > 1000\ \boldsymbol{sq.mi}.$$

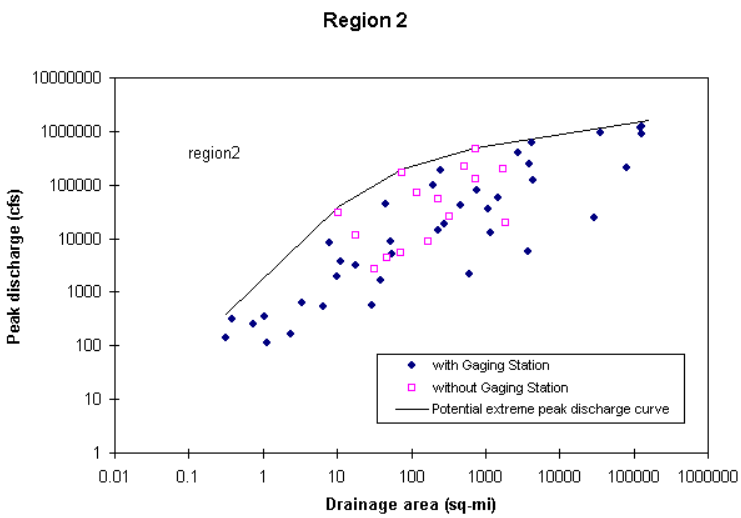


Figure 5.2 Discharge vs. Drainage Area for Hydrologic Region 2 in Texas

Equations for Hydrologic Region 2:

$$Q = 1{,}824\ A^{1.32} \quad for\ A = 0 - 10\ sq.mi.$$
$$Q = 6{,}017\ A^{0.81} \quad for\ A = 10 - 75\ sq.mi.$$
$$Q = 34{,}959\ A^{0.40} \quad for\ A = 70 - 1000\ sq.mi.$$
$$Q = 121{,}475\ A^{0.21} \quad for\ A > 1000\ sq.mi.$$

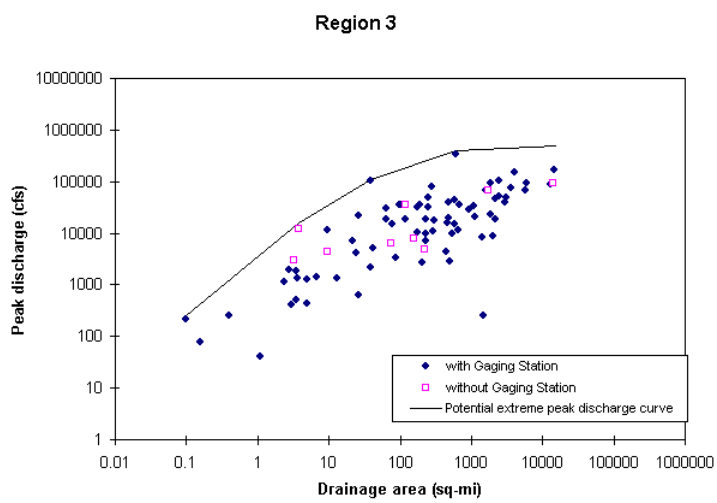


Figure 5.3 Discharge vs. Drainage Area for Hydrologic Region 3 in Texas

Equations for Hydrologic Region 3:

$$Q = 3{,}437\ A^{1.14} \quad for\ A = 0 - 4\ sq.mi.$$
$$Q = 5{,}108\ A^{0.84} \quad for\ A = 4 - 40\ sq.mi.$$
$$Q = 20{,}653\ A^{0.46} \quad for\ A = 40 - 1000\ sq.mi.$$
$$Q = 252{,}734\ A^{0.12} \quad for\ A > 1000\ sq.mi.$$

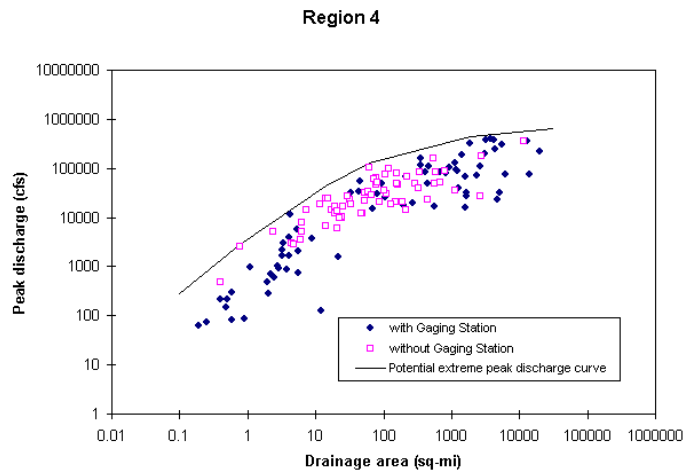


Figure 5.4 Discharge vs. Drainage Area for Hydrologic Region 4 in Texas

Equations for Hydrologic Region 4:

$$Q = 3{,}849\ A^{1.14} \quad for\ A = 0-1\ sq.mi.$$
$$Q = 3656\ A^{0.95} \quad for\ A = 1-15\ sq.mi.$$
$$Q = 6{,}939\ A^{0.71} \quad for\ A = 15-60\ sq.mi.$$
$$Q = 27{,}455\ A^{0.37} \quad for\ A = 60-1850\ sq.mi.$$
$$Q = 178{,}803\ A^{0.12} \quad for\ A > 1850\ sq.mi.$$

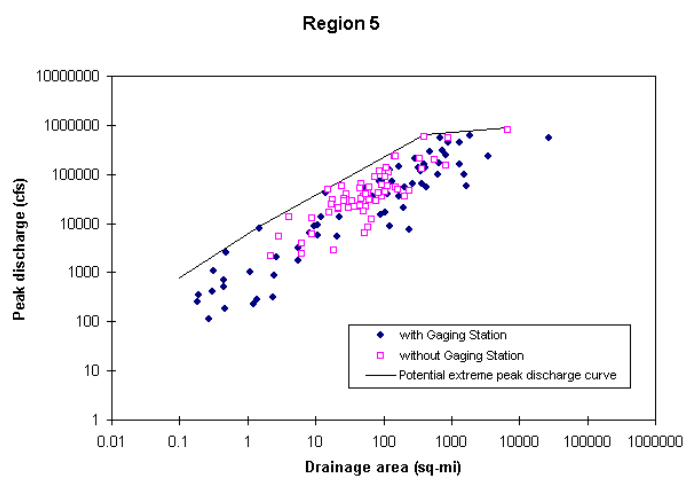


Figure 5.5 Discharge vs. Drainage Area for Hydrologic Region 5 in Texas

Equations for Hydrologic Region 5:

$$Q = 6{,}206\ A^{0.89} \quad for\ A = 0-1.5\ sq.mi.$$
$$Q = 6{,}544\ A^{0.76} \quad for\ A = 1.5-400\ sq.mi.$$
$$Q = 301{,}606\ A^{0.12} \quad for\ A > 400\ sq.mi.$$

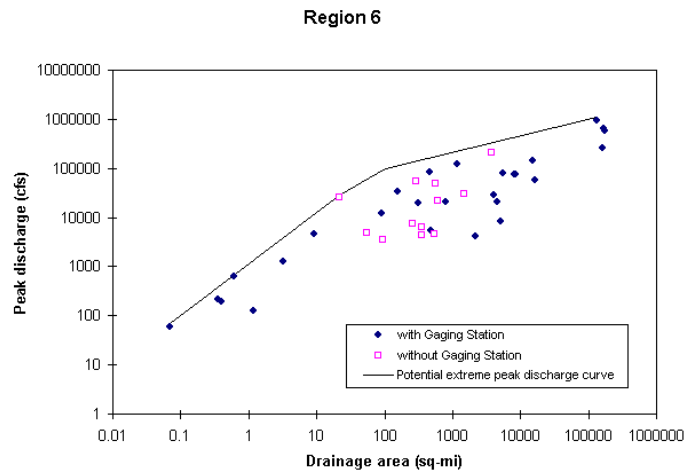


Figure 5.6 Peak Discharge vs. Drainage Area for Hydrologic Region 6 in Texas

Equations for Hydrologic Region 6:

$$Q = 1{,}146\ A^{1.05} \quad for\ A = 0 - 20\ sq.mi.$$

$$Q = 2{,}302\ A^{0.82} \quad for\ A = 20 - 100\ sq.mi.$$

$$Q = 21{,}255\ A^{0.34} \quad for\ A > 100\ sq.mi.$$

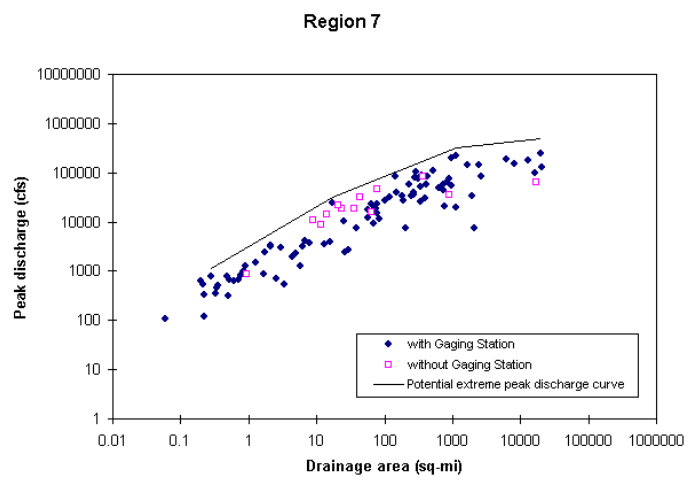


Figure 5.7 Peak Discharge vs. Drainage Area for Hydrologic Region 7 in Texas

Equations for Hydrologic Region 7:

$$Q = 3{,}168\ A^{0.82} \quad for\ A = 0 - 16\ sq.mi.$$

$$Q = 6{,}790\ A^{0.55} \quad for\ A = 16 - 1155\ sq.mi.$$

$$Q = 101{,}713\ A^{0.16} \quad for\ A > 1155\ sq.mi.$$

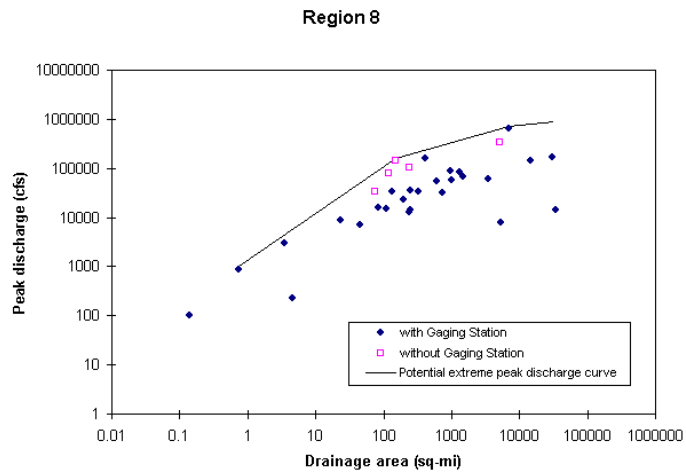


Figure 5.8 Peak Discharge vs. Drainage Area for Hydrologic Region 8 in Texas

Equations for Hydrologic Region 8:

$$Q = 1{,}318\ A^{0.96} \quad for\ A = 0 - 150\ sq.mi.$$

$$Q = 22{,}895\ A^{0.39} \quad for\ A = 150 - 7000\ sq.mi.$$

$$Q = 181{,}400\ A^{0.15} \quad for\ A > 7000\ sq.mi.$$

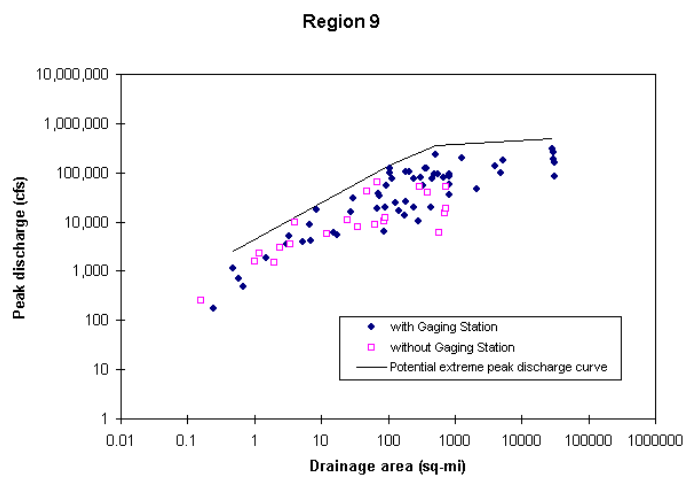


Figure 5.9 Peak Discharge vs. Drainage Area for Hydrologic Region 9 in Texas

Equations for Hydrologic Region 9:

$$Q = 4{,}345\ A^{0.75} \quad for\ A = 0 - 100\ sq.mi.$$

$$Q = 9{,}300\ A^{0.58} \quad for\ A = 100 - 500\ sq.mi.$$

$$Q = 207{,}940\ A^{0.09} \quad for\ A > 500\ sq.mi.$$

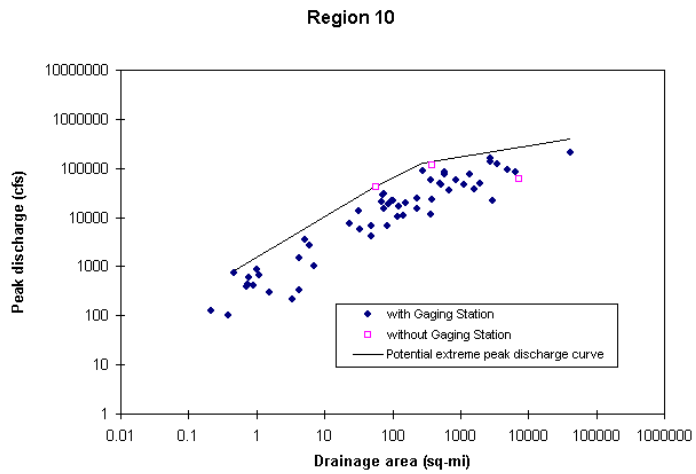


Figure 5.10 Peak Discharge vs. Drainage Area for Hydrologic Region 10 in Texas

Equations for Hydrologic Region 10:

$$\boldsymbol{Q} = 1{,}577\ \boldsymbol{A}^{0.82} \quad \textit{for}\ \boldsymbol{A} = 0 - 60\ \boldsymbol{sq.mi}.$$

$$\boldsymbol{Q} = 3{,}011\ \boldsymbol{A}^{0.66} \quad \textit{for}\ \boldsymbol{A} = 60 - 280\ \boldsymbol{sq.mi}.$$

$$\boldsymbol{Q} = 34{,}609\ \boldsymbol{A}^{0.23} \quad \textit{for}\ \boldsymbol{A} > 280\ \boldsymbol{sq.mi}.$$

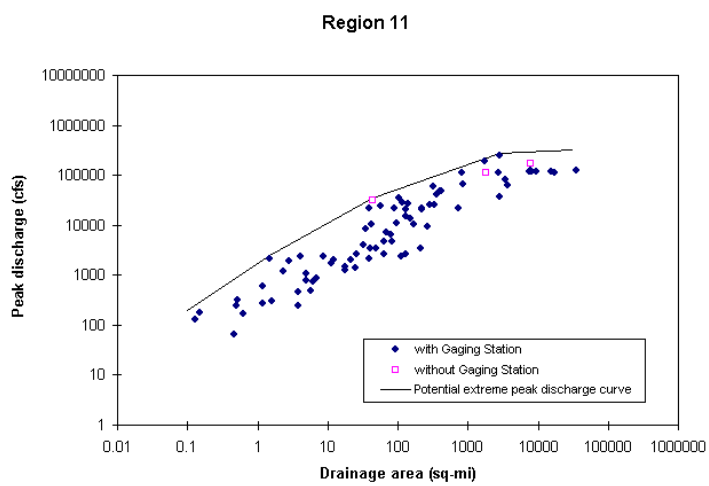


Figure 5.11 Peak Discharge vs. Drainage Area for Hydrologic Region 11 in Texas

Equations for Hydrologic Region 11:

$$\boldsymbol{Q} = 1{,}757\ \boldsymbol{A}^{0.94} \quad \textit{for}\ \boldsymbol{A} = 0 - 1.5\ \boldsymbol{sq.mi}.$$

$$\boldsymbol{Q} = 1{,}871\ \boldsymbol{A}^{0.78} \quad \textit{for}\ \boldsymbol{A} = 1.5 - 45\ \boldsymbol{sq.mi}.$$

$$\boldsymbol{Q} = 5{,}405\ \boldsymbol{A}^{0.50} \quad \textit{for}\ \boldsymbol{A} = 45 - 2800\ \boldsymbol{sq.mi}.$$

$$\boldsymbol{Q} = 193{,}327\ \boldsymbol{A}^{0.05} \quad \textit{for}\ \boldsymbol{A} > 2800\ \boldsymbol{sq.mi}.$$

The equations determined with this methodology apply to natural basins in which the peak discharges are not affected by regulation, reservoirs, diversions, urbanization, or other human-related activities. These equations, therefore, should not be applied to basins in close downstream proximity to reservoirs or cities.

The reader is referred to Asquith and Slade (1995) for detailed discussion of the methodology used to establish the relation between potential peak discharge, drainage area, and flood region.

Spatial data developed for Texas and used to calculate the drainage areas were obtained from different sources and processed in different forms, as explained below. Drainage area calculations for the entire state of Texas required additional spatial data developed for areas out of the state whose drainage flows into Texas (i.e., the southern part of Oklahoma, the western part of Louisiana, the eastern part of New Mexico, and the northern part of Mexico). In other words, the spatial data set required for this project covered all of the drainage basins contributing flow to the Gulf of Mexico, from the Sabine River to the Rio Grande. To assemble a consistent data set, all spatial data were projected into the Albers projection, and — additionally — raster data were defined at a cell size of 500 m to make it consistent with the United States 15-minute DEM. The topography of the study area was described by the United States 15-minute DEM and by the North American 30-minute DEM for the northern part of Mexico.

Starting from the DEM, hydrologic features of the terrain were determined using standard functions included in commercially available GIS software that operates on raster terrain data. In order to delineate accurate streams, the DEM was modified by *burning-in* the digitized streams. The digitized stream network used for burning-in was taken from EPA's River Reach file RF1. Next, the DEM was filled to eliminate spurious terrain pits; then, the flow direction of each cell was determined; and finally, the drainage area of each cell — in units of grid cells — was calculated. This process is discussed in further detail in Chapter 3.

The grid of hydrologic regions was produced by rasterizing the polygon coverage of hydrologic regions developed by the USGS. Scanned USGS maps of the state of Texas — at a scale of 1:2,000,000 — were used as background to facilitate the use of the GIS.

Finally, the drainage area grid, in units of the grid cells mentioned above, was multiplied by the grid cell area (0.0965 sq. mi.) to produce a drainage area grid in square miles. This methodology, used to calculate the drainage area, is more accurate when applied to large watersheds, in which the absolute errors tend to offset each other and 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 10 square miles or less would result in inaccurate drainage area calculations.

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

The resulting product of this work is a grid of precomputed potential extreme peak discharges that can be displayed and queried within GIS.

5.2 APPLICATION

The computation of the hydrologic parameters of the watershed becomes much faster and accurate when using a GIS developed for that specific purpose. Without using the GIS presented here, determination of potential extreme peak discharges would require manually delineating each watershed from topographic maps before applying the corresponding peak discharge equations. Because the calculation of the drainage areas has been automated, peak discharges can be calculated by clicking the point of interest on the map.

The spatial data developed for this application is stored in the *PEAKFLOW* folder of the *Hydrologic Modeling in Texas Using GIS* CD-ROM.

To query the values of the potential extreme peak discharge grid, ArcView is opened, the Spatial Analyst extension loaded, and the following themes added to a *View* window:

PFReg_Gr (grid of hydrologic regions), ***PFRegion*** (polygon coverage of hydrologic regions), ***Stations*** (point coverage of flow gaging stations), ***DA_SqMi*** (grid of drainage area in sq.mi.), ***DA_OK*** (grid of streams draining more that 10 sq.mi.), ***PeakFlow*** (floating point grid of peak flows in cfs), ***PF_Kcfs*** (integer grid of peak flows in thousands of cfs), and ***TxAlb*** (image of the 1:2,000,000 map of Texas). Themes should be displayed as necessary to ease the query of peak flows. Finally, with the ***PeakFlow*** or ***PF_Kcfs*** theme active, the *Identify* tool is used to query the peak flow values from the pre-computed grid.

Figure 5.12 shows the resulting screen after applying the GIS to a tributary of the Angelina River in Nacogdoches County in Texas. The arrow on the map points to the location at which the peak discharge has been calculated and the *Identify Results* window indicates a value of 152 (in thousands of cfs) for the potential extreme peak discharge. Results can be obtained almost instantaneously.

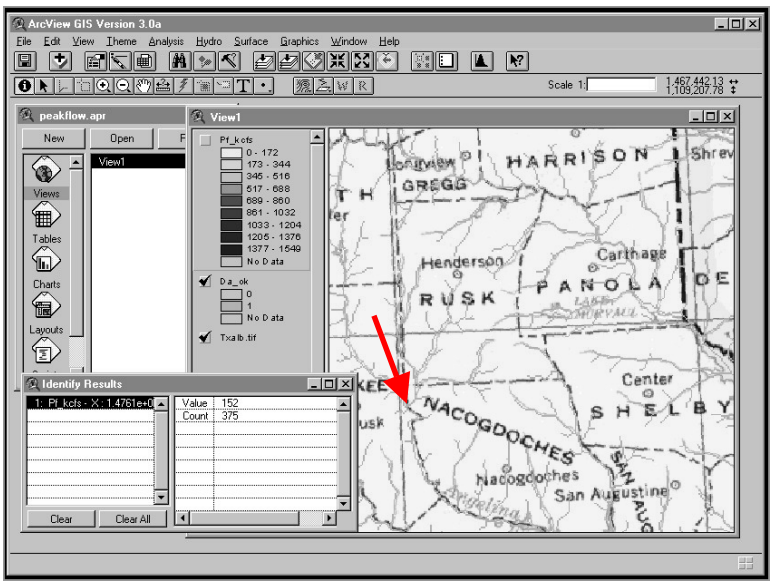


Figure 5.12 Query of potential extreme peak discharges from the pre-computed raster map. A potential extreme peak discharge of 152,000 cfs was obtained for the tributary of the Angelina River, in Nacogdoches County, Texas.

CHAPTER 6. FLOOD FLOW CALCULATOR

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 flowpath, slope of longest flowpath, 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's (1997) TxDOT Statewide Regional Rural Regression Equations. Isochrone lines are determined as the contour lines of a 3-D surface representing flowtimes to the watershed outlet, according to a velocity field defined previously. Runoff curve numbers are calculated from land use data, STATSGO soil data, and a look-up table that relates land use and percentage of hydrologic soil group with curve number.

The GIS has been developed independently of specific spatial data sets, and consequently can be applied to other regions if the required spatial database is prepared. However, changes in some of the scripts, 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 for application with other data sets. Likewise, peak discharge equations for the new study site would be necessary. All of these changes are minor modifications and by no means should be interpreted as a limitation in the applicability of the system.

The current version of the extension assumes meters as the horizontal units of the spatial data, feet as the vertical units of the DEM, and 500 meters as the cell size of the raster data. Likewise, because Asquith and Slade (1997) equations were considered, it applies only to Texas.

6.1 METHODOLOGY

The methodology of the ***Flood Flow Calculator*** ArcView extension has been subdivided into four sections: (1) determining watershed parameters, (2) determining peak discharges, (3) determining isochrone lines, and (4) determining runoff curve numbers. Each of these calculations is explained in detail in the following sections.

6.1.1 Determining Watershed Parameters

The spatial data developed for Texas were used in this case to determine the watershed parameters listed above. The topography of the study area was described by the United States 15-minute DEM, and by the North America 30-minute DEM for the northern part of Mexico, with vertical units of feet and horizontal units of meters, and projected into the Albers projection.

Starting from the DEM, hydrologic features of the terrain were determined using standard GIS functions that operate on raster terrain data. In order to delineate accurate streams, the DEM was modified by burning-in the digitized streams. The digitized stream network used for burning-in was taken from EPA's River Reach File RF1. Next, the DEM was filled to eliminate spurious terrain pits; the flow direction of each cell was determined; the drainage area of each cell — in units of grid cells — was calculated. Finally, the flow lengths downstream from each cell to the outlet, and upstream to the watershed divide, were determined.

For determining the watershed parameters, the GIS requires the following input data: raw DEM grid, burned-in DEM grid (optional), filled DEM grid, flow direction grid, flow accumulation grid, flow length upstream grid, flow length downstream 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.

At any location selected by the user (by clicking the mouse), the GIS delineates and creates a polygon coverage of the watershed. The watershed area is calculated as the flow accumulation value at the outlet (selected point) multiplied by the cell area. The longest flow path is identified as the set of cells within the watershed for which the sum of the upstream flow length plus the downstream flow length is a maximum (Smith 1995), and 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 defined 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 bounding 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, if the user selects one point that is 85% of the length of the longest flow path from the outlet and the other is 10% from the outlet, the distance between the two points will be 75% of the length of the longest flow path. 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.

6.1.2 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 United States were proposed by Jennings et al. (1994) in cooperation with the Federal Highway Administration and the Federal Emergency Management Agency.

According to Asquith and Slade (1997), peak discharges for natural basins in Texas are expressed as:

$$Q = a\ A^b\ SH^c\ SL^d \qquad \textbf{(6.1)}$$

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 were taken from the USGS (Asquith and Slade, 1997) regional equations.

6.1.3 Determining Isochrone Lines

Isochrone lines are a basic concept for modeling watershed responses when the spatial variability of the hydrologic system significantly affects its behavior. 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 calculates flow time. Therefore, before determining isochrone lines, a velocity field has to be defined. According to Maidment et al. (1996a), the flow velocity can be represented as

$$\boldsymbol{v = p\, A^q\, S^r} \qquad \textbf{(6.2)}$$

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 the velocity values are bound by minimum and maximum limits.

6.1.4 Determining Runoff Curve Numbers

The Soil Conservation Service (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 widespread because it allows one to estimate abstractions with relatively few data points. Runoff curve numbers depend on land use and soil properties.

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

With respect to the input data sets, the curve number script makes the following assumptions:

1. The attribute table of the soil polygon theme has fields *A-pct*, *B-pct*, *C-pct* and *D-pct*, which store the percentage of soil of each hydrologic soil group in the polygon (Figure 6.1).

Attributes of STATSGO Hydrologic Soil Group Percentage

Shape	Area	Statsgo#	Statsgo-id	A-pct	B-pct	C-pct	D-pct
Polygon	75214519.14337	2	488	0	76	15	9
Polygon	22580243.25861	3	489	0	64	29	7
Polygon	42040885.23668	4	490	2	62	0	36
Polygon	23767613.61345	5	491	0	64	29	7
Polygon	145636914.13935	6	493	1	98	1	0
Polygon	697174179.52854	7	492	0	88	4	8
Polygon	88240197.54008	8	494	2	62	0	36
Polygon	27489149.76845	9	497	0	24	16	60
Polygon	655824957.47657	10	495	0	64	29	7
Polygon	667393888.62752	11	498	0	24	16	60
Polygon	173584424.43211	12	499	0	88	4	8
Polygon	147802068.15238	13	501	2	62	0	36

Figure 6.1 Attribute Table of the Soil Polygon Theme with Fields A-Pct, B-Pct, C-Pct, and D-Pct

2. The attribute table of the land use theme has field *LUCode*, which stores a land use code (Figure 6.2). No standard land use code is required here, but it should be consistent with the look-up table mentioned below.

Attributes of Land Use

Shape	Area	Tplus#	Tplus-id	Lucode	Description
Polygon	436212.375	22	22	41	Deciduous_Forest
Polygon	1081715.000	23	20	43	Mixed-Forest
Polygon	88082456.000	24	10	32	Shrub-and-Brush
Polygon	731509.438	25	26	32	Shrub-and-Brush
Polygon	563979.938	26	27	32	Shrub-and-Brush
Polygon	1091327.875	27	25	43	Mixed-Forest
Polygon	2121895.500	28	28	43	Mixed-Forest
Polygon	301249.906	29	30	43	Mixed-Forest
Polygon	2186957.250	30	35	32	Shrub-and-Brush
Polygon	689712.063	31	0	0	Incase-of-zero
Polygon	2423884.500	32	32	43	Mixed-Forest
Polygon	197470.859	33	0	0	Incase-of-zero

Figure 6.2 Attribute Table of the Land Use Theme with Field Lucode

3. The look-up table records are identifiable uniquely by a *LUCode* field, and have fields *Hyd_A*, *Hyd_B*, *Hyd_C*, and *Hyd_D*, which store the curve number value for the hydrologic soil group defined by the field and the land use defined by the *LUCode* (Figure 6.3).

rcn.txt

Lucode	Des_a	Des_b	Hyd_a	Hyd_b	Hyd_c	Hyd_d
0	Incase-of-zero	data	100	100	100	100
11	Residential	Level_2	77	85	90	92
111	Residential	1/8_acre	77	85	90	92
112	Residential	1/4_acre	61	75	83	87
113	Residential	1/3_acre	57	72	81	86
114	Residential	1/2_acre	54	70	80	85
115	Residential	1_acre	51	68	79	84
116	Residential	2_acre	46	65	77	82
12	Urban_85%_imperv	Comm_&_business	89	92	94	95
13	Urban_72%_imperv	Industrial	81	88	91	93
14	Streets_&_roads	Level_2	98	98	98	98
141	Paved	parking_lots-roofs	98	98	98	98

Figure 6.3 Look-up Table for Relating Land Use and Hydrologic Soil Group with Curve Number Values

6.2 APPLICATION

The ***Flood Calculator*** ArcView extension and the sample spatial data developed for this application is stored in the *NFF* folder of the *Hydrologic Modeling in Texas Using GIS* CD-ROM.

To load the ArcView extension ***TxDOT1.avx*** and the necessary sample data, double click on the ***TxDOT.apr*** file icon within the Windows Explorer. The ***TxDOT1.avx*** extension can also be used independently from the ArcView project (and sample data) by storing it in the *Ext32* folder and loading it through the *Extensions* window. Once the ArcView project ***TxDOT.apr*** has been opened, display the themes as necessary to facilitate the identification of the catchment outlets.

Before determining the watershed parameters and peak discharges, the theme names of the input data sets must be entered. To do so, the user clicks on *TXDOT/Watershed Data* and populates the *Flood Flow Properties* window with the corresponding theme names. Next, the user clicks on the tool and then on the point corresponding to the watershed outlet. Figure 6.4 presents the report message box for Walnut Creek, a tributary of the Colorado River in Travis County, Texas. In this case, a drainage area of 148 km^2, a channel slope of 1.48 m/km, the length of longest flow path of 28.11 km, and a shape factor of 5.34 were calculated. An average curve number value of 83.81, according to the precomputed curve number grid, was also determined. This precomputed curve number grid is a very conservative data set recommended for worst-case scenarios only.

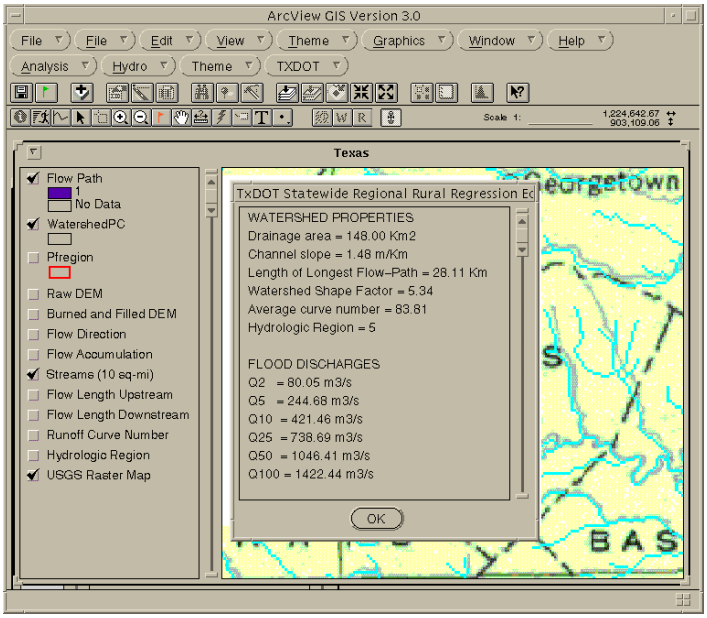


Figure 6.4 Report Message Box Generated by the Flood Flow Calculator Extension

Additionally, Figure 6.5 shows the delineated watershed and the longest flow path, so that not only the watershed parameters are calculated but also its shape and location.

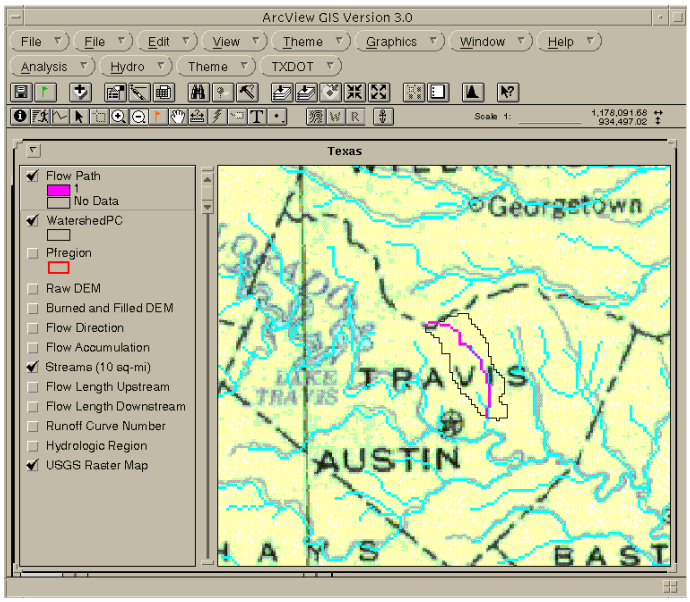


Figure 6.5 Drainage Area and Longest Flow path Generated by the Flood Flow Calculator Extension

Calculation of the isochrone lines consists of defining a velocity field and a flow-time grid. The user clicks on *TXDOT/Flow Velocity and Travel Time*, sets the analysis extent and cell size in the *Conversion Extent* window, and populates the *Input Parameters to Calculate Flow Velocity* window. Figure 6.6 presents the velocity field for Barton Creek, a tributary of the Colorado River in Travis County, TEXAS. The flow velocity was defined as

$$\boldsymbol{v} = 2\ \boldsymbol{A}^{0.5}\ \boldsymbol{S}^{0.5} \qquad \textbf{(6.3)}$$

where v is the flow velocity in m/s, S is the terrain slope in fraction, and A is the drainage area in km^2. Maximum and minimum values of 10 m/s and 0.1 m/s were used, although further calibration of the model might be necessary. It can be seen that, as expected, the main channel has a higher velocity, while sheet flow is relatively slow, even compared with small creeks.

Figure 6.6 Flow Velocity Field for Barton Creek in Travis County, Texas

Figure 6.7 shows the distribution of the flow time to the outlet; the changes in color within the grid represent isochrone lines. It can be seen that those cells that are close to the outlet or to the streams have shorter flow times, while those areas that undergo sheet flow for a long distance tend to have longer flow times.

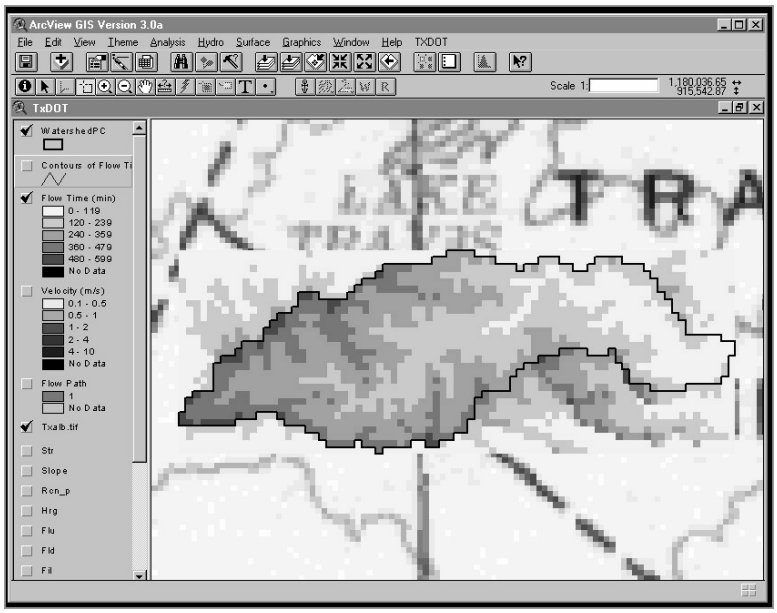


Figure 6.7 Flow-Time Distribution for Barton Creek in Travis County, Texas

Before determining curve number values, the theme names of the input data sets have to be entered. To do so, the user clicks on *TXDOT/Curve Number Data* and populates the *RCN Properties* window with the corresponding theme names. Next, the user clicks on *TXDOT/Curve Number Grid*, and sets the analysis extent and cell size in the *Conversion Extent* window for the curve number grid. Figure 6.8 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 grid, and is developed when the user has site-specific land use and soils data for the particular area of interest.

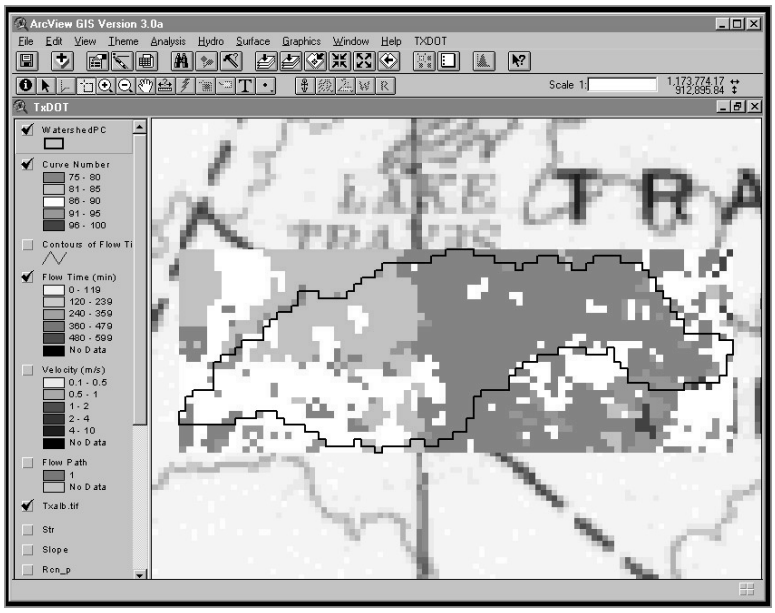


Figure 6.8 SCS Runoff Curve Number Grid for Barton Creek in Travis County, Texas

The ***Flood Flow Calculator*** extension also provides the capability of averaging grid values within polygons and storing these average values in a new field of the attribute table of the polygon theme (a message box also displays the average value on screen). To do so the user clicks on *TXDOT/Average Number* with the polygon and grid themes active. The new attribute table field and the text in the message box display the same grid theme name.

CHAPTER 7. RAINFALL RUNOFF MODEL

Rainfall runoff modeling and flood discharge estimation have always been important tasks in hydrologic sciences and engineering. Flood flow estimation, in particular, has been given special attention because of the impact that accurate forecasts have on the management of flood-related emergency programs. Probably more than other concerns in hydrology, the estimation of flood discharges is oriented toward saving human lives and protecting people's property.

The Hydrologic Modeling System (HMS), developed by the Hydrologic Engineering Center of the United States Army Corps of Engineers, is a software package used to model rainfall and runoff processes in a watershed or region, and is a further development of the well-known HEC program HEC-1. For rainfall runoff modeling, HMS requires three input components:

1. A *basin* component, which is a description of the different elements of the hydrologic system (sub-basins, channels, junctions, sources, sinks, reservoirs, and diversions) including their hydrologic parameters and topology.
2. A *precipitation* component, which is a description — in space and time — of the precipitation event to be modeled, and which consists of a time series of precipitation at specific points or areas and their relation to the hydrologic elements.
3. A *control* component, which defines the time window for the precipitation event and for the calculated flow hydrograph.

The first two components, basin and precipitation, depend strongly on spatial factors, so geographic information systems constitute a powerful tool to generate this type of input data.

CRWR-PrePro is a system of ArcView scripts and associated controls that was developed to extract topographic, topologic, and hydrologic information from digital spatial

data of a hydrologic system, and to prepare ASCII files for the basin and precipitation components of HEC-HMS. These files, when opened by HEC-HMS, automatically create: (1) a topologically correct schematic network of sub-basins and reaches attributed with hydrologic parameters, and (2) a protocol to relate gage to sub-basin precipitation time series.

HEC-HMS is a very flexible program that allows the user to choose among different loss rates, sub-basin routing scenarios, and baseflow models for the sub-basins, as well as different routing methods for the reaches. However, because some of these models and methods depend on hydrologic parameters that cannot be extracted from readily available spatial data, CRWR-PrePro does not estimate parameters for all of the methods supported by HEC-HMS. At the moment, CRWR-PrePro calculates or imports parameters for:

- The SCS curve number method and the initial plus constant loss method for loss rate calculations;
- The SCS unit hydrograph model for sub-basin routing for which the lag-time can be calculated with the SCS lag-time formula or as a fraction of the length of the longest channel divided by the flow velocity; and
- The Muskingum and lag methods for flow routing in the reaches (depending on the reach length).

SI units are required for all input data. Calculated parameters and HEC-HMS input files are also calculated in SI units. In terms of spatial data, this implies that horizontal and elevation units should be SI. Although the vertical units in DEMs can be easily converted from SI by multiplying the DEM values by 3.28 (to convert feet into meters), the conversion of horizontal units requires a reprojection of the DEM.

Using CRWR-PrePro, the determination of the spatial parameters for HEC-HMS is an automatic process that accelerates the development of a hydrologic model for HEC-HMS and leads to reproducible results.

Additional information regarding CRWR-PrePro, such as ArcView projects, parameter transfer tables, sample parameter tables, sample look-up tables, conference papers, slide presentations, tutorial exercises and tutorial movies, can be found in the *CRWR-PrePro: An ArcView Pre-processor for HEC's Hydrologic Modeling System (HMS)* CD-ROM.

7.1 PREVIOUS WORK

CRWR-PrePro is the synthesis of ArcView applications developed over the last years at the ESRI and CRWR. The *Watershed Delineator* ArcView extension (Djokic et al., 1997; ESRI 1997), developed by the Applications Programming group at ESRI for the Texas Natural Resources Conservation Commission (TNRCC), can be used to delineate watersheds to a point, line segment, or polygon, selected interactively by the user from a map. The ***Flood Flow Calculator*** ArcView extension (Olivera et al., 1997; Olivera and Maidment, 1998b), developed at the Center for Research in Water Resources (CRWR) for TxDOT, can be used to estimate flood peak flows according to the regional regression equations developed by Asquith and Slade (1997) for Texas. All hydrologic parameters required by these equations, such as drainage area, watershed shape factor, and slope of the longest flow path, are extracted automatically from the spatial data. ***HECPREPRO*** (Hellweger and Maidment, 1999), developed at the CRWR for the HEC, can be used to establish the topology of the hydrologic elements, and write an input ASCII file readable by HEC-HMS with all this information. CRWR-PrePro combines the terrain analysis capabilities of the ***Watershed Delineator*** with the hydrologic parameter calculation capabilities of the ***Flood Flow Calculator*** and the topologic analysis capabilities of ***HECPREPRO***, to develop a hydrologic modeling tool that prepares the input file for the HEC-HMS basin component. CRWR-PrePro uses code originally developed for the ***Watershed Delineator***, ***Flood Flow Calculator*** and ***HECPREPRO***, although modifications have been made to meet the specific needs of this system.

Additionally, precipitation interpolation methods, developed at CRWR and HEC, have been included in CRWR-PrePro for determining the HEC-HMS precipitation input

component. A Thiessen-polygon-based method (Dugger, 1997), developed at the CRWR, can be used to estimate sub-basin precipitation as a weighted average of gage precipitation. ***GridParm*** (HEC 1996), originally developed at HEC in AML and rewritten at CRWR as an Avenue script, can be used to determine parameters of precipitation cells for use with the ModClark sub-basin routing method of HEC-HMS. ModClark, a variation of the original Clark unit hydrograph model, has been developed for HEC-HMS as a sub-basin routing option suitable to support NEXRAD precipitation data.

7.2 METHODOLOGY

CRWR-PrePro generates data for the basin and precipitation input components of HEC-HMS.

7.2.1 Input Data for the HEC-HMS Basin Component

The process of generating input data for the basin component has been divided into six conceptual modules: (1) raster-based terrain analysis, (2) raster-based sub-basin and reach network delineation, (3) vectorization of sub-basins and reach segments, (4) computation of hydrologic parameters of sub-basins and reaches, (5) extraction of hydrologic sub-system (if necessary), and (6) topologic analysis and preparation of the HEC-HMS *basin file*.

7.2.1.1 Raster-Based Terrain Analysis

The raster-based GIS environment is very suitable for hydrologic modeling, mainly because raster systems have been used for years, achieving a mature understanding of the concept and facilitating the development of efficient and useful algorithms for terrain analysis. Grid systems are ideal for modeling topographically driven flow, because with this type of flow, flow directions do not depend on any time-dependent variables, such as flow or water depth. Consequently, raster-based GIS algorithms for hydrologic analysis have been developed (Jensen and Domingue, 1988; Jensen, 1991) and included in commercially available GIS software. Functions to delineate reaches and sub-basins that use Jensen and

Domingue's algorithms are available in ArcView 3.0a Spatial Analyst 1.1 through Avenue requests and also through the Hydrologic Modeling ArcView extension distributed by ESRI with the Spatial Analyst. Likewise, DEMs have been developed for different parts of the world at different resolutions (USGS a, USGS b, USGS c), and further developments of these data have been aimed towards improving its spatial resolution. Other spatial data sets such as land use and soil type have also been developed for different parts of the world.

Raster-based terrain analysis for hydrologic purposes uses Jensen and Domingue's (1988) algorithms. By running the ***flowdirection*** Avenue request, a single downstream cell — out of its eight neighbor cells — is defined for each terrain cell. This downstream cell is selected so that the descent slope from the cell is the steepest. Therefore, a unique path from each cell to the basin outlet is determined. This process produces a reach-network, with the shape of a spanning tree, that represents the paths of the watershed flow system. However, because a flow direction cannot be determined for cells that are lower than their surrounding neighbor cells, a process of filling the spurious terrain pits is necessary before determining the flow directions (ESRI 1992). Once the terrain depressions have been filled and the flow directions are known, the drainage area — in units of cells — is calculated with the ***flowaccumulation*** Avenue request. The flow accumulation grid stores the number of cells located upstream of each cell (the cell itself is not counted) and, if multiplied by the cell area, equals the drainage area. Figure 7.1 shows an example of how the ***flowdirection*** and ***flowaccumulation*** requests work when applied to a DEM.

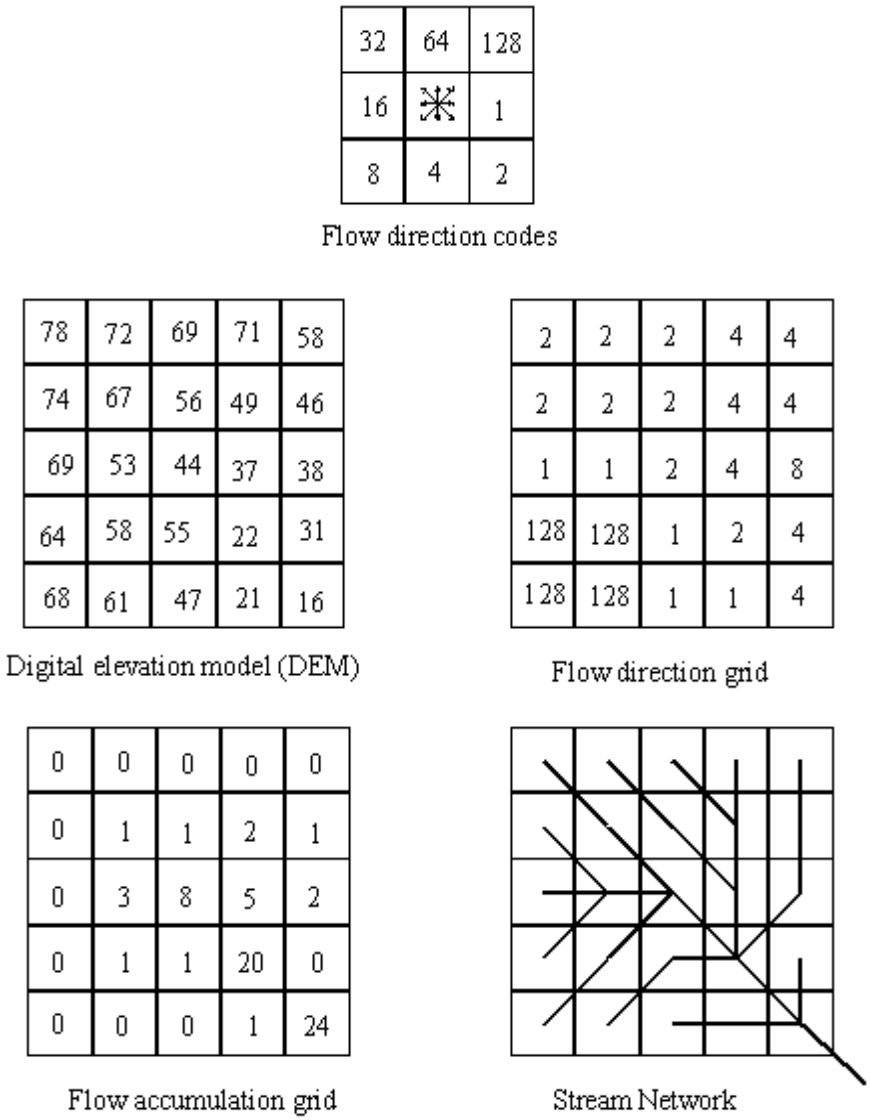


Figure 7.1 Raster-Based Functions for Terrain Analysis for Hydrologic Purposes

Modification of the DEM, to account for digitized stream data, is also supported by CRWR-PrePro through the stream-burning algorithm. If modification of the DEM is deemed necessary, it should be done prior to running the ***flowdirection*** and ***flowaccumulation*** requests.

7.2.1.2 Raster-Based Sub-Basin and Reach Network Delineation

The DEM cells that form each reach are defined as the union of two sets of grid cells. The first set consists of all cells whose flow accumulation is greater than a user-defined threshold value. This set identifies the reaches with the largest drainage area, but not necessarily with the largest flow because flow depends on other variables that are not related exclusively to topography. The second set is defined interactively by the user by clicking on a certain point on the map, which results in an automatic selection of all downstream cells. This capability allows the user to select a particular reach that might have a small drainage area (low flow accumulation), without having to lower the threshold value for the entire system or unnecessarily define a denser reach network. After the reach cells have been defined, a unique identification number, *grid code,* is assigned to each reach segment. Figure 7.2 shows threshold-based and user-defined reaches, as well as their corresponding reach segments. On the lefthand-side of the figure, blue cells correspond to drainage areas greater than 3000 grid cells, whereas red cells are defined interactively. On the righthand-side of the figure, each reach segment has been identified with a different grid code and displayed with a different color.

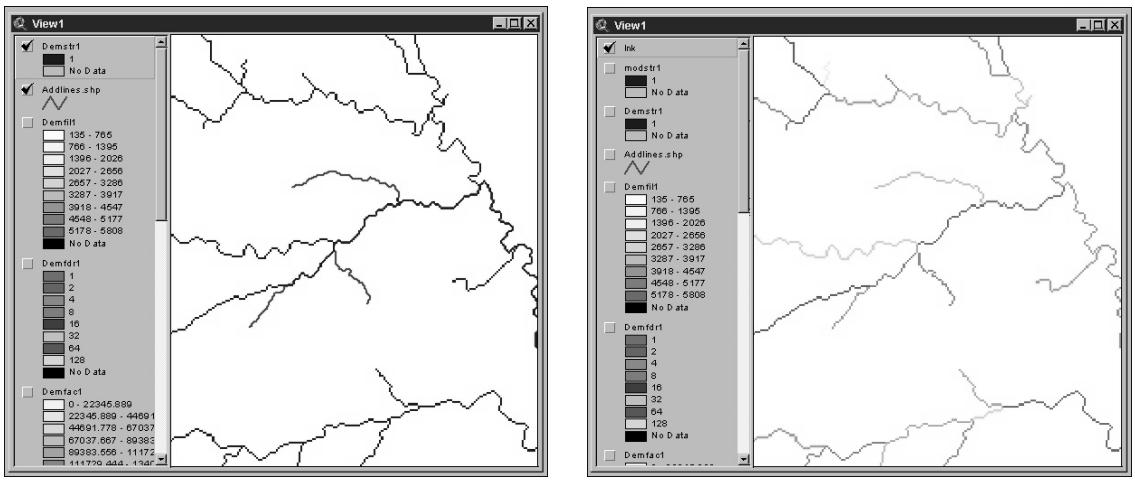


Figure 7.2 Reach Network Delineation

Sub-basin outlets are also defined as the union of two sets of grid cells. The first set, based on the reach network, consists of all cells located just upstream of the junctions. Consequently, at a junction, two outlet cells are identified, one for each of the upstream branches. The system outlet is also identified as a sub-basin outlet. Since these outlets are the most-downstream cells of the reach segments, their grid code is the same as their corresponding reach segment. The second set is defined interactively by the user by clicking on any cell of the reach network, such as those associated with flow gages, reservoirs, or other water control points. The grid code of each new interactively-defined outlet is obtained by adding one to the highest grid code value available. Reach segments containing interactively-defined outlets are subdivided at the clicked cells, so that the new segments — upstream of the new outlets — are assigned the same grid code as their corresponding new outlet. Outlets associated with reservoirs can be identified so that HEC-HMS recognizes them as both reservoirs and sub-basin outlets. Figure 7.3 shows threshold-based and user-defined outlets, as well as the corresponding reach segments. On the lefthand-side of the figure, blue cells represent the stream network in raster format, colored cells the sub-basin outlets located just upstream of the junctions, and red dots interactively-defined outlets. On the righthand-side of the figure, each stream segment is displayed in a different color, and segments containing red dots have been subdivided into two or more segments.

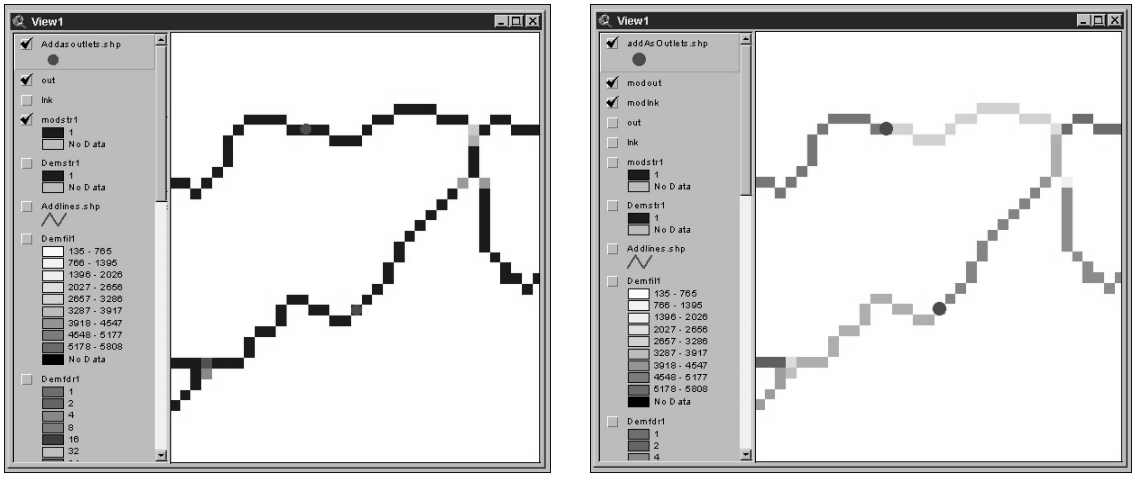


Figure 7.3 User-Defined Sub-Basin Outlets

The ***watershed*** Avenue request is then used to delineate the areas draining to each sub-basin outlet. Sub-basins are assigned the same grid code as their corresponding outlet and reach segment. Figure 7.4 shows the delineated sub-basins and reach network in raster format.

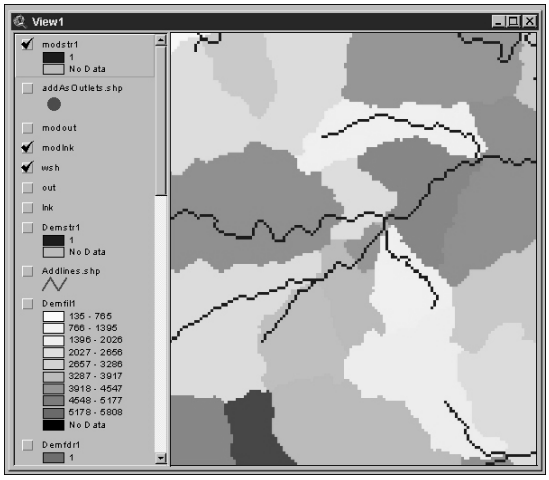


Figure 7.4 Delineated Sub-Basins and Reach Network in Raster Format

At this point, a one-to-one relation between reach segments and sub-basins is maintained because a unique sub-basin outlet has been identified for each reach segment. Because of this one-to-one relation, the grid code of each sub-basin and its corresponding reach segments are the same.

7.2.1.3 Vectorization of Sub-Basins and Reach Segments

Because HEC-HMS applies lumped models within each hydrologic element, hydrologic parameters have to be calculated for the sub-basins and reach segments, and not for the individual grid cells. After the reach segments and their corresponding drainage areas have been delineated in the raster domain, a vectorization process is performed using raster-to-vector conversion functions. This process consists of creating a polyline feature data set of reaches, and a polygon feature data set of sub-basins. When doing so, the grid code values are transferred to the attribute tables of the feature data sets, thus preserving a method to directly link sub-basins and reaches.

A common problem in this vectorization process consists of sub-basins represented by more than one polygon. This situation occurs when a group of grid cells of a sub-basin is connected to the main set of cells of the sub-basin only through a corner or through a side (Figure 7.5). In such a case, the dangling set of cells will be recognized as a different polygon, thus creating a second polygon for the same sub-basin (with the same grid code). Merging of all polygons of a sub-basin into one polygon is necessary to ensure that each sub-basin is represented by a single polygon, and that the one-to-one reach/sub-basin relation established in the raster domain is preserved in the vector domain.

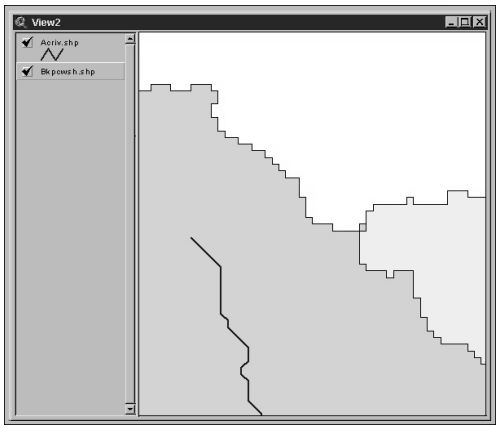


Figure 7.5 Dangling Cells of a Sub-Basin in the Vector Domain

Figure 7.6 shows the delineated sub-basins and reach network after vectorization.

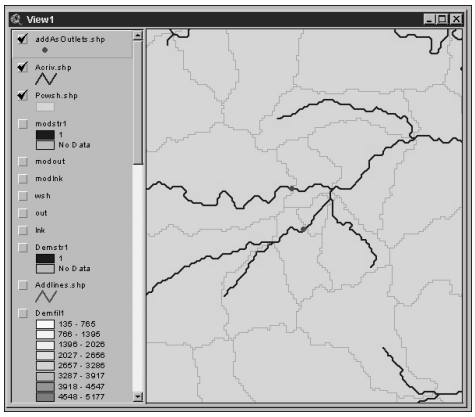
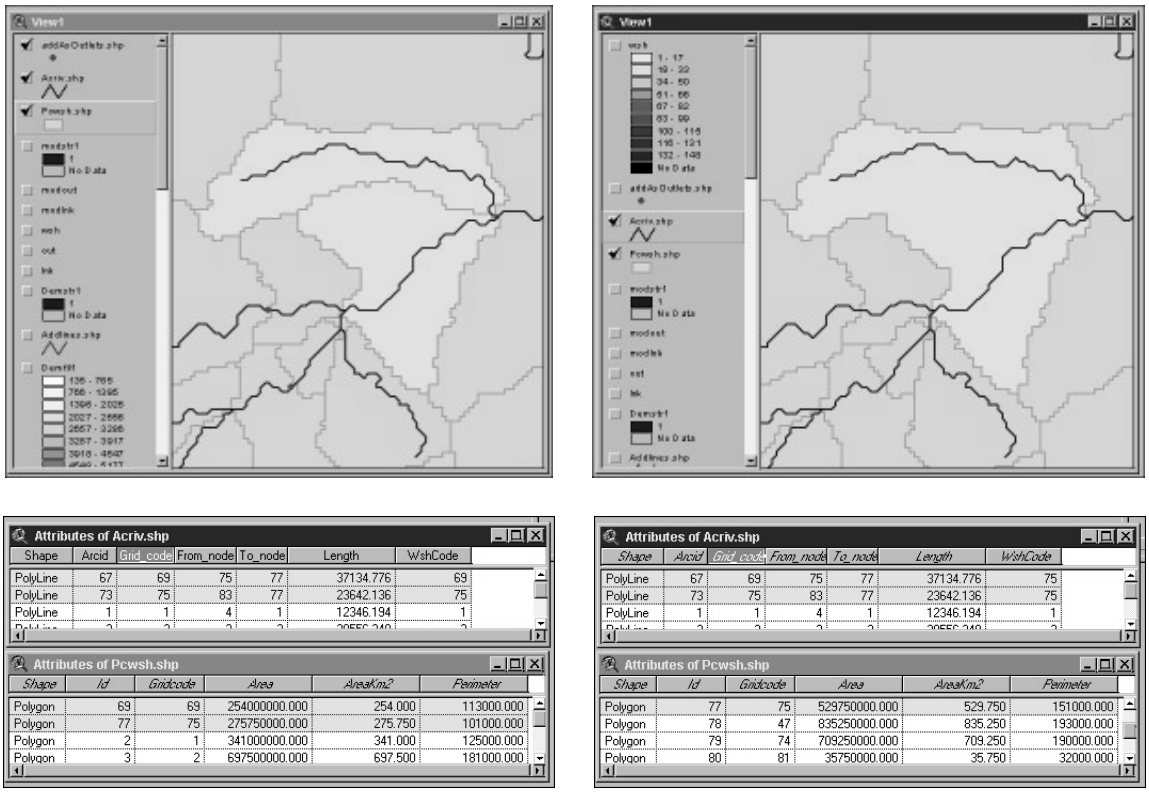


Figure 7.6 Delineated Sub-Basin Polygons and Reach Network Polylines after Vectorization

The one-to-one reach/sub-basin relation can be relaxed by merging adjacent sub-basin polygons, so that a sub-basin contains more than one reach. In such a case, a new field is necessary in the attribute table of each reach to account for the grid code of the sub-basin in which the reach is located after merging the polygons. For merging two sub-basins, the polygons have to share the same outlet or drain one toward the other. Figure 7.7 shows the merging of two sub-basins that share the same outlet, as well as the attribute tables of the

sub-basin and reach network data sets before and after the merging. In this case, the two merged polygons share a common outlet.



Before Merging **After Merging**

Figure 7.7 Sub-Basin Polygons and Attribute Tables before and after Merging Polygons

CRWR-PrePro also has the capability of identifying, for each sub-basin polygon, all the sub-basin polygons located upstream of it, so that they can be easily retrieved when delineating a watershed from a point.

7.2.1.4 Computation of Hydrologic Parameters of Sub-Basins and Reaches

The sub-basin parameters calculated by CRWR-PrePro are: (1) area, (2) lag-time, and (3) average curve number. The other parameters needed for estimating the lag-time, such

as length, and slope of the longest flow path, are also calculated and stored in the sub-basin attribute table. The calculation of lag-time might depend entirely on spatial data (i.e., DEM, land use, and soils), or it might require additional externally supplied input, depending on the algorithm. The average curve number can be used to calculate the sub-basin lag-time and the sub-basin loss rate, depending on the method selected. Figure 7.8 shows the attribute table of the sub-basins data set with the calculated hydrologic parameters appended. The appended fields are comprised of: the area in km^2 (Areakm2), the length of the longest flow path (Lngflwpth), the slope of the longest flow path (Slope), the baseflow method (Baseflow), sub-basin routing method (Transform), average curve number (Curvenum), and sub-basin lag-time (Lagtime).

Attributes of Pcwsh.shp

Shape	Id	Gridcode	Area	AreaKm2	Perimeter	LngFlwPth	Slope	Baseflow	Transform	CurveNum	LagTime
Polygon	25	28	486750000.000	486.750	198000.000	51334.5078	0.0035	None	SCS	85.6119	1615.3280
Polygon	40	29	820500000.000	820.500	192000.000	70183.7344	0.0026	None	SCS	81.0727	2804.3778
Polygon	24	30	418500000.000	418.500	106000.000	35727.9258	0.0038	None	SCS	82.4433	1292.8682
Polygon	33	31	509250000.000	509.250	155000.000	46041.9375	0.0040	None	SCS	84.0697	1461.6324
Polygon	31	32	85000000.000	85.000	54000.000	18985.2813	0.0023	None	SCS	85.2711	910.0928
Polygon	30	33	64750000.000	64.750	53000.000	16363.9600	0.0030	None	SCS	85.5036	701.7632
Polygon	29	34	291000000.000	291.000	97000.000	31263.4609	0.0044	None	SCS	83.3809	1046.6376
Polygon	41	35	625500000.000	625.500	171000.000	59526.8906	0.0031	None	SCS	88.5953	1729.0834

Figure 7.8: Sub-Basin Attribute Table Showing the Calculated Hydrologic Parameters Stored in Appended Fields

The sub-basin area is calculated automatically in the process of vectorizing the sub-basin polygons.

The sub-basin lag-time can be calculated with either of the following formulas, depending on the user's selection

$$\boldsymbol{t_p} = \max\left(\frac{\boldsymbol{L_W}^{0.8}\left[(1000/\boldsymbol{CN})-9\right]^{0.7}}{31.67\,\boldsymbol{S}^{0.5}},\ 3.5\,\Delta\boldsymbol{t}\right) \qquad \textbf{(7.1)}$$

$$\boldsymbol{t_p} = \max\left(0.6\,\frac{0.3048\,\boldsymbol{L_W}}{60\,\boldsymbol{v_W}},\ 3.5\,\Delta\boldsymbol{t}\right) \qquad \textbf{(7.2)}$$

where t_p (minutes) is the sub-basin lag-time measured from the centroid of the hyetograph to the peak time of the hydrograph, L_w (feet) is the length of the longest flow-

path, S (%) is the slope of the longest flow-path, CN is the average curve number in the sub-basin, t (min) is the analysis time-step, and v_w (m/s) is a representative velocity in the longest flow-path. In equation (7.1), the first term in the parentheses corresponds to the lag-time according to the SCS (1972), whereas the second term is a minimum lag-time value required by HEC-HMS (HEC 1990). In equation (7.2), the first term corresponds to the lag-time defined as 60% of the sub-basin time of concentration, and again the second term is a minimum lag-time value required by HEC-HMS.

The longest flow path of a sub-basin is identified as the set of cells for which the sum of the downstream flow length to the outlet plus the upstream flow length to the drainage divide is a maximum (Smith 1995). As can be seen in Figure 7.9, the lines in red represent the upstream flow length to the drainage divide, while these red lines combined with the blue lines represent the downstream flow length to the outlet.

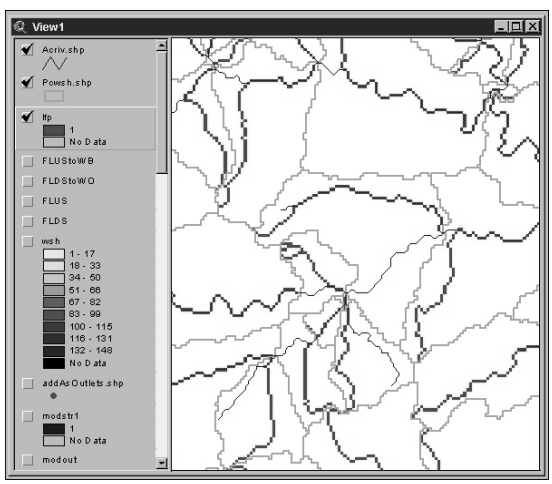


Figure 7.9 Longest Flowpath of Watershed

The downstream flow length to the sub-basin outlet is equal to the distance along the flow path from the grid cell to the outlet of the sub-basin in which the cell is located (Figure 7.10). After running the (downstream) flowlength Avenue request — which calculates the flow distance to the border of the analysis window or to the closest nodata cell (whichever is

found first) — the downstream flow length to the sub-basin outlet is calculated as the difference between the flow length value of the cell minus the flow length value of its corresponding outlet cell.

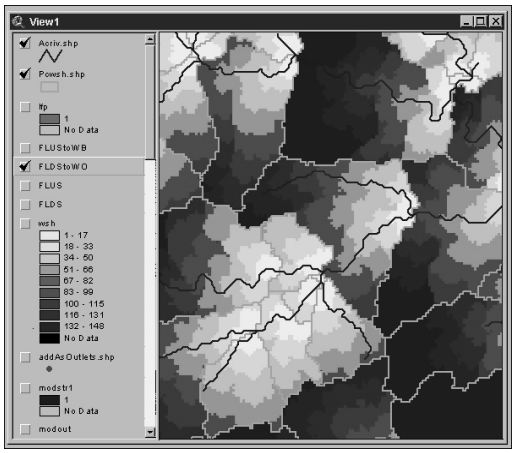


Figure 7.10 Flow Length Downstream to Watershed Outlet

The upstream flow length to the drainage divide is equal to the distance along the flow path from the grid cell to the most-upstream location within its sub-basin, and does not necessarily follow the main channel (Figure 7.11). After assigning nodata values to all sub-basin outlet cells, the (upstream) flowlength Avenue request — which calculates the flow distance to the most upstream cell of the analysis window or to the closest nodata cell (whichever is found first) – is used to calculate the upstream flow length to the sub-basin boundary. Nodata values are assigned to the sub-basin outlets to keep the flowlength request from searching for longer flow-paths in the upstream sub-basins.

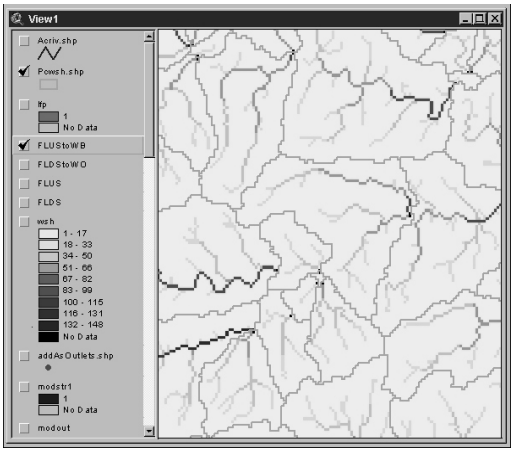


Figure 7.11 Flow Length Upstream to Watershed Boundary

The length of the longest flow path Lw is equal to the maximum value of the sum of the downstream flow length to the sub-basin outlet plus the upstream flow length to the drainage divide. The slope of the longest flow path S is determined as the elevation drop between two arbitrarily defined points of the flow path, divided by their distance along the channel. The points can be located at any user-defined distance from the sub-basin outlet, expressed as a percentage of the length of the longest flow-path. For instance, if the user selects one point that is 85% of the length of the longest flow path from the outlet and the other is 10% from the outlet, the distance between the two points will be 75% of the length of the longest flow-path. The raw DEM, not the burned DEM, should be used to calculate the elevation drop in the flow path, because the most upstream point of the channel might be located off the burned streams. Inconsistencies might arise from this process (i.e., flat or negative slopes), which are a consequence of the stream burning. A minimum slope value of 0.001 has been set as a lower limit to avoid problems in the ensuing calculations.

Values of *vw* cannot be estimated from spatial data and have to be supplied by the user.

CN is calculated as the average of the curve number values within the sub-basin polygon. A curve number grid is calculated using land use data described by Anderson land use codes, percentage of hydrologic soil group (A, B, C and D) according to STATSGO soils

data, and a look-up table that relates land use and soil group with curve numbers (Smith 1995).

Traditionally, curve numbers were calculated as a single lumped parameter for the watershed. A lumped curve number value, though, is not intrinsically wrong given that curve numbers are parameters of a lumped abstractions model. However, an inconvenience arises when the curve number of a sub-basin is to be calculated, and no information on the spatial variability of land use and hydrologic soil group within the basin has been recorded when calculating its curve number. In such a case, little can be used of the information extracted for the larger basin. Additionally, lumped curve numbers are scale dependent parameters since they relate to the overall conditions in the basin and on the definition of the basin itself, instead of relating exclusively to the local conditions (land use and soils). A more appropriate method to calculate curve numbers, that addresses the problem of scale dependency, consists of developing a curve number map — either in raster or vector format — that stores local curve numbers. Local curve numbers, in turn, are used for calculating average curve numbers for any defined area or watershed.

The tools included in CRWR-PrePro for calculating curve numbers allow the creation of raster curve number maps at a user-defined resolution. The spatial data needed are land use and soils. A look-up table that relates land use and hydrologic soil group to curve number values is also required. Land use data store a description of the land use within the polygon (Figure 7.12), while soils data store the percentage of each hydrologic soil group within the polygon (Figure 7.13). In Figure 7.12, the second and third fields of the table correspond to second and first level Anderson's land use codes. In Figure 7.13, the second through fifth fields of the table correspond to the percentage of soil groups A, B, C, and D.

Land Use

Shape	Land use - Level 2	Land use - Level 1
Polygon	42	4
Polygon	43	4
Polygon	42	4
Polygon	43	4
Polygon	43	4
Polygon	43	4
Polygon	33	3
Polygon	85	8
Polygon	43	4
Polygon	32	3
Polygon	41	4
Polygon	43	4

Figure 7.12 Attribute Table of the Land Use Map

Soils

Shape	A %	B %	C %	D %
Polygon	0	76	15	9
Polygon	0	64	29	7
Polygon	2	62	0	36
Polygon	0	64	29	7
Polygon	1	98	1	0
Polygon	0	88	4	8
Polygon	2	62	0	36
Polygon	0	24	16	60
Polygon	0	64	29	7
Polygon	0	24	16	60
Polygon	0	88	4	8
Polygon	2	62	0	36

Figure 7.13 Attribute Table of the Soil Map

Land use polygons intersected with soil polygons (red lines) create a new map in which each polygon is related to a unique combination of land use and soil type (Figure 7.14). Each resulting polygon corresponds to a unique combination of land use and soil type. The data corresponds to downtown Austin, Texas.

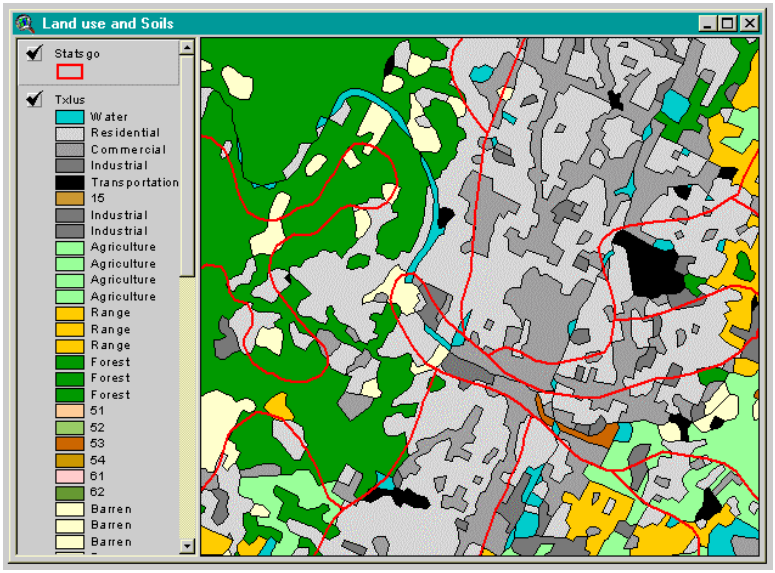


Figure 7.14 Intersection of STATSGO Soil Polygons with Land Use Polygons

Each of these polygons is then assigned a curve number value according to a look-up table (Figures 7.15 and 7.16). In Figure 7.16 the land use and soil polygons are displayed for reference purpose only.

rcn.txt

Anderson	Land use	Land use (detail)	A	B	C	D
0	Incase-of-zero	data	100	100	100	100
11	Residential	Level_2	77	85	90	92
111	Residential	1/8_acre	77	85	90	92
112	Residential	1/4_acre	61	75	83	87
113	Residential	1/3_acre	57	72	81	86
114	Residential	1/2_acre	54	70	80	85
115	Residential	1_acre	51	68	79	84
116	Residential	2_acre	46	65	77	82
12	Urban_85%_imperv	Comm_&_business	89	92	94	95
13	Urban_72%_imperv	Industrial	81	88	91	93
14	Streets_&_roads	Level_2	98	98	98	98
141	Paved	parking_lots-roofs	98	98	98	98
142	Streets_&_roads	Paved-curbs/gutter	98	98	98	98
143	Streets_&_roads	Paved-open-ditches(w/ROW)	83	89	92	93

Figure 7.15 Look-Up Table Relating Land Use and Hydrologic Soil Group with Curve Number Value

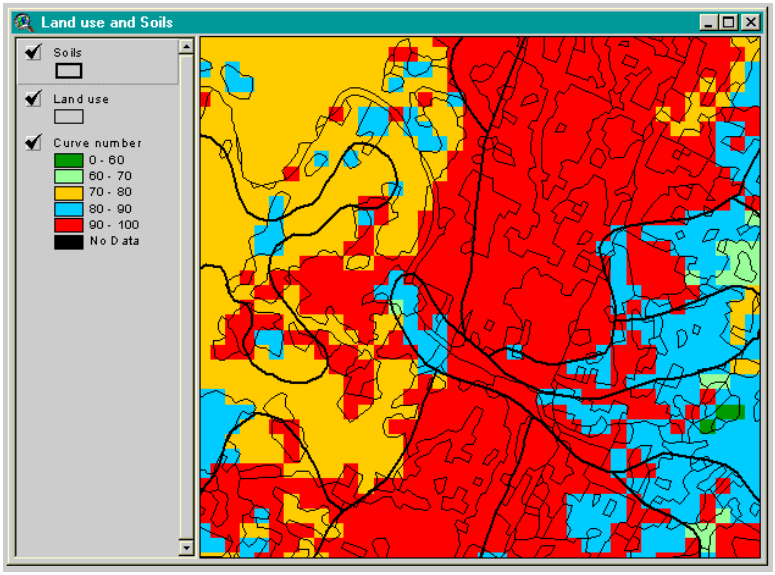


Figure 7.16 Curve Number Map Generated with CRWR-PrePro

Curve number maps generated with CRWR-PrePro are as accurate as the input data. Since land use and soils data are continuously being improved, these tools allow straightforward revision of the curve number maps in the future.

Loss rate in the sub-basins can be calculated with either the SCS curve number method or the initial plus constant loss rate method (for which the initial and constant rate values have to be supplied by the user). It is likely that in the near future it will be possible to establish a relationship between terrain properties and loss rate parameters.

The reach parameters determined by CRWR-PrePro are the length, the routing method (either Muskingum or pure lag), the Muskingum K, and either the number of sub-reaches into which the reach is subdivided (in the case when Muskingum is used for routing) or the flow time (in the case when pure lag is used for routing). Other reach parameters like the flow velocity and the Muskingum X cannot be computed from spatial data and must be supplied by the user. Figure 7.17 shows the attribute table of the reach network data set with the following calculated hydrologic parameters appended: reach velocity (StreamVel), Muskingum X (MuskX), reach routing method (Route), reach flow time in hours or Muskingum K (MuskK), number of sub-reaches (NumReachN), reach flow time in minutes

or lag-time (LagTime). The reach length L (m) is determined automatically in the process of reach vectorization.

Attributes of Acriv.shp

Shape	Arcid	Grid_code	From_node	To_node	Length	WshCode	StreamVel	MuskX	Route	MuskK	NumReachN	LagTime
PolyLine	1	1	4	1	12346.194	1	1.0	0.2	Muskingum	3.4295	2	0.0000
PolyLine	2	2	3	2	28556.349	2	1.0	0.2	Muskingum	7.9323	3	0.0000
PolyLine	3	3	5	12	22788.582	3	1.0	0.2	Muskingum	6.3302	3	0.0000
PolyLine	4	8	11	12	1560.660	8	1.0	0.2	Lag	0.0000	0	26.0110
PolyLine	5	4	8	15	20235.281	4	1.0	0.2	Muskingum	5.6209	2	0.0000
PolyLine	6	12	16	15	4457.107	12	1.0	0.2	Muskingum	1.2381	1	0.0000
PolyLine	7	5	7	17	52412.951	5	1.0	0.2	Muskingum	14.5592	5	0.0000
PolyLine	8	9	12	17	8414.214	9	1.0	0.2	Muskingum	2.3373	1	0.0000
PolyLine	9	15	18	19	750.000	15	1.0	0.2	Lag	0.0000	0	12.5000
PolyLine	10	18	21	22	1060.660	19	1.0	0.2	Lag	0.0000	0	17.6777

Figure 7.17 Reach Attribute Table Showing the Calculated and Appended Fields

The Muskingum method is used for routing in reaches long enough not to present numerical instability problems. In short reaches, in which the flow time is shorter than the time-step, the pure lag method is used. In very long reaches, again to avoid numerical instability, reaches are subdivided into shorter equal-length sub-reaches, so that the flow time in each of them satisfies the condition:

$$2\,\boldsymbol{X}\,\boldsymbol{k} < \Delta\boldsymbol{t} < \boldsymbol{k} \qquad \textbf{(7.3)}$$

(HEC 1990), where X is the Muskingum parameter and k (min) is the flow time in the sub-reach. Since the flow time in the sub-reaches is equal to:

$$\boldsymbol{k} = 60\,\boldsymbol{K}\,/\,\boldsymbol{n} = (\boldsymbol{L}\,/\,60\,\boldsymbol{v})\,/\,\boldsymbol{n} \qquad \textbf{(7.4)}$$

where K (hrs) is the flow time in the reach, v (m/s) is the reach flow velocity, and n (an integer value greater than zero) is the number of sub-reaches, then it follows that:

$$2\,\boldsymbol{X}\,\frac{\boldsymbol{L}\,/\,60\,\boldsymbol{v}}{\Delta\boldsymbol{t}} < \boldsymbol{n} < \frac{\boldsymbol{L}\,/\,60\,\boldsymbol{v}}{\Delta\boldsymbol{t}} \qquad \textbf{(7.5)}$$

Moreover, because n should be at least equal to 1, $L/60v$ should be greater than t, otherwise the pure lag method must be used as mentioned above. Thus, the minimum number of sub-reaches into which the reach should be subdivided is given by:

$$\boldsymbol{n} = \mathrm{int}\left(2\,\boldsymbol{X}\,\frac{\boldsymbol{L}\,/\,60\,\boldsymbol{v}}{\Delta\boldsymbol{t}}\right) + 1 \qquad \textbf{(7.6)}$$

whereas the maximum number of sub-reaches is given by:

$$\boldsymbol{n} = \text{int}\left(\frac{\boldsymbol{L}/60\,\boldsymbol{v}}{\Delta \boldsymbol{t}}\right) \qquad \textbf{(7.7)}$$

where *int* takes the integer part of the argument (*int* does not round the number). To avoid unnecessary computations, the number of sub-reaches is taken as the minimum value given by Equation 7.6.

K (hrs) for the Muskingum method is equal to *L/3600v*, and the lag-time (min) for the pure lag method is equal to *L/60v*.

As mentioned above, at present CRWR-PrePro supports only digital spatial data in horizontal meters and DEM elevations in meters. It also generates parameters for use with the HEC-HMS SI units option only.

7.2.1.5 Extraction of Hydrologic Sub-System

Extraction of a hydrologic sub-system consists of detaching from the overall study area a set of sub-basin polygons and corresponding reach polylines for further hydrologic analysis with HEC-HMS.

Sub-systems can be defined either by: (1) manually selecting the sub-basin polygons, or (2) manually selecting the most downstream sub-basin polygon (and automatically selecting the sub-basin polygons of its contributing drainage area).

The first method is more flexible, although more tedious to implement. It has no restriction on the polygons that can be selected, and supports the use of inlets (sources according to the HEC-HMS terminology) to represent areas draining to the sub-system. Reach polylines contained within — as well as those draining toward — the selected polygons are selected automatically. Reach polylines draining toward the selected polygons are used to identify the sub-system inlets. Figure 7.18 shows a sub-system extraction when the polygons are manually selected. In the figure, upstream reaches have been selected to help identify system sources.

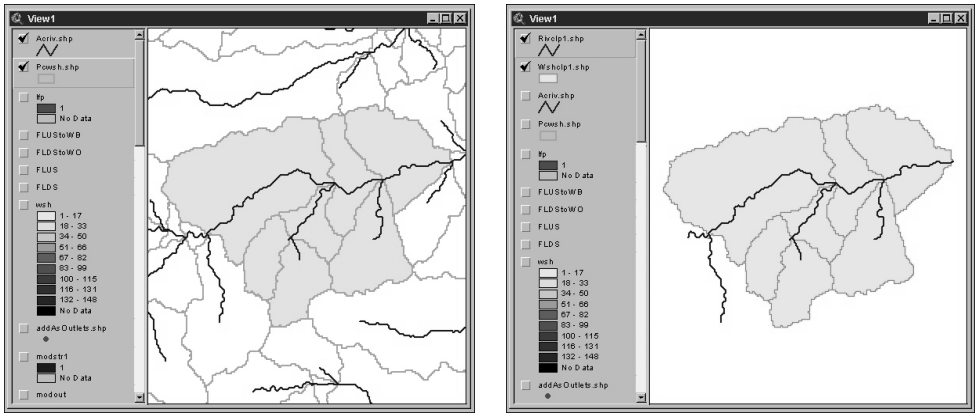


Figure 7.18 Sub-System Extraction by Selecting Sub-Basin Polygons

The second method is less flexible, but easier to implement. After manually selecting the downstream sub-basin polygon, it automatically identifies and selects all the sub-basin polygons located upstream, and consequently does not support the use of inlets. Reach polylines contained within the selected polygons are selected automatically. This method is convenient when dealing with a significant number of polygons in the study area. Figure 7.19 shows a sub-system extraction when only the most-downstream polygon is manually selected.

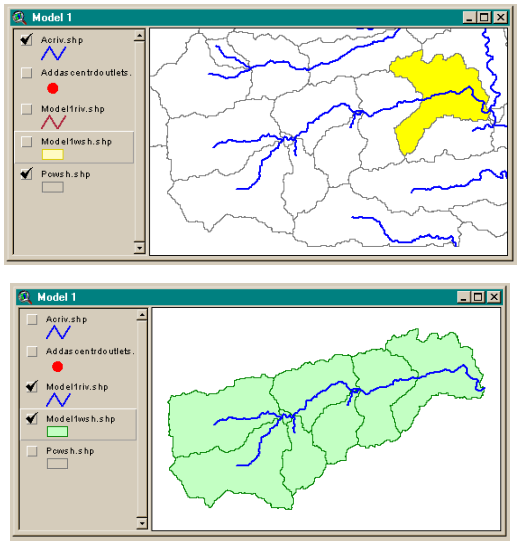


Figure 7.19 Sub-System Extraction by Selecting the Downstream Sub-Basin Polygon which Automatically Selects all other Upstream Polygons

7.2.1.6 Topologic Analysis and Preparation of HEC-HMS Basin File

Establishing the topology of the hydrologic system consists of determining the element located downstream of each element. Since the HEC-HMS hydrologic schematic allows only one downstream element, no ambiguity is introduced in this process. After establishing the system topology based on the sub-basin and reach data sets, an ASCII file — readable by HEC-HMS — is used to record the type (i.e., sub-basin, reach, source, sink, reservoir, or junction), hydrologic parameters, and downstream element of each hydrologic element of the system. A background map file — also readable by HEC-HMS — is used to graphically represent sub-basins and reaches, and ease the identification of hydrologic elements. These files constitute the input to the basin component of HEC-HMS. Figure 7.20 presents three different sections of the basin file. Hydrologic parameters that have been calculated in GIS and stored in the attribute tables are transferred to the basin file.

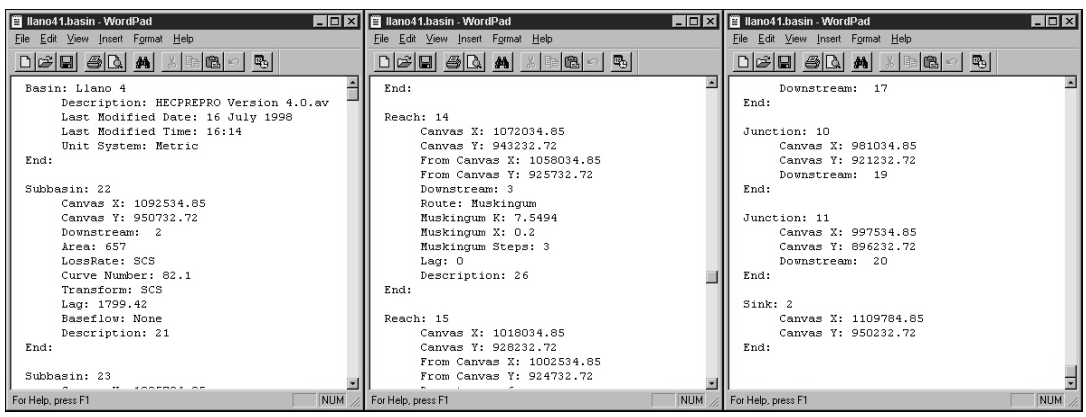


Figure 7.20 HEC-HMS Basin File in ASCII Format

This basin file, when opened with HEC-HMS, generates a topologically correct schematic network of hydrologic elements and displays it in the HEC-HMS - Schematic window, together with the background map. Figure 7.21 shows a detail of a HEC-HMS schematic and the corresponding sections of the basin file used to build it. Figure 7.22 shows the HEC-HMS – Schematic window after opening the basin file.

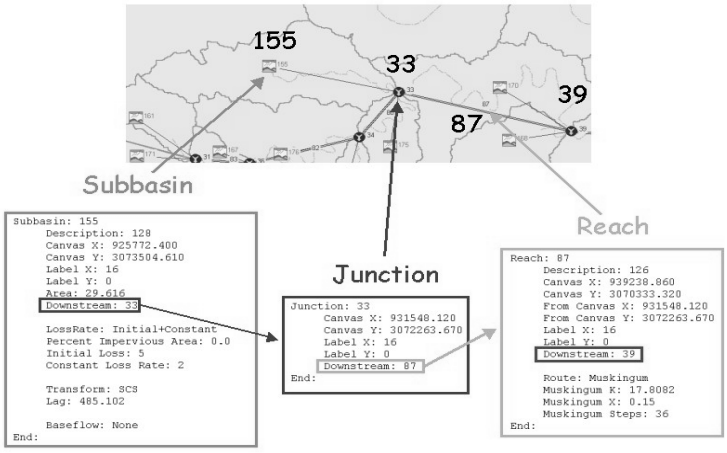


Figure 7.21 HMS Schematic of the Hydrologic System Constructed from the Basin File

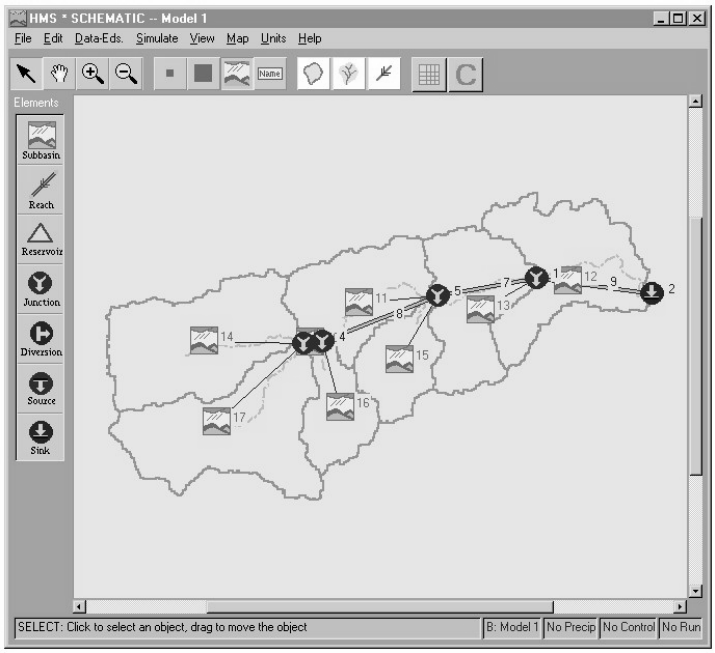


Figure 7.22 HEC-HMS Display of the Schematic of the Hydrologic System

7.2.2 Input Data for the HEC-HMS Precipitation Component

The process of generating input data for the precipitation component of HEC-HMS consists of calculating precipitation time series for sub-basin polygons from precipitation time series at precipitation gages or precipitation cells (i.e., NEXRAD cells). At present, two precipitation methods are supported by CRWR-PrePro: (1) user-specified gage weighting, and (2) GridParm. Automatic determination of gage weights, based on Thiessen and sub-basin polygon data sets, was developed by Dugger (1997). Precipitation time series at sub-basins are estimated as an area-weighted average of precipitation time series at gages. GridParm (HEC 1996), as mentioned above, was originally developed at HEC in AML and rewritten at CRWR as an Avenue script. GridParm (short for GRID cell PARaMeters) is used to determine parameters of precipitation cells for use with the ModClark sub-basin routing method of HEC-HMS.

7.2.2.1 User-Specified Gage Weighting

Sub-basin precipitation time series are calculated as the weighted average of gage precipitation time series. For this purpose, a set of weights that capture the relative importance of the precipitation at each gage on the precipitation of each sub-basin is calculated. Precipitation time series at the gages are stored in Data Storage System (DSS) format (HEC 1995).

Given a set of points that represent gages for which precipitation time series are known, Thiessen polygons are used to establish the area of influence of each precipitation gage. Thiessen polygons are constructed by drawing perpendicular lines at the midpoints of the segments that connect the gages, so that all points within a polygon are closer to the polygon gage than to any other gage. By intersecting the Thiessen polygon with the sub-basin polygons, a new set of smaller polygons is defined in such a way that each new polygon is related to one (and only one) Thiessen polygon and one (and only one) sub-basin polygon. Figure 7.23 shows the polygons resulting of the intersection of Thiessen polygons and sub-basin polygons. The red dots in the figure indicate precipitation drainage gages.

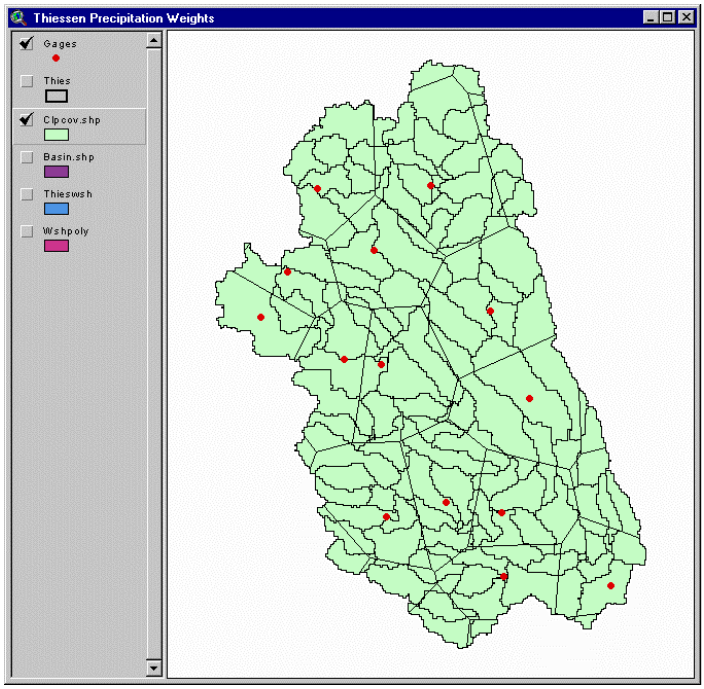


Figure 7.23 Intersection of Sub-Basin Polygons with Thiessen Polygons

The ratio of the area of a new polygon to the area of its corresponding sub-basin polygon represents the weight of the gage for the sub-basin. This can also be expressed as:

$$w_{ij} = \frac{A_{ij}}{S_j} \tag{7.8}$$

where A_{ij} is the area of the polygon generated by intersecting sub-basin j with the Thiessen polygon of gage i, S_j is the area of sub-basin j, and w_{ij} is the weight of gage i for sub-basin j. The sum of the weights of a sub-basin should add up to one. In Figure 7.24, the three selected polygons originally formed a complete sub-basin, and their weight is proportional to their area. In the table below, the area of each of the yellow polygons is stored in the Area field, the sub-basin area in the *WtshdArea* field, and the weights (the ratio of these two areas) in the *%WshArea* field.

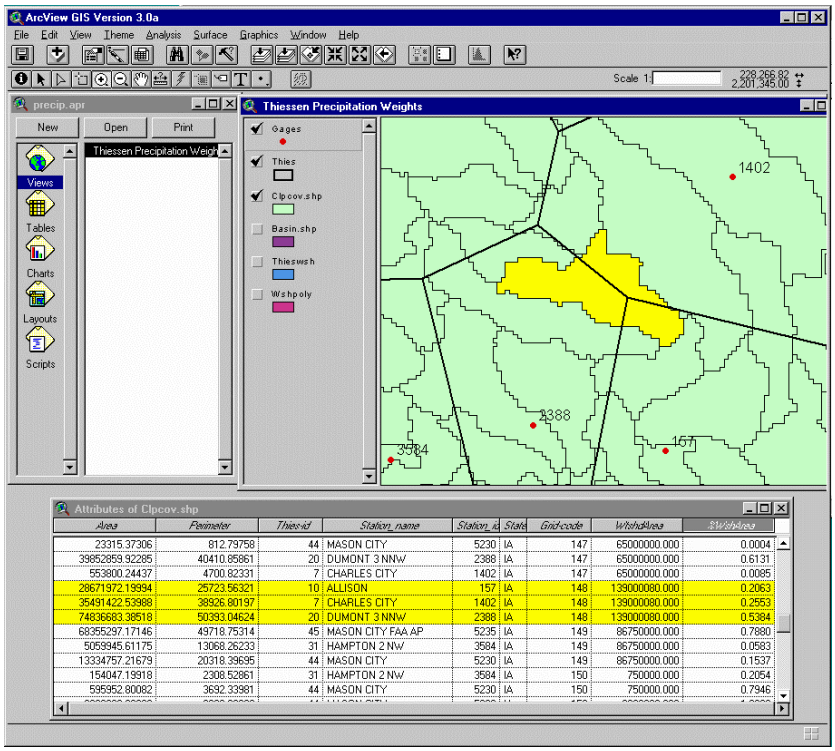
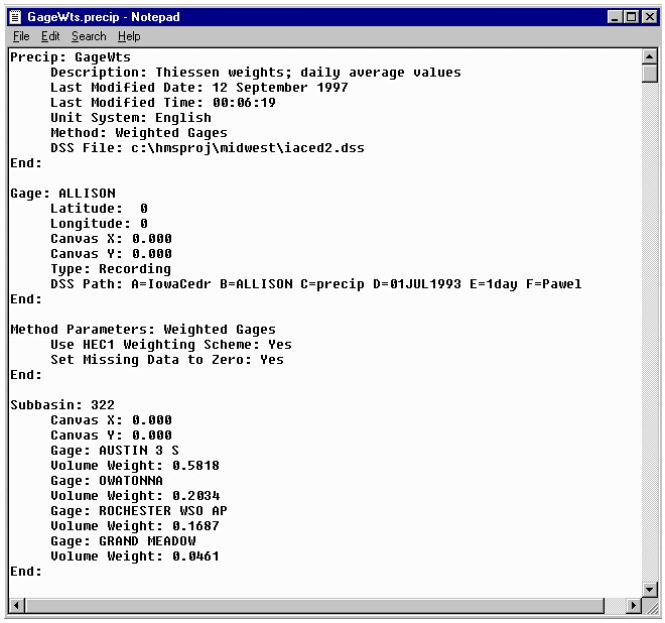


Figure 7.24 Intersection of a Sub-Basin Polygon with Thiessen Polygons

After establishing the weight values based on the sub-basin and Thiessen polygon data sets, an ASCII file — readable by HEC-HMS — is used to record the gage and sub-basin information. The gage information consists of the gage name, location, type (i.e., incremental or cumulative), and reference to the precipitation time series in the DSS file. The sub-basin information consists of the sub-basin name or identification code, and the name of each gage with its corresponding weight. Figure 7.25 shows the HEC-HMS precipitation weights input text file. Gage weights calculated in GIS and stored in the attribute tables are transferred to the precipitation weights input file. From there, HEC-HMS is able to recognize the weighted volume of precipitation that each gage contributes to the sub-basin of interest (Figure 7.26).



```
GageWts.precip - Notepad
File  Edit  Search  Help
Precip: GageWts
     Description: Thiessen weights; daily average values
     Last Modified Date: 12 September 1997
     Last Modified Time: 00:06:19
     Unit System: English
     Method: Weighted Gages
     DSS File: c:\hmsproj\midwest\iaced2.dss
End:

Gage: ALLISON
     Latitude:  0
     Longitude: 0
     Canvas X: 0.000
     Canvas Y: 0.000
     Type: Recording
     DSS Path: A=IowaCedr B=ALLISON C=precip D=01JUL1993 E=1day F=Pawel
End:

Method Parameters: Weighted Gages
     Use HEC1 Weighting Scheme: Yes
     Set Missing Data to Zero: Yes
End:

Subbasin: 322
     Canvas X: 0.000
     Canvas Y: 0.000
     Gage: AUSTIN 3 S
     Volume Weight: 0.5818
     Gage: OWATONNA
     Volume Weight: 0.2034
     Gage: ROCHESTER WSO AP
     Volume Weight: 0.1687
     Gage: GRAND MEADOW
     Volume Weight: 0.0461
End:
```

Figure 7.25 HEC-HMS Precipitation Weights Input File in ASCII Format

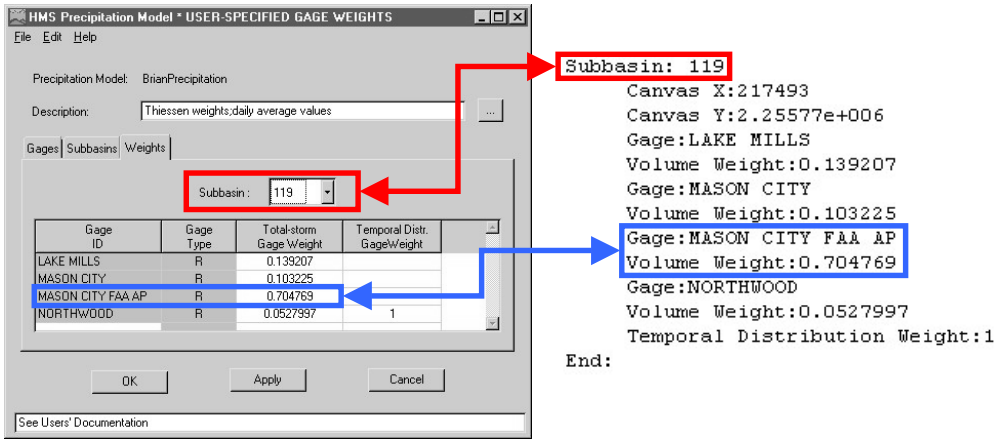


Figure 7.26 HEC-HMS Precipitation Weights Output

Finally, the sub-basin precipitation time series are calculated by HEC-HMS as:

$$P_j(t) = \sum_i p_i(t)\, w_{ij} \tag{7.9}$$

where $p_i(t)$ is the precipitation time series at gage i, and $P_j(t)$ is the representative precipitation time series in sub-basin j.

7.2.2.2 GridParm

GridParm is used to determine parameters of precipitation cells for use with the ModClark sub-basin routing method of HEC-HMS. ModClark, a variation of the Clark unit-hydrograph model (Clark 1945), has been developed by HEC for HEC-HMS as a sub-basin routing option suitable to support NEXRAD precipitation data. In the ModClark method, the drainage area is subdivided into elementary cells in which precipitation is uniform and known, and the hydrograph is calculated as the sum of the contribution of each cell (or fraction of cell) within the sub-basin. Although cells are usually rectangular since the method was developed to support NEXRAD precipitation data, no restriction on the cell shape exists. Calculation of the routing parameters, area, and flow distance to the outlet (to track the water from the precipitation cell to the outlet) is done by ***GridParm***.

To calculate these parameters, three data sets are required: (1) sub-basin polygons, (2) precipitation cell polygons, and (3) flow-length downstream to the sub-basin outlet grid. Sub-basin polygons are intersected with precipitation cell polygons yielding a new set of polygons, which are complete cells in the case when they were completely within a sub-basin, or fractions of cells in the case when they were partially contained by two or more sub-basins. Each of these new polygons is called *GridCell*, and is related to one (and only one) sub-basin polygon. Figure 7.27 shows the intersection of precipitation cells with sub-basin polygons. The flow-length to the sub-basin outlet grid is displayed as the background of the figure.

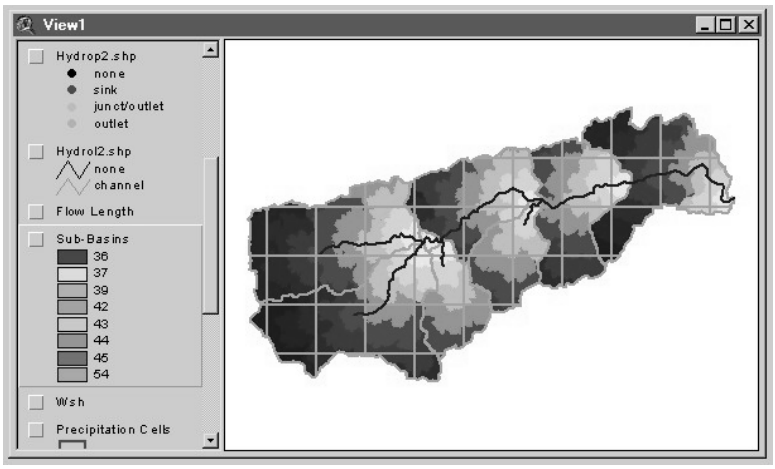


Figure 7.27 Intersection of Precipitation Cells with Sub-Basin Polygons

Figure 7.28 presents the intersection of precipitation cells with one particular watershed. The average distance from the *GridCell* to the sub-basin outlet is calculated as the mean of the flow-length grid values within the *GridCell*.

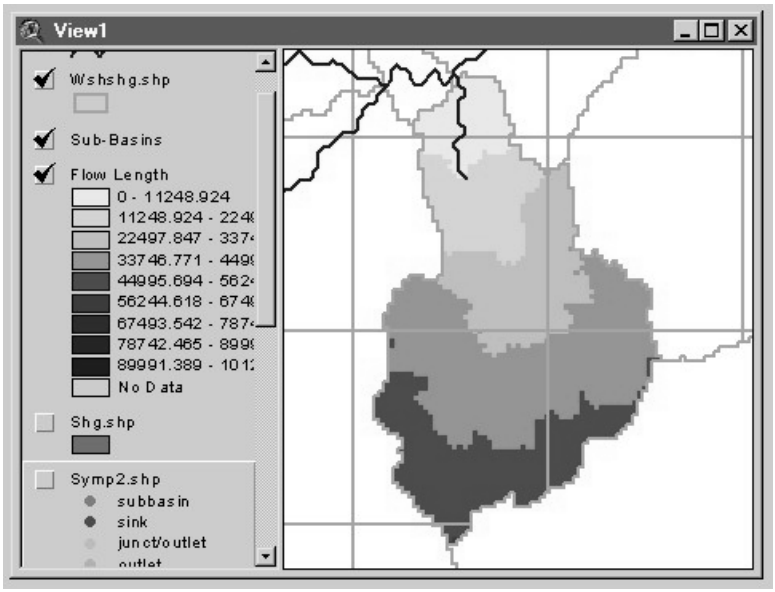
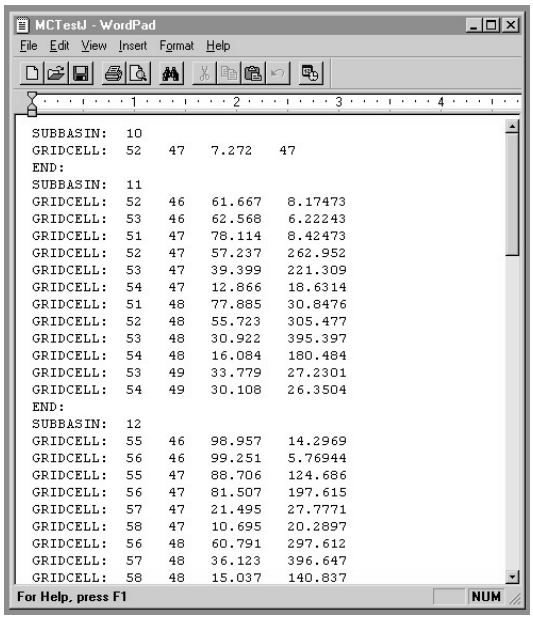


Figure 7.28 Intersection of Precipitation Cells with Individual Watershed

After establishing the *GridCell* parameters, an ASCII file — readable by HEC-HMS — is used to record the sub-basin and *GridCell* information. The sub-basin information consists of the sub-basin name. The *GridCell* information consists of the location, area and distance to the sub-basin outlet. Figure 7.29 shows the text file with *GridCell* parameters as prepared by ***GridParm***.



```
SUBBASIN:  10
GRIDCELL:  52   47   7.272   47
END:
SUBBASIN:  11
GRIDCELL:  52   46   61.667   8.17473
GRIDCELL:  53   46   62.568   6.22243
GRIDCELL:  51   47   78.114   8.42473
GRIDCELL:  52   47   57.237   262.952
GRIDCELL:  53   47   39.399   221.309
GRIDCELL:  54   47   12.866   18.6314
GRIDCELL:  51   48   77.885   30.8476
GRIDCELL:  52   48   55.723   305.477
GRIDCELL:  53   48   30.922   395.397
GRIDCELL:  54   48   16.084   180.484
GRIDCELL:  53   49   33.779   27.2301
GRIDCELL:  54   49   30.108   26.3504
END:
SUBBASIN:  12
GRIDCELL:  55   46   98.957   14.2969
GRIDCELL:  56   46   99.251   5.76944
GRIDCELL:  55   47   88.706   124.686
GRIDCELL:  56   47   81.507   197.615
GRIDCELL:  57   47   21.495   27.7771
GRIDCELL:  58   47   10.695   20.2897
GRIDCELL:  56   48   60.791   297.612
GRIDCELL:  57   48   36.123   396.647
GRIDCELL:  58   48   15.037   140.837
```

Figure 7.29 ASCII File with Precipitation Cell Parameters for use with the ModClark Sub-Basin Routing Method

7.3 APPLICATION

Application examples of CRWR-PrePro can be found in the *CRWR-PrePro: An ArcView Pre-processor for HEC's Hydrologic Modeling System (HMS)* CD-ROM. In this CD-ROM the following tutorial material is included:

1. **Tutorial Movies**: A set of eight tutorial movies developed with Lotus ScreenCam for Windows 95 by Francisco Olivera for ***prepro03.apr*** are included. The eight movies present in sequence the entire process of preparing a HMS Basin File. The

whole package of movie and player files takes approximately 60 Mb. The movies are:

- Getting started (3 min. 53 sec. - 4.9 Mb)
- Terrain Analysis (3 min. 28 sec. - 12.8 Mb)
- Stream and watershed delineation (10 min. 46 sec. - 22.7 Mb)
- Stream and watershed vectorization (4 min. 35 sec. - 5.4 Mb)
- Calculation of hydrologic parameters (4 min. 6 sec. - 2.9 Mb)
- Clipping out a sub-model (2 min. 37 sec. - 5.0 Mb)
- Generating the HMS schematic (5 min. 16 sec. - 5.5 Mb)
- Opening the basin file in HMS (3 min. 30 sec. - 1.7 Mb)

2. **Tutorial Exercises**: Two tutorial exercises that walk the user step-by-step through the processes of delineating streams and watersheds, and developing a hydrologic model for HMS, are included. The exercises are:
    - Delineating the Watershed and Stream Network of the Guadalupe Basin
    - Developing a Hydrologic Model of the Guadalupe Basin

CHAPTER 8. FLOODPLAIN MAPPING

The Texas Department of Transportation is responsible for thousands of drainage control structures along highways throughout the State of Texas. These include facilities such as storm drains, culverts, bridges, and water quality and quantity control structures. An important design component of these facilities involves hydraulic analyses to determine conveyance capacity. Computer models play a pivotal role in these analyses by aiding in the determination of water surface profiles associated with different flow conditions. Unfortunately, a consistent deficiency of these programs has been their inability to connect the information describing the water profiles with their physical locations on the land surface. Often the computed water surface elevations are manually plotted on paper maps in order to delineate floodplains. Automating this manual plotting results in significant savings of both time and resources. GIS offers the ideal environment for this type of work.

This section presents a GIS approach for automated floodplain mapping to aid in the design of drainage facilities. The approach establishes a connection between the HEC-RAS hydraulic model and the ArcView GIS, allowing for improved visualization and analysis of floodplain data. It also permits GIS to function as an effective planning tool by making hydraulic data easily transferable to floodplain management, flood insurance rate determination, economic impact analysis, and flood warning systems. The primary objective is to develop a procedure to take computed water surface profiles generated from the HEC-RAS hydraulic model and draw a map of the resulting floodplain in ArcView GIS.

Attaining this objective requires translating hydraulic modeling output from HEC-RAS to ArcView. The difficulty stems from the fact that each program uses an entirely different coordinate system to define its spatial data.

HEC-RAS is a one-dimensional (1-D) model, intended for 1-D hydraulic analyses of river channels. In HEC-RAS, the stream morphology is represented by a series of cross sections called river stations. Proceeding from downstream to upstream, the river station number increases. The distance between adjacent cross sections is termed the reach length.

Figure 8.1 shows part of a typical HEC-RAS stream schematic. The numbers on the figure denote the river station and the polygons indicate river stations containing a bridge or culvert.

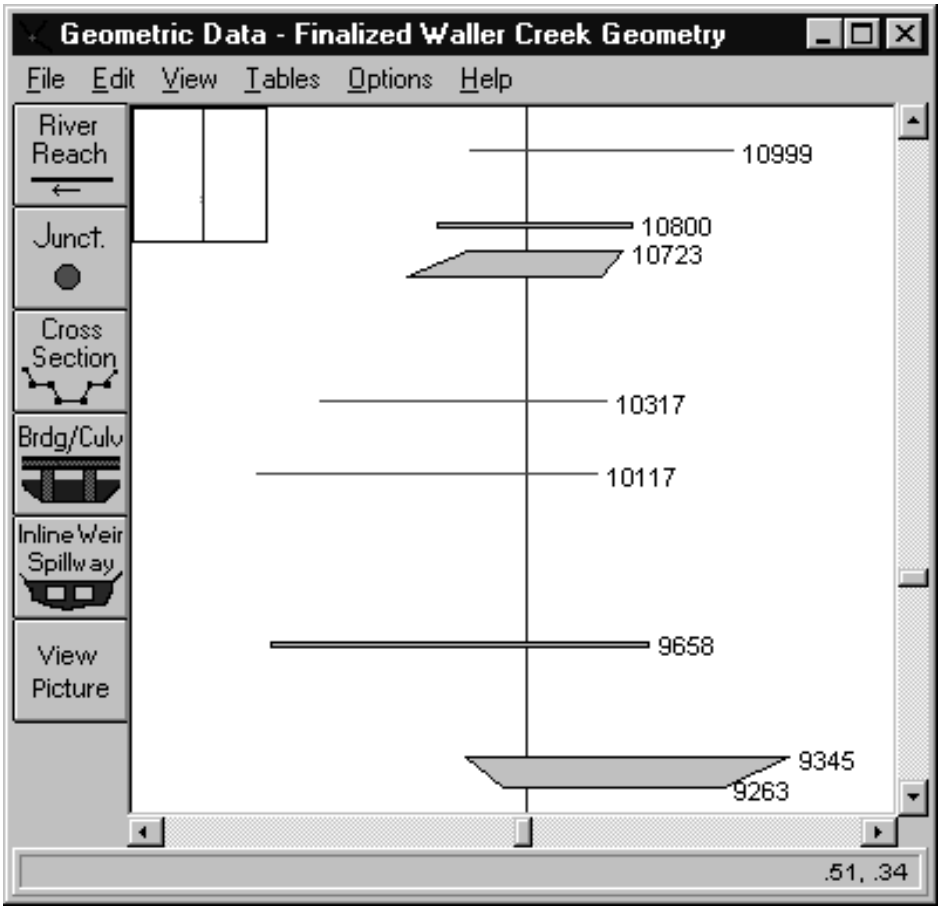


Figure 8.1 HEC-RAS One-Dimensional Stream Schematic

Each cross section is defined by a series of lateral and elevation coordinates, which are typically obtained from land surveys. The numbering of the lateral coordinates begins at the left end of the cross section (looking downstream), and increases until reaching the right end. The value of the starting lateral coordinate is arbitrary; only the distance between points is important. For example, the lateral coordinates numbering for one cross section may begin

at 1000, whereas it may begin at a value of 800 in an adjacent cross section. The result is that, in effect, each cross section has its own local coordinate system (Figure 8.2).

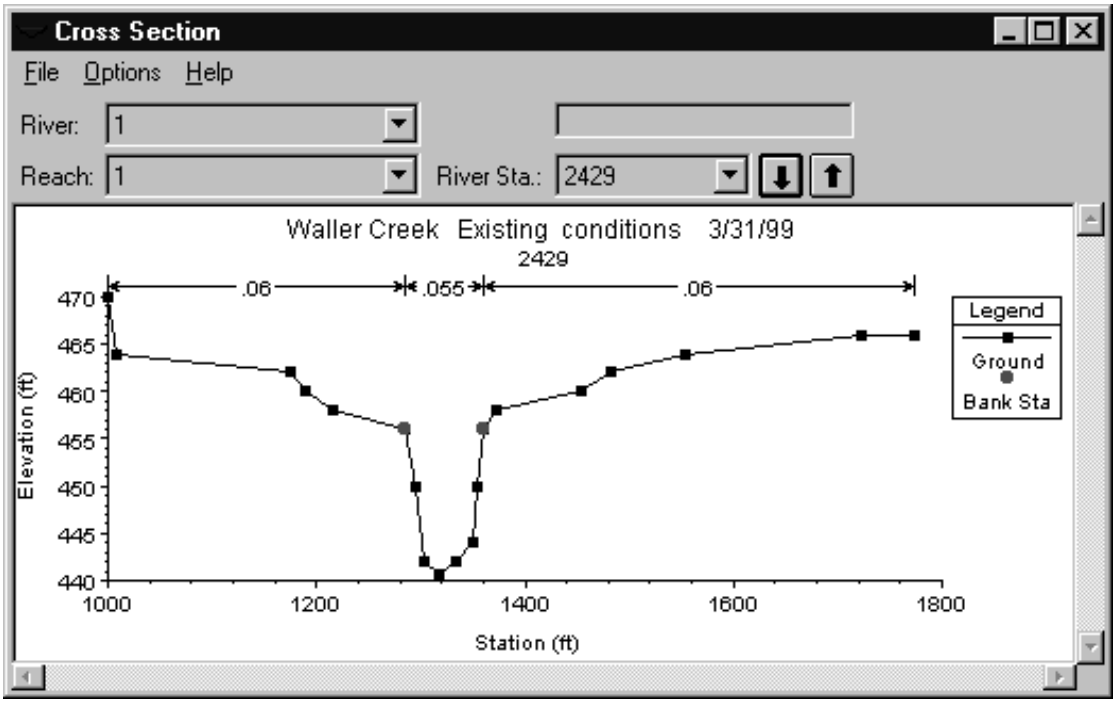


Figure 8.2 HEC-RAS Cross-Section Coordinates

In the HEC-RAS coordinate system, the coordinate of any given point is based on its river station along a one-dimensional stream centerline, its location along the cross-section line, and its elevation. In contrast, data in ArcView are attributed with real-world map coordinates, so that the location of a given point in space is based on its easting (x-coordinate), northing (y-coordinate), and elevation (z-coordinate). Moreover, where HEC-RAS represents the stream as a straight line in model coordinates, ArcView represents it as a curved line in map coordinates (Figure 8.3). In order to map the hydraulic modeling output in GIS, the differences between the HEC-RAS and ArcView coordinate systems must be resolved.

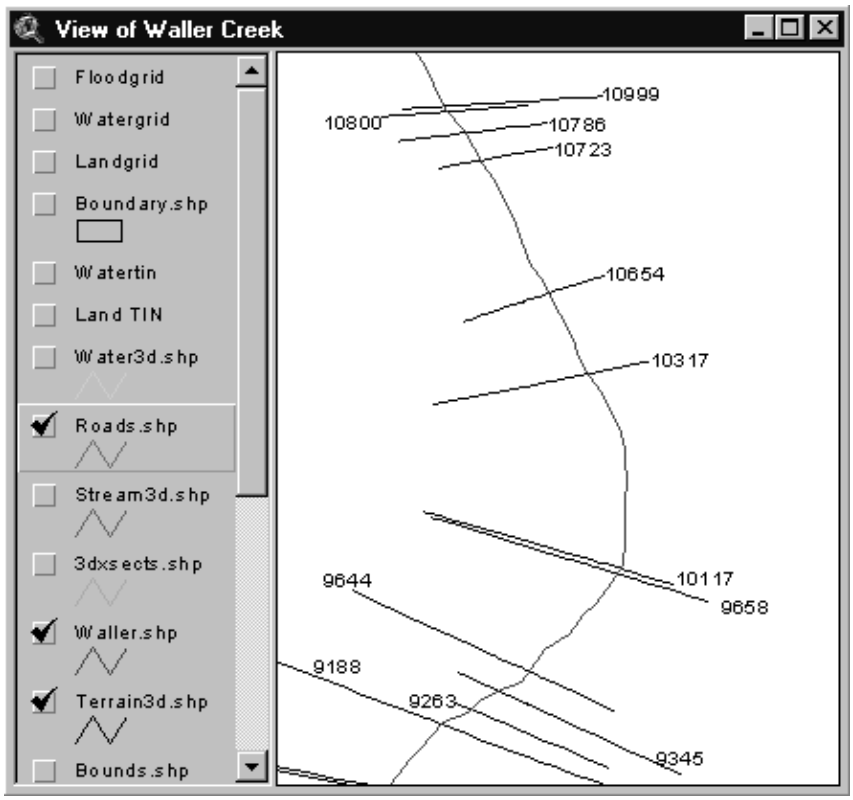


Figure 8.3 GIS Two-Dimensional Stream Schematic

The methods that have been developed to accurately map floodplains have been applied to Waller Creek in Austin, Texas, for demonstration purposes. Waller Creek is an urban stream that flows south through the University of Texas main campus and downtown Austin (Figure 8.4). Due to its proximity to numerous school buildings, homes, and businesses, the location of Waller Creek's floodplain is of great interest to city planners, developers, and property owners. As such, the City of Austin has expended a great deal of effort developing detailed HEC-RAS model data describing the stream flow and channel geometry. These model data were made available for use on this research project.

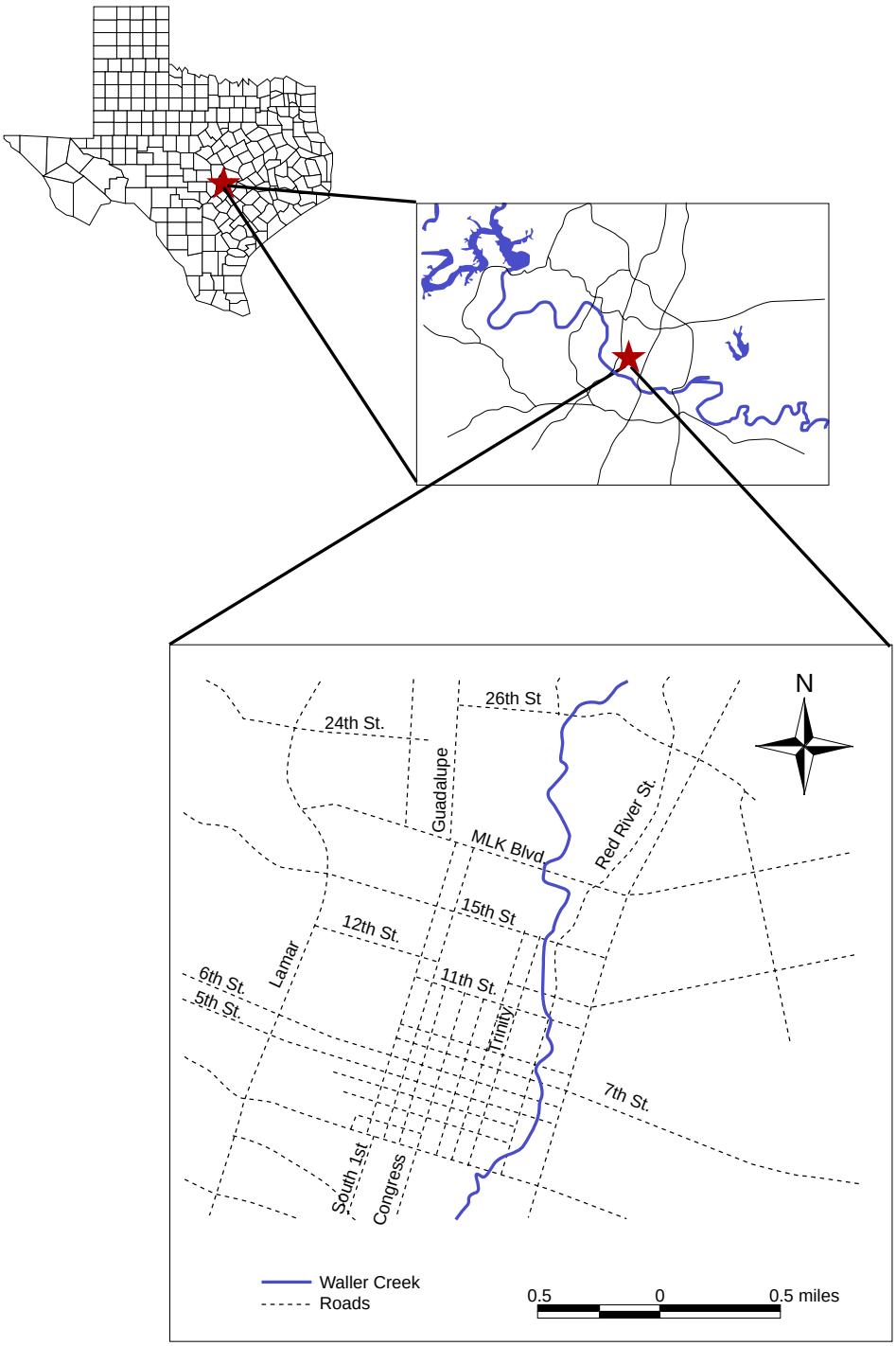


Figure 8.4 Waller Creek Study Area in Austin, Texas

The spatial data input into the system to evaluate Waller Creek consisted of:

- HEC-RAS flow and geometry files provided by the City of Austin;
- 10 and 30 m resolution DEMs from TNRIS;
- 1 m resolution digital orthophotography purchased from TNRIS; and
- Vector shapefile of Austin roads provided by the City of Austin.

Because specialized software is required to project images, the projection of the digital orthophoto was chosen as the standard map projection. DOQs available from TNRIS are cast in the UTM Zone 14 projection and are based on the North American Datum of 1983 (NAD83).

8.1 METHODOLOGY

This section details the procedure developed to process HEC-RAS output for terrain modeling and floodplain delineation in the ArcView GIS. Application of the methodology reduces the analysis time and improves accuracy by integrating spatial stream geometry with hydraulic analysis. The approach is based on assigning map coordinates to stream cross-sections and computed water surface profile data stored in HEC-RAS model coordinates. The procedure consists of five primary steps: (1) data import from HEC-RAS, (2) stream centerline definition, (3) cross section georeferencing, (4) terrain modeling, and (5) floodplain mapping. These steps are discussed in detail in the following subsections.

8.1.1 Data Import from HEC-RAS

In order to move into the GIS environment, the HEC-RAS output data must be extracted. Because in this research it is assumed that input terrain model is not the source of the cross-section descriptions, the GIS data export option available in HEC-RAS is not employed. Instead, an output report using the *File/Generate Report* menu option from the

HEC-RAS main project window is used. In the resulting *Report Generator* window, *Plan Data* and *Geometric Data* should be checked as the general input data, *Reach Lengths* under the summary column, and *Cross Section Table* under the specific tables output option (Figure 8.5).

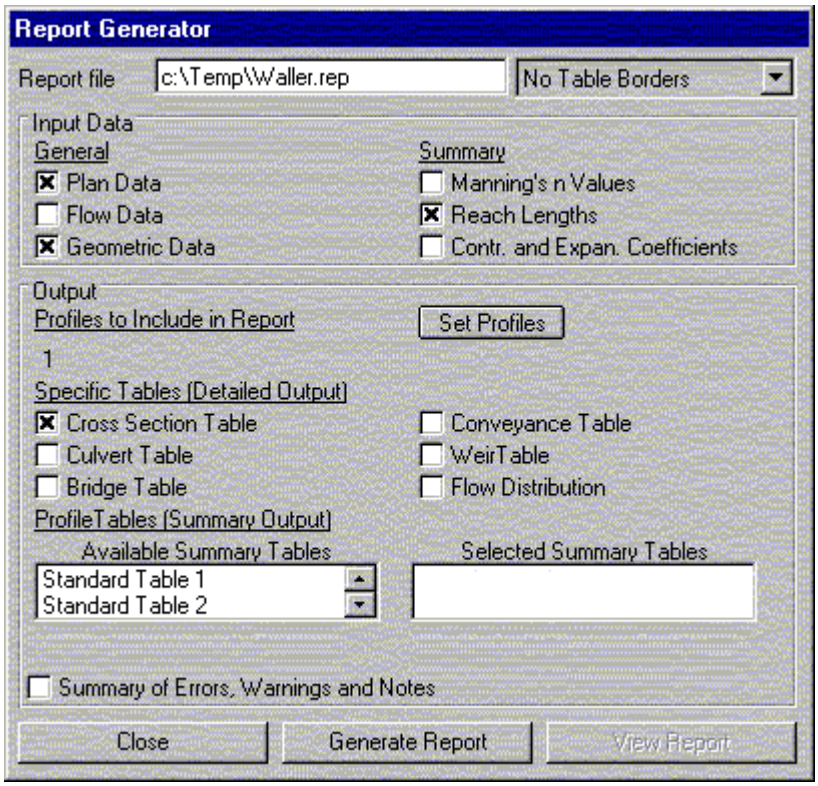


Figure 8.5 HEC-RAS Output Report Generator

It is important that only one profile is selected for the output report and that the modeled stream has only one branch (the approach cannot currently operate on multiple flow profiles or stream networks). If the model includes more than one flow profile, the specific profile used for the output report can be selected using the *Set Profiles* button. After clicking the *Generate Report* button, the output report is created. The report is a text file that contains input data describing cross-sectional geometries and stream flow rates, and output data describing computed water surface profiles (Figure 8.6).

```
CROSS SECTION          RIVER: 1
REACH: 1                  RS: 32093

INPUT
Description: 32093
Station Elevation Data    num=      12
     Sta    Elev     Sta    Elev     Sta    Elev     Sta    El
  1044.9  686.66  1095.1  682.76    1166  679.86  1184.6  673.
  1204.4   680.1  1291.9  682.23  1321.9  680.88  1360.2  679.
    1400  680.16    1400   690.2

Manning's n Values        num=       7
     Sta   n Val     Sta   n Val     Sta   n Val     Sta   n V
  1044.9     .04    1166     .05  1204.4     .08  1291.9   99.
  1360.2     .02  1389.3     .04

Bank Sta: Left   Right    Lengths: Left Channel   Right     Co
          1166  1204.4              132     132     132

CROSS SECTION OUTPUT    Profile #PF 4

  E.G. Elev (ft)             681.60   Element
  Vel Head (ft)                0.95   Wt. n-Val.
  W.S. Elev (ft)             680.65   Reach Len. (ft)
  lines omitted....
  Crit W.S. (ft)             680.65   Flow Area (sq ft)
```

Figure 8.6 Example HEC-RAS Output Report

An Avenue script named ***RAS-Read.ave*** was developed to read the HEC-RAS output text file and write stream parameters to ArcView. The parameters processed at each cross section include the following:

- River station (cross section) number;
- Coordinates of the stream center, located at the point of minimum channel elevation;
- Floodplain boundary locations, as measured from the stream center;
- Bank station locations, as measured from the stream center;
- Reach lengths; and
- Water surface elevation.

Figure 8.7 shows a HEC-RAS cross-section plot, in which these parameters can be seen. In the figure legend, EG stands for energy grade line, and WS refers to the water surface.

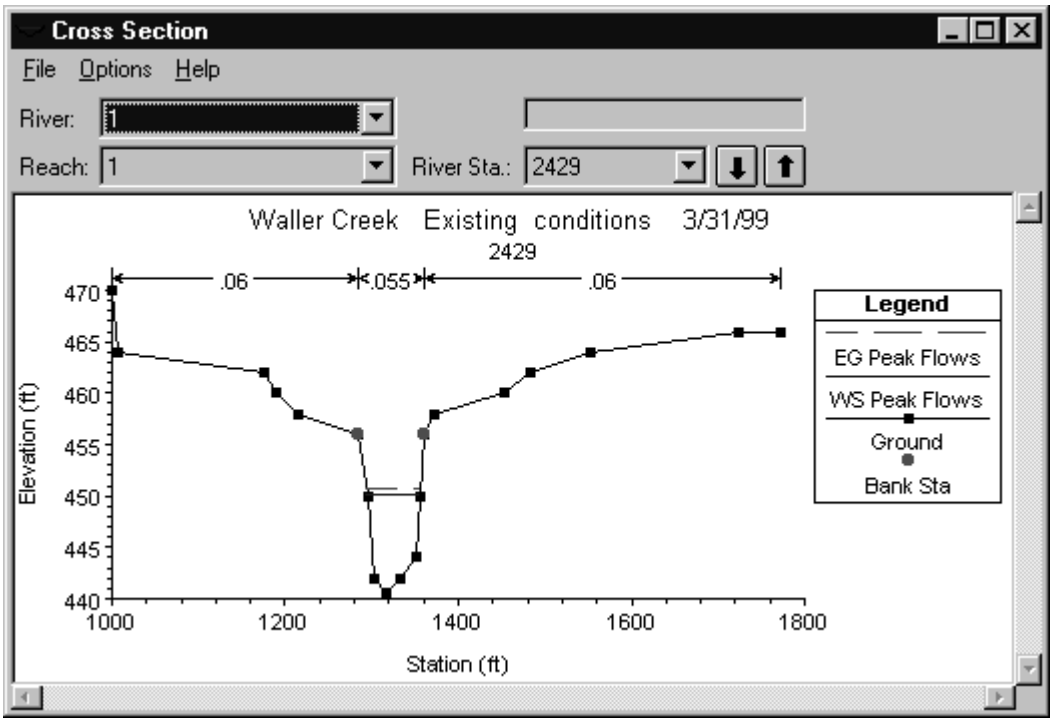


Figure 8.7 HEC-RAS Cross-Section Plot

For each cross section, the lateral and elevation coordinates of all points (black square markers in Figure 8.7) are read and stored in an ArcView global variable. Using these points, the coordinates of the point possessing the minimum channel elevation in the cross section is determined. If there are multiple points possessing the same minimum channel elevation, the lateral coordinate of the channel center is calculated by averaging the lateral coordinates of all points with the same minimum elevation.

In order to determine the lateral coordinates of the floodplain boundaries, the computed water surface elevation is used. The cross-section coordinates are read from the left end of the cross section to the right end. When the computed water surface elevation falls

between the elevation coordinates of two adjacent points, the floodplain boundary is calculated by linear interpolation.

With the lateral coordinates of the floodplain boundaries known, the lateral distance from the stream center is calculated and stored in an ArcView table. In the same manner, the lateral distances from the bank stations (red circular markers in Figure 8.7) to the stream center are calculated and stored in the table along with the elevation coordinates. The remaining cross-section parameters, written to the ArcView table, are the river station number, any text description of the cross section, reach lengths, and the computed water surface elevation.

The ***RAS-Read.ave*** script assumes the output report file has coordinates measured in feet, and prompts the user for the units to be used in ArcView (feet or meters). If *meters* is selected, all coordinates written to the ArcView table are converted to meters by multiplying by the factor 0.3048.

Figure 8.8 shows an example of the ArcView cross-section parameter table. Descriptions of the data stored in each of the columns are provided in Table 8.1.

HEC-RAS Cross-Section Parameter Table

Station	Descriptio	Type	FloodElev	LFloodN	LBankX	LBankZ	ChannelN	ChannelZ	RBankX	RBankZ	RFloodN
28490	55 1/2 St	Culver			11.2	197.8		195.8	4.1	197.7	
28465			198.7	75.1	11.2	197.8	1117.1	195.8	4.1	197.7	56.3
28428			198.5	42.2	7.0	197.6	1153.7	195.8	3.7	197.7	53.6
28308			197.9	29.0	7.0	197.2	1211.6	195.4	3.7	197.3	45.1
28118			197.6	66.1	10.0	197.1	1219.5	195.3	8.5	197.1	36.1
28092			197.6	71.9	9.4	197.0	1235.0	195.1	9.1	197.1	42.7
28066	55th Stre	Culver			9.4	197.0		195.1	9.1	197.1	
28041			197.6	69.5	9.4	197.0	1247.2	195.1	9.1	197.1	40.6
28001			197.4	61.3	3.4	196.8	1277.7	194.9	7.6	196.9	34.4
27901			197.1	55.5	3.4	196.5	1309.1	194.6	7.6	196.6	32.9
27798			197.2	74.5	8.7	196.2	1316.1	194.2	6.5	196.4	40.8
27775			197.2	72.3	7.0	196.2	1330.1	194.2	8.3	196.4	42.3
27752	Nelray St	Culver			7.0	196.2		194.2	8.3	196.4	
27729			197.2	77.0	7.0	196.2	1339.3	194.2	8.3	196.4	45.3

Figure 8.8 ArcView Cross-Section Parameter Table

Table 8.1 Cross-Section Parameter Table Data Descriptions

Column Title	Data Description
Station	River station number
Description	Short text description of the cross-section location (if included in the HEC-RAS geometry file)
Type	Hydraulic structure (bridge or culvert) at the cross section
FloodElev	Computed water surface elevation
LfloodX	Lateral distance from the stream center to the left floodplain boundary
LbankX	Lateral distance from the stream center to the left bank station
LbankZ	Left bank station elevation
ChannelY	Cumulative reach length, beginning at the upstream end
ChannelZ	Channel center elevation
RightBankX	Lateral distance from the stream center to the right bank station
RightBankZ	Right bank station elevation
RightFloodX	Lateral distance from the stream center to the right floodplain boundary

The purpose of the data import step is to transform HEC-RAS output from text file format into a tabular format readable by ArcView. However, the cross-section coordinates are still tied to the HEC-RAS coordinate system. In order to map the floodplain, the cross sections must be assigned map coordinates. This requires associating the HEC-RAS stream cross sections with a geographically referenced digital representation of the stream.

8.1.2 Stream Centerline Definition

After importing the HEC-RAS output data into ArcView, it is necessary to link the HEC-RAS stream representation to the digital representation of the stream in ArcView. There are four primary ways to obtain a digital representation of the stream centerline; they are presented in the following sub-sections.

8.1.2.1 Reach Files

Reach files are a series of national hydrologic databases that uniquely identify and interconnect the stream segments or reaches that comprise the nation's surface water drainage system. The databases include such information as unique reach codes for each stream segment, upstream/downstream relationships, and stream names (where possible). The latest release, Reach File 3 (RF3), consists of attributed 1:100,000 scale digital line graph hydrography. The data can be downloaded from the EPA BASINS website at http://www.epa.gov/OST/BASINS/gisdata.html.

Reach (in particular RF3) files were evaluated for use on this project but attempts to use them were discontinued early on because the RF3 stream centerline representation was often inconsistent with the representation derived from a 30 meter DEM and digitizing from a DOQ (Figure 8.9).

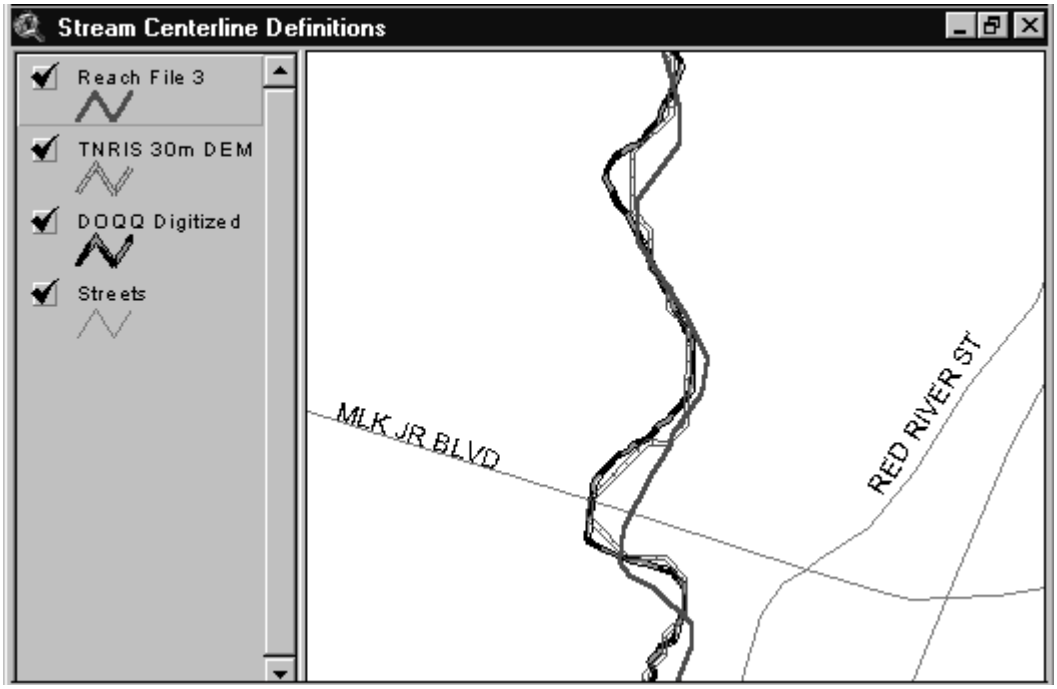


Figure 8.9 Stream Centerline Representations

8.1.2.2 DEM-Based Delineation

Using the capabilities of the ArcView Spatial Analyst extension, a vector stream network can be derived using a DEM as the sole input. An example of a tool for developing such a vector stream network is CRWR Pre-Pro.

DEM-based stream delineation was also evaluated for this project, and was found to be an acceptable method for stream centerline definition. However, the accuracy of the stream centerline definition by this method depends on the resolution of the DEM and the orthophotography, respectively. For this research, 1 meter resolution orthophotography of the Austin East 7.5-minute quadrangle was obtained from TNRIS. In ArcView, the digital imagery was used as a base map upon which to digitize Waller Creek.

8.1.2.3 On-Screen Stream Digitization

Using either orthophotography or a digital raster graphic (DRG) as base map, the stream centerline can be digitized in ArcView. DRGs are digitized and geographically referenced topographic maps. DRGs and DOQs for the state of Texas can be obtained from the TNRIS website at http://www.tnris.state.tx.us/digital.htm.

This method of stream centerline definition was also evaluated on this project, and was found to be an acceptable method for stream centerline definition, along with DEM-based delineation. This method also has similar limitations, however; the accuracy of the stream centerline definition also depends on the resolution of the DEM and the orthophotography.

8.1.2.4 Land Surveys

Data representing the stream centerline may be available from land surveys. If these data are tied to a global coordinate system, they can be used as vector representations of the stream. This method was not evaluated for this project.

8.1.3 Cross-Section Georeferencing

The first step in geographically referencing the cross sections is to compare the definition of the HEC-RAS stream and its digital counterpart. It is possible for example, that the digital stream centerline is defined to a point farther upstream than the HEC-RAS stream, or vice versa. Hence, it is necessary to define the upstream and downstream boundaries of the HEC-RAS stream on the digital stream. To this end, the Avenue script ***Addpnt.ave*** was developed, with which the upstream and downstream boundaries can be established with a click of the mouse. Intermediate stream definition points corresponding to known HEC-RAS cross-sections such as bridges or culverts can also be defined. This process takes advantage of HEC-RAS models in which descriptions of cross-section locations are included. These descriptions are brought into ArcView during the data import step, and can be used to help define intermediate stream definition points.

In order to use the script ***Addpnt.ave***, a stream centerline shapefile is required. When the user clicks on a point, the script determines the nearest point along the stream centerline and snaps the point onto the digital stream. The output of the script is a point shapefile. Often, the definition points are more easily pinpointed by comparison to the location of an existing structure (e.g., road, bridge, etc). As such, a theme of roads can be used in addition to the DOQ to assist in the point selection process. As the number of defined points increases, so does the accuracy of the resulting cross-section locations. In Figure 8.10, seven stream definition points are shown. Of these, two represent the upstream and downstream boundaries, and five are intermediate stream definition points.

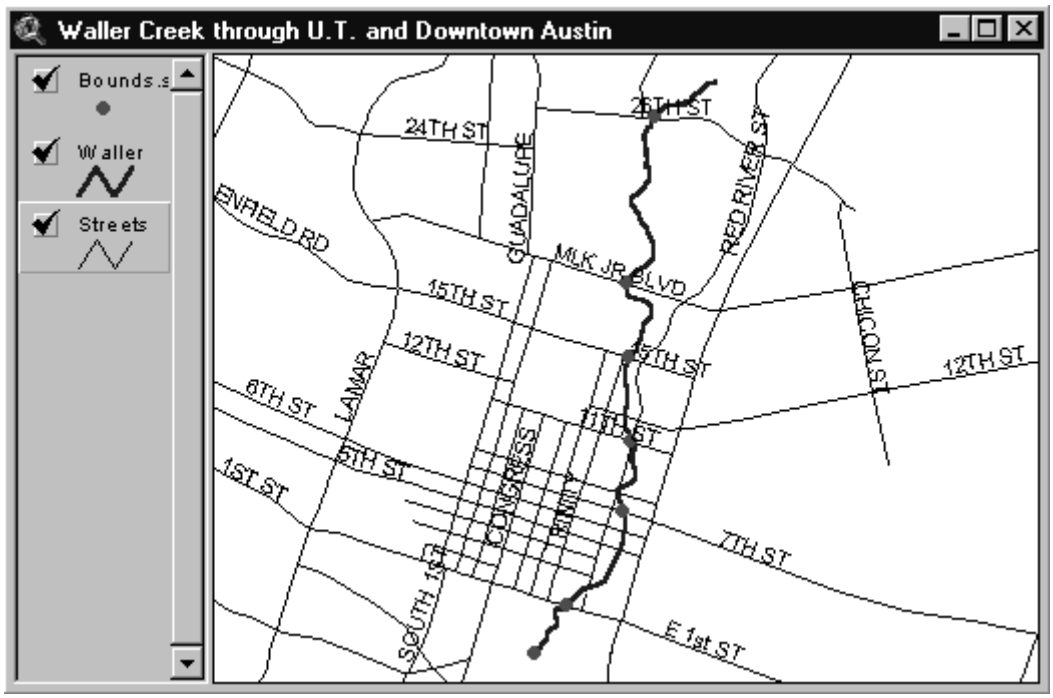


Figure 8.10 Stream Definition Points

Once the stream definition points are established, the next step is to add the cross sections between them. To do this, two attributes must be known for each cross section: (1) location along the stream, and (2) orientation. The Avenue script ***Terrain3D.ave*** aids in the determination of these attributes. As input, the script requires the stream centerline theme and the stream definition point theme. In order to determine the location of each cross section along the stream centerline, a one-to-one relationship is established between each stream definition point and its associated cross-section record in the cross-section parameter table (Figure 8.11).

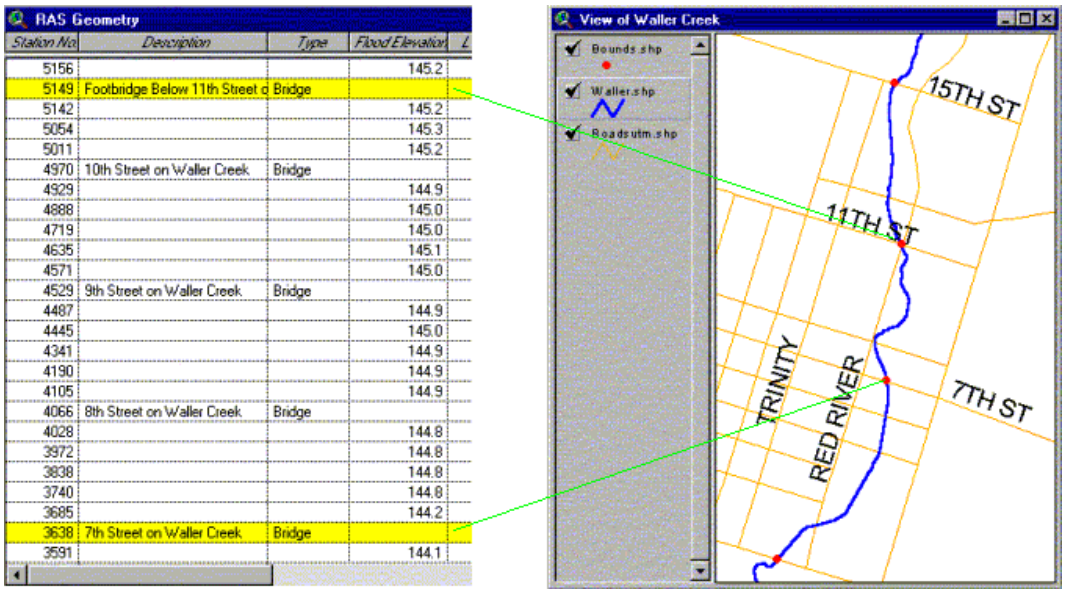


Figure 8.11 One-to-One Relationship Between Table Records and Definition Points

The HEC-RAS stream centerline definition is based on land surveys and topographic maps, whereas the basis for the GIS stream centerline is aerial photogrammetry and digitizing. Because of these differences, the length along the stream between any two points likely varies to some degree. To evaluate the difference in length between each set of adjacent definition points, ***Terrain3d.ave*** calculates the ratio of the length of the HEC-RAS-modeled stream to that of the digital stream. The length of the HEC-RAS stream segment is determined as the difference in cumulative reach lengths stored in the cross-section parameter table. To determine the length of the digital stream segment, the position of each definition point is calculated as a percentage of the total digital line length. The percentage difference is then multiplied by the total line length.

If the HEC-RAS reach lengths and digital stream representation are accurate, and the streams definition points were precisely placed, then the ratio of segment lengths should be nearly one. If the length of the HEC-RAS stream segment exceeds that of the digital stream, the reach lengths between cross sections are compressed by the ratio. However, if the HEC-RAS stream length is less than the digital stream length, the reach lengths between cross sections are expanded by the same ratio. In this manner, the proportionality of HEC-RAS

reach lengths is preserved. In the Waller Creek data sets, the ratio generally ranged between 0.98 and 1.02.

At this point, the cross-section locations along the stream centerline are known, but not their orientation. The HEC-RAS model requires cross sections to be defined such that they are perpendicular to flow lines in the floodways and main channel. Within relatively straight portions of the channel, this means straight-line cross sections. Near bends in the stream, the cross sections sometimes are doglegged in the floodways to ensure perpendicularity to flow. Unfortunately, information concerning the orientation of each cross section is typically indicated on survey maps, but is not stored by HEC-RAS. Therefore, an assumption of orientation is required in order to map the cross sections in GIS. In this case, all cross sections are assumed to occur in straight lines, perpendicular to the stream centerline.

In order to determine the direction of a perpendicular line to the stream centerline, the bearing of the centerline must first be known. The centerline direction can be determined by calculating the bearing between two points located (immediately) upstream and downstream of the cross-section location along the stream. The bearing of the cross section is subsequently calculated as the negative inverse of the centerline bearing.

However, assuming absolute perpendicularity could result in intersecting cross sections at bends in the stream, a condition that is unrealistic. As such, the user is prompted to assign the distance between the cross-section location and the points used for determining centerline bearing, a number termed the *distance value*. The *distance value* is input as a percentage of the total stream length (Figure 8.12).

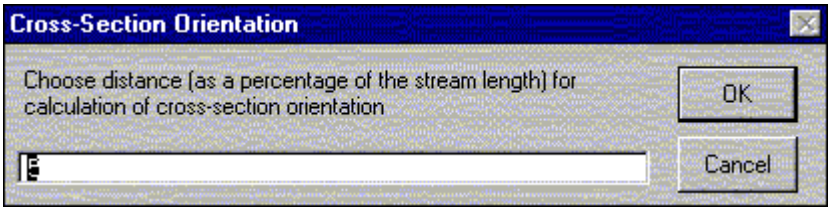


Figure 8.12 User Prompt for Assignment of Cross-Section Orientation

With the cross-section locations and orientations known, a line representing each cross section can be mapped. If the resulting cross sections intersect near bends in the stream (Figure 8.13), ***Terrain3D.ave*** can be re-run using a higher distance value. As the distance value increases, so does the departure from true perpendicular cross sections (Figure 8.14).

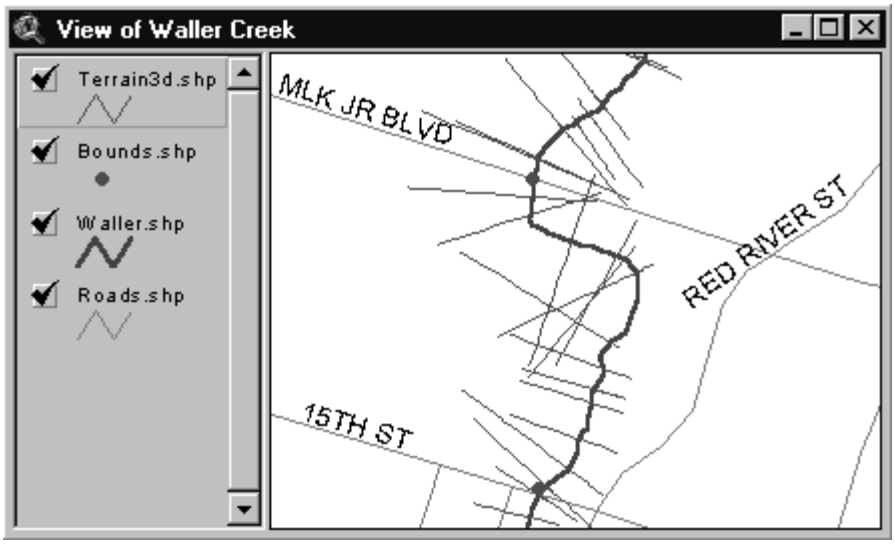


Figure 8.13 Cross-Section Mapping Using a Distance Value of 1%

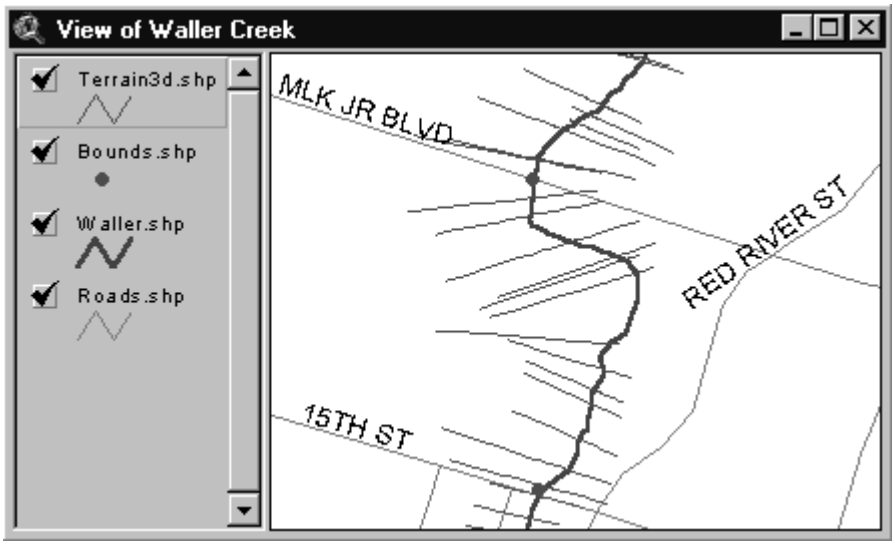


Figure 8.14 Cross-Section Mapping Using a Distance Value of 5%

For this project, a distance value of 5% was used to map the cross sections, which corresponds to a distance of approximately 200 meters. Each cross section is attributed with river station number, cross-section length, and the location of the stream center and bank stations.

8.1.4 Floodplain Mapping

HEC-RAS represents stream floodplains as a computed water surface elevation at each cross-section. During the data import step (Subsection 8.1.1), these elevations, along with the distance from the stream centerline to the left and right floodplain boundaries, are brought into ArcView and stored in the cross-section parameter table. Hence, two things are known about the floodplain at each cross section: (1) water surface elevation, and (2) extent. The script ***Water3D.ave*** was developed to map these attributes. On Figure 8.15, the water surface profiles (heavy blue lines) are mapped based on the cross-section line theme (green).

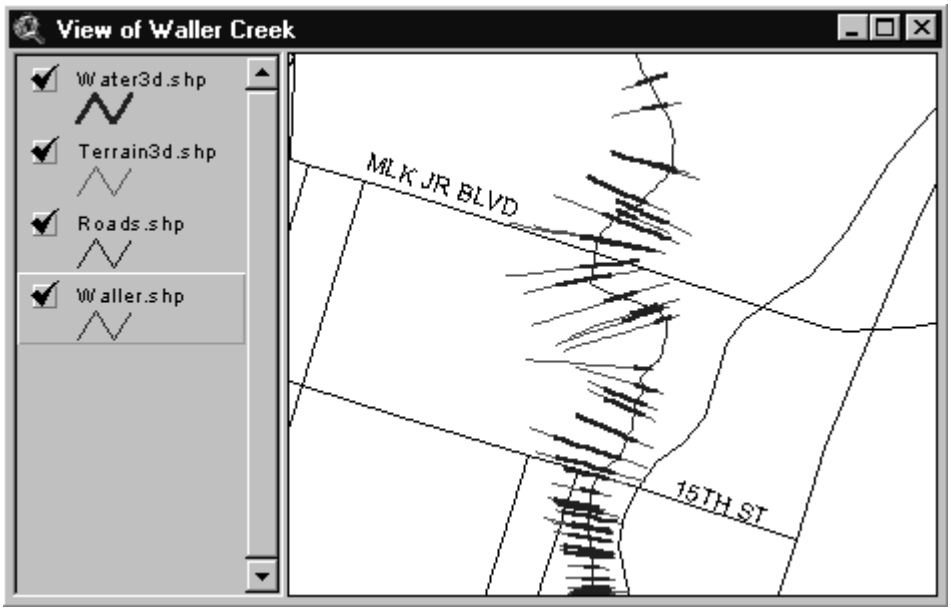


Figure 8.15 Water Surface Profiles

As inputs, the script requires the cross-section line theme and the cross-section parameter table. The output is a line theme that is identical to the cross-section theme in location and orientation, but is not as wide. In a properly set up HEC-RAS model, the cross sections should be designed wide enough such that the computed water surface elevations are contained within them.

Using the water surface profile at each cross section, a TIN representing the entire floodwater surface can be constructed using the *Surface/Create TIN from Features* menu option in ArcView. The water surface lines are used as *breaklines*, and the cross-section bounding polygon is used to bind the aerial extent of the water surface. When viewed in conjunction with the terrain TIN created from the cross-section data and DEM, flooded areas can be seen (Figure 8.16).

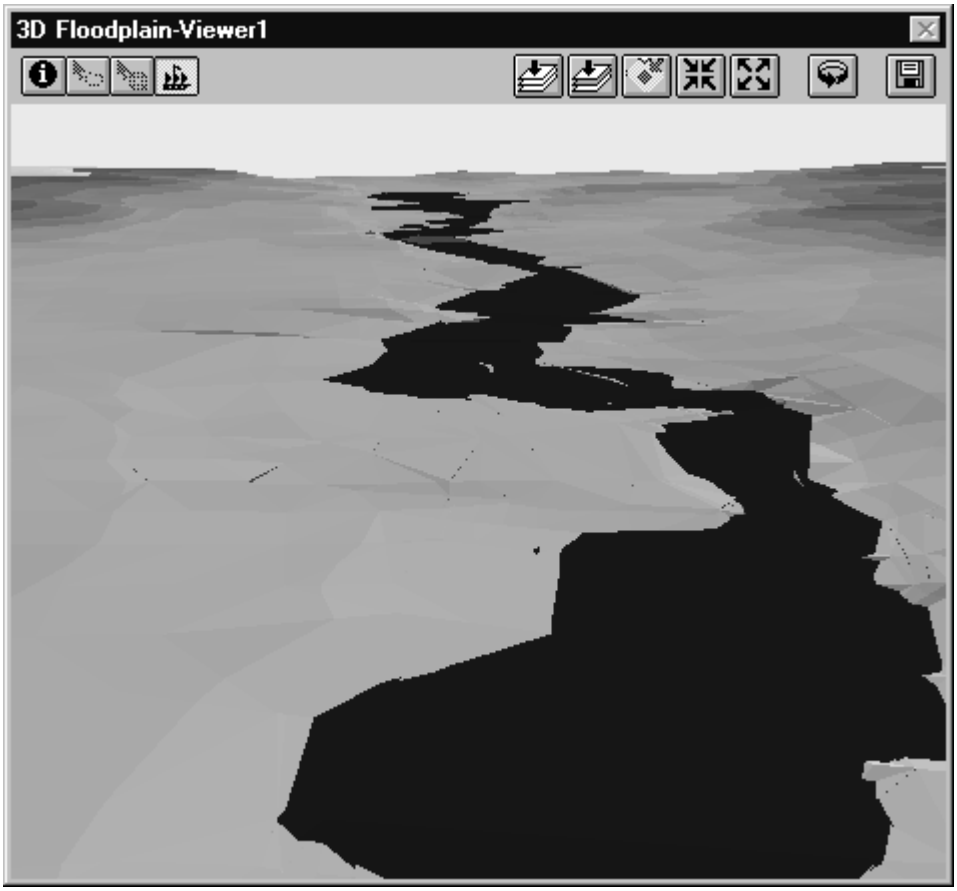


Figure 8.16 Three-Dimensional Floodplain Rendering

The three-dimensional floodplain view is quite useful for floodplain visualization, but the view shown in Figure 8.16 doesn't appear much like the actual landscape. To remedy this, themes of roads, buildings, railroads, and other typical landscape features can be added to the view to more closely approximate reality. If building elevation information is not available, building elevations can be measured on a DOQ based on shadow length.

Figure 8.17 shows the level of detail that can be obtained by building a detailed TIN surface model that includes buildings and roads. The view shows the Colorado River south of downtown Austin.

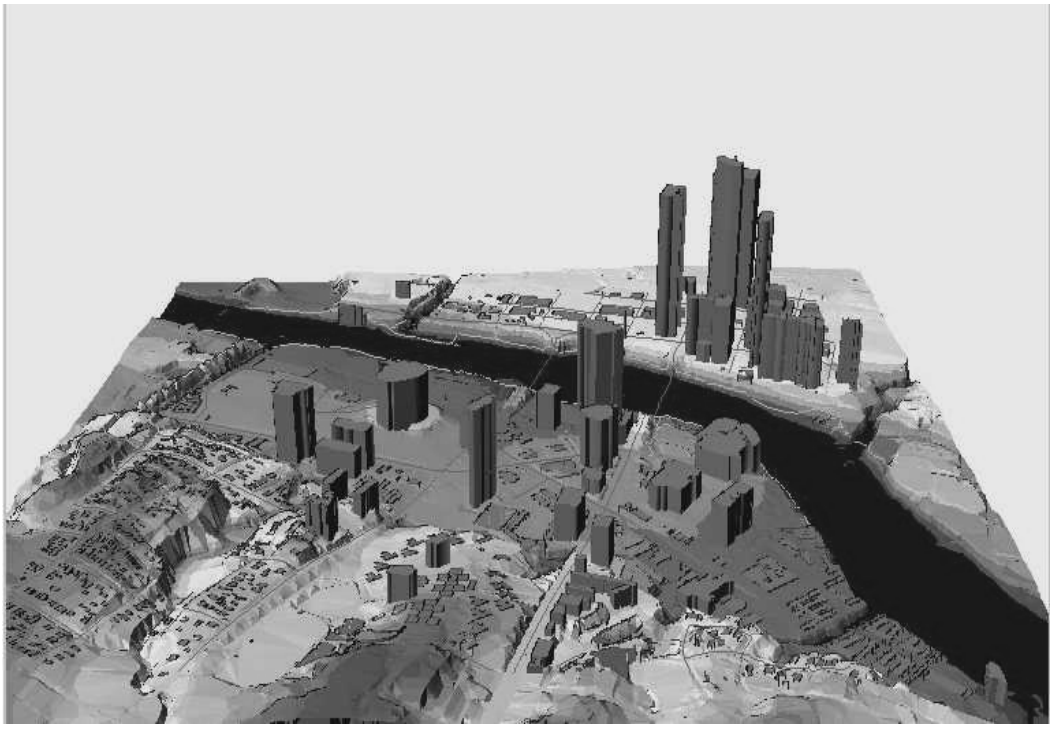


Figure 8.17 Potential Level of TIN Detail

For detailed analysis, the floodplain can also be viewed with a planimetric perspective using a digital orthophotograph as a base map. However, the method developed for planimetric floodplain visualization is different from that for three-dimensional floodplain visualization because it is based on the raster data model instead of the TIN. By definition,

areas inundated by floodwaters occur wherever the elevation of the water exceeds that of the land surface. In terms of the data sets developed thus far, the floodplain exists wherever the elevation of the water surface TIN exceeds the terrain TIN. However, the delineation of these areas is more readily performed using the raster data model instead of TINs. In the raster domain, grid cells of water surface elevation and grid cells of land surface elevation can be easily compared.

However, in order to be consistent, the inundated areas should not be delineated using the integrated (resampled) terrain TIN. This is because the HEC-RAS water surface profiles used to create the water surface TIN were computed using the original HEC-RAS cross sections and not the resampled cross sections. As such, the cross-section elevation correction should be neglected so that the terrain TIN is reconstructed using the original cross-section line theme. As before, the TIN is created using three input data sources: the DEM point theme, original cross-section line theme, and the centerline and banks line theme. TIN nodes are formed from the DEM points and the vertices of the cross-section lines. The stream centerline and bank lines are enforced in the TIN as breaklines. The *Surface/Create TIN from Features* menu selection is used to build the TIN.

Using the *Theme/Convert to Grid* menu selection available in the ArcView view window, the terrain and water surface TINs are subsequently each converted to grids, with the same analysis extent and resolution. An output grid resolution of 1 meter is used for the TIN to raster conversion. The Avenue script ***Floodpln.ave*** is then used to compare the two grids and delineate areas inundated by floodwater. The script employs the following steps:

1. Subtract the terrain grid from the water surface grid to create a grid of flood depths. In the flood depth grid, cells with positive values represent areas inundated by floodwater; cells with negative values denote unflooded areas.
2. Query the flood depth grid for all cells with a value greater than zero. In the resulting query grid, flooded cells are assigned a value of one (true) and unflooded cells receive a value of zero (false).

3. Divide the flood depth grid by the query grid to create a revised flood depth grid. In this step, flooded cells are simply divided by one and thus retain their original value. However, unflooded cells are divided by zero, and are therefore assigned a value of *NODATA* by ArcView. So, in the revised depth grid, only cells inundated by floodwater possess a numerical value.

The revised flood depth grid can be overlaid on the orthophoto to facilitate spatial analysis of both floodplain extent and depth (Figure 8.18).

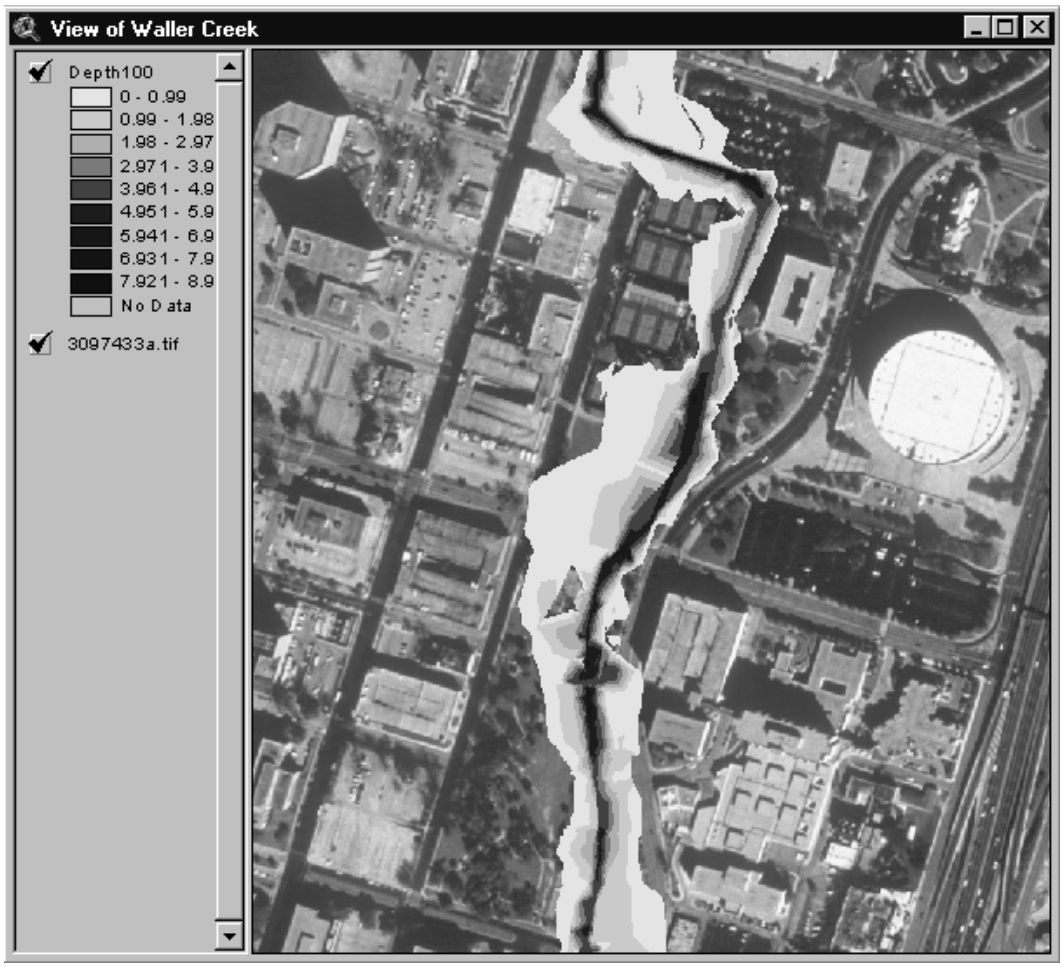


Figure 8.18 Planimetric View of Grid-Based Floodplain Delineation

8.1.5 Validation

In order to assess the accuracy of the terrain model and floodplain map, they must be validated against independent data sources.

8.1.5.1 TIN Terrain Model

The terrain TIN, created from the cross-section and DEM data, was compared with a TIN generated by the Capital Area Planning Council (CAPCO). CAPCO is an agency tasked with obtaining and developing aerial photogrammetry data for the Austin area and nine surrounding counties. The photogrammetry data, which includes (among other things) digital orthophotographs, DEMs, spot elevations, hydrography, and hypsography, were collected between 1996 and 1998. To validate the terrain TIN, CAPCO spot elevation coordinates for the Waller Creek area were used to create a digital terrain model of the land surface. The resulting DTM has a very high resolution, with a data point density of up to one per square foot in some areas. To generate cross-section profiles of the terrain TIN and CAPCO DTM, the ***Compare.ave*** script was employed. The script is designed to operate on grids, so the TIN and DTM were first converted to 1 meter resolution grids before the script was applied. The resulting profiles are shown on Figures 8.19 through 8.21.

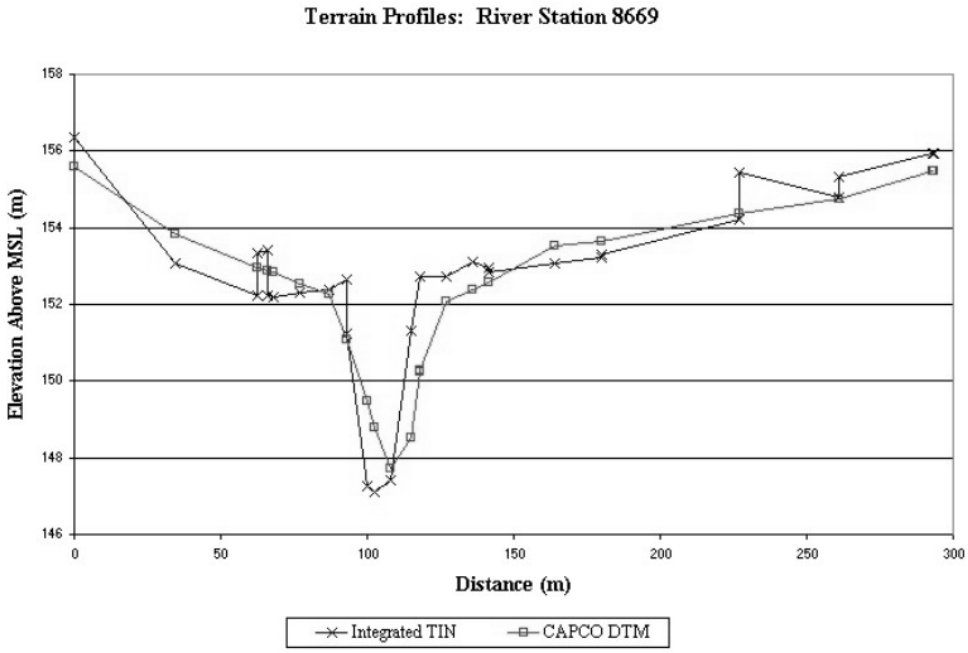


Figure 8.19 Integrated TIN and CAPCO DTM Comparison, Station 8669

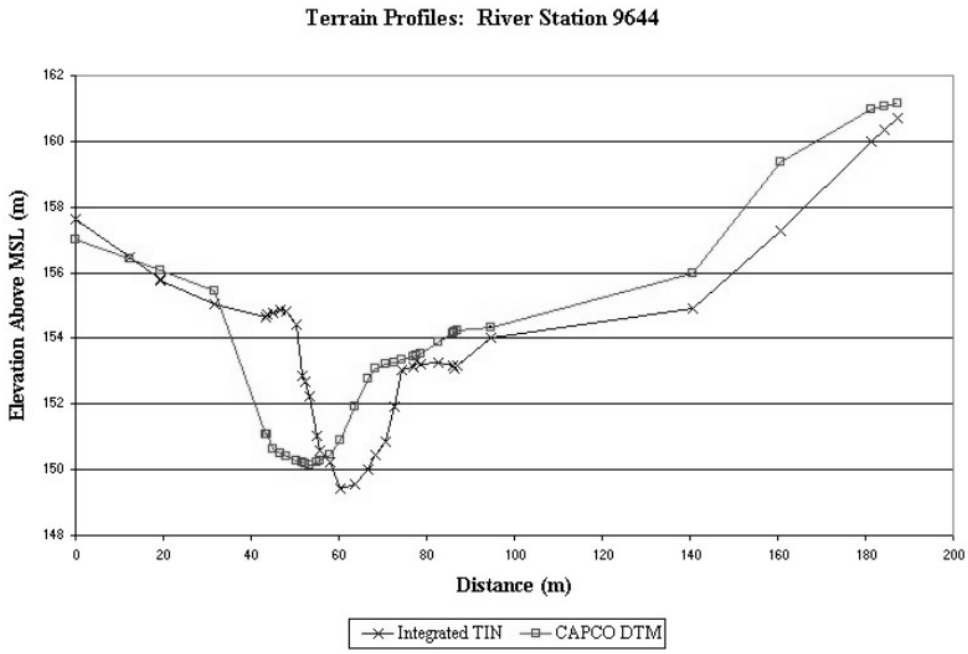


Figure 8.20 Integrated TIN and CAPCO DTM Comparison, Station 9644

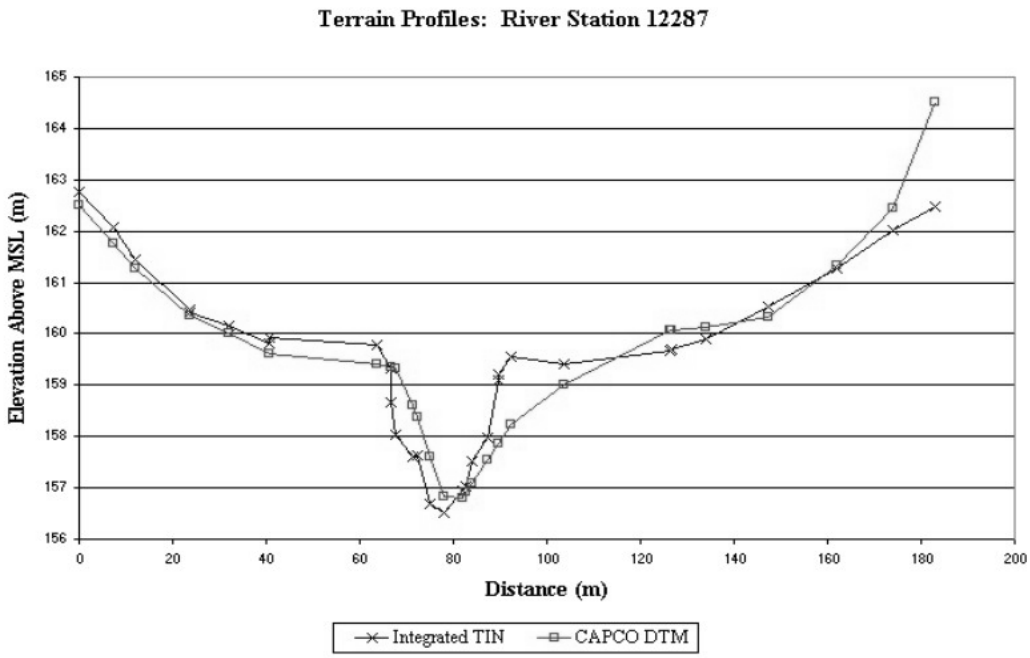


Figure 8.21 Integrated TIN and CAPCO DTM Comparison, Station 12287

The general shapes of the profiles are quite similar, but a horizontal offset ranging between 5 and 15 meters between the data sets is consistent. Given that the profile shapes are so similar, this offset could be indicative of differences between the CAPCO stream centerline and the stream centerline representation used in this research. Perhaps if the stream centerline for the integrated TIN were defined based on a DEM, the offset would be less. Neglecting the horizontal shift, the elevation offset is significantly less, typically ranging between 0 and 2 meters. Both the integrated TIN and the CAPCO DTM have a high density of points within the channel. As such, it appears that both terrain models could be used as a source of cross-sectional data for river hydraulic modeling. However, the availability of the input data distinguishes the two terrain models. Although more and more cities and agencies are contracting aerial photogrammetry projects, photogrammetry spot elevation data

currently are not generally available. In contrast, in many areas, both developed HEC-RAS models and 30 m DEMs are easily available.

8.1.5.2 Floodplain Delineation

Digital Quality Level 3 (Q3) flood data were used to validate the floodplain delineation. Digital Q3 flood data are developed by FEMA by scanning hardcopy Federal Insurance Rate Maps (FIRM). FIRMs, issued by FEMA as the official standard for floodplain delineation, identify areas of 100-year flood hazard in a community (FEMA, 1999b). Digital Q3 data for certain counties are available over the Internet from FEMA's website. The Q3 data for Travis County, Texas, were downloaded, imported into ArcView, and projected to UTM Zone 14, NAD83. In ArcView, the Q3 data are represented as a polygon shapefile; but, unlike the grid-based delineation, Q3 has no attribute of water depth. Still, the two floodplains can be compared based on floodplain location/extent.

As shown in Figure 8.22, the general shapes of the floodplain representations are similar, but far from identical. In addition, the raster floodplain representation is often narrower than the Q3 polygon. Unfortunately, a head-to-head comparison of the grid and Q3 floodplains is not necessarily valid due to fundamental differences with the input data used to develop each floodplain map. It is likely that FEMA's HEC-2 model and the City of Austin's HEC-RAS model use different stream cross-sectional and 100-year flow data. The Q3 data are based on a 1993 FIRM, while the HEC-RAS geometry and 100-year flows were last updated in 1998.

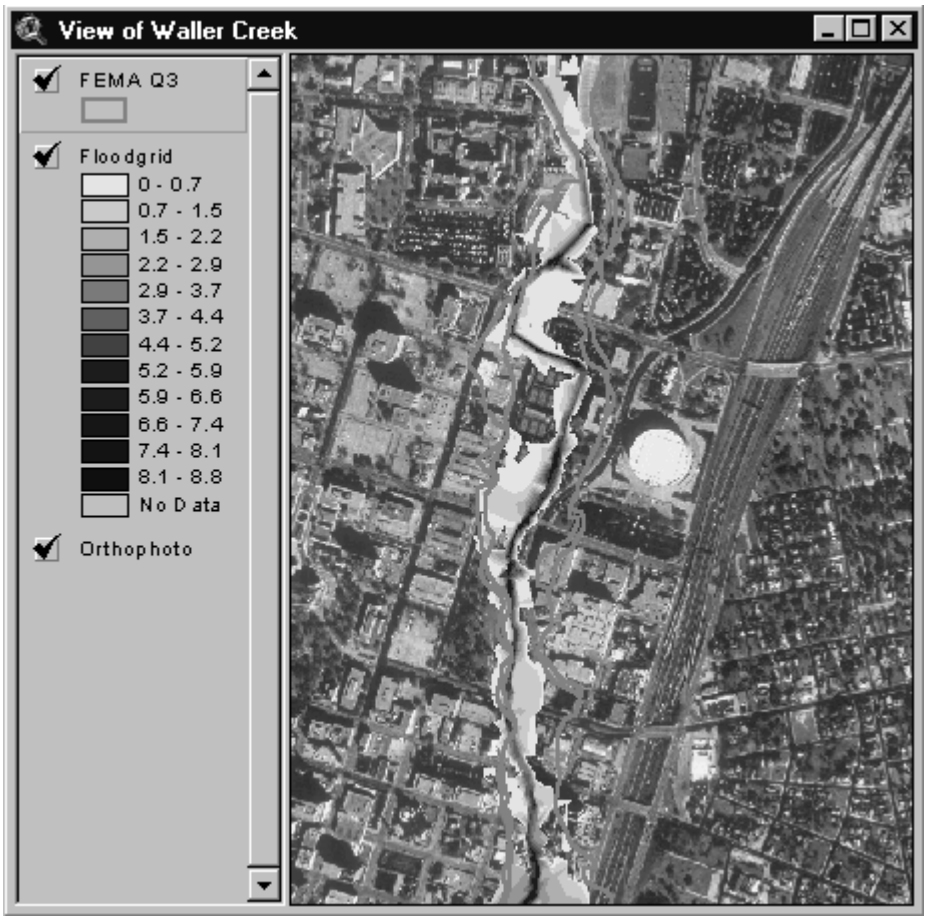


Figure 8.22 Comparison of Floodplain with FEMA Q3

Based on these differences, the grid and Q3 floodplains cannot be closely compared. Unfortunately, FEMA's Q3 is the only widely accepted digital floodplain data available for Waller Creek. As such, the validation of the raster floodplain delineation cannot be completely confirmed.

8.2 APPLICATION

The research described in this section offers procedures for the automation of floodplain mapping based on hydraulic modeling output. The Avenue scripts are associated with menu items in ArcView, so the user can easily map floodplains. The GIS-based delineation should result in significant savings of time and resources when compared to

manually plotting the HEC-RAS output. Some potential applications for this work include the following:

- **Hydraulic design**: An important design component of bridges, culverts, and other drainage control facilities involves hydraulic analyses to determine conveyance capacity. Using the grid-based floodplain delineation, a hydraulic engineer can zoom in on the area of a particular drainage control structure, and view the floodplain extent and query the flood grid for water depth at various locations of interest.
- **Terrain modeling**: As more local and state governments invest in photogrammetry studies such as CAPCO, more-detailed DTMs will become available. However, these studies often do not obtain elevation data for areas perennially inundated by water. Hence, a method to integrate the DTMs with surveyed channel elevation data obtained for hydraulic modeling is important. As stated previously (Subsection 8.3), the HEC-RAS model contains a user option to import three-dimensional river reach and cross-sectional data from a GIS. The integrated TIN accurately describes both the floodway and channel morphology to a degree required for hydraulic modeling.
- **Flood warning systems**: Real-time analysis during an intense storm would involve using measured rainfall as input for hydrologic modeling, applying the output flow rates to hydraulic modeling, and finally mapping the output in a GIS. Theoretically, this information could then be used to coordinate flood-warning activities such as road closures and evacuations.

Tutorial exercises of the Floodplain Mapping model, as well all Avenue scripts and code needed to run it, can be found in the *Floodplain Mapping Model* CD-ROM. In this CD-ROM, the following material is included:

- **Tutorial Exercises**: Two tutorial exercises that walk the user step-by-step through the processes of delineating streams and watersheds, and developing a hydrologic

model for HMS, are included. The exercises are: (1) Floodplain Mapping and Terrain Modeling Using HEC-RAS and ArcView GIS, and (2) Introduction to HEC-RAS.

- **Avenue scripts and code**

CHAPTER 9. CONCLUSIONS

Over the last years, GIS tools have been developed for automated hydrologic and hydraulic distributed modeling — tools that make use of readily available digital spatial data of different parts of the country. This research project has focused specifically on using GIS to accomplish two main tasks: (1) determining flood peak discharges and hydrographs, and (2) floodplain mapping. The results of this project provide proof that GIS is an excellent environment for developing water resources planning and management tools.

It was observed that, although there are many hydrologic and hydraulic models available, most of them are lumped models. In many cases, the spatial variability of the hydrologic system, which precludes the modeler from applying lumped models, is addressed by dividing the system into a series of sub-systems, each of them with different hydrologic properties. Even though an improvement with respect to the lumped approach, this alternative cannot be considered pure distributed modeling.

Development of distributed hydrologic modeling requires a distributed model (i.e., a set of rules that represent the physical processes that take place in a system and that accounts for the spatial variability of the properties of the objects that undergo these processes), and a spatial database (i.e., a consistent spatial data set of the system that includes the properties of the objects that undergo these processes).

Although the mathematical representation of the distributed physical processes is a complex task by itself, storing and handling the amount of data required by distributed models is an even more difficult task. Thus, it has become apparent that software specifically developed for managing large amounts of spatially distributed data — i.e., GIS — is necessary, and that ideally the distributed hydrologic models should be developed to operate within the GIS environment.

Another difficulty found in the process of accounting for the spatial variability of the system is the lack of spatial data for large areas. In other words, it is possible that after successfully developing a distributed model and its corresponding computer code, the model parameters cannot be populated because of lack of information. This difficulty, though, will

always confront the modeling community because as more data becomes available, models become more complex, and more data is needed. Fortunately, a significant amount of spatial data of Texas has been developed by different federal, state, and local agencies, and has been made available to the public. Development of spatial data, however, will always be an ongoing task.

Finally, presenting the engineering community — a community of professionals with well-established working habits — with a new approach for hydrologic and hydraulic analysis constitutes also a challenge. Engineers have been working for years using standard hydrologic and hydraulic models, with much success, and have been making a significant contribution to society. It is therefore difficult to expect them to drastically change their working approach, and to replace it with a *new-and-better* modeling philosophy. A transition period, in which the new GIS approach is coupled with the traditional models, is therefore necessary. In fact, it has been observed that making a connection between ArcView and standard software packages, like HEC-HMS or HEC-RAS, allows the modeler to get the most out of GIS (i.e., to capture the spatial variability of the system), while continuing to work with well-known tools.

The determination of flood peak discharges and hydrographs is a complex problem that could not be approached all at once. As explained below, the case of peak flows that depend solely on location was addressed first; subsequently, the case of peak flows that depend on location and return period; and finally, the case in which time is also a variable and a hydrograph has to be determined.

A raster map of precomputed values of potential extreme peak discharges (i.e., the highest peak discharge expected to occur at a certain location) was developed according to Asquith and Slade (1995) equations. In these equations, discharges are expressed as a function of drainage area and hydrologic region only. Thus, GIS functions that operate on raster data were used to develop raster data sets of the drainage area of each terrain pixel and of the hydrologic region in which each pixel is located. These raster data sets were then used as input to the discharge equations and applied to each pixel, resulting in a raster map of

precomputed discharge values. The retrieval of these values is immediate because no on-the-fly calculations are involved. This raster map is a powerful tool that avoids having to delineate the watershed, calculate its area, and apply the corresponding equation. However, it tends to overestimate flows since some watershed characteristics, such as land use, soil type, or geology, have been ignored and worst-case values have been predicted. The effect of reservoirs and cities on the downstream water bodies has not been considered either. However, it does not seem to imply a drastic change of methodology, since only the areas in close downstream proximity to dams and urban centers would have to be corrected. A disadvantage of the concept of potential extreme peak discharge is that discharges are estimated for the worst-case scenario and are not related to a specific return period. Because worst-case scenario discharges might be too conservative for design purposes, a new method was proposed to account for the discharge frequency.

In response to the tendency of worst-case scenario discharges to be too conservative, the **Flood Flow Calculator**, an ArcView extension for calculation of peak discharges for different return periods, was developed according to the TxDOT Statewide Regional Rural Regression Equations. According to these equations, peak discharges are a function of drainage area, length and slope of the longest flow path within the watershed, shape factor of the watershed (ratio of the square of the length to the area of the watershed), average curve number, and return period. In this case, since the input parameters for the discharge equations have to be calculated on a cell-by-cell basis, no raster map of precomputed discharge values could be developed. Instead, discharges are calculated on-the-fly, after the user selects the location from the map. This time, GIS functions that operate on raster data were used to develop the necessary raster data sets and calculate the necessary watershed parameters before estimating peak discharges for different design return periods. Tools to generate raster maps of curve numbers and flow time to the watershed outlet, and to calculate average values of a physical property within a watershed, are also included. Although this method is more developed than the previous one, dependence of flow on time is still not considered. A model that generates hydrographs is presented next.

Finally, a connection between GIS data sets describing a hydrologic system and HEC's Hydrologic Modeling System (HEC-HMS) has been developed. CRWR-PrePro extracts topographic, topologic, and hydrologic information from digital spatial data, and prepares an input file for the basin component of HEC-HMS, which when opened automatically creates a topologically correct schematic network of sub-basins and reaches, and attributes each element with selected hydrologic parameters. CRWR-PrePro also generates an input file for the precipitation component of HEC-HMS. Two methods to interpolate precipitation records are supported: (1) Thiessen polygons to calculate average precipitation at the sub-basins, and (2) GridParm to calculate routing parameters of the precipitation cells for use with the ModClark sub-basin routing method. At the moment, CRWR-PrePro calculates or imports parameters for: (1) the SCS curve number method and the initial plus constant loss method for loss rate calculations; (2) the SCS unit hydrograph model for sub-basin routing for which the lag-time can be calculated with the SCS lag-time formula or as a fraction of the length of the longest channel divided by the flow velocity; and (3) the Muskingum method and the lag method for flow routing in the reaches (depending on the reach length). Using CRWR-PrePro, the determination of physical parameters for HEC-HMS is a simple and automatic process that accelerates the setting up of a hydrologic model and leads to reproducible results.

A methodology for automated floodplain mapping has also been developed. The work provides a link between hydraulic modeling using HEC-RAS, and spatial display and analysis of floodplain data in ArcView. As inputs, the model requires a completed HEC-RAS model simulation and a GIS stream centerline representation. The procedure consists of several steps: (1) data import from HEC-RAS, (2) stream centerline representation, (3) cross-section georeferencing, (4) terrain modeling, and (5) floodplain mapping. The output is a digital floodplain map that shows both extent and depth of inundation.

The process developed for automating terrain modeling and floodplain delineation has several noteworthy benefits. First, it has a user-friendly interface. Using menu items, floodplain mapping is automated and simplified. Second, it has a digital output. Rendering

the floodplain in digital format allows the floodplain data to be easily compared with other digital data, such as digital orthophotography and GIS coverages of infrastructure, buildings, and land parcels. In addition to showing the aerial extent of flooding, the floodplain delineation includes flood depth information. Lastly, the process results in resource savings. Many floodplain maps need to be revised because they become outdated. The automated mapping approach developed for this research saves time and resources versus conventional floodplain delineation on paper maps. Thus, floodplain maps can be updated more frequently, as changes in hydrologic and hydraulic conditions warrant.

The main limitation of this approach is the assumption of straight-line cross sections. The HEC-RAS model requires cross sections to be defined such that they are perpendicular to the flow lines in both the floodways and main channel. As a result, land surveys of river cross sections observe the perpendicularity requirement. Within relatively straight portions of the channel, this requirement equates to straight-line cross sections. However, near bends in the stream, the cross sections are surveyed perpendicular to the channel, but doglegged in the floodways to ensure perpendicularity to flow. Unfortunately, information concerning the orientation of each cross section is indicated on survey maps, but is not routinely stored by HEC-RAS cross-section data. Consequently, because no information on cross-section doglegging is available, the approach in this research assumes that all cross sections occur in straight lines. The effect of the straight-line assumption on the accuracy of the resulting terrain models and floodplain maps varies with the distance from the stream channel.

It was observed that 30 m and 10 m DEMs do not provide sufficiently detailed channel representations to be used as the source of cross-sectional data for floodplain modeling. In addition, because of the small distances inherent to floodplain mapping, map projection consistency is of significant importance. The number of cross sections should also be great enough to capture bends and sharp elevation changes in the channel. The appropriate density of cross sections should be determined based on the shape of the channel and requirements for hydraulic modeling. To increase the density of cross sections in HEC-RAS, the cross-section interpolation menu option can be employed.

Further development on the use of GIS for hydrologic and hydraulic modeling should include support of more modeling options of the software packages, as well as development of a more efficient and GIS-supported connection between the hydrologic and hydraulic packages for flow value transfers. Future development in this field, though, is strongly dependent on the availability of terrain data at a resolution consistent with its use.

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