GIS-BASED HYDROLOGIC AND HYDRAULIC MODELING FOR FLOODPLAIN DELINEATION AT HIGHWAY RIVER CROSSINGS

by

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GIS-BASED HYDROLOGIC AND HYDRAULIC MODELING FOR FLOODPLAIN DELINEATION AT HIGHWAY RIVER CROSSINGS

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Francisco Olivera

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ABSTRACT

GIS-BASED HYDROLOGIC AND HYDRAULIC MODELING FOR FLOODPLAIN DELINEATION AT HIGHWAY RIVER CROSSINGS

by

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The importance of the spatial variability inherent to a watershed contributing flow to highway drainage structures can greatly affect the time and resources dedicated to the design process, as well as the size and cost of the structure. Evaluating extreme storm events and the resulting floodplain is a time-consuming process that, in the past, has been accomplished by manually plotting the extent of the floodplain on paper maps. Automating this process, with the aid of geographical information systems (GIS), could result in significant time and resource savings in the design process. This research investigates the synthesis of previously developed hydrologic and hydraulic modeling tools for digital floodplain analysis at two locations - Castleman Creek (McClennan County, TX) and Pecan Bayou (Brown County, TX). The methodology proposed consists of site-specific terrain data development for hydrologic analysis and parameter extraction using CRWR-PrePro, terrain data development and floodplain delineation using CRWR-FloodMap and

HEC-GeoRAS, and lumped parameter hydrologic modeling and steady flow hydraulic analysis using HEC-HMS and HEC-RAS. The results of the research indicate that although the availability of digital terrain data at an appropriate resolution may limit the application of these tools at small-scale sites such as are found at some highway river crossings, the methodology presented is an effective tool for representing the spatial variability of the watershed characteristics, integrating hydrologic and hydraulic modeling processes with GIS, and displaying an accurate floodplain map of the project site.

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1 INTRODUCTION

The design, construction, and maintenance of highway drainage structures are major expenditures for the Texas Department of Transportation (TxDOT) every year. One aspect of this design process involves a determination of the quantity of water expected to be conveyed by each structure. The peak flows associated with an extreme storm event can cause flooding of the areas adjacent to the structure and road. As practiced currently, hydrologic modeling is often used to calculate the quantity of runoff that is generated for each rainfall event that occurs in a particular watershed. Hydraulic modeling is also used to determine the water surface profiles that can be expected from the runoff calculated as a result of hydrologic modeling. Evaluating the resulting floodplain is a time-consuming process that, in the past, has been accomplished by manually plotting the extent of the floodplain on paper maps. Automating this process, with the aid of geographic information systems (GIS), could result in significant time and resource savings in the design process.

1.1 Background

From 1996 to 1999, TxDOT funded the Center for Research in Water Resources (CRWR) at the University of Texas at Austin to develop hydrologic and hydraulic modeling tools for the purpose of floodplain delineation at highway river crossings. From 1999 to 2000, TxDOT funded CRWR to implement those tools on two case study projects. This research, supported and funded by TxDOT, investigates the possibility of combining existing GIS-based development tools, lumped parameter hydrologic and one-dimensional hydraulic models, and the visual display capabilities of GIS to overcome the historical limitations of floodplain mapping. The focus of this thesis is the implementation of the above methodology at two existing TxDOT highway drainage structures to determine if site-specific data available at the district level, combined with state and national digital data, are sufficient to produce an accurate representation of the floodplain resulting from selected design storm events.

1.2 Site Selection

The selection of the two study areas was made jointly by TxDOT engineers and researchers at CRWR in 1999. To evaluate the floodplain delineation methodology adequately, sites were selected that were comprised of differing watershed, channel, and drainage structure characteristics. Based on these requirements, the Castleman Creek watershed, located in McLennan County, Texas, and the Pecan Bayou watershed, located in Brown County, Texas, were selected.

1.2.1 Castleman Creek

The Castleman Creek watershed is located just south of the town of Robinson, Texas and drains to main and relief bridge structures on US Highway 77 (US 77) (Figure 1-1).

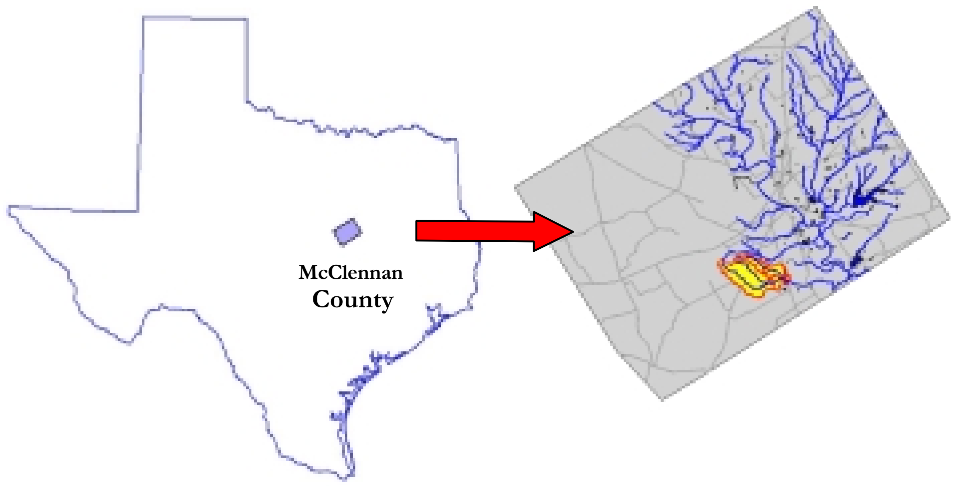

Figure 1-1 Location Map of Castleman Creek Watershed

This watershed encompasses approximately 20.1 square miles (sq mi), or 52.1 square kilometers (sq km), and is bisected by Interstate 35 (I-35) near the small community of Hewitt, Texas. It contains three primary waterways; Crow Creek and Chambers Creek flow into Castleman Creek as it exits the watershed and proceeds to the Colorado River. Two Soil Conservation Service (SCS) flood control dams are located on Crow Creek and one flood control dam is located on Castleman Creek, although there are no flow gages associated with any of the creeks in the watershed. Agricultural land use dominates the watershed except for areas immediately adjacent to US 77, I-35, and the town of Hewitt.

TxDOT is currently in the design phase of the main and relief bridge structures at US 77. Four cross-sections have been surveyed on Castleman Creek that cover approximately 400 meters upstream of the main bridge, and four cross-sections are also available that cover approximately 330 meters downstream of the bridge. High-resolution photogrammetrical survey data is also available for US 77 and areas immediately adjacent to the east and west of the highway as it traverses the creek crossings. In early 1999, TxDOT completed two HEC-1 hydrologic analyses on the watershed; a SCS Type 2 storm was applied to the watershed and routed to the bridge without considering the effects of the flood control structures and again when considering the effects of the dams. TxDOT also completed three HEC-RAS analyses (prior to the completion of this research) on the watershed: 1) without considering the effects of the dams on the existing bridges; 2) with considering the effects of the dams on the existing bridges; and 3) with considering the effects of the dams on the proposed bridge upgrades. This information provides an excellent opportunity for a comparison of the effects of the spatial variability of the watershed characteristics on the hydrologic response of the system, and provides adequate data for floodplain delineation using existing cross-sectional data.

1.2.2 PECAN BAYOU

The portion of the Pecan Bayou watershed selected for investigation in this research encompasses the city of Brownwood, Texas (City) and lies directly downstream of Lake Brownwood, a water supply and flood control structure that discharges to Pecan Bayou as it proceeds to the Brazos River (Figure 1-2).

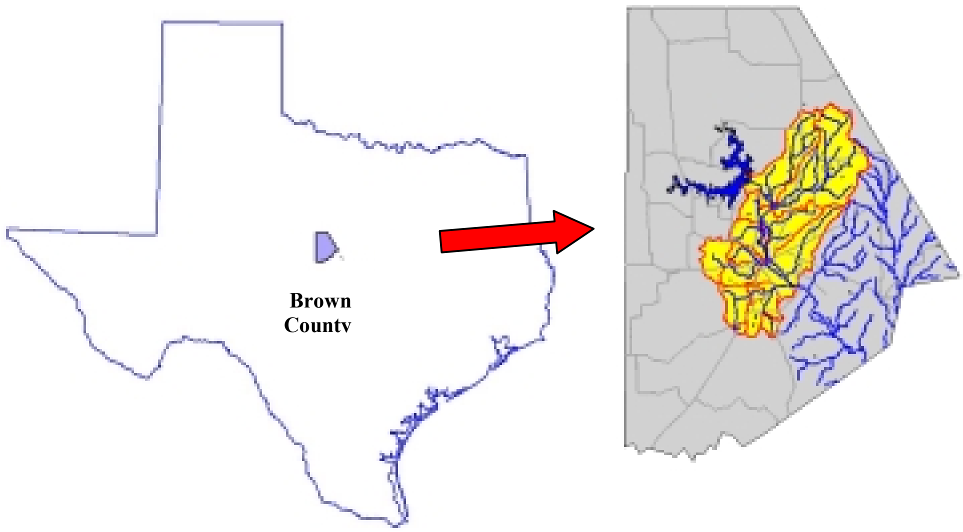

Figure 1-2 Location Map of Pecan Bayou Watershed

A USGS flow gage site is located on Pecan Bayou near Mullin, Texas (downstream of the Brown County line), which records the flow in Pecan Bayou on 15-minute intervals. This watershed, as delineated from Lake Brownwood to the USGS gage station, is approximately 515.2 sq mi (1334.4 sq km), and consists of many small creeks, including Adams Branch, Willis Creek, and Delaware Creek, which all flow into Pecan Bayou above the main structure of interest, the bridge located on FM 2126, just south of the Atchison, Topeka, and Santa Fe rail line running southeast from the city. The watershed contributing flow to the bridge at FM2126 is significantly smaller at 168.4 sq mi (436 sq km). Lake Brownwood is an uncontrolled release reservoir, with a known stage-discharge curve for the reservoir spillway. Only one precipitation gauge, located approximately 26 mi (41 km) southwest of Mullin, TX has adequate historical data for use in this project. The portion of the Pecan

Bayou watershed upstream of FM 2126 is comprised primarily (70%) of rangeland, although in the vicinity of Brownwood, urban land use dominates the landscape.

The bridge at FM 2126 has seen significant flooding, evidenced by flood records for severe precipitation events in 1991 and 1992. The City and TxDOT are interested in obtaining a reliable model of the floodplain based on existing river stage data from those storms. The City of Brownwood provided Microstation® files for the majority of the city that supply two-foot contours of the terrain; the U.S. Army Corps of Engineers (USACOE) has also conducted flood studies on Pecan Bayou and made cross-section data available for use on the project.

1.3 Objectives

The objectives of this project are three-fold:

1. To implement a seamless methodology for floodplain delineation in the digital domain using modified ArcView GIS scripts and software along with public-domain hydrologic and hydraulic modeling packages (HEC-HMS and HEC-RAS, respectively).
2. To evaluate the applicability of these tools on small-scale applications such as areas immediately adjacent to highway river crossings.
3. To evaluate the availability of digital and site-specific data available within, and external to, TxDOT at a resolution adequate for accurate floodplain delineation.

The methodology developed to meet these objectives is comprised of six steps, summarized in Table 1-1. The synthesis of the tools presented above yields a physical representation of the effects of flooding on areas immediately adjacent to the highway drainage structures being evaluated, and can be used to supplement floodplain planning and emergency response activities for TxDOT along with local and regional planning agencies.

Table 1-1 Summary of Floodplain Delineation Methodology

Methodology	Software	Description
Terrain Data Development	ArcView, CRWR-PrePro, CRWR-FloodMap	Consists of terrain development for hydrologic analysis in raster and vector domains, and terrain development for hydraulic analysis using triangular irregular networks (TINs)
GIS-Based Hydrologic Parameter Extraction	ArcView, CRWR-PrePro	Extracts spatially variable hydrologic parameters from GIS for export to HEC-HMS.
GIS-Based Hydraulic Geometry Extraction	ArcView, HEC-GeoRAS	Extracts topographic information from a terrain TIN and provides data as input to HEC-RAS.
Hydrologic Modeling	HEC-HMS	Lumped model using basin data imported from CRWR to produce discharge hydrograph
Hydraulic Modeling	HEC-RAS	One-dimensional hydraulic model that generates water surface profile for design storm.
Floodplain Delineation	ArcView, HEC-GeoRAS	Imports water surface profiles from HEC-RAS and displays the floodplain in GIS.

1.4 Organization

The research presented in this thesis provides a realistic view of the applicability of integrating GIS analysis and display capabilities with hydrologic and hydraulic modeling tools for floodplain delineation and visualization. This chapter provides an introduction to the study areas and identifies the objectives of the research. Chapter 2 investigates historical work and other technical literature related to GIS-based hydrologic and hydraulic modeling for floodplain delineation. Chapter 3 presents a discussion on the raw data used during the project, while Chapter 4 focuses on the methodology behind the application of each set of tools used in this research, including ArcView GIS, HEC-HMS, HEC-RAS, and HEC-GeoRAS. Chapter 5 presents the site-specific implementation procedures followed to generate a floodplain map for each project location. Chapter 6 contains a discussion of the results of the floodplain modeling and compares the results to existing data where available, and Chapter 7 provides conclusions and recommendations.

An invaluable part of the modeling process is the necessity to have access to complete sets of data for each natural system that is to be modeled to fully understand and be able to apply the results obtained. Appendix A provides a data dictionary for both implementation sites that specifies the type and origin of each dataset used, while Appendix B presents a list of ArcView scripts utilized in the methodology. Appendices C and D provide existing hydrologic and hydraulic data and modeling results for Castleman Creek and Pecan Bayou, respectively.

2 LITERATURE REVIEW

As digital terrain data becomes more readily available (with increasing accuracy and resolution) and computer processing become more efficient, the role of GIS in hydrologic and hydraulic modeling will continue to expand. At the present time, significant work has been accomplished to represent water surface elevations generated from hydrologic and hydraulic models in a three-dimensional terrain model, thereby providing the user with a representation of the spatial extent of the floodplain resulting from a particular precipitation event.

This chapter investigates historical data and literature related to GIS-based terrain analyses, and has been divided into several sections to parallel subsequent discussions in the text. The first section addresses development of digital terrain models (DTMs) to represent the land surface in a GIS platform. GIS-based preprocessors used to represent the spatial variability of the hydrologic parameters of a watershed are then presented, followed by hydraulic modeling processes that are discussed in light of the use of GIS to extract channel properties from the land surface. Floodplain mapping in GIS is the final topic presented.

2.1 Digital Terrain Models

Much emphasis has been placed on the development of distributed and lumped models to represent complex land-water interactions in last 30 years (Azagra, 1999). As currently practiced, the primary limitation in accurate floodplain mapping may not be found in representing these interactions, however, but rather in the existence of accurate DTMs that can be obtained cost-effectively.

GIS uses a DTM to describe the spatially distributed attributes of the terrain. DTMs describe the topography of the terrain by defining the elevation surface, while the geospatial data needed to define the "connectivity" of each terrain element is represented by the topology of the DTM (i.e., points make up a line, lines make up an area). A DTM can be defined with the following data formats:

- Raster (grid) data;
- Vector (point, line, polygon) data; and
- Triangular irregular networks (TINs).

The most common type of raster data used for DTM development is a digital elevation model (DEM). The popularity of DEM data is attributed in part to cost-effective access to the data, a complete coverage of the contiguous United States at various resolutions (i.e., 1 arc-second, 3 arc-second), and ever-increasing capabilities of GIS to process the data. The United States Geological Survey (USGS) provides DEMs for the United States and various countries around the world – at this time, DEM selection for a particular application is generally driven by data availability as opposed to quality and resolution (Garbrecht and Starks, 1998). Currently, the automated extraction of topographic parameters from DEMs in GIS is recognized as a viable alternative to traditional surveys and manual evaluation of topographic maps, particularly as the quality and coverage of DEM data increases. Garbrecht and Martz (1999) provide commentary on the production, availability, quality, resolution, and capabilities of DEMs with respect to the derivation of topographic data in support of hydrologic and water resources investigations. Surface drainage, channel networks, and drainage divides can also be extracted from DEMs in the GIS domain (Jenson and Domingue, 1988; Martz and Garbrecht, 1992). Development of DEM data is often necessary in very flat areas to create a topologically correct representation of the land surface. O'Callaghan and Mark (1984) and Jenson (1991) have demonstrated techniques for locating and removing depressions in gridded DEM data.

Vector data consists of discrete spatial features, such as stream networks, elevation contour lines, or polygons representing areas with similar topographic or topologic properties. Digitized channel network data can be obtained from the USGS in the form of Digital Line Graphs (DLGs) or from the EPA in the form of RF1 and RF3 river reach files. This hydrographic coverage provides information on flowing water, standing water (lakes), and wetlands. More recently, the National Hydrography Dataset (NHD) has been developed by the USGS and EPA as a more complete vector representation of these waterways. The NHD is based upon the content of DLG hydrography data integrated with reach-related information from RF3 data (USGS, 1999). The United States Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS) provides information on land use and soil properties in the form of polygon coverages for the entire country. Ragan (1991) developed a personal computer-based GIS named GIS-HYDRO to assemble predetermined land use, soil, and slope data clipped within a user-defined boundary. Look up tables relating land use types (classified by the Anderson system) to establish curve numbers for the USDA Soil Conservation Service (SCS) have been proposed by Maidment (1993) to further develop vector-based data for hydrologic analysis purposes.

Triangular irregular networks (TINs) are a collection of irregularly spaced points connected by lines. Delauney triangulation is most often used to generate

TINs, and is based on the principal of maximizing the minimum angle of all triangles produced by connector lines to nearest neighbor points (Lee and Schacter, 1980). Breaklines are used to control the smoothness and continuity of the surface – these lines can represent such features as ridgelines, riverbanks, or roads. TINs can be generated from raster data, vector data, or a combination of both. Long (1999) describes techniques that can be used to develop quality TINs for automated floodplain delineation with HEC-RAS using ArcInfo methodology based on cross-section data in HEC-2 format. Elevation contour data generated from orthophotography has been successfully used to generate accurate elevation TINs in ArcView as part of a flood inundation study at Vandenberg Air Force Base (Buntz, 1998), and in a similar study, elevation contour data was successfully imported into GIS from a computer aided drafting (CAD) platform in *.dxf* file format at União da Vitória City, Paraná, Brazil (de Camargo, 2000). The use of coarse DEM surfaces is generally not suitable for the large-scale terrain representation required for hydraulic analysis of river channels (Tate, 1999) – because they cannot vary in spatial resolution, DEMs may poorly define stream channels in areas of complex relief (Carter, 1988). For this reason, the hydraulic modeling of river channels may best be accomplished using TINs. TINs allow for a dense network of points where the land surface is complex and detailed, such as river channels, and for a lower point density in flat or gently sloping areas.

GIS provides the links between the discrete data formats presented above by geo-referencing the spatial data, thus creating a DTM that can be used to facilitate spatially variable land-water interactions. Speight (1980) provides a complete list of spatially variable land surface attributes that can be derived from a DTM.

2.2 GIS in Hydrologic Modeling

"The use of computers in hydrologic analysis has become so widespread that it provides the primary source of data for decision making for many hydrologic engineers. Since so much of hydrology is linked to processes at the earth's surface, the connection to the topographic, computer-based methodology of GIS is a predictable step in the evolution of hydrologic engineering" (DeVantier and Feldman, 1993). Once an acceptable DTM has been adequately defined, the spatial variability of the terrain and corresponding hydrologic parameters can be evaluated in a GIS for use in event-based and continuous hydrologic models. DeVantier and Feldman (1993) present a summary of past efforts in using DTMs and GIS to perform hydrologic analyses using grid, vector, and TIN data.

The first application of GIS in hydrologic modeling utilized grid cell storage of information (Pentland and Cuthbert, 1971). Since then, spatial analysis capabilities in GIS have increased tremendously. In 1989, Cline *et al* developed an AutoCAD® based watershed information system to extract and calculate the data necessary to create HEC-1 input files for a sample watershed in Idaho. Jensen and Domingue (1988) and Jensen (1991) present a methodology to delineate watershed boundaries and stream networks based on gridded elevation data to defined outfalls. The scheme uses the eight-direction pour-point model to define surface water flow from each cell in a grid to one (and only one) of its eight neighboring cells according to the path of steepest decent. The cells contributing flow to the outfall can be counted to represent drainage area, and cells with no contributing flow define the watershed boundaries. Tarboton (1997) developed a similar procedure that represents flow direction as a single angle taken as the steepest downwards slope on the eight triangular facets centered at each grid point. Martz and Garbrecht (1992) present a set of ten algorithms to automate the determination of drainage network and subcatchment areas from DEMs. These algorithms perform such tasks as: DEM aggregation; depression identification and treatment; relief incrementation of flat areas; flow vector determination; watershed boundary delineation; drainage network and subcatchment area definition and systematic indexing; tabulation of channel and subcatchment area properties; and evaluation of drainage network composition. Procedures for delineating streams and watersheds from DEMs can be found in Maidment (1997), Meijerink *et al* (1994) and ESRI (1992).

The advantage of using GIS in hydrologic modeling is to provide spatially derived hydrologic parameters (such as watershed area, curve number, gridded precipitation, flow length in each watershed, and slope) for input into more powerful hydrologic models. Some of the earliest work by HEC related to GIS hydrology involved the development of a systematic methodology for automating the data preparation process in grid format (Davis, 1978). Grid-based GIS is 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, 1992). Stuebe and Johnston (1990) present a comparison of rainfall-runoff relationships calculated in GRASS (a USACOE grid-based hydrologic analysis system) to GIS-based watershed delineation and runoff routing procedures using the SCS Curve Number method, with results indicating that GIS is an acceptable alternative to the conventional rainfall-runoff method for watersheds lacking relatively flat terrain. This work has led to the development of several procedures for calculating spatially variable hydrologic parameters from

DEMs. Maidment (1993) outlines a conceptual grid model that incorporates flow direction and a runoff velocity field to develop unit hydrographs from isochrones. The *Watershed Delineator* extension to ArcView GIS (Djokic *et al* 1997, ESRI 1997) was developed to delineate watersheds to a point, line segment, or polygon, selected interactively by the user from a map. Similarly, Hellweger and Maidment (1997) present a procedure called HEC-PREPRO that automates the translation of data from a GIS to a hydrologic data structure used by lumped parameter hydrologic modeling programs. Olivera et. al. (1998) developed CRWR-PrePro (a more recent version of which is used in this thesis) that combines the terrain analysis capabilities of the Watershed Delineator with hydrologic parameter calculation capabilities and the topologic capabilities of HECPREPRO to conform a hydrologic modeling tool that prepares – from readily available digital spatial data – the input file for the HEC-HMS basin component (Olivera, 1999). Doan (1999) demonstrated that the development of a hydrologic model in HMS is practical with the aid of GIS software and spatial data by implementing CRWR-PrePro on the Buffalo Bayou watershed near Houston, Texas. HEC is currently undergoing the development of public-domain software to integrate GIS capabilities with the HEC-HMS rainfall-runoff model based on the tools discussed previously.[1] This software, known as HEC-GeoHMS is scheduled to be released in the latter part of 2000 or early in 2001.[2]

There have been several applications of GIS-based hydrologic preprocessors developed primarily to support the design of highway drainage structures, the focus

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[1] Personal communication with David Maidment, Center for Research in Water Resources, University of Texas at Austin on August 20, 2000.

[2] Personal communication with David Maidment, Center for Research in Water Resources, University of Texas at Austin on October 18, 2000.

of this thesis. GISHYDRO was developed and installed in the Maryland State Highway Administration's (MSHA) Division of Bridge Design in 1991 (Ragan, 1991). This GIS permitted the user to assemble the land use, soil, and slope for any watershed in the state and interface with the SCS TR-20 rainfall-runoff model. The Hydrologic Data Development System (HDDS) was developed by Smith (1995) as a set of integrated ARC/INFO programs that utilize readily available spatial data to define drainage basin boundaries, areas, maximum flowpath length, estimated travel time, slope, soil group, rainfall, and runoff coefficients at catchments defined by a highway river crossing (Olivera, 1999).

2.3 GIS in Hydraulic Modeling

The advantage of using GIS in hydraulic modeling is the potential for extracting topographically correct cross-section data from a DTM that can be used to determine river stage and floodplain extent as calculated in hydraulic modeling software packages. Beavers (1994) commenced the initial work to link hydraulic modeling data and GIS. ARC/HEC2, an interface between the HEC-2 hydraulic model and the ArcInfo GIS system, extracts channel geometry from elevation contour data and utilizes user-supplied information such as Manning's roughness values and channel contraction/expansion coefficients for export to HEC-2. Upon completion of the water surface elevation calculations in HEC-2, an ArcInfo TIN coverage of the floodplain is produced.

In 1997, data exchange modules were developed for HEC-RAS (by Thomas Evans) to permit the transfer of physical element descriptions to GIS software

(HEC, 1997). These modules enable a user to import cross-section locations as three-dimensional coordinates (XYZ) from DTMs to develop channel and reach geometry. This work was related to Beavers' 1994 work, but permitted data exchange between ArcView GIS and HEC-RAS, the successor to HEC-2, with improved graphical user interface (GUI) capabilities.

In 1998, ESRI translated and improved Evans' AML code and added GUIs in the GIS environment, resulting in an ArcView extension called AVRAS. Azagra (1999) utilized AVRAS on the Waller Creek watershed in Austin, Texas (encompassing approximately 5.8 square miles) using a TIN provided by the local municipality. Topographic information was extracted from the TIN and imported as channel geometry for use in a HEC-RAS hydraulic model, resulting in an adequate representation of the floodplain for the 100-year storm event. De Camargo (2000) also utilized the AVRAS methodology to compare modeled floodplain results to actual flood events in União da Vitória City, Paraná, Brazil. In 1999, AVRAS was released as a commercial product by Dodson & Associates, Inc. under the trade name of GIS StreamPro. Kraus (1999) presents a methodology to extract channel geometry data from a TIN using GIS StreamPro on a watershed covering approximately 3.42 square miles. Also in 1999, HEC released HEC-GeoRAS as the public-domain version of GIS StreamPro. Ackerman *et al* (1999) present the development of HEC-GeoRAS as an interface between ArcInfo and HEC-RAS. This specific version of GeoRAS uses ArcInfo to develop geometric data for import into HEC-RAS using a TIN as the basis of a DTM, and allows the user to view exported water surface profile data.

A similar methodology for linking GIS DTM capabilities with hydraulic modeling software was presented when the Danish Hydraulic Institute (DHI) released MIKE 11 GIS in 1999. This software provides an interface between the world's most widely applied dynamic modeling tool for rivers in channels (MIKE 11) and ArcView GIS. To develop a MIKE 11 GIS application, essential information comprising a MIKE 11 river network, a MIKE 11 hydraulic simulation, and a DEM is required. The MIKE 11 river network is geo-referenced in MIKE 11 GIS, and when combined with water surface elevation data, can produce several types of flood maps.[3]

Because of the reliability of these methodologies on the existence of TINs or high-resolution DEMS to provide accurate channel geometry, further work has been undertaken to integrate readily available field-surveyed cross-section data and lower-resolution 30-meter DEM data defining the surrounding terrain. Tate (1999) developed Avenue scripts for ArcView GIS called CRWR-FloodMap to integrate field-surveyed stream geometry within a floodplain from a HEC-RAS model into a GIS-based DTM, generated from digital orthophotography, on Waller Creek in Austin, TX. Andrysiak (2000) applied Tate's scripts to evaluate a 165 square mile watershed along Beargrass Creek near Cincinnati, Ohio using a DEM with 30-meter accuracy.

[3] Danish Hydraulic Institute web site: http://www.dhisoftware.com/mike11/Description/MIKE_11_GIS.htm. Accessed: August 24, 2000.

2.4 Synthesis of GIS-Based Hydrologic and Hydraulic Modeling for Floodplain Delineation

The majority of the work completed to date focuses on the use of GIS-based pre- and post-processing methodologies applied to either hydrologic or hydraulic models to reproduce actual conditions. However, few models have been developed that investigate the effects of spatially variable hydrologic and hydraulic parameters on flow hydrographs, water surface profiles, and the floodplain extent resulting from recorded storm events. The Pecan Bayou watershed model developed in this thesis addresses this issue.

In addition, the GIS-based hydraulic modeling performed to date has evaluated floodplain delineation on watersheds in excess of 3 square miles. The floodplain model developed for the Castleman Creek watershed focuses on the feasibility of the HEC-GeoRAS methodology at highway river crossings, where detailed terrain data in the form of highly accurate TINs or DEMs may not be readily available. The extent of the modeled area upstream and downstream of the river crossing (approximately 0.5 river miles) encompasses approximately 4000 acres (0.1 sq mi).

3 DATA

The data used during the development of the floodplain delineation models at each implementation site was obtained from a variety of public agencies. Because of the multitude of sources, the data was also provided in several different projections. In order to utilize this information within GIS, all spatial data was converted to a common map projection. The projection used throughout this project (for both Castleman Creek and Pecan Bayou) was defined by the Texas State Mapping System parameters:

```
PROJECTION ALBERS
UNITS METERS
PARAMETERS
1ST STANDARD PARALLEL:                    27 25 0.00
2ND STATNDARD PARALLEL:                   34 55 0.00
CENTRAL MERIDIAN:                        -100 0 0.00
LATITUDE OF PROJECTION'S ORIGIN:          31 10 0.00
FALSE EASTING (METERS):                   1000000.00
FALSE NORTHING (METERS):                  1000000.00
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This chapter is organized by location, with each subsection identifying the raw data available at each site, and the data development activities necessary to ensure the homogeneity, spatial connectivity, and completeness of each dataset. A data dictionary that documents the properties of each dataset is included in Appendix A.

3.1 Castleman Creek

The data available for use in the Castleman Creek watershed consisted of raw data sources and several datasets that required further development to become usable inputs to modeling activities.

3.1.1 Raw Data

The raw data used as inputs for model development at the Castleman Creek site consisted of terrain data (DEM and high-resolution photogrammetric survey data along US 77), stream network data, regional regression peak flow data, existing HEC-HMS and HEC-RAS project information, and infrastructure data (TxDOT road coverages).

3.1.1.1 Terrain data

A digital representation of the terrain at the Castleman Creek site was developed primarily from the USGS National Elevation Dataset (NED). This dataset provided seamless raster elevation data at a scale of 1:24,000 in one-degree blocks. The data was originally digitized from existing contour information and provided elevation data in one arc-second (approximately 30 meter) resolution. The NED was provided in a geographic projection (with units of decimal degrees) according to the NAD83 horizontal datum, and yielded elevation data in units of decimal-meters. At this site, the NED ID 9832 was sufficient to cover the entire watershed – therefore, merging adjacent grids was not necessary.

Aerial photogrammetric survey data describing US 77 and the areas immediately adjacent to it was also available (Figure 3-1). This elevation data was provided by TxDOT as a point elevation theme in the Texas State Plane – Zone 14 projection using the NAD83 horizontal datum and the NGD29 vertical datum. The source of the data was unknown.

Figure 3-1 TIN Elevation Data for US 77 in Castleman Creek Watershed

3.1.1.2 Stream Network

The stream network at the site was defined by the NHD, a feature-based dataset that interconnects and uniquely identifies the stream segments or "reaches" that make up the Nation's surface water drainage system. It is based upon the content of USGS Digital Line Graph (DLG) hydrography data integrated with reach-related information from the EPA Reach File Version 3 (RF3)[4], and provides not only river reach data, but water body coverages as well. The NHD is currently based on the content of the USGS 1:100,000-scale data, giving it accuracy consistent with those data. Data for this project was provided in geographic coordinates (with units

[4] National Hydrography Dataset web site: http://nhd.usgs.gov. Accessed: August 20, 2000.

of decimal degrees) on the North American Datum of 1983.[5] The Castleman Creek network includes approximately 51 km. of waterways within the 52.1 sq. km. watershed, but is only comprised of three waterways and as such is well defined by the NHD and required no modifications. Figure 3-2 provides a representation of the Castleman Creek Stream Network shown as projected into the Texas State Mapping System at a scale of approximately 1:12,000.

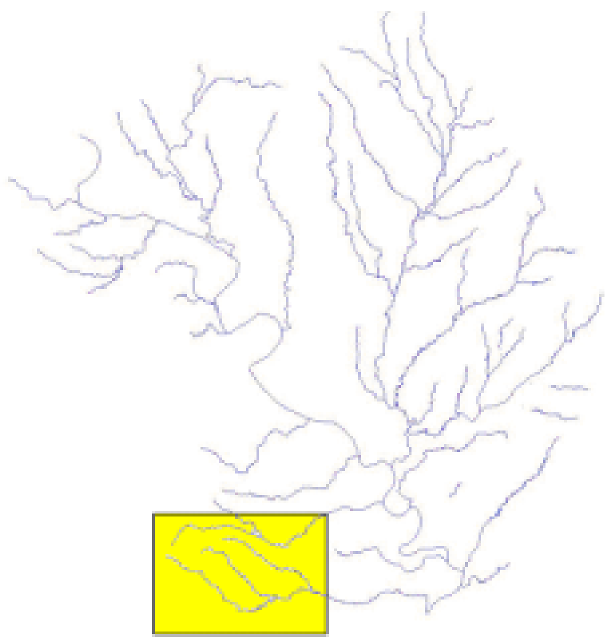

Figure 3-2 Castleman Creek Stream Network

3.1.1.3 Precipitation Data

Due to the size and the rural location of the Castleman Creek watershed, no flow gages were available for rainfall-runoff calibration and gauged precipitation data

[5] National Hydrography Dataset web site: http://mapping.usgs.gov/mac/isb/pubs/factsheets/fs10699.html. Accessed: August 20, 2000.

was not necessary for development of the model at this site. However, SCS Type 2 synthetic storms were applied to the watershed to model rainfall-runoff relationships. This data was obtained from existing HEC-1 models previously developed by the TxDOT Bridge Hydraulics Division in Austin, TX. For use in this research, these synthetic storms were extracted from the HEC-1 model for use in modeling the watershed using CRWR-PrePro and HEC-HMS. This data consists of cumulative 15-minute interval precipitation measured to 0.001 inches over a 24-hour period for storm return periods of 2, 5, 10, 25, 50, and 100 years. Appendix C.1 presents the original synthetic storm data developed for the Castleman Creek site.

3.1.1.4 Flood Control Structure Data

The Castleman Creek site includes three SCS flood control structures – all of which lie upstream of the US 77 river crossing. SCS-1 is found on Castleman Creek, while SCS-2 and SCS-3 are found on Crow Creek. Figure 3-3 depicts the locations of the flood control structures as shown on the USGS DOQQ.

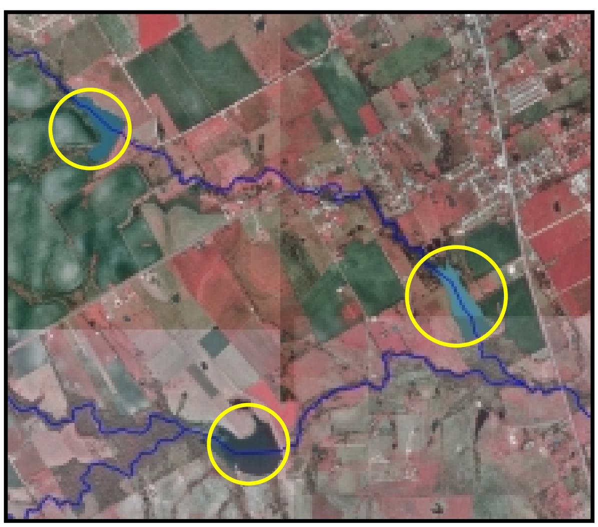

Figure 3-3 Locations of SCS Flood Control Structures in Castleman Creek Watershed

The elevation-storage-discharge relationships for all of these structures were incorporated into the original HEC-1 model developed by TxDOT; this data was extracted for use in HEC-HMS to simulate rainfall-runoff relationships. Appendix C.1 presents the original elevation-storage-discharge data used by TxDOT personnel to develop the HEC-1 model.

3.1.1.5 Flow

As stated previously, no historical flows were recorded at the Castleman Creek site, so calibration of the model was not possible with recorded flow data. Standard TxDOT practice is to model such watersheds without any flow control structures and compare the resulting data to regression equations developed to estimate peak flows based on historical data.[6] Regional regression equations have been developed by the USGS in 1993 to estimate the magnitude and frequency of floods for ungaged sites in six separate regions with Texas based on the area and slope of the watershed of interest.[7] Additional regression equations were developed specifically for Texas in 1997 by the USGS (in cooperation with TxDOT) that considered regionally variant conditions not considered in the 1993 equations.[8] These equations considered watershed shape factor in addition to the two parameters mentioned previously, and differentiated expected peak flows based on watershed size. Figure 3-4 presents a comparison of the 1993 and 1997 regional regression equations for Castleman Creek.

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[6] Personal communication with David Stolpa, TxDOT, on May 12, 2000.

[7] Jennings et. al., *Nationwide Summary of U.S. Geological Survey Regional Regression Equations for Estimating Magnitude and Frequency of Floods for Ungaged Sites*, 1993 – Water-Resources Investigations Report 94-4002.

[8] Asquith, W.H. and R.M. Slade, *Regional Equations for Estimation of Peak-Streamflow Frequency for Natural Basins in Texas*, 1997 – Water-Resources Investigations Report 96-4307.

Storm Return Period (yrs)	Regional Regression Equations	
	1993	1997
2	$Q2=216A^{0.574}S^{0.125}$	$Q2=832A^{0.368}S^{0.283}$ (for A<32 sq mi) $Q2=129A^{0.578}S^{0.264}$ (for A>32 sq mi)
5	$Q5=322A^{0.620}S^{0.184}$	$Q5=584A^{0.618}$ (for A<32 sq mi) $Q5=133A^{0.603}S^{0.570}$ (for A>32 sq mi)
10	$Q10=389A^{0.646}S^{0.234}$	$Q10=831A^{0.392}$ (for A<32 sq mi) $Q10=178A^{0.644}S^{-0.695}SH^{-0.220}$ (for A>32 sq mi)
25	$Q25=485A^{0.668}S^{0.226}$	$Q25=1196A^{0.376}$ (for A<32 sq mi) $Q25=219A^{0.631}S^{-0.776}SH^{-0.267}$ (for A>32 sq mi)
50	$Q50=555A^{0.682}S^{0.230}$	$Q50=1505A^{0.366}$ (for A<32 sq mi) $Q50=261A^{0.630}S^{-0.837}SH^{-0.291}$ (for A>32 sq mi)
100	$Q100=628A^{0.694}S^{0.261}$	$Q100=1780A^{0.440}$ (for A<32 sq mi) $Q100=313A^{0.634}S^{-0.848}SH^{-0.316}$ (for A>32 sq mi)

For 10 mi^2 < Contributing Area < 100 mi^2 $Q=[2-\log(A)]Q1+[\log(A)-1]Q2$

A = Watershed Area (sq. mi.)

S = Watershed Slope (ft./mile)

SH = Watershed Shape Factor (dimensionless)

Figure 3-4 Comparison of Regional Regression Equations for Castleman Creek

3.1.1.6 Infrastructure

A coverage of Texas roads, developed by TxDOT in the Texas Statewide Mapping System (TSMS) projection (in NAD27 format with units of feet), was clipped to the extents of the Castleman Creek watershed and utilized to identify the location of the US 77 main and relief bridges.

3.1.1.7 Existing Models

Both HEC-1 and HEC-RAS models have been developed previously for the Castleman Creek site by TxDOT personnel. This section presents a summary of the data available for use in the development of floodplain delineation models at both sites.

3.1.1.7.1 HEC-1

The status of the bridge modification project at the Castleman Creek crossing is ongoing, and this project was undertaken to further understand the impact the modifications may have on the stage and spatial extent of flooding resulting from extreme precipitation events.

Two HEC-1 models were developed for Castleman Creek in 1990 – one evaluated peak flow as a result of SCS Type 2 synthetic storm events applied over the watershed without considering the effects of the flood retarding structures. This was performed to facilitate a comparison of the results to the regional regression equations. The other model considered the effects of the flood control structures on the expected peak flow at the US 77 Bridge.

The input data for these models consisted of 15-minute cumulative precipitation data for storm return periods of 2, 5, 10, 25, 50, and 100 years (the discharges associated with these storms are presented in Chapter 6). Watershed areas were provided as inputs into the model based on delineation activities using USGS 7.5' quadrangle maps (quads). An SCS lag-time (in hours) and curve number were also provided for each watershed, along with Muskingum routing parameters (K, X) specified for each routing reach. These were developed based on the protocol presented in the TxDOT Bridge Division Hydraulic Manual, with revisions dated June 6, 1986. When the flood control structures were considered, the storage-elevation-discharge relationships were provided for each of the three SCS flood control structures. Finally, a schematic of the stream network was provided which yielded the connectivity of the network as understood from the USGS 7.5' quads. Appendix C.1 provides the input and output files for both HEC-1 runs.

3.1.1.7.2 HEC-RAS

A one-dimensional HEC-RAS hydraulic model for the Castleman Creek site was developed by TxDOT personnel prior to the implementation of this project. Several different scenarios were employed to estimate the peak stage at the bridge for the six storm return periods noted previously. Models were developed without consideration of the flood control structures, with consideration of the flood control structures at the existing bridge, and with consideration of the flood control structures at the proposed bridge upgrade. This study focuses on the results of the HEC-RAS model that accounted for the effects of the flood control structures on the proposed bridge modifications.

Five cross-sections were surveyed upstream of the bridge and four cross-sections were surveyed downstream of the bridge. Figure 3-5 presents a schematic of the original cross-sections.

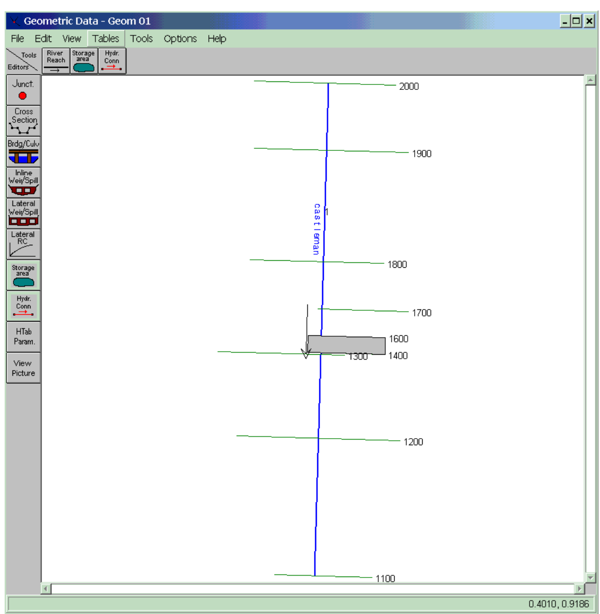

Figure 3-5 HEC-RAS Schematic of Surveyed Cross-Sections on Castleman Creek

The most-upstream cross-section (Station 2000) is located approximately 402 meters upstream of the bridge, and the most-downstream cross-section (Station 1100) is located approximately 332 meters downstream of the bridge. It is evident that the distance between the most upstream and downstream cross-section stations (900 m) does not match the reach lengths detailed in the existing HEC-RAS model (734 meters); this research assumes that the reach lengths provided in the HEC-RAS model were more accurate. Each cross-section provided data on the downstream reach lengths at the channel and left- and right-overbanks. Similarly, Manning's Roughness coefficients were provided for the channel, and left- and right-overbanks. Finally, expansion and contraction coefficients were provided for each cross-section. The original sketches of the cross-section orientations were also made available.

The bridge crossing was modeled as a "multiple opening" due to the presence of a flood relief bridge south of the primary bridge structure. Geometric data was provided for each bridge in the HEC-RAS model that detailed the deck width, distance to upstream cross-section, and weir coefficient in the event that the peak flow stage overtopped the structure. Data was also provided on the high and low chord elevations for each bridge deck, along with the upstream and downstream embankment side slopes. The bridge was modeled using the energy approach for both low and high flows. Steady-flow boundary conditions were also assumed in the HEC-RAS model – normal depths were assumed at both the upstream and downstream cross-sections, with corresponding water surface slopes of 0.00084 and 0.00239, respectively. Appendix C.2 presents a summary of this data.

3.1.2 DATA DEVELOPMENT

While the data discussed in Section 3.1.1 encompasses the raw data that was used for the Castleman Creek model, modification was required for a number of data sets to facilitate accurate floodplain delineation models. This section addresses modifications to the terrain and stream networks, and the development of a curve number grid necessary to employ the SCS curve number method to determine rainfall-runoff relationships. Site-specific data development, necessary to populate the HEC hydrologic and hydraulic models with spatially derived terrain data, is addressed in Chapter 4.

3.1.2.1 Terrain

The raw DEM covering the Castleman Creek site did not adequately represent the rise in elevation due to the presence of US 77, and therefore would produce erroneous results during watershed delineation activities. The solution to this problem was to create an artificial wall along the highway, forcing any runoff to be routed parallel to the highway until it reached the main and relief bridge structures.

Unfortunately, the TxDOT road coverage did not match the more accurate coordinates provided by the aerial photogrammetric survey along the highway, nor did it match the representation of the roads provided in the Digital Orthophoto Quarter Quadrangles (DOQs) for McClennan County. Figure 3-6 depicts the discrepancies between the three data sets.

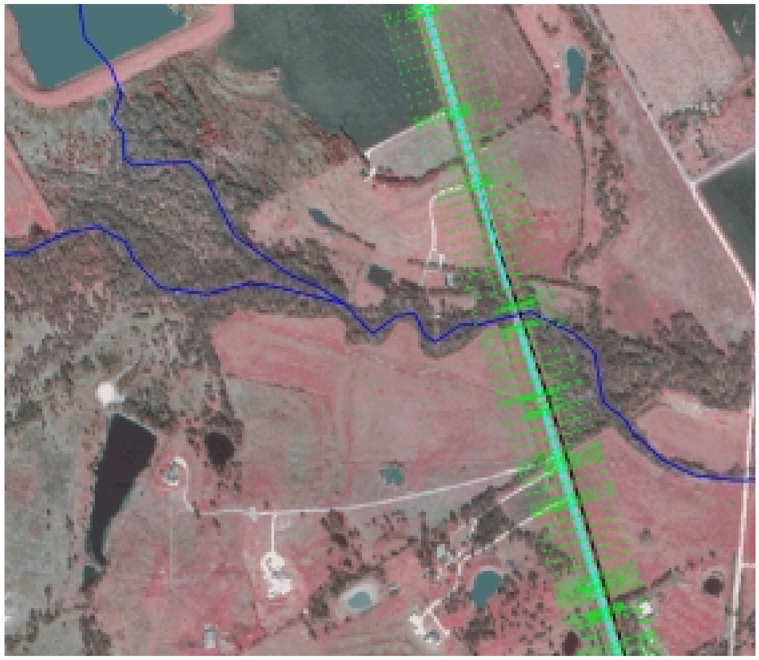

Figure 3-6 Discrepancies between DOQ, Photogrammetric Coordinates, and Texas Road Coverage

The green points present the results of the photogrammetric survey overlain on the DOQ and the black line the TxDOT road coverage supplied by TxDOT. It is evident from this figure that the DOQ and the photogrammetric data correlate well with each other. The light blue line was manually added to match US 77 as shown in the DOQ, and was converted to a grid (with an elevation attribute of 10,000 meters) and merged with the surrounding DEM to ensure the no runoff would overtop the road during watershed delineation calculations (Figure 3-7).

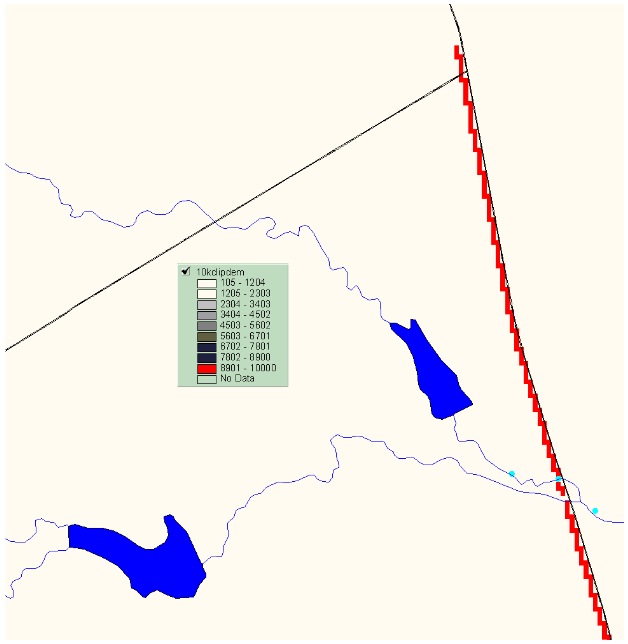

Figure 3-7 Artificial Wall Integrated in the DEM along US 77

3.1.2.2 SCS Curve Number

The development of a curve number grid at the Castleman Creek site was necessary to estimate the spatial variability of runoff resulting from a precipitation event that would be subsequently used in HEC-HMS to calculate the discharge hydrograph at US 77. The SCS curve number method calculates the quantity of precipitation falling onto the land surface that is converted to runoff based on the depth of precipitation, the potential maximum soil moisture storage after runoff begins, and an estimate of the initial quantity of infiltration at the beginning of the storm event. The soil storage and initial abstractions can be considered a function of soil type and land use and land cover (LULC) characteristics.

The curve number grid for this project was taken from the Blacklands Research Center in Temple, TX. This statewide grid was produced by combining the

USDA/NRCS STATSGO soil coverage with the USGS LULC coverage. A lookup table was used to translate the combinations of soil and land use into curve numbers using the 1972 SCS Engineering Hydrology Handbook as a reference. The LULC and STATSGO files are both 1:250,000 scale map products, so the resulting curve number grid was relatively coarse compared to the DEMs and stream networks at both sites. Figure 3-8 presents the curve number grid used at the Castleman Creek site.

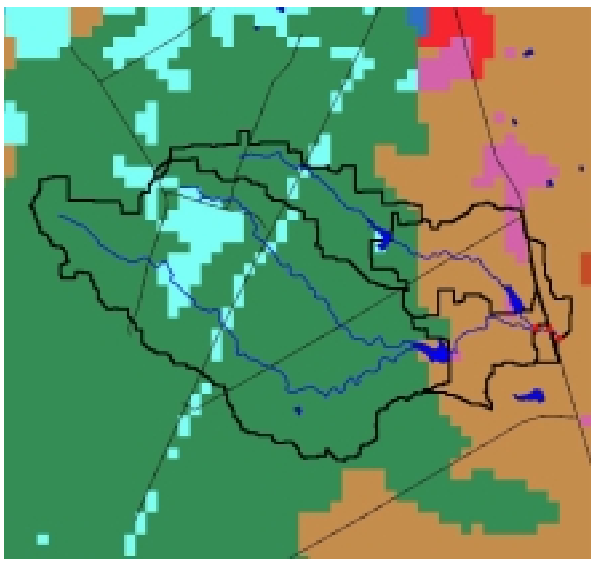

Figure 3-8 SCS Curve Number Grid Coverage at the Castleman Creek Watershed

The light blue cells in this curve number grid represent a curve number of 90 – a surface that generates significant runoff – and correspond to the presence of Interstate Highway 35 in the central portion of the watershed. The majority of the western side of the watershed has a curve number of 85 (the dark green cells), while the eastern portion was dominated by curve numbers of 70 (the brown cells). The average curve number for the Castleman Creek watershed was calculated to be 82.6.

3.2 Pecan Bayou

The data available for use in the Pecan Bayou watershed consisted of raw data sources and several datasets that required further development to become usable inputs to modeling activities.

3.2.1 Raw Data

The raw data used to define the Pecan Bayou watershed consisted of a DEM, contour information extracted from Microstation® drawings provided by the City of Brownwood, stream network data, precipitation data, reservoir storage and discharge data, USGS stream gage data, and existing HEC-RAS project information.

3.2.1.1 Terrain Data

At the Pecan Bayou site, the majority of the terrain was defined by 2-foot contour data provided on CD-ROM by the City of Brownwood as 152 Microstation® drawings (Figure 3-9).

The contours were derived from aerial mapping activities conducted by United Aerial Mapping on February 21, 1995. The scale of each drawing was 1 inch = 100 feet. The contours were provided in the Texas State Plane – Zone 14 projection using the NAD83 horizontal datum (with units of meters) and the NGD29 vertical datum (with units of feet).

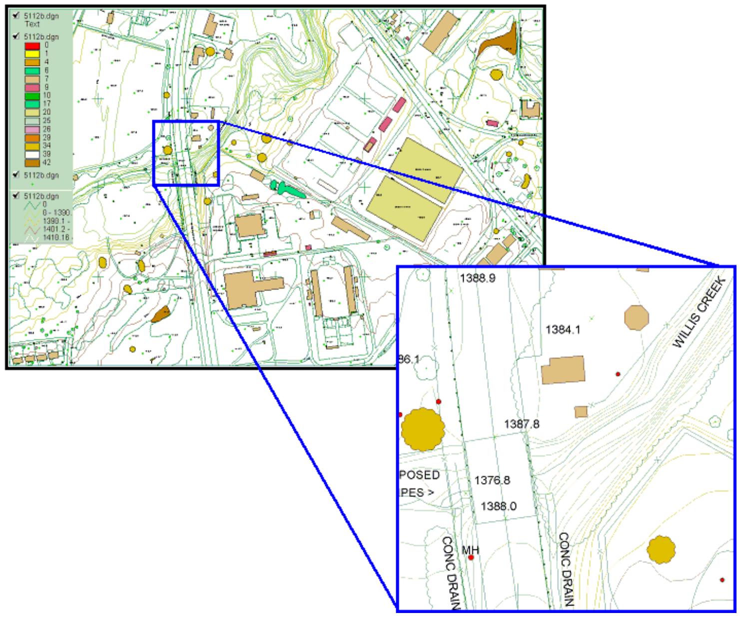

Figure 3-9 Example Microstation® Drawing for Pecan Bayou Watershed

Each drawing also contained the following additional information in the form of lines, polygons, points, and text annotations:

- Improved and unimproved roads;
- Cultural features, such as buildings, property lines, and natural landscape features;
- Existing and abandoned railroads and their associated infrastructure;
- Water features, such as wetlands, creeks, dams, and water supply and treatment infrastructure;
- Utility features;
- Vegetation features; and
- Drawing information such as latitude/longitude labels, sheet outlines, and title blocks.

Building footprint information was extracted from each drawing to supplement the definition of the terrain in urban areas along Pecan Bayou. Water features were also extracted and compared to stream network data to verify the orientation and connectivity of the stream network.

The portion of Pecan Bayou to be modeled for floodplain delineation, between bridges located on US 183 and FM 2126, was located almost entirely within the limits of the terrain defined by the contour data. However, in the overbank areas east of the bayou, no contour data was available; in this area, elevation data derived from the NED coverage for Brown County was used.

3.2.1.2 Stream Network

The Pecan Bayou stream network was defined by the NHD, but required modifications to remove pipelines, drainage ditches, and other water supply appurtenances. The Pecan Bayou flow network was defined for this study to include only the portions of Pecan Bayou and its tributaries found south of Lake Brownwood and north of USGS Gage 08143600 near Mullin, TX (Figure 3-10). The network includes 367 records representing a total stream length of over 952 km in a 1334 sq km study area.

Although the NHD was adequate for modeling the hydrologic response of the system in GIS, it was evident from the detailed contour data that a more detailed stream centerline would be necessary for accurate floodplain modeling. A line theme was digitized from US 183 to FM 2126 to reflect the detailed channel centerline in this area.

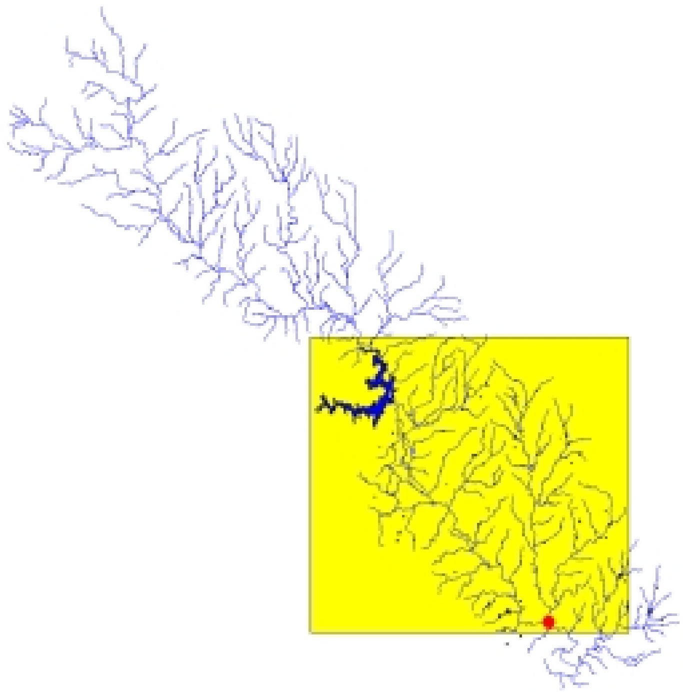

Figure 3-10 Pecan Bayou Stream Network

3.2.1.3 Precipitation Data

At the Pecan Bayou site, peak flows and stages were recorded at USGS Gage 08143600 for high flow conditions in December 1991; this data was used to calibrate the rainfall-runoff relationships and hydraulic characteristics of the Pecan Bayou channel. Unfortunately, while there were several gage stations within Brownwood and the surrounding vicinity, there was only one rainfall gage with a significant, continuous, period of record. This hourly precipitation data (recorded in 0.1-inch increments) was obtained from NOAA Cooperative Station 419817 at Winchell, TX through the National Climatic Data Center (NCDC) web site.[9] Figure 3-11 presents a summary of this data.

Date	Precipitation (in)
14-Nov-91	0.1
17-Nov-91	0.1
1-Dec-91	0.2
2-Dec-91	0.1
8-Dec-91	0.1
10-Dec-91	0.1
11-Dec-91	0.4
18-Dec-91	0.5
19-Dec-91	1.4
20-Dec-91	3.1
21-Dec-91	0.2
22-Dec-91	0.1
26-Dec-91	0.4
Total	**6.8**

Figure 3-11 Precipitation Data Recorded at NOAA Cooperative Station 419817 at Winchell, TX in Pecan Bayou Watershed

The NOAA station has an elevation of 445 meters above mean sea level (msl) and lies approximately 41 km. west-southwest of USGS Gage 08143600 (Figure 3-12).

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[9] National Climatic Data Center web site: http://www.ncdc.noaa.gov/ol/climate/stationlocator.html. Accessed June 15, 2000.

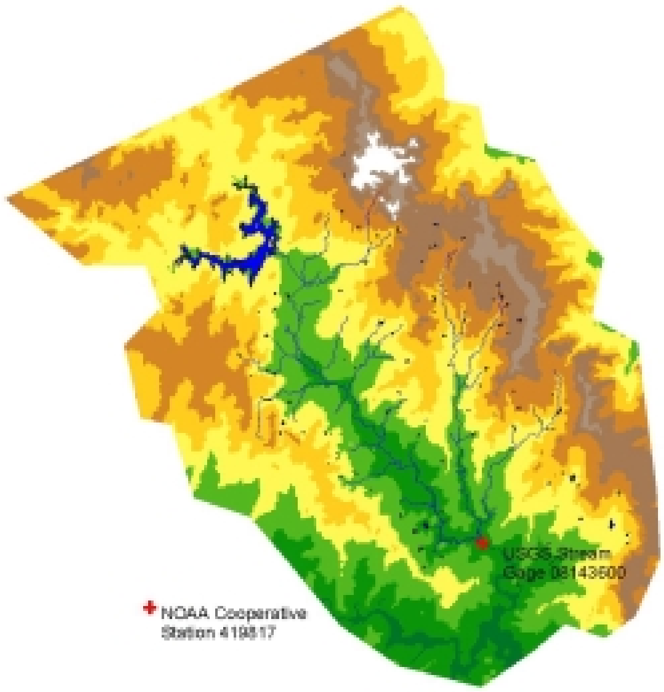


Figure 3-12 Location of NOAA Cooperative Station 419817 in Pecan Bayou Watershed

3.2.1.4 Reservoir Data

Lake Brownwood was defined as the upstream flow source for the Pecan Bayou model. Lake elevation data was provided by the Brown County Water Improvement District No. 1 (BCWID) for December 1991 and January 1992. Lake elevation data (accurate to 0.1 ft.) was recorded sporadically throughout the months of interest, and therefore required interpolation to estimate hourly elevation levels. Figure 3-13 presents a summary of the recorded lake elevations during the Christmas 1991 storm event. Unfortunately, continuous lake elevation data was not available between December 21 and January 6, 1991; this data was estimated via linear interpolation between known data points.

Date	Lake Elevation (ft)	Discharge (cfs)
10/7/91 8:00	1425.00	465.00
10/14/91 8:00	1424.80	464.40
10/21/91 8:00	1424.50	463.50
11/4/91 8:00	1425.70	1308.35
11/11/91 8:00	1425.25	647.71
11/18/91 8:00	1425.30	701.62
11/25/91 8:00	1424.90	468.18
12/9/91 8:00	1424.60	467.19
12/16/91 8:00	1425.30	701.62
12/19/91 8:00	1425.60	1134.25
12/20/91 7:00	1428.30	9097.44
12/20/91 8:00	1428.70	10713.61
12/20/91 9:00	1428.85	11343.80
12/20/91 10:00	1429.00	11985.00
12/20/91 10:30	1429.15	12639.70
12/20/91 11:00	1429.25	13082.36
12/20/91 12:00	1429.50	14211.16
12/20/91 12:30	1429.70	15137.67
12/20/91 13:00	1429.75	15373.05
12/20/91 14:00	1429.90	16084.12
12/20/91 15:00	1430.10	17050.09
12/20/91 15:30	1430.20	17540.27
12/21/91 9:00	1432.60	30635.53
12/30/91 8:00	1427.00	4537.94
1/6/92 8:00	1425.90	1694.49
1/13/92 8:00	1425.50	974.12
1/20/92 8:00	1425.40	829.29

Figure 3-13 Recorded Lake Brownwood Elevation Data during December 1991 Storm Event

The BCWID also provided elevation-discharge relationships for flow above the spillway at Lake Brownwood, which was used to develop the inflow hydrograph for the December 1991 storm event. Appendix C.1 presents the spillway-rating curve supplied by the BCWID.

3.2.1.5 Flow Data

At the Pecan Bayou site, stream flow and stage data was available at USGS Gage 08143600. This gage is located approximately 43.5 km downstream of the FM 2126 Bridge, so the watersheds contributing flow between the bridge and the gage were evaluated as part of the Pecan Bayou hydrologic model. Hourly flow and stage data recorded between November 19, 1991 and January 2, 1992 was provided by the Abilene, TX USGS office (acquired from the USGS Federal Records archives in

Denver, CO) in paper format. The discharge rating curve for the USGS Gage was also provided to allow interpolation of flow and stage at time intervals during which the gage was offline. The flow data was accurate to 1 cfs, while the stage data was accurate to 0.01 ft. Appendix D.1 presents the recorded flow data for December 1991 and January 1992 at USGS Gage 08143600.

3.2.1.6 Infrastructure

Several additional datasets were also utilized during the development of the floodplain delineation models in the Pecan Bayou watershed. The same TxDOT road coverage used at the Castleman Creek was clipped to provide roadway data within the extents of the Pecan Bayou watershed. A point coverage of hydrologic and hydraulic gauging sites was also generated from geographical coordinates supplied by web sites designated for each gage; these are presented in Table 3-1.

Table 3-1 Point Coverage of Hydrologic and Hydraulic Gauging Sites

Gage	Latitude		Longitude	
	Degrees	Minutes	Degrees	Minutes
USGS Gage 08143600	31	31	-98	44
NOAA Cooperative Station 419817	31	27	- 99	10

3.2.1.7 Existing Models

A HEC-RAS model was developed for ongoing flood mitigation studies in the Pecan Bayou watershed by the U.S. Army Corps of Engineers (USACOE) Ft. Worth District, which provided critical channel cross-sections for Pecan Bayou from

Lake Brownwood to its confluence with the Colorado River. The survey dates for these cross-sections is unknown, but estimated to be in the early 1990s.[10] For the purposes of this study, only the cross-sections between US Highway 183 and FM 2126 were utilized. Figure 3-14 presents a schematic of the USACOE cross-sections on Pecan Bayou in the area of interest.

Pecan Bayou flows under three bridges in the area of interest for this project. The first is at US 183, approximately 18.5 km downstream of Lake Brownwood; the second is at FM 2525 (also known as Hawkins St.), 375 meters south of the US 183 Bridge; the third is at FM 2126, approximately 8.1 km south of the FM 2525 bridge. Figure 3-15 presents the location of the three bridges of interest in the Pecan Bayou watershed (although FM 2525 does not appear to continue southwest over Pecan Bayou, there is a structure present at that location).

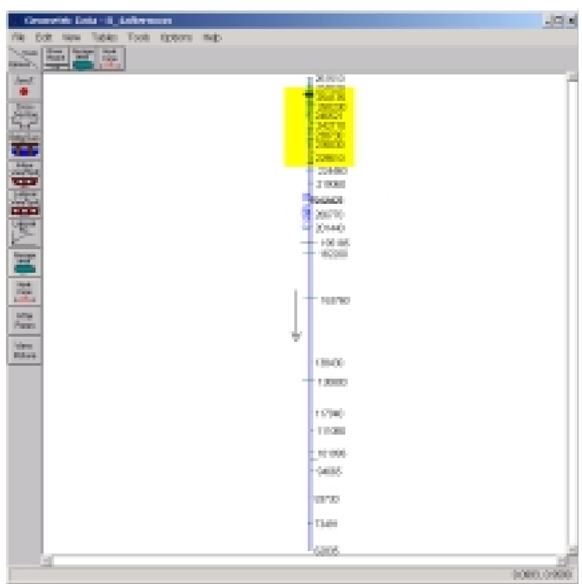


Figure 3-14 HEC-RAS Schematic of Surveyed Cross-Sections on Pecan Bayou

[10] Personal communication with Craig Lofton, USACOE, Ft. Worth District on August 1, 2000.

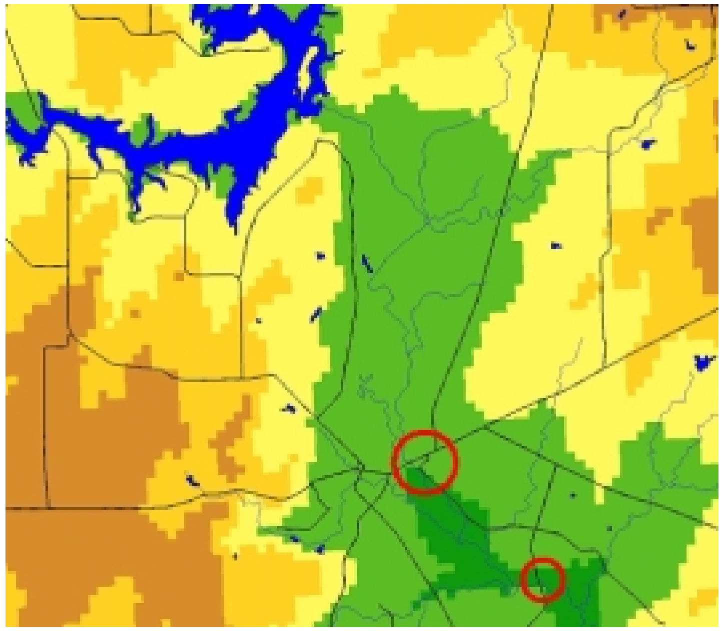


Figure 3-15 Locations of Bridges of Interest in Pecan Bayou Watershed

3.2.2 Data Development

While the data discussed in Section 3.2.1 represents the raw data that was used to initially define the Pecan Bayou watershed, further development was required for a number of datasets to facilitate accurate floodplain delineation models. This section addresses data development for the Pecan Bayou stream network, development of a curve number grid, adjustment of precipitation data based on areal-reduction factors, interpolation of reservoir discharge data, and interpolation of recorded flow and stage data at USGS Gage 08143600.

3.2.2.1 Development of Stream Network

The Pecan Bayou stream network was developed from the NHD and, due to the completeness of the dataset, was clipped to be more manageable in size. Figure

3-16 presents the full extent of the Pecan Bayou NHD *route.rch* file, while Figure 3-17 depicts the clipped *route.rch* coverage, highlighted in purple.

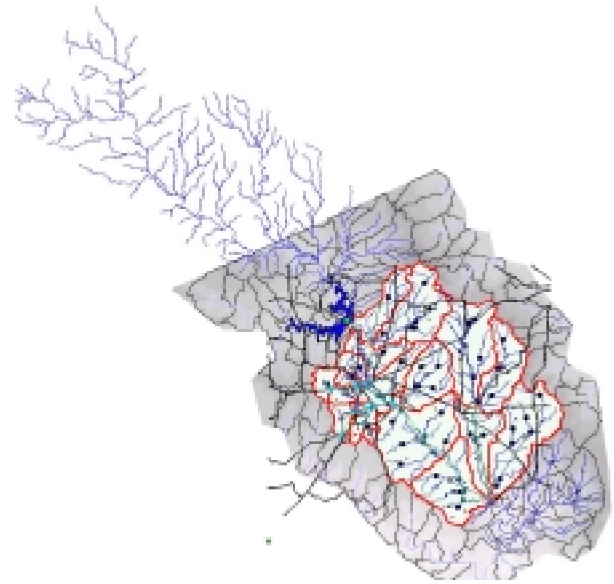


Figure 3-16 Extent of Pecan Bayou NHD route.rch Coverage

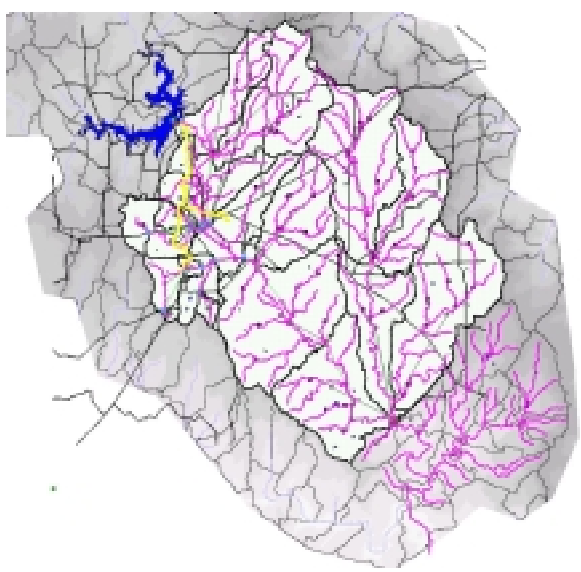
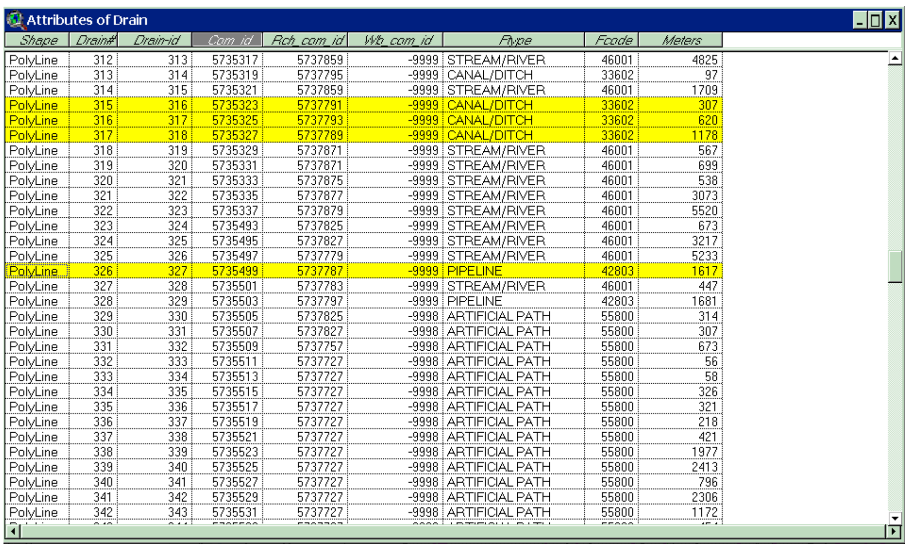


Figure 3-17 Clipped NHD route.rch Coverage

The structure of the NHD coverage is much more detailed than previous river network files, such as the RF3 files developed by the EPA. As shown in Figure 3-18 in the attribute table associated with the *route.drain* file (a sister file to *route.rch*), stream segments are identified by type, and some types are not appropriate for inclusion in modeling the hydrologic or hydraulic routing relationships within a watershed.


Attributes of Drain

Shape	Drain#	Drain-id	Com_id	Rch_com_id	Wb_com_id	Ftype	Fcode	Meters
PolyLine	312	313	5735317	5737859	-9999	STREAM/RIVER	46001	4825
PolyLine	313	314	5735319	5737795	-9999	CANAL/DITCH	33602	97
PolyLine	314	315	5735321	5737859	-9999	STREAM/RIVER	46001	1709
PolyLine	315	316	5735323	5737791	-9999	CANAL/DITCH	33602	307
PolyLine	316	317	5735325	5737793	-9999	CANAL/DITCH	33602	620
PolyLine	317	318	5735327	5737789	-9999	CANAL/DITCH	33602	1178
PolyLine	318	319	5735329	5737871	-9999	STREAM/RIVER	46001	567
PolyLine	319	320	5735331	5737871	-9999	STREAM/RIVER	46001	699
PolyLine	320	321	5735333	5737875	-9999	STREAM/RIVER	46001	538
PolyLine	321	322	5735335	5737877	-9999	STREAM/RIVER	46001	3073
PolyLine	322	323	5735337	5737879	-9999	STREAM/RIVER	46001	5520
PolyLine	323	324	5735493	5737825	-9999	STREAM/RIVER	46001	673
PolyLine	324	325	5735495	5737827	-9999	STREAM/RIVER	46001	3217
PolyLine	325	326	5735497	5737779	-9999	STREAM/RIVER	46001	5233
PolyLine	326	327	5735499	5737787	-9999	PIPELINE	42803	1617
PolyLine	327	328	5735501	5737783	-9999	STREAM/RIVER	46001	447
PolyLine	328	329	5735503	5737797	-9999	PIPELINE	42803	1681
PolyLine	329	330	5735505	5737825	-9998	ARTIFICIAL PATH	55800	314
PolyLine	330	331	5735507	5737827	-9998	ARTIFICIAL PATH	55800	307
PolyLine	331	332	5735509	5737757	-9998	ARTIFICIAL PATH	55800	673
PolyLine	332	333	5735511	5737727	-9998	ARTIFICIAL PATH	55800	56
PolyLine	333	334	5735513	5737727	-9998	ARTIFICIAL PATH	55800	58
PolyLine	334	335	5735515	5737727	-9998	ARTIFICIAL PATH	55800	326
PolyLine	335	336	5735517	5737727	-9998	ARTIFICIAL PATH	55800	321
PolyLine	336	337	5735519	5737727	-9998	ARTIFICIAL PATH	55800	218
PolyLine	337	338	5735521	5737727	-9998	ARTIFICIAL PATH	55800	421
PolyLine	338	339	5735523	5737727	-9998	ARTIFICIAL PATH	55800	1977
PolyLine	339	340	5735525	5737727	-9998	ARTIFICIAL PATH	55800	2413
PolyLine	340	341	5735527	5737727	-9998	ARTIFICIAL PATH	55800	796
PolyLine	341	342	5735529	5737727	-9998	ARTIFICIAL PATH	55800	2306
PolyLine	342	343	5735531	5737727	-9998	ARTIFICIAL PATH	55800	1172

Figure 3-18 Attribute Table for NHD route.drain Coverage

The attribute table of the *route.drain* coverage was linked to the *route.rch* attribute table to facilitate selection of inappropriate stream reaches for inclusion in the Pecan Bayou watershed model. These reaches are highlighted in yellow in Figure 3-17 above, and were deleted from the final Pecan Bayou stream network.

Once these modifications were completed, the network was overlain on a digital raster graphic (DRG) image of the watershed to ensure that the NHD coverage matched the network as portrayed on the appropriate USGS 7.5' quads.

DRGs are scanned images of USGS topographic maps, provided in this case at 1:24,000 scale by the USGS in UTM – Zone 14 projection. DRGs may be used as a source or background layer in GIS as a means to perform quality assurance on other digital data.[11] Figure 3-19 presents an example of manually editing of the river network for connectivity. The blue segment inside the purple circle was not originally included in the NHD coverage and was added manually.

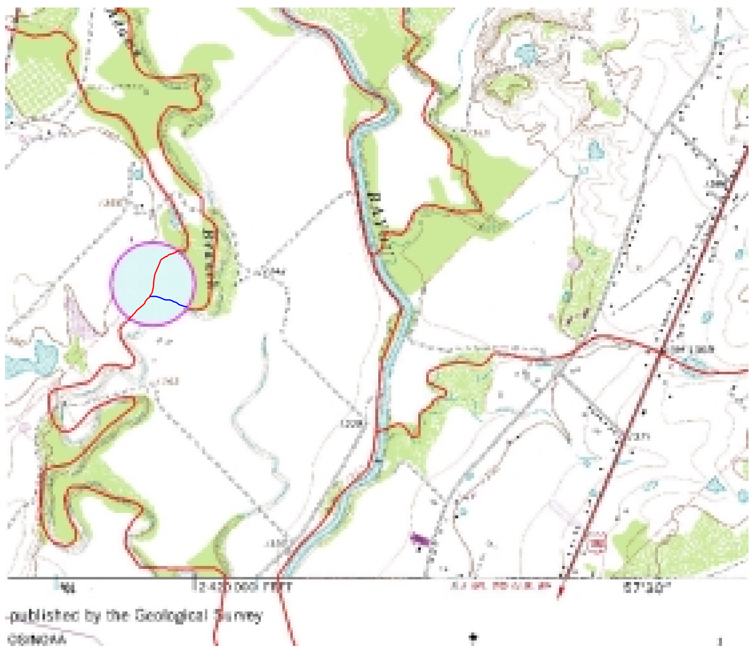


Figure 3-19 Manual Editing of NHD route.rch Coverage with DRG

[11] USGS web site: http://edcwww.cr.usgs.gov/glis/hyper/guide/drg. Accessed: August 20, 2000.

3.2.2.2 SCS Curve Number

The same curve number grid was used on the Pecan Bayou watershed that was used at the Castleman Creek site. The original grid coverage is statewide, so the grid was simply clipped to cover the extent of the Pecan Bayou watershed.

3.2.2.3 Precipitation

The precipitation data available for the December 1991 storm event at Pecan Bayou was recorded at NOAA Cooperative Station 419817 near Winchell, TX and yielded greater-than-expected flows within the Pecan Bayou channel when modeled hydrologically in HEC-HMS. Further development of this precipitation data was warranted, and the concept of areal-reduction factors was investigated.

The reduction of precipitation depths from a given storm to an effective (mean) depth over a watershed often is important for cost-effective design of hydraulic structures by reducing the volume of precipitation. An effective depth can be calculated by multiplying the precipitation depth at a point by an areal-reduction factor (ARF). ARFs range from 0 to 1, vary with the recurrence interval of the storm, and are a function of watershed characteristics such as size and shape, geographic location, and time of year that the design storm occurs.[12] ARFs for Austin, Dallas, and Houston have been derived from several precipitation-station monitoring networks in the vicinity of each city, with varying periods of record. The large daily precipitation databases available in Texas allowed an approach that considered the distribution of precipitation concurrent with, and surrounding, an annual precipitation maxima.

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[12] Asquith, W.H., *Areal-Reduction Factors for the Precipitation of the 1-Day Design Storm in Texas*, 1999 – Water Resources Investigations Report 99-4267.

Because NOAA Coop Station 419817 did not correspond directly with the location of the ARFs currently available for Texas, a conservative approach was used to estimate an ARF applicable to the Pecan Bayou watershed. Figure 3-20 presents the equations used to estimate the ARF for the Dallas area, which were also implemented at the Pecan Bayou site. The watershed was estimated to be circular, with a radius of approximately 13.6 miles. According to the equations provided, the ARF was estimated conservatively to be 0.67.

Equations that define the estimated 2-year or greater depth-distance relation and the areal-reduction factor for circular watersheds for Austin, Dallas, and Houston, Texas

City	Estimated 2-year or greater depth-distance relation (figs. 14–16) for distance (r), in miles	Areal-reduction factor for circular watersheds having radius (r), in miles	Equation limits
Dallas	$S_2(r) = 1.0000 - 0.0600(r)$	$ARF_2(r) = 1.0000 - 0.0400(r)$	$0 \leq r \leq 2$
	$S_2(r) = 0.9670 - 0.0435(r)$	$ARF_2(r) = 0.9670 - 0.0290(r) + (0.0440 / r^2)$	$2 \leq r \leq 4$
	$S_2(r) = 0.8910 - 0.0245(r)$	$ARF_2(r) = 0.8910 - 0.0163(r) + (0.4493 / r^2)$	$4 \leq r \leq 6$
	$S_2(r) = 0.8760 - 0.0220(r)$	$ARF_2(r) = 0.8760 - 0.0147(r) + (0.6293 / r^2)$	$6 \leq r \leq 8$
	$S_2(r) = 0.8460 - 0.0183(r)$	$ARF_2(r) = 0.8460 - 0.0122(r) + (1.2693 / r^2)$	$8 \leq r \leq 12$
	$S_2(r) = 0.8130 - 0.0155(r)$	$ARF_2(r) = 0.8130 - 0.0103(r) + (2.8533 / r^2)$	$12 \leq r \leq 16$
	$S_2(r) = 0.7650 - 0.0125(r)$	$ARF_2(r) = 0.7650 - 0.0083(r) + (6.9493 / r^2)$	$16 \leq r \leq 18$
	$S_2(r) = 0.7200 - 0.0100(r)$	$ARF_2(r) = 0.7200 - 0.0067(r) + (11.8093 / r^2)$	$18 \leq r \leq 24$
	$S_2(r) = 0.6880 - 0.0087(r)$	$ARF_2(r) = 0.6800 - 0.0058(r) + (17.9533 / r^2)$	$24 \leq r \leq 27$
	$S_2(r) = 0.6228 - 0.0063(r)$	$ARF_2(r) = 0.6228 - 0.0042(r) + (33.8091 / r^2)$	$27 \leq r \leq 31$
Dallas	$S_2(r) = 0.5563 - 0.0041(r)$	$ARF_2(r) = 0.5563 - 0.0027(r) + (55.1070 / r^2)$	$31 \leq r \leq 50$

Figure 3-20 Areal-Reduction Factor Equations for Dallas, TX [12]

The incremental precipitation depths recorded in December 1991 and January 1992 were multiplied by this ARF to produce a 33% reduction in precipitation depth. Figure 3-21 presents a comparison of the original incremental precipitation depths to the adjusted values.

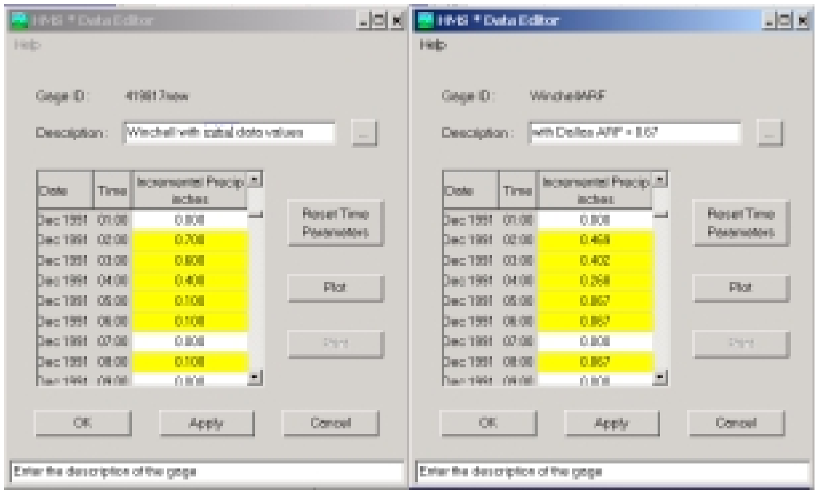


Figure 3-21 Comparison of Recorded Incremental Precipitation to Precipitation Adjusted with ARF

3.2.2.4 Reservoirs

Interpolation of lake elevation and discharge data was necessary at Lake Brownwood to facilitate hourly hydrologic modeling in HEC-HMS. Unfortunately, only sporadic data was recorded during the Christmas 1991 storm. Adequate data was recorded at the beginning of the storm, but few data points were recorded after the peak elevation, assumed to occur at 9:00 am on December 21. A linear relationship was assumed to describe the lake elevation as it fell to normal elevation levels as the effects of the storm dissipated. These lake elevations were then cross-referenced with the spillway-rating curve to determine the hourly discharge from the reservoir. Figure 3-22 depicts the linear tendencies of the discharge hydrograph from Lake Brownwood.

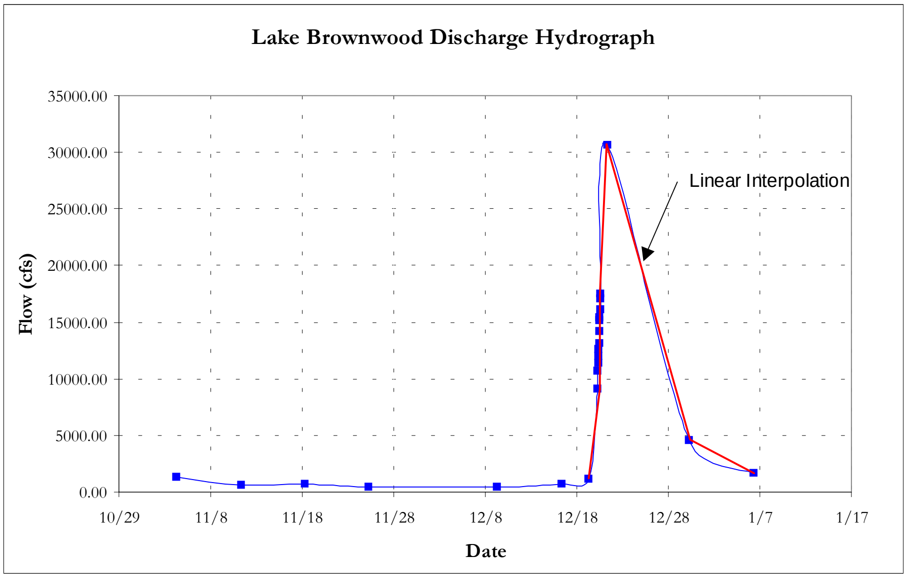


Figure 3-22 Lake Brownwood Discharge Hydrograph

3.2.2.5 Flow

The flow and stage data recorded at USGS Gage 08143600 near Mullin, TX was available in hourly increments for the majority of the December 1991 storm. This data was used to develop a flow-discharge relationship for the gage site (Figure 3-23).

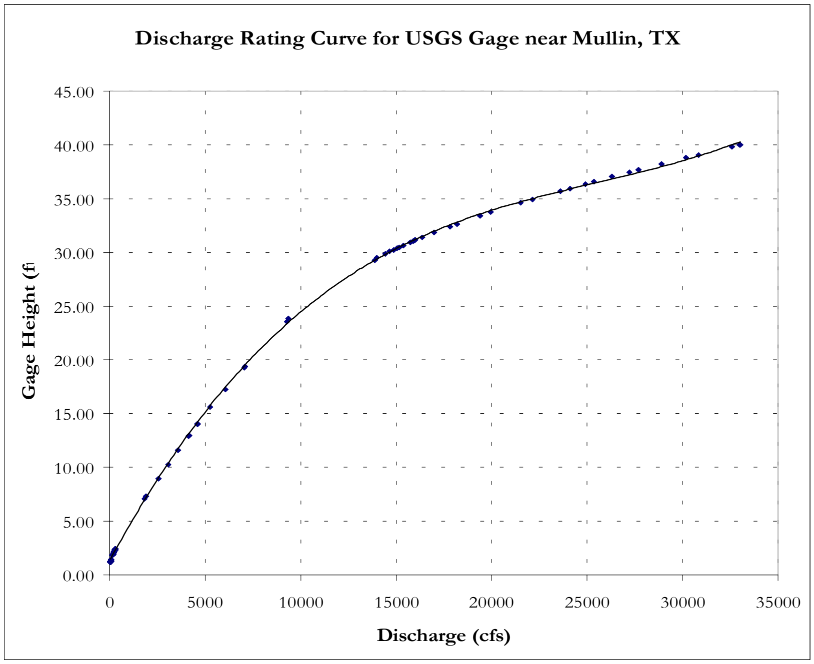


Figure 3-23 Rating Curve at USGS Gage 08143600 near Mullin, TX

During the highest flow conditions (December 21-24), the gage was damaged and flow was recorded manually at intervals greater than one hour. The rating curve was then used to determine stage elevation and flow in the hourly increments not recorded.

4 METHODOLOGY

The methodology presented in this chapter results in a seamless procedure for generating a floodplain at highway river crossings given digital terrain, hydrologic, and hydraulic data. Although the data sources available for each site differed, both the Castleman Creek and Pecan Bayou models were developed using the following methodology:

1. Site Specific Terrain Data Development
    a. Terrain Development for Hydrologic Analysis
    b. Terrain Development for Floodplain Delineation
2. GIS-based Hydrologic Parameter Extraction
3. GIS-based Hydraulic Geometry Extraction
4. Hydrologic Modeling
5. Hydraulic Modeling
6. Floodplain Delineation

Figure 4-1 presents a schematic of this methodology. It is evident from the figure the importance of an accurate DTM, as it affects both hydrologic and hydraulic modeling activities. While CRWR-PrePro contains adequate tools for the development of the terrain for hydrologic purposes, the steps shown on the bottom of the figure (HEC-RAS → CRWR-Floodmap → HEC-GeoRAS) represent the detailed terrain development necessary for accurate floodplain delineation. As shown, detailed terrain development activities can occur simultaneously to hydrologic and hydraulic modeling activities – and should – to optimize the efficiency of the process.

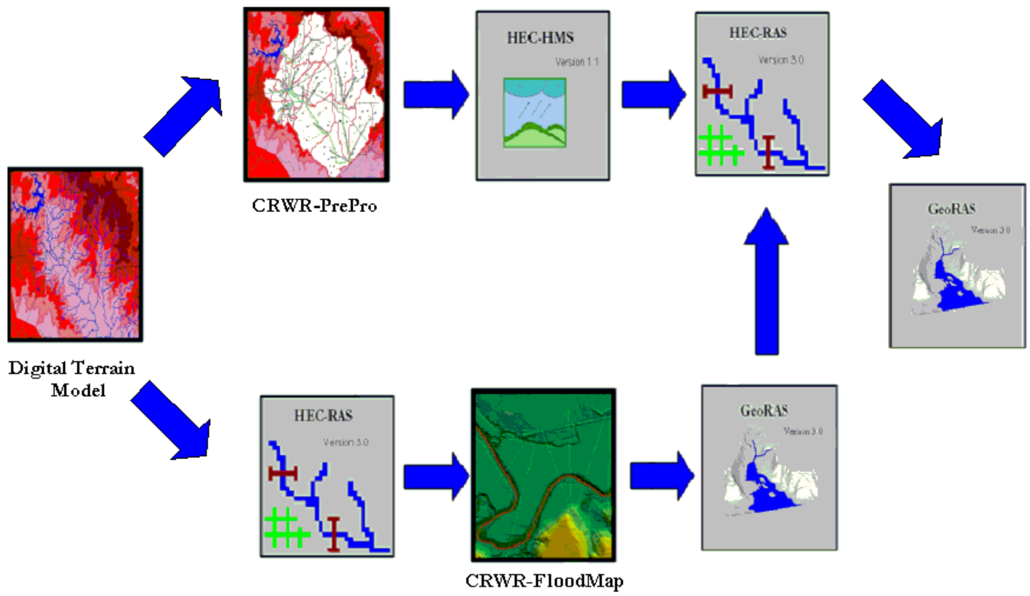


Figure 4-1 Schematic of Floodplain Delineation Methodology

The theory behind each step of the methodology is presented in this chapter; a systematic implementation procedure – presented subsequently in Chapter 5 – highlights the applicability of the methodology to each of the two sites selected as part of this research project.

4.1 Site Specific Terrain Data Development

Although general data development activities were presented in Chapter 3 that addressed the homogeneity, spatial connectivity, and completeness of each dataset, site specific data development activities are necessary to preprocess the terrain data for use in the HEC programs for hydrologic and hydraulic modeling (HEC-HMS and HEC-RAS, respectively).

4.1.1 TERRAIN DEVELOPMENT FOR HYDROLOGIC ANALYSIS

The procedure for processing raw raster terrain data is comprised of three conceptual modules: 1) raster-based terrain analysis, 2) raster-based subbasin and stream network delineation, and 3) vectorization of subbasins and reach segments. These activities were carried out in the GIS domain using CRWR-PrePro, a system of ArcView scripts and associated controls developed at the CRWR to extract topographic, topologic, and hydrologic information from the digital spatial data of a hydrologic system for eventual export to HEC-HMS. [13] The procedure implemented at both sites was identical, and followed the steps presented in the ArcView pull-down menu displayed in Figure 4-2.

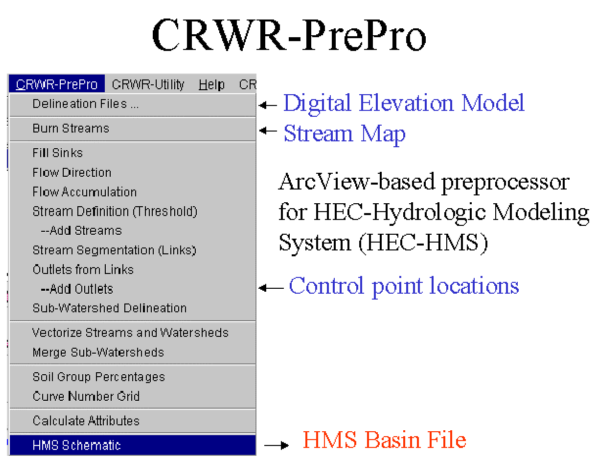


Figure 4-2 CRWR-PrePro Implementation Procedures

Olivera and Maidment (1999) present an excellent discussion of DEM-based terrain analysis using CRWR-PrePro. Beginning with a DEM and a stream network

[13] CRWR Pre Pro website: http://civil.ce.utexas.edu/prof/olivera/esri99/p801.htm. Accessed: August 1, 2000.

file (in this case, NHD files), the *Burn Streams* menu item is selected, which raises the land surface cells that are off the streams by an arbitrary elevation so that the streams delineated from the DEM exactly match those in NHD network file. The *Fill Sinks* menu item is then activated which ensures that there are no cells within the DEM that would adversely affect the flow direction of surface runoff applied over the watershed. In practice, DEM cells may contain errors that create artificially raised or depressed cells within the grid. The *Fill Sinks* algorithm (Figure 4-3) iteratively raises or lowers the cell to match the elevation of the lowest surrounding cell elevation.

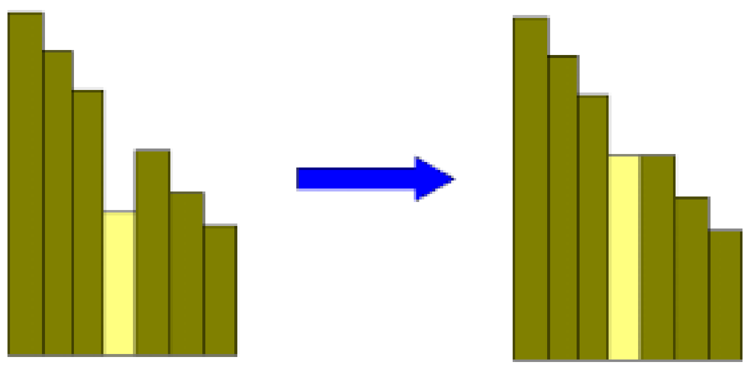


Figure 4-3 Fill Sinks Algorithm

CRWR-PrePro then calculates the direction that any runoff would take on the DEM surface according to the eight-direction pour point model (Figure 4-4) and generates a flow direction grid covering the same extent as the original DEM.

32	64	128
16	✳	1
8	4	2

Flow direction codes

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

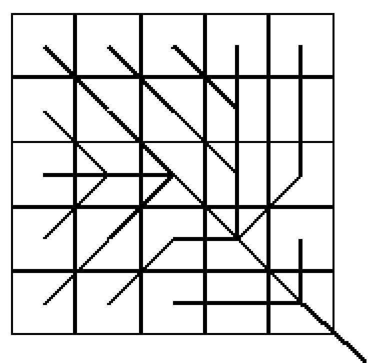
Digital elevation model (DEM)

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

Flow direction grid

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

Flow accumulation grid



Stream Network

Figure 4-4 Raster-Based Functions for Terrain Analysis

The flow direction grid is determined by finding the direction of steepest descent from each cell, and is calculated as the change in elevation divided by the horizontal distance between the center of each cell. From this point, the number of cells contributing flow to one – and only one – downstream cell are calculated, and, if multiplied by the cell area, equal the drainage area. This flow accumulation grid represents the amount of precipitation that would flow into each cell assuming that all precipitation becomes runoff (assuming no interception, evapotranspiration, or infiltration). A raster-based stream network can then be developed based on the flow accumulation grid and the definition of the minimum number of cells (and corresponding drainage area based on the grid cell size) that contribute flow to a certain point in the DEM, defined as the stream threshold. This stream threshold is user-defined, which permits the delineation of streams to match existing stream network files. CRWR-PrePro also permits the user to add streams manually to further ensure that the resolution of the resulting stream network meets the requirements of the project.

The *Stream Segmentation (Links)* menu item is then activated, which allows the user to identify unique stream segments within the stream network. This is followed by the *Outlets from Links* command, which identifies the most-downstream cell on a stream segment as an outlet. This can be followed by the *Add Outlets* command, which permits the user to manually identify additional outlets, such as the presence of flow gage or water rights locations. Finally, with the outlets and stream network identified and the elevation in each cell known, CRWR-PrePro delineates the subbasins contributing flow to each outlet.

Once the stream network and subbasin extents have been identified in the raster domain, CRWR-PrePro converts the raster data to vector format using the *Vectorize Streams and Watersheds* command. Subbasins can be merged as necessary using the *Merge Sub-Watersheds* command. This is the final step prior to the extraction of the spatially variable hydrologic parameters intrinsic to each subbasin, which is addressed in Section 4.2 of this chapter. The methodology presented in this section, as it relates to the overall methodology developed in this thesis, is highlighted in Figure 4-5.

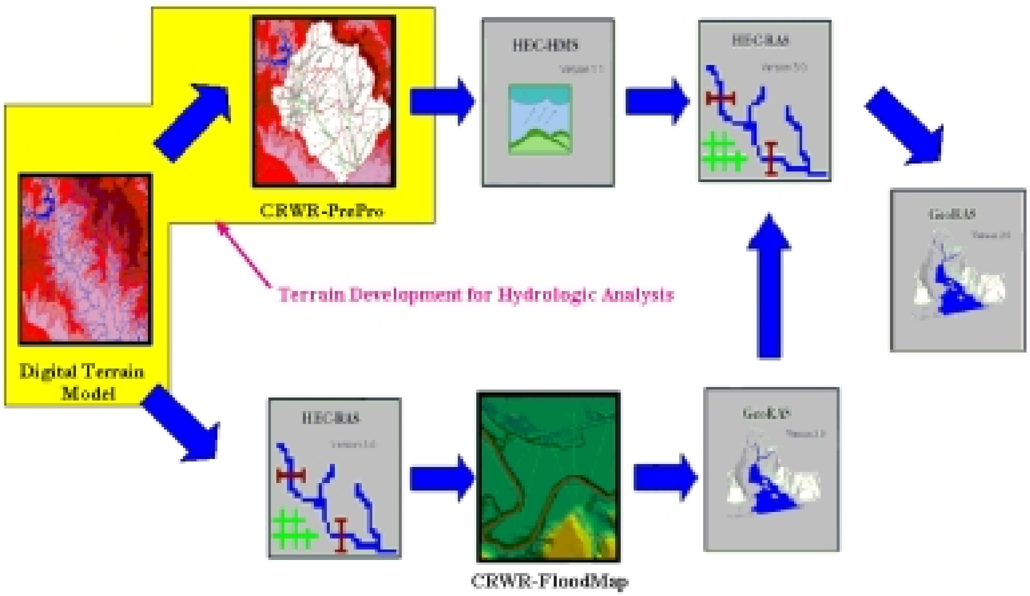


Figure 4-5 Terrain Development for Hydrologic Analysis

4.1.2 Terrain Development for Floodplain Delineation

The development of terrain data at a resolution that facilitates an accurate representation of a floodplain is critical in obtaining the realistic extent of potentially impacted surface features resulting from an extreme precipitation event. The use of coarse DEM surfaces is generally not suitable for the large-scale terrain representation required for floodplain delineation activities because they cannot vary in spatial resolution (Carter, 1988). For this reason, the hydraulic modeling of river channels and the associated floodplain may best be accomplished using TINs.

Tate (1999) developed a system of ArcView GIS scripts called CRWR-FloodMap to import cross-sectional geometry into GIS and ultimately define the floodplain resulting from water surface profiles modeled hydraulically in HEC-RAS (Figure 4-6).

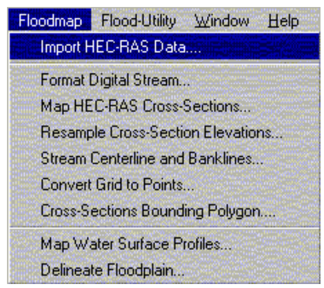


Figure 4-6 CRWR-FloodMap Menu

In this thesis, selected ArcView scripts created by Tate have been modified strictly to supplement existing terrain data (such as DEMs and photogrammetric survey data) and therefore provide a more accurate representation of the terrain in the channel and overbank areas (all scripts used in this methodology are presented in Appendix B.1). Thus, Tate's floodplain mapping scripts are not used – the floodplain mapping capabilities of HEC-GeoRAS are instead ultimately utilized (Figure 4-7) for that purpose.

Parts of the following text documenting the CRWR-FloodMap methodology are excerpted from Tate's 1999 thesis. Scripts modified for this thesis are noted as such.

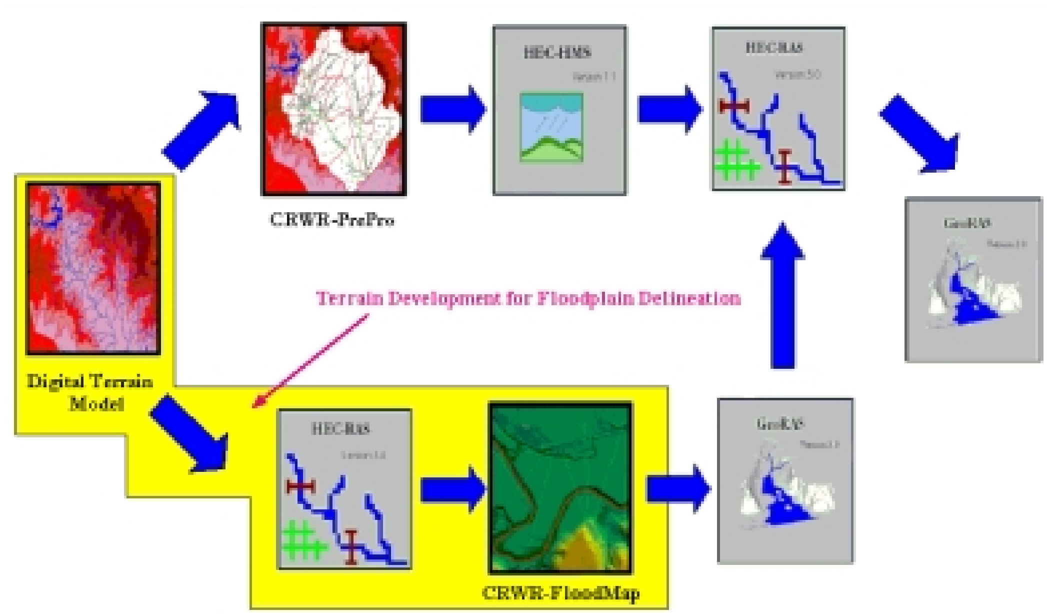


Figure 4-7 Terrain Development for Floodplain Delineation

The methodology presented subsequently assumes that cross-sectional geometry data is available in HEC-RAS (or HEC-2) format. The methodology developed by Tate, and used in HEC's GeoRAS software, assumes that the stream centerline defined at each cross-section is connected linearly (with a straight line) to the subsequent cross-section. Therefore, there is a possibility that, for tortuous streams (streams that meander), it may be necessary to interpolate between surveyed cross-sections to adequately model the tortuous nature of the stream (Figure 4-8). As applicable to this work, this is especially important when considering small areas (less than 100 acres) prone to flooding at highway river crossings. This methodology assumes the user interpolates an adequate number of cross-sections to effectively represent the tortuous nature of the stream.

Once an acceptable number of cross-sections have been defined in HEC-RAS, hydraulic model output information must be extracted and imported into the

GIS environment. After the HEC-RAS report has been generated, the user selects the first CRWR-FloodMap menu item *Import HEC-RAS Data* (shown in Figure 4-6).

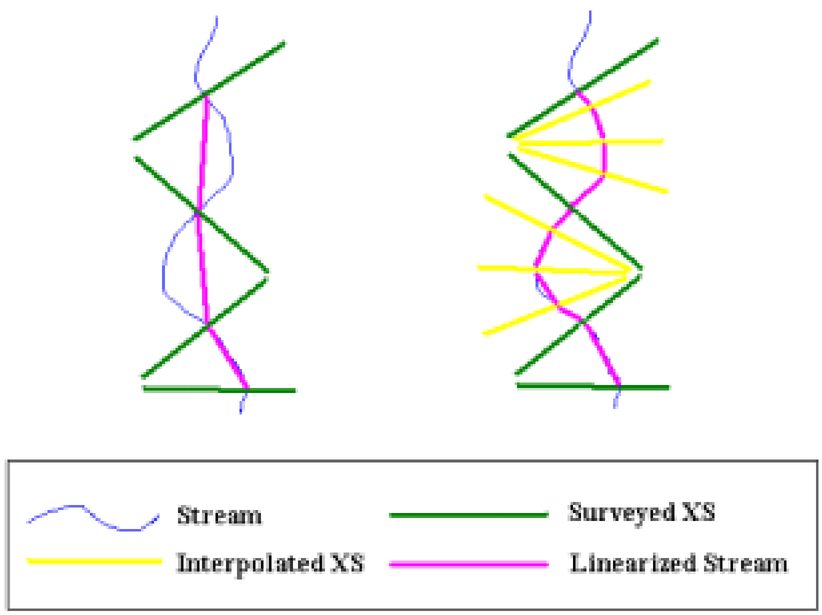


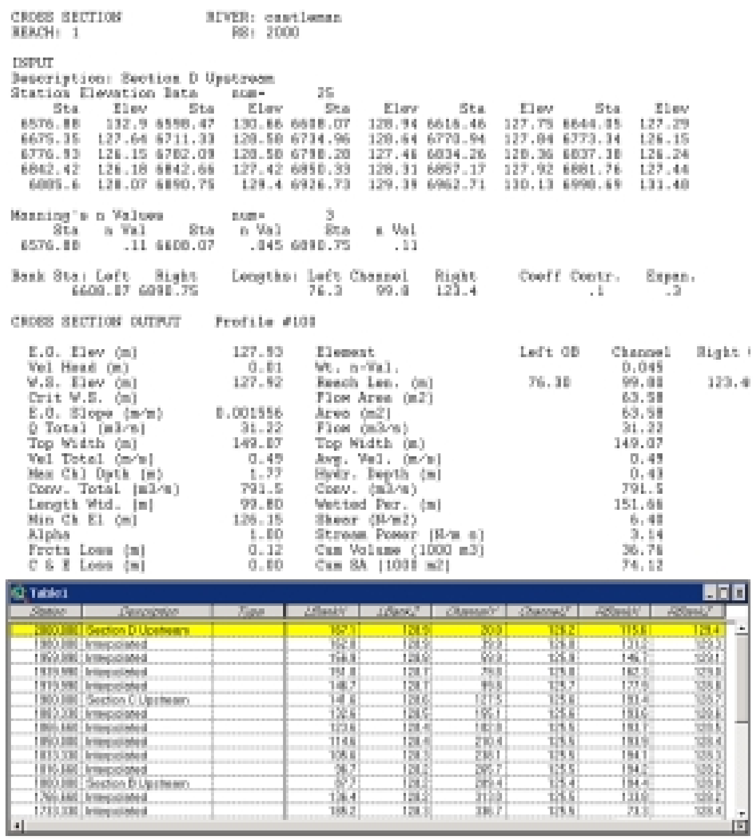
Figure 4-8 Surveyed and Interpolated Cross-Sections

Upon activation of this menu item, the user is prompted to specify the units desired for analysis in GIS. The *Import HEC-RAS Data* script (modified in this thesis), called *FloodRasRead*, reads the HEC-RAS output file (that consists of cross-sectional geometries and reach lengths between each cross-section) and creates a table in ArcView that specifies:

- River station ID;
- A text description of the cross-section;
- Coordinates of the stream centerline, located at the point of minimum channel elevation;
- Bank station locations as measured from the stream centerline; and

- Reach lengths.

Figure 4-9 presents an example of the HEC-RAS output file and the corresponding table created in ArcView GIS.



```
CROSS SECTION          RIVER: castleman
REACH: 1                  RS: 2000

INPUT
Description: Section D Upstream
Station Elevation Data    num=      25
     Sta     Elev      Sta     Elev      Sta     Elev      Sta     Elev      Sta     Elev
 6576.88    132.9  6598.47   130.66  6608.07   128.94  6618.46   127.75  6644.85   127.29
 6675.35   127.64  6711.33   128.58  6734.96   128.64  6770.94   127.04  6773.34   126.15
 6776.93   126.15  6782.09   128.58  6798.28   127.46  6834.26   128.36  6837.38   126.24
 6842.42   126.18  6842.66   127.42  6850.33   128.31  6857.17   127.92  6881.76   127.44
  6885.6   128.07  6890.75    129.4  6926.73   129.39  6962.71   130.13  6998.69   131.48

Manning's n Values        num=       3
     Sta    n Val      Sta    n Val      Sta    n Val
 6576.88      .11  6608.07     .045  6890.75      .11

Bank Sta: Left   Right    Lengths: Left Channel   Right     Coeff Contr.   Expan.
       6608.07 6890.75             76.3    99.8   123.4              .1       .3

CROSS SECTION OUTPUT   Profile #100

  E.G. Elev (m)           127.93   Element                 Left OB   Channel   Right
  Vel Head (m)              0.01   Wt. n-Val.                          0.045
  W.S. Elev (m)           127.92   Reach Len. (m)            76.30     99.80    123.40
  Crit W.S. (m)                    Flow Area (m2)                      63.58
  E.G. Slope (m/m)      0.001556   Area (m2)                           63.58
  Q Total (m3/s)           31.22   Flow (m3/s)                         31.22
  Top Width (m)           149.87   Top Width (m)                      149.87
  Vel Total (m/s)           0.49   Avg. Vel. (m/s)                      0.49
  Max Chl Dpth (m)          1.77   Hydr. Depth (m)                      0.43
  Conv. Total (m3/s)       791.5   Conv. (m3/s)                        791.5
  Length Wtd. (m)          99.80   Wetted Per. (m)                    151.68
  Min Ch El (m)           126.15   Shear (N/m2)                         6.48
  Alpha                     1.00   Stream Power (N/m s)                 3.14
  Frctn Loss (m)            0.12   Cum Volume (1000 m3)                36.78
  C & E Loss (m)            0.00   Cum SA (1000 m2)                    74.12
```

Table1

Figure 4-9 HEC-RAS Output File and Imported ArcView GIS Table

The lateral and elevation coordinates of each surveyed cross-section point are read and stored as ArcView global variables. The coordinates of the point possessing the minimum channel elevation are also determined – if there are multiple points with the same minimum elevation, the average lateral coordinate of all points with the same elevation is used. Similarly, the distance from the centerline of a cross-section to the bank station is also identified and written to the table.

The next step is to link the HEC-RAS stream representation to the digital representation of the stream in ArcView GIS. This is accomplished by the *Format Digital Stream* menu, which calls the *FloodFormatStream* script. Any vectorized representation of the stream can be used, but it must reflect the attributes of the surrounding terrain. Therefore, it may be necessary to digitize the stream from DOQs or obtain the stream centerline from surveyed information as opposed to using low-resolution stream network files.

Georeferencing the surveyed cross-sections to known landmarks (such as bridges, culverts, or distinct terrain features) occurs next. The user selects the  button, which calls the *Addpnt* script, and clicks on the upstream, intermediate, and downstream boundaries to tie the cross-section data imported from HEC-RAS to known landmarks in ArcView GIS by snapping to the closest point on the digital stream.

Once this is accomplished, the *Map HEC-RAS Cross-Sections* menu is selected and the *FloodTerrain3d* script is called. This script requires the user to define the stream centerline theme, stream definition point theme, as well as the HEC-RAS import table with the surveyed cross-sections corresponding to the boundaries identified highlighted. Because there can be differences between the stream length represented in GIS and those surveyed or derived from stream network files, *FloodTerrain3d* calculates the ratio of the length of the RAS-modeled stream to that of the digital stream and places the georeferenced cross-sections at the boundaries, while adjusting the locations of the intermediate cross-sections accordingly.

The *FloodTerrain3d* script, as modified for this thesis, then prompts the user to define the orientation of each cross-section (Figure 4-10).

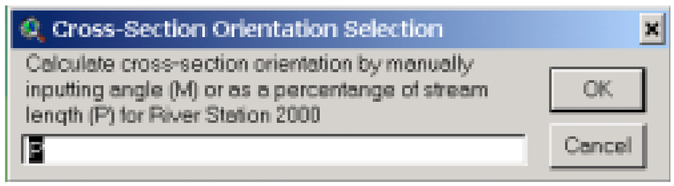


Figure 4-10 Cross-Section Orientation Selection Menu

The user has the option of manually inputting the angle of the cross-section (as measured from a horizontal line proceeding left to right across the screen that equals 0º) or allowing the *FloodTerrain3d* script to define the perpendicular orientation of each cross-section by calculating the bearing between two points located immediately upstream and downstream of the cross-section location (the locations of the upstream and downstream points are calculated as a percentage of the total stream length) and drawing a perpendicular line at that location. Figure 4-10 presents a modification to Tate's 1999 work; this change was driven by the fact that intersecting cross-sections may be acceptable depending on the degree to which the water surface profile has migrated above the bank station elevations. If the floodplain to be modeled is inside of the limits of the intersection cross-sections, the fact that they intersect is not of concern. However, due to the linear nature of HEC-RAS cross-section interpolation algorithms, interpolated cross-sections that intersect within the limits of the floodplain do present unrealistic terrain features (Figure 4-11) and should be edited manually in HEC-RAS prior to generation of a terrain TIN if required.

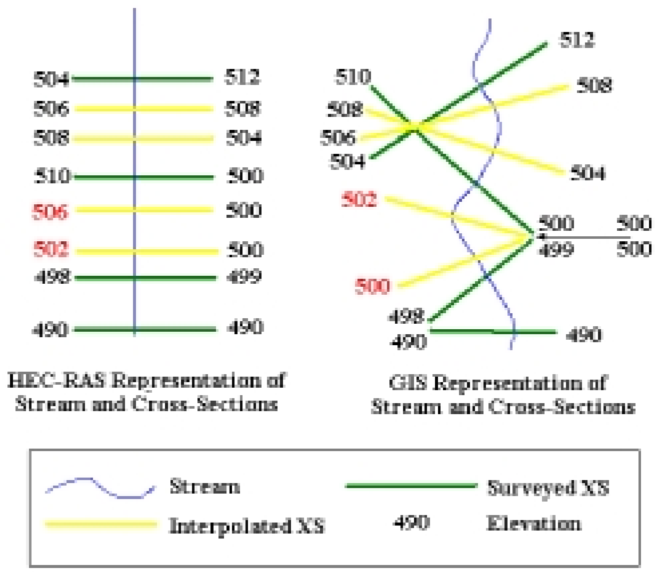


Figure 4-11 Interpolated Cross-Section Discrepancies

Although the interpolation of elevations at each point in the cross-section is a time-consuming process, the user is able to calculate the expected change in elevation for the interpolated cross-section because it is a linear interpolation. This amended methodology permits the user to duplicate field survey sketches and actual conditions more realistically in the GIS domain. Each cross-section is then attributed with river station ID, cross-section length, and the location of the stream centerline and bank stations as a function of the percentage of the length of the cross-section (measured from the outer-most cross-section lateral coordinate left of the main channel).

The result of the cross-section georeferencing is that every vertex on each cross-section is assigned a series of three-dimensional map coordinates in GIS – the easting and northing are derived from the mapping process in GIS, and the elevation coordinate from the global variable created in the data import step. Using these three-dimensional points, in conjunction with surrounding terrain data, a TIN model of the stream channel and surrounding floodplain can be created.   It is important to synthesize this detailed channel and overbank data with the surrounding terrain because many cross-sections surveyed in the field many not fully define the lateral extent of the overbanks. Figure 4-12 presents an example of a hydraulic model in which the water surface elevation extends beyond the limits of the cross-section.

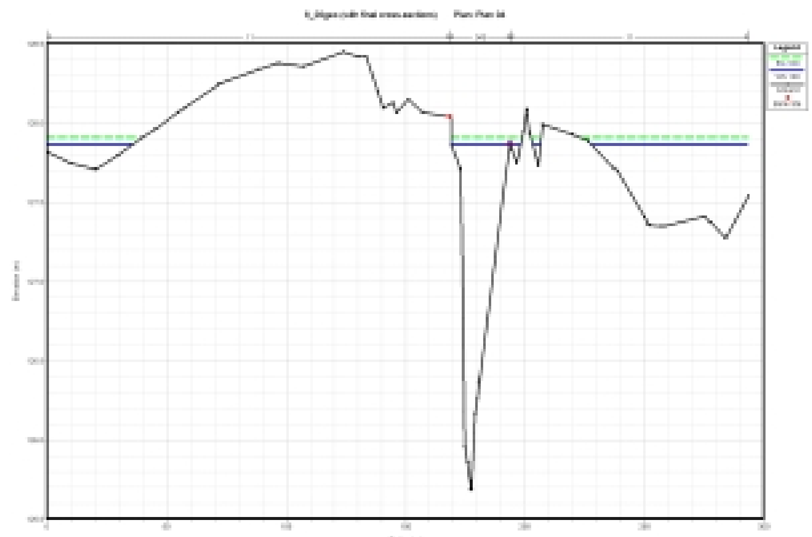


Figure 4-12 Cross-Sections Inadequately Defined for Expected Water Surface Profile

In this figure, the black line represents the ground surface, the blue line the modeled water surface profile, and the green dashed line the energy grade line. By combining the detailed channel and overbank coordinates with surrounding terrain data, and re-cutting the cross-sections (using HEC-GeoRAS), the lateral extent of the resulting water surface elevations can be more realistically defined and re-analyzed in HEC-RAS. Tate (1999) has developed a script to resample the resulting georeferenced cross-sections with surrounding digital terrain data such as DEMs or photogrammetrical survey data. The *FloodNewXSects* script called by the *Resample*

Cross-Sections menu recalculates the elevation of every cross-section point outside of the main channel, and creates a smooth transition from the bank elevations to the surrounding elevations of the DEM or additional survey data.

The user then calls the *FloodBanklines* script by selecting the *Stream Centerline and Banklines* menu. This script, as modified for this thesis, takes channel cross-sections and creates a three-dimensional theme of the stream centerline that will ultimately be used with the three-dimensional cross-section points to create the terrain TIN.

Once the above methodology has been implemented, there is enough information to create a TIN. However, there may be additional data that the user may be able to take advantage of to further define the terrain. On many TxDOT projects, more reliable elevation data than that resulting from field surveys may be available immediately adjacent to the road or bridge being evaluated in the form of aerial photogrammetric survey information (this is true because of the difficulty of duplicating the orientation of the surveyed cross-sections within GIS). Many projects utilize software packages such as GeoPAK® to calculate cut and fill based on detailed aerial survey information, which also have the capability to create an output XYZ file that can be used to supplement or replace cross-section information in the immediate vicinity of the drainage structure of interest. The user should use good engineering judgment in determining what data is most accurate, and can edit the cross-sections generated in CRWR-FloodMap as necessary to take advantage of this additional data. Many cities also have detailed elevation contour data in highly populated areas that may have a higher resolution than standard 30-meter DEMs and take into consideration buildings and other relevant structures.

A TIN can be created from the any of the following types of data using the 3D Analyst extension in ArcView GIS:

- 3D cross-section points;
- 3D DEM points (converted from grid format using the *Convert Grid to Points* menu and the *FloodR2Vpoint* script;
- 3D points from photogrammetric surveys or any other point elevation data;
- Hard breaklines representing the stream centerline and banklines;
- Hard breaklines representing building footprints, or
- Soft Breaklines representing elevation contours.

The more data used to create the TIN, the more accurate the representation of the terrain and, thus, the more realistic the resulting floodplain once hydraulic modeling is complete.

4.2 GIS-based Hydrologic Parameter Extraction

The extraction of spatially variable hydrologic parameters can be accomplished using the bottom four menu items shown on the CRWR-PrePro menu in Figure 4-2. In this research, a curve number grid has already been defined, so only the bottom two menu items need to be activated. Olivera and Maidment (1999) present a detailed discussion of this methodology.

4.2.1 Extraction of Hydrologic Parameters from Subbasins

CRWR-PrePro calculates the following parameters for each subbasin:

- Area;

- Lag time; and
- Average curve number.

The other parameters needed for estimating lag time, such as the length and slope of the longest flowpath, are also calculated and stored in the subbasin attribute table. The calculation of lag time might depend solely on spatial data (i.e., DEM, land use, soils), or it might require additional externally supplied input, depending on the algorithm.

The subbasin area is calculated as a result of the vectorization procedure discussed previously. The lag time is calculated with the following formula:

$$\boldsymbol{t_p} = \max\left(\frac{\boldsymbol{L_w}\left[\left(1000/\boldsymbol{CN}\right)-9\right]^{0.7}}{31.67\boldsymbol{S}^{0.5}}, 3.5\Delta\boldsymbol{t} \right) \qquad \textbf{Equation 4.1}$$

where $\mathbf{t}_p$ (minutes) is the subbasin lag time measured from the centroid of the hyetograph to the peak time of the hydrograph, $\mathbf{L}_w$ (feet) is the length of the longest flowpath, **S** (%) is the slope of the longest flowpath, **CN** is the average curve number in the subbasin, and **t** (min) is the analysis time-step. The first term in the parentheses corresponds to the lag time according to the SCS (1972), and the second term is the minimum lag time value required by HEC-HMS (HEC, 1990).

The longest flowpath, as calculated in CRWR-PrePro, is the distance from the centroid of the furthest cell in the watershed to the outlet of the subbasin. This distance may not follow the main channel in all cases (Figure 4-13).

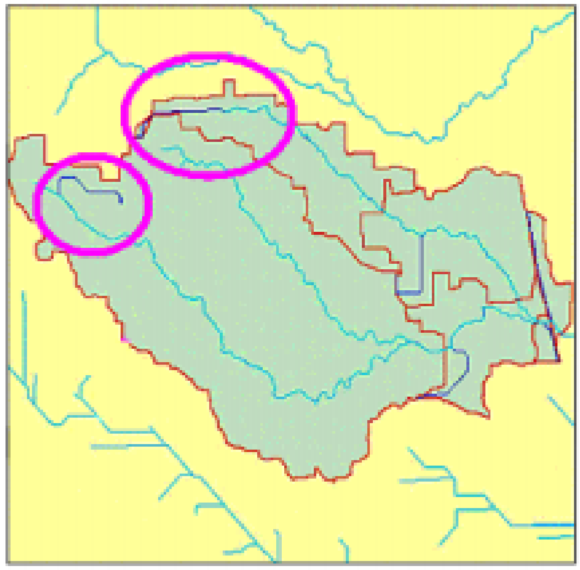


Figure 4-13 Longest Flowpath Calculation

The light blue lines in the figure represent the main channel, while the dark blue lines depict the longest flowpath as determined by CRWR-PrePro algorithms.

CN is calculated as the average of the curve number values within the subbasin polygon and is derived from the curve number grid developed from land use and land cover data, along with STATSGO soil data. The curve number grid used in this thesis was provided by the Blacklands Research Institute.

4.2.2 Extraction of Hydrologic Parameters from Reaches

CRWR-PrePro calculates the following parameters for each reach:

- Reach length;
- Reach routing method (Muskingum or Lag); and
- Either the number of sub-reaches into which the reach is subdivided (when Muskingum routing is used), or
- The flow time (when pure lag routing is used).

Other reach parameters such as flow velocity and Muskingum X cannot be computed from spatial data and must be supplied by the user.

The Muskingum flow routing method (the method used in this research) models the volume of water stored in a stream as the sum of a prism and a wedge, as presented in Figure 4-14.

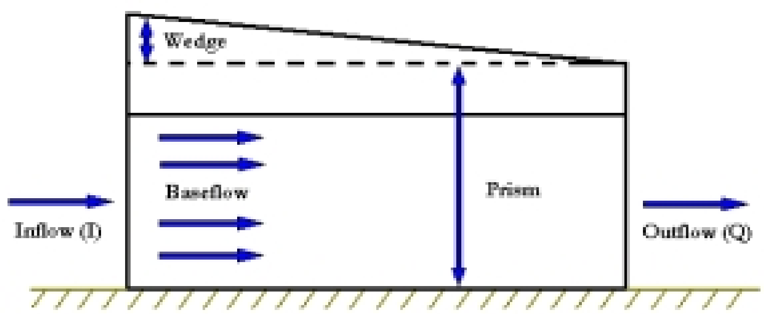


Figure 4-14 Prism and Wedge Storage in Muskingum Routing

The prism represents storage across a constant cross-section along the length of the channel, while the wedge represents the surface "wave" of water that enters the section with the inflow. Assuming a constant velocity, there is a constant ratio between the flow rate and the cross-sectional area. This means that flow is also directly dependent on the volume of prism storage, a function of reach length and cross-sectional area, by a factor of K (prism storage = K*Q). K, therefore, represents the time of travel of the flood wave through the modeled reach. The volume of the wedge of water is dependent on the difference between the inflow and outflow, such that storage can be calculated according to the following equation:

$$\boldsymbol{S = K[XI + (1 - X)Q]} \qquad \textbf{Equation 4.2}$$

where **X** is a weighting factor ranging from 0 to 0.5 depending on the shape of the wedge. This 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 of routing is used. In very long reaches, each reach is subdivided into shorter reaches to again avoid numerical instability such that the flow time satisfies the condition:

$$2\boldsymbol{Xk} < \Delta \boldsymbol{t} < \boldsymbol{k} \qquad \textbf{Equation 4.3}$$

(HEC, 1990), where **X** is the Muskingum parameter and **k** (min) is the flow time in the sub-reach. As calculated by CRWR-PrePro:

$$\boldsymbol{K\ (hrs)} = \frac{\boldsymbol{L}}{3600\boldsymbol{v}} \qquad \textbf{Equation 4.4}$$

where **L** (meters) is the length of the sub-reach and **v** (m/s) is the velocity in the sub-reach. In the case of pure lag:

$$\boldsymbol{Lag}(\text{min}) = \frac{\boldsymbol{L}}{60\boldsymbol{v}} \qquad \textbf{Equation 4.5}$$

A more detailed explanation of the algorithms used in CRWR-PrePro to calculate Muskingum and pure lag routing parameters can be found in Olivera and Maidment (1999).

The above parameters are extracted (and the user prompted for the necessary inputs) using the *Calculate Attributes* menu in CRWR-PrePro (Figure 4-2). Once the parameters have been defined for each subbasin and reach, sub-systems are defined for export to HEC-HMS. This is accomplished by selecting the individual subbasin polygons of interest, activating the vectorized stream theme, and clipping the resulting watershed and its associated attributes using the  button in the ArcView GIS view.

CRWR-PrePro then performs a topologic analysis of the watershed and prepares a HEC-HMS input file from the *HMS Schematic* menu item. The topology of the hydrologic system is established by determining the element located downstream of each subsequent element. An ASCII file is used to record the type (i.e., subbasin, reach, source, sink, reservoir, or junction), hydrologic parameters, and downstream element of each hydrologic element in the system. The input file, when opened in HEC-HMS, generates a topologically correct schematic network of hydrologic elements.

4.3 GIS-based Hydraulic Geometry Extraction

This section presents the algorithms applicable to hydraulic geometry extraction from a DTM prior to hydraulic modeling (Figure 4-15).

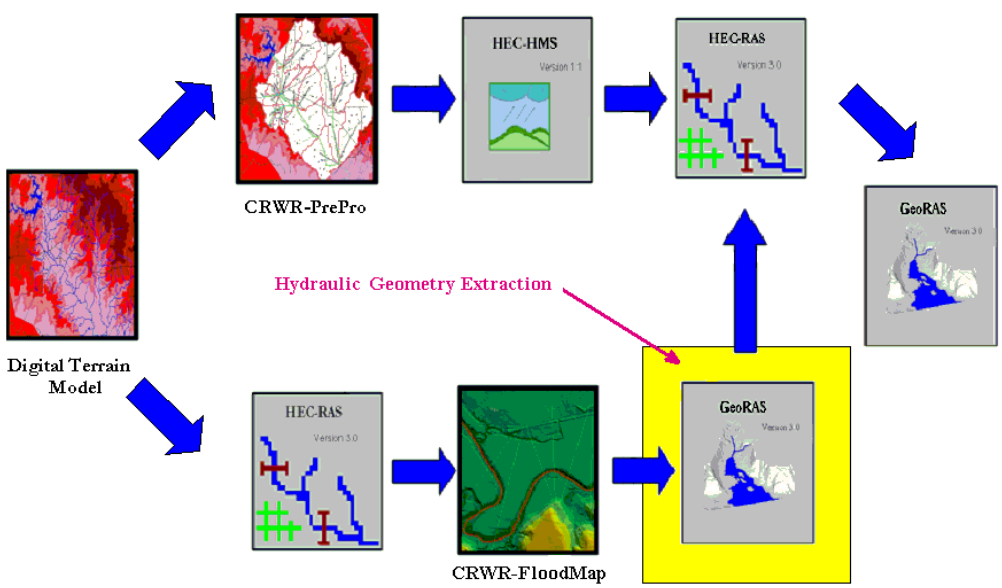


Figure 4-15 GIS-Based Hydraulic Geometry Extraction

HEC-GeoRAS is a set of procedures, tools, and utilities for processing geospatial data in ArcView GIS for export into HEC-RAS (and subsequent hydraulic modeling). In addition, HEC-GeoRAS provides the capabilities to import process simulation results from HEC-RAS back into ArcView GIS for mapping purposes. HEC (2000) provides a User's Manual for HEC-GeoRAS that describes these procedures in greater detail.

Figure 4-16 depicts a flow diagram[14] for the complete HEC-GeoRAS process, and presents an excellent summary of the methodology implemented in this thesis.

The HEC-GeoRAS *PreRas* menu, shown in Figure 4-17, is the ArcView GIS interface for geometric data pre-processing and takes the user through the steps necessary to create an export file for hydraulic modeling in HEC-RAS. The geometric data necessary for hydraulic modeling in HEC-RAS is developed from an existing DTM of the channel and surrounding land surface; the development of this DTM is presented in Section 4.1.2.

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[14] USACOE Hydrologic Engineering Center, *HEC-GeoRAS An Extension for Support of HEC-RAS Using ArcView User's Manual*. Version 3.0. April, 2000

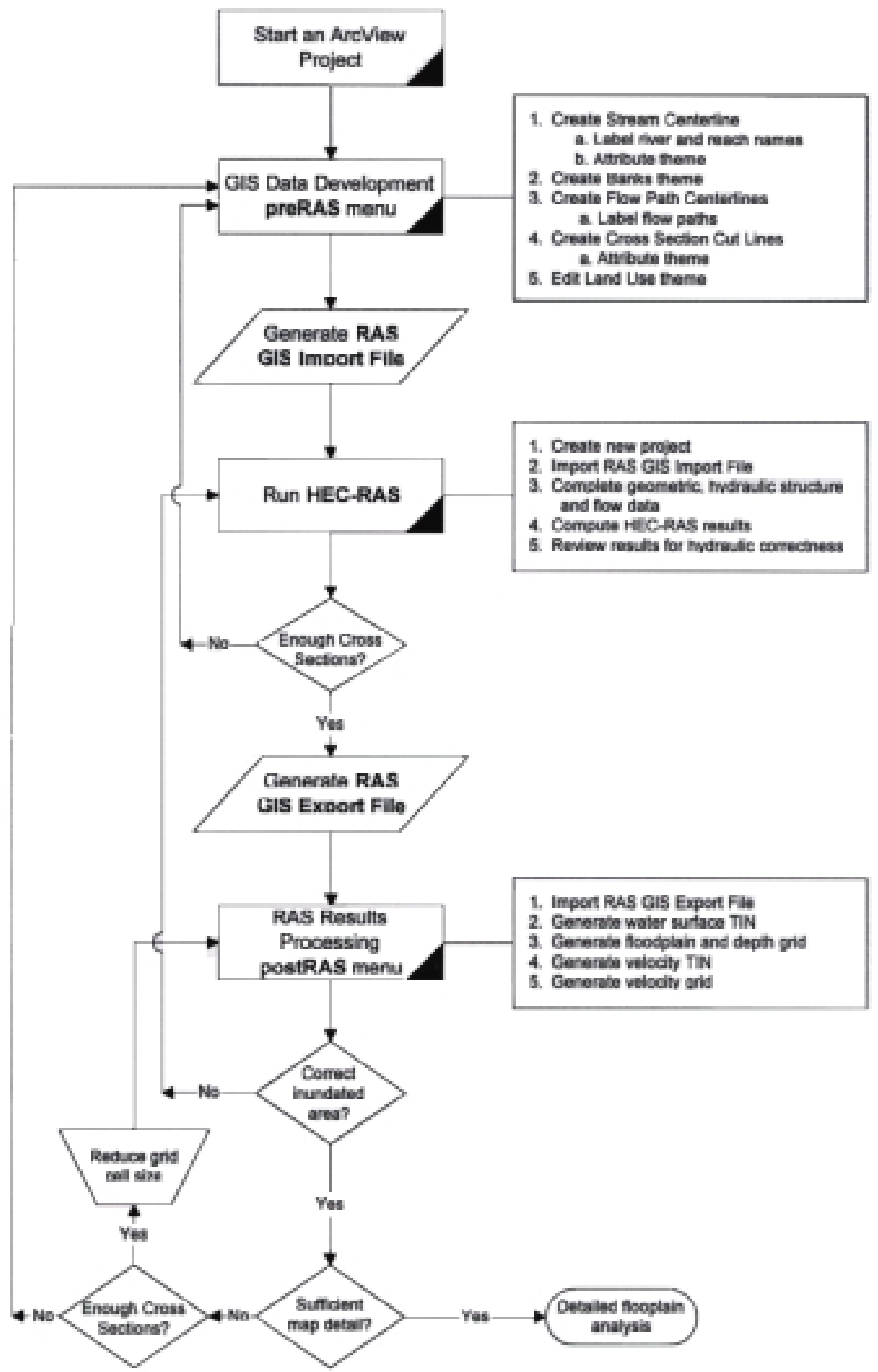


Figure 4-16 HEC-GeoRAS Flow Diagram

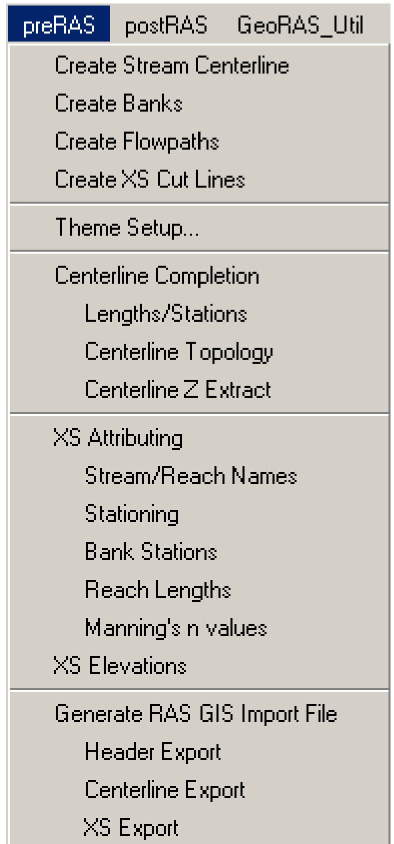


Figure 4-17 HEC-GeoRAS preRAS Methodology

The first step in the *preRAS* methodology consists of the creation of a series of two-dimensional line themes that represent particular topographic elements of the stream network. The following themes are created using existing ArcView GIS tools:

- The centerline of the streams;
- The main channel banks;
- The flowpaths of the stream and overbanks; and
- The cross-section cut lines.

The river and reach network is represented by the *Stream Centerline* theme, and is created on a reach-by-reach basis, starting from the upstream end and working downstream following the channel thalweg. The *Stream Centerline* theme is used for assigning river stationing for the cross sections and to display the network as a schematic in the HEC-RAS Geometric editor. All river reaches must be connected by junctions and must point downstream. Each river reach must have a unique combination of its River Name (Stream ID) and Reach Name (Reach ID). Stream centerlines should not intersect except at junctions. In practice, the *Create Stream Centerline* menu item is used to create a new editable shapefile (with a default name of *Stream.shp*) that is added to the current view, where it can be manually entered and/or modified by the user. After creating the river network, the user completes the Stream Centerline theme by adding river and reach identifiers using the River ID tool (Figure 4-18).

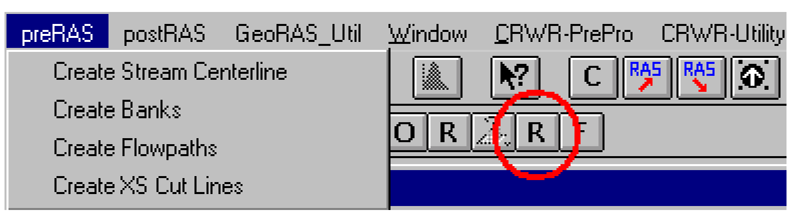


Figure 4-18 HEC-GeoRAS River ID Tool

The *Create Banks* menu item is selected next, which separates the main channel from the overbank areas. *Create Banks* creates a new shapefile named *Banks.shp* and adds it to the current view, where it is editable by the user. The creation of this theme is optional, and is used to determine the bank stationing in HEC-RAS (this data may be supplied by the user manually in HEC-RAS if the theme is not created in HEC-GeoRAS). Bank station lines should be created on either side of the channel to identify the main conveyance channel from the overbank areas. Bank lines may be broken, and their orientation is not important; however, exactly two bank lines must cross each cross-section cut line once they are created.

The *Create Flowpaths* menu item is used to identify the hydraulic flow path in the left overbank, main channel, and right overbank. *Create Flowpaths* creates a new shapefile named *Flowpath.shp* in the current view that is editable by the user. The Flowpath ID tool is used to specify the designation of each flowpath according to the geometry of the stream network (Figure 4-19).

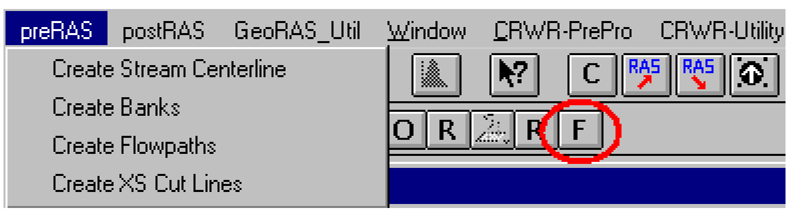


Figure 4-19 HEC-GeoRAS Flowpath ID Tool

If the *Stream Centerline* theme already exists, the user may select this as the main channel flowpath. Flow paths must be created in the direction of flow. Downstream reach lengths are calculated between cross-section cut lines along the flow path centerlines. The creation of a flowpaths theme is also optional.

The *Create XS Cut Lines* menu item is selected last, where the user can identify the location, position, and expanse of each cross-section. *Create XS Cut Lines* creates an editable theme called *Xscutlines.shp*. While these cut lines represent the planar location of the cross-sections, the station elevation data is extracted along the cut line from the DTM. Cross-section cut lines must be drawn from the left overbank to right overbank (looking downstream), and must cross each of the three flow path lines and two bank station lines exactly once. Cross-sectional cut lines should be drawn perpendicular to the direction of flow and should not intersect.

A polygon theme is an optional procedure for estimating Manning's *n* values along each cut line based on land use by using the *GeoRAS_Util* menu (Figure 4-20).

Figure 4-20 Creating the Land Use Table

This menu provides functionality to create a summary table of land uses and user specified *n* -values. The table of *n* -values is then joined to the land use data tables.

Once these themes have been created, the geometric data extraction process begins. The first step is the selection of the Theme Setup menu, where the appropriate themes are specified for input data (Figure 4-21) and the user specifies the RAS GIS Import file.

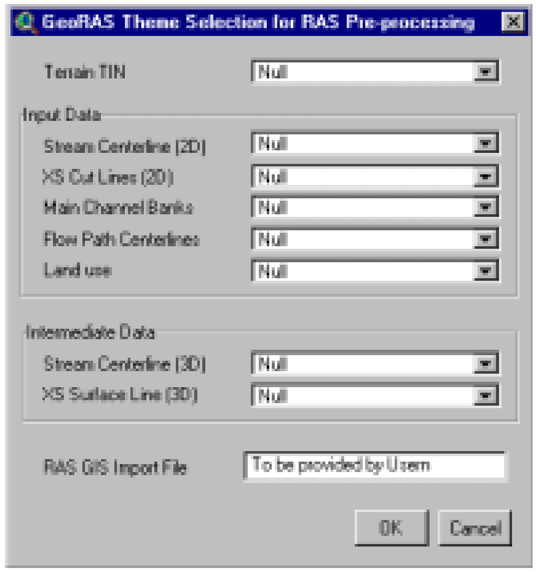


Figure 4-21 HEC-GeoRAS Theme Setup Dialog Box

There are three processes that take place once the appropriate themes have been identified:

- Centerline Completion
- Cross-section Attributing
- Cross-section Elevations

Each of the above items can be accomplished in one step, but are comprised of several algorithms that can be activated individually if desired by the user.

The *Centerline Completion* menu computes the river reach lengths (*Lengths/Stations* menu item), establishes the connectivity and orientation of the river network (*Centerline Topology* menu item), and creates a 3D shapefile from the Stream Centerline theme (*Centerline Z Extract* menu item).

Cross-section attributes are added to the *Cross-Section Cut Line* theme using the *XS Attributing* menu item. *XS Attributing* adds stream and reach names to the *Cross-Section Cut Line* theme, adds the cross-sectional stating data based on the intersection of the cross-sectional cut lines and the stream centerline, extracts Manning's *n*-values from the ***Land Use*** theme, computes bank station positions for each cross section from the intersection of the cross-sectional cut lines and bank station lines (calculated as the percent distance along the cut line from its start in the left overbank), and adds downstream reach lengths to each cross-section cut line based on the intersection of the flow path centerlines and the cut lines.

The ***XS Elevation*** function creates a 3D shapefile from the ***Cross-Section Cut Line*** theme, where station-elevation data is extracted from the terrain TIN at the edge of each triangle along a cut line.

The final step in the ***preRAS*** menu is the ***Generate RAS GIS Import*** function, where header information is written (in ASCII format) to a text file that contains general information based on the ***3D Stream Centerline***, ***Cross-Section Surface Line***, and ***Terrain TIN*** data. Stream network data is also written that specifies each river reach endpoint, the stream centerline coordinates, and the distance to the downstream endpoint. Finally, the geometric data for each cross-section is written to the import file, including river and reach identifiers, cross-section stationing, bank station locations, downstream reach lengths, Manning's n-values, cross-section cut line coordinates (x, y), and cross section surface line coordinates (x, y, z).

A detailed step-by-step procedure for completing the ***preRAS*** methodology is provided in the HEC-GeoRAS User's Manual (HEC, 2000).

4.4 Hydrologic Modeling

The hydrologic modeling of any natural system consists of understanding the relationships between the amount of precipitation falling on a land surface and the quantity of runoff generated from that storm event, how the runoff becomes channelized flow, and how that flow proceeds to the outlet of a subbasin or watershed. In this thesis, HEC-HMS is used to model the response of a watershed to a precipitation event (synthetic or historical). The hydrologic modeling of the watersheds presented in this research occurs after DTM development activities (Section 4.1.1) and prior to hydraulic modeling using HEC-RAS (Figure 4-22).

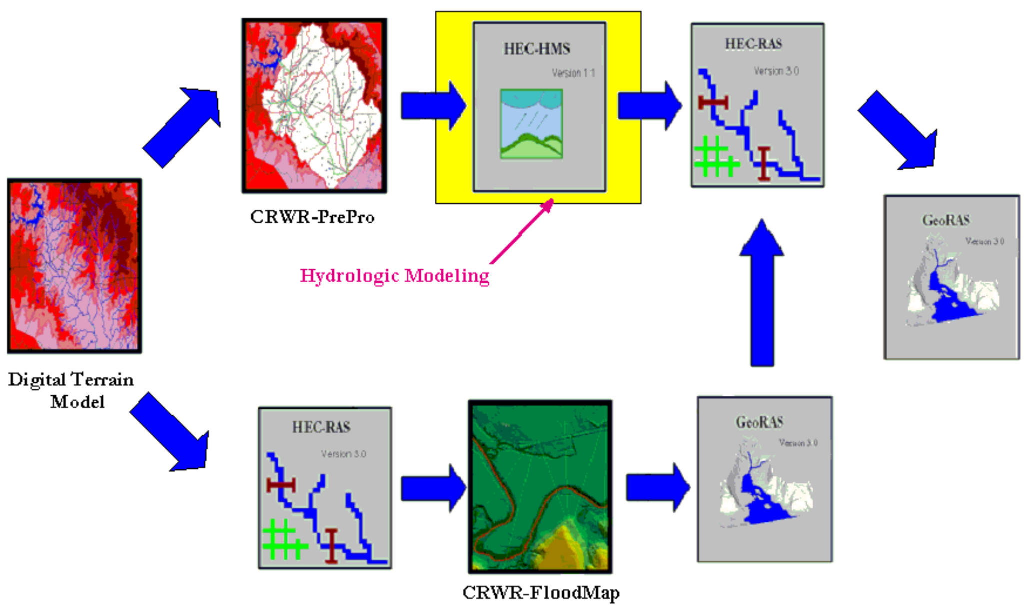


Figure 4-22 Hydrologic Modeling Using HEC-HMS

HEC-HMS was designed as a part of HEC's "Next Generation (NexGen) Software Development Project" to replace the commonly used HEC-1 program with an improved GUI and advanced technical capabilities (Peters and Feldman, 1997).

HEC-HMS requires a basin model, a precipitation model, and a set of control specifications to run successfully (Figure 4-23).

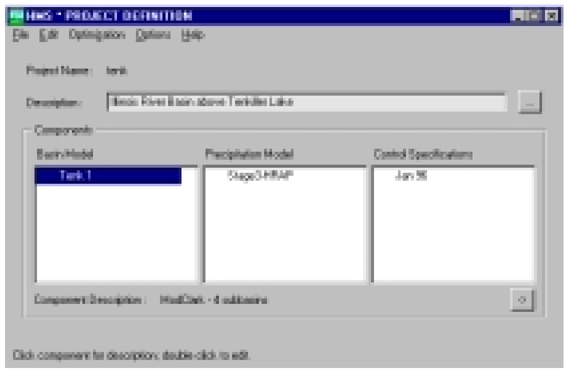


Figure 4-23 Components of HEC-HMS Model

The HEC-HMS basin model is capable of simulating subbasin runoff, losses due to soil abstraction and storage, transformation of excess precipitation into runoff, routing of runoff into and through channels, and diversions in the natural flow path. Table 4-1 presents a summary of the HEC-HMS *Basin* component, highlighting the analyses selected for this thesis.

Table 4-1 HEC-HMS Basin Component Summary

Hydrologic Parameter	Method of Analysis	Additional Options
Losses	SCS Curve Number	Initial/Constant, Green & Ampt, Gridded SCS Loss, Deficity/Constant
Runoff Transformation	SCS Unit Hydrograph	Clark and Snyder Unit Hydrographs, Kinematic Wave, Modified Clark Method, Input Ordinates
Routing	Muskingum and Lag	Modified Puls, Muskingum-Cunge (Standard and 8 pt.), Kinematic Wave
Reservoir Routing	None	User-Specified
Diversion	None	User-Specified
Source	None	User-Specified

GIS can be used to represent the effects of spatially variable parameters on the hydrologic response of the natural system. In this thesis, the hydrologic parameters and connectivity of the basins evaluated are generated from CRWR-PrePro as described in Section 4.2, and result in a basin model that is already populated with the appropriate subbasin and reach data. Section 4.2 also presents the theoretical basis for the analysis methods used in this research.

Precipitation values and distribution over the region are specified in the HEC-HMS *Precipitation* component; this data can be historical or hypothetical. The model is capable of interpreting precipitation values in a variety of formats, including cell-based distribution (i.e., NEXRAD radar data), spatially-averaged values, and measured data from rain gages with user-specified or model-derived associated gage weights. Table 4-2 presents a summary of the HEC-HMS *Precipitation* component, with the precipitation models used in this thesis noted. A hypothetical SCS Type 2 storm event was used at Castleman Creek, while a historical hyetograph was utilized at Pecan Bayou.

Table 4-2 HEC-HMS Precipitation Component Summary

Hydrologic Parameter	Method of Analysis	Additional Options
Historical	User-Specified Hyetograph	Cell-Based Precipitation, Spatially Averaged Precipitation, Weighted Gages Using Inverse Distance-Squared Weighting
Hypothetical	User-Specified Hyetograph	Specified Frequency Storms

Control specifications allow the user to specify the variables for a given simulation, such as starting and ending dates and a calculation time interval. HEC

(1986) provides a detailed description of this hydrologic modeling methodology in the HEC-HMS User's Manual.

4.5 Hydraulic Modeling

In 1964, HEC released the HEC-2 computer model to aid hydraulic engineers in stream channel analysis and floodplain determination. In 1997, HEC-RAS was developed to replace HEC-2. This Windows®-based software is a one-dimensional steady flow model intended for computation of water surface profiles, and it contains data exchange modules that enable the transfer of physical element descriptions to the GIS domain. Figure 4-24 presents the contribution of hydraulic modeling with HEC-RAS to the overall floodplain delineation methodology presented in this thesis.

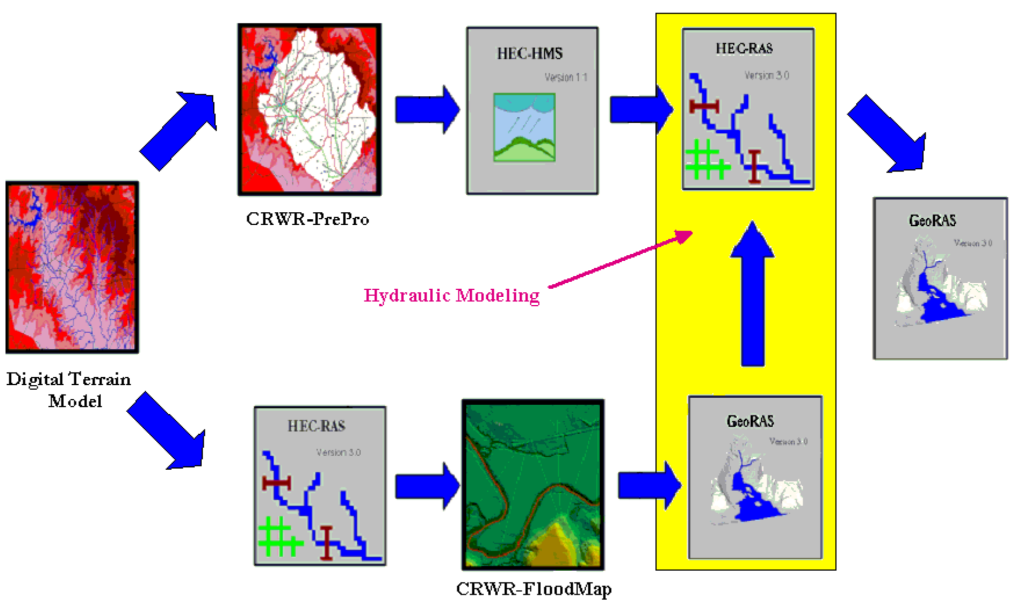


Figure 4-24 Hydraulic Modeling with HEC-RAS

The combination of extracting geometric data from GIS with traditional HEC-RAS hydraulic modeling makes full use of the spatial capabilities of GIS and ultimately provides an accurate floodplain model given accurate terrain data. HEC-RAS was selected as the hydraulic model for this research because of the presence of existing geometric data in HEC-RAS format and the fact that TxDOT, the funding agency for this research, is familiar with HEC models.

HEC-RAS calculates the flow and stage expected from a precipitation event (the resulting hydrograph modeled in HEC-HMS) by assuming steady and uniform flow characteristics as they relate to an open channel. It has the capability to model subcritical, critical, and supercritical flow as defined by the Froude number:

$$\boldsymbol{Fr} = \frac{\boldsymbol{V}}{\sqrt{\boldsymbol{gy}}} \qquad \textbf{Equation 4.6}$$

where **Fr** = Froude number, **V** = mean fluid velocity (m/s), **g** = gravitational acceleration (m/s^2), and **y** = water depth (m). Subcritical flow occurs when the Froude number is less than 1; supercritical flow occurs when the Froude number is greater than 1. Critical flow is defined at the point where the total energy head is a minimum and the Froude number equals 1. Flow and conveyance in HEC-RAS are calculated according to the continuity equation; for open channel flow, Manning's equation is used to model the momentum of the system:

$$\boldsymbol{Q} = \boldsymbol{K}\sqrt{\boldsymbol{S_f}} \qquad \textbf{Equation 4.7}$$

$$\boldsymbol{K} = \frac{1}{\boldsymbol{n}}\boldsymbol{AR}^{2/3} \qquad \textbf{Equation 4.8}$$

where **R** equals the hydraulic radius (m), **n** equals Manning's roughness coefficient, **K** equals the conveyance ($\overline{m^{5/3}}$), and $\mathbf{S_f}$ equals the average friction slope between adjacent cross-sections. HEC-RAS assumes that the energy head is constant across each cross-section and is calculated in this research with the energy equation for open channel flow:

$$\boldsymbol{H} = \boldsymbol{Z} + \boldsymbol{Y} + \frac{\boldsymbol{\alpha}\boldsymbol{v}^2}{2\boldsymbol{g}} \qquad \textbf{Equation 4.9}$$

where **H** equals the energy head (m), **Z** equals the channel bed elevation (m), **Y** equals the pressure head (m), and **α** equals the velocity weighting coefficient. For a given water surface elevation, the mean velocity head is obtained by computing a flow-weighted velocity head over the cross-section. Based on channel geometry, channel contractions and expansions, and flow obstructions from hydraulic structures in the floodway, this flow velocity can vary from one end of the cross-section to another. Therefore, HEC-RAS subdivides the cross-sections into left floodway, main channel, and right floodway (Figure 4-25).

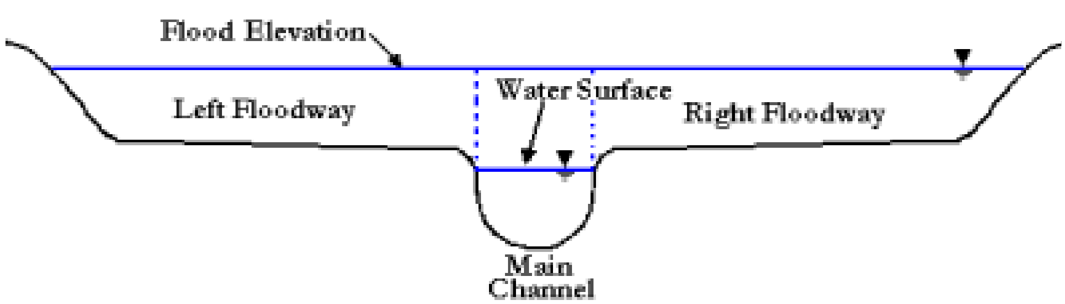


Figure 4-25 Stream Cross-Section Schematic

HEC-RAS uses the following input parameters for hydraulic analysis of the stream channel geometry and flow regime:

- River station;
- 3D coordinates describing the natural terrain;

- Left and right bank station locations;
- Reach lengths between the left floodway, stream centerline, and right floodway and the next downstream cross-section;
- Manning's roughness coefficients (*n*-values);
- Channel contraction and expansion coefficients; and
- Geometric description of hydraulic structures in the floodway.

Cross-sections are developed along the stream channel that contain the above information, which can be manually inputted by the user or may be extracted from terrain data contained in GIS format.

For steady, gradually varied flow, this methodology assumes the direct step method for computation of the water surface profile at each cross-section, which is based on an iterative solution to the energy equation. Under this assumption, the user must supply the flow and water surface elevations at the boundaries of the system.

Many texts carry in-depth discussions of the hydraulic calculations and assumptions presented above. Tate (1999) also provides additional discussions on the applicability of HEC-RAS hydraulic modeling for floodplain delineation purposes. HEC (1997) provides a systematic procedure for using HEC-RAS in the *HEC-RAS River Analysis System: Hydraulic Reference Manual*.

4.6 Floodplain Delineation

HEC-GeoRAS was designed to integrate HEC-RAS hydraulic model output into the GIS domain (Figure 4-16). While Section 4.3 presented a methodology for processing terrain data in GIS prior to hydraulic modeling in HEC-RAS, this section describes the methodology for processing hydraulic modeling output in GIS using HEC-GeoRAS once the hydraulic modeling is complete (Figure 4-26).

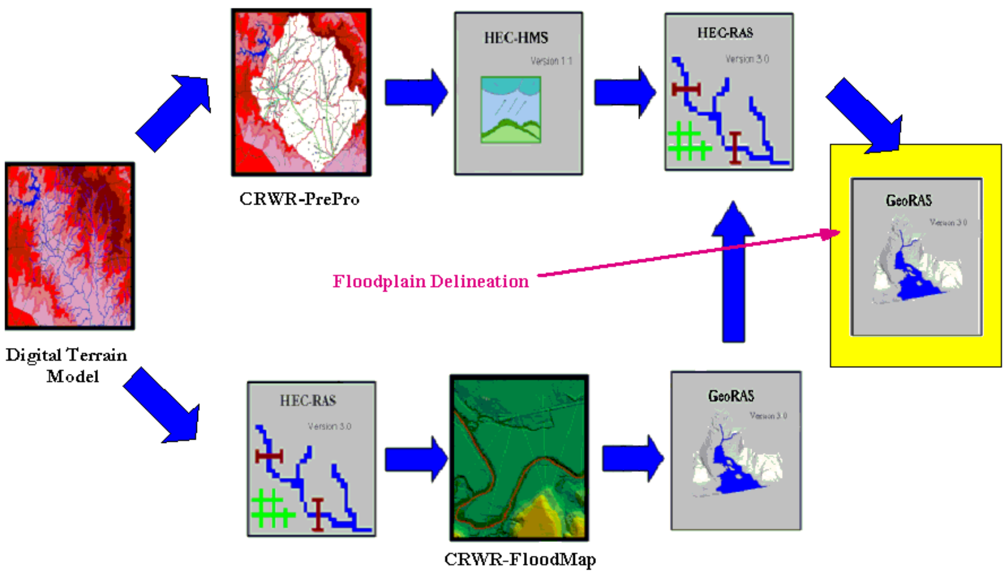


Figure 4-26 Floodplain Delineation Using HEC-GeoRAS

To import HEC-RAS data into GIS, the user must identify the export file and specify the location to store results to pre-process the raw data via the HEC-GeoRAS *PostRAS* menu (Figure 4-27).

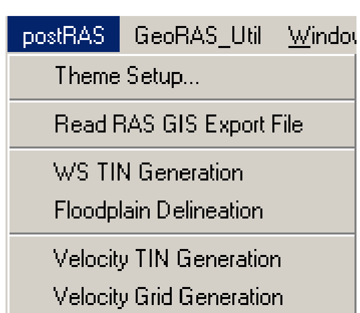


Figure 4-27 HEC-GeoRAS postRAS Methodology

The *Theme Setup* menu item is selected first, which allows the user to specify the RAS GIS export file, Terrain TIN, output directory, and rasterization cell size. The first three items are self-explanatory, but the selection of the rasterization cell size can greatly impact the mapping of the floodplain resulting from the hydraulic modeling. The rasterization cell size is used to transform the terrain TIN and resulting water surface TINs into raster format to permit grid cell computations; the smaller the cell size, the longer the processing time, but depending on the resolution of the TIN, the more accurate the spatial resolution of the floodplain. Once this step is complete, the *Read RAS GIS Export File* menu item is selected, which reads the HEC-RAS results and creates a database for GIS post-processing. The initial themes created include: stream network, cross-sectional cut lines, cross-sectional surface lines, bank station lines, and water surface profile bounding polygons.

The stream network theme identifies the location of the stream centerline as represented in HEC-RAS and contains the River and Reach names. The cross-sectional cut line theme includes the stream, reach, and station identifiers for each cross-section location, along with the water surface elevations for each flood event modeled. A 3D shapefile of cross-sections is also created that contains the attributes of the cross-sectional cut line theme. A line theme of bank station locations will also be created if bank station data is available from HEC-RAS. Finally, a bounding polygon theme is created that defines the HEC-RAS model extent, thereby limiting the edge of the water surface to the end of each cross-section.

Water surface elevations are written to the *RAS GIS Export File* at each cross section for each flood event modeled. This water surface data is used in conjunction with the terrain elevation data to create a water surface TIN using the *WS TIN* menu item (Figure 4-28). In practice, this water surface TIN is compared to the surrounding terrain TIN, and where the water surface elevations are greater than the terrain, flooding occurs to a depth equal to the difference between the two elevations.

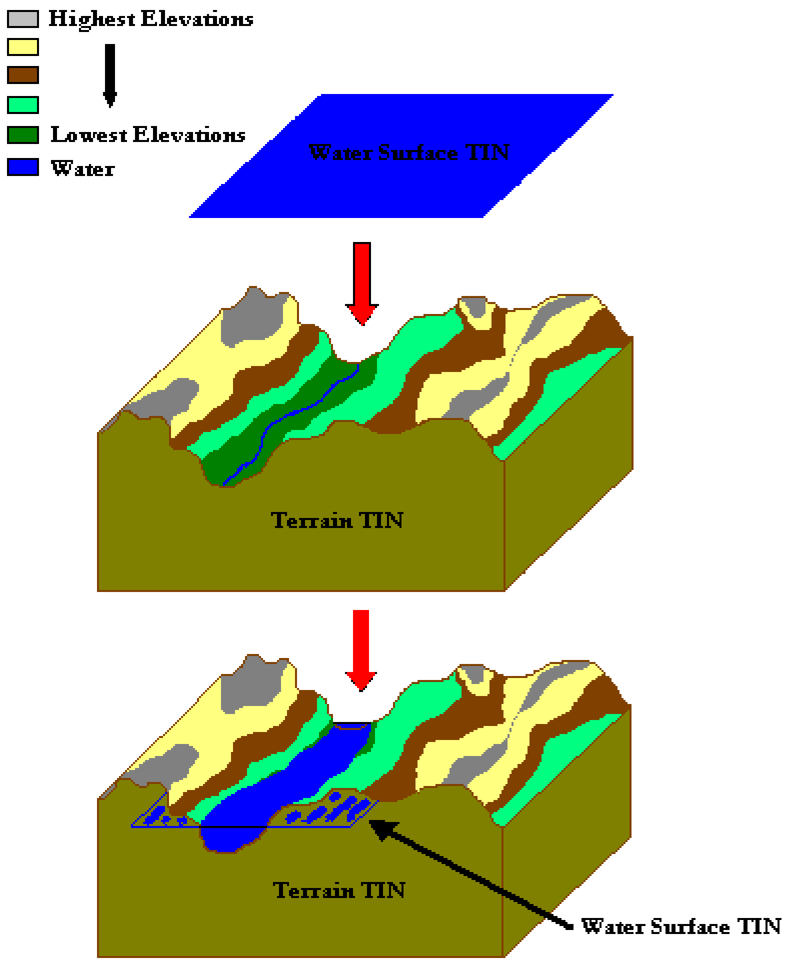


Figure 4-28 Schematic of Water Surface and Terrain TINs

Floodplain delineation in HEC-GeoRAS is performed using the *Floodplain Delineation* menu item, which rasterizes both the terrain and water surface TINs. The grids are created using the *Rasterization Cell Size* specified in the post-processing theme setup dialog box. The floodplain is delineated where the water surface grid and terrain grid have the same elevation. The rasterized terrain TIN is then subtracted from the water surface TIN to create a water depth grid. The floodplain delineation process in HEC-GeoRAS is an iterative process that should be used to refine the HEC-RAS hydraulic model.

5 IMPLEMENTATION PROCEDURES

This chapter presents a systematic procedure for implementing the methodology described in Chapter 4 at both the Castleman Creek and Pecan Bayou sites. Appendix A provides a data dictionary for the files created during the implementation process.

5.1 Castleman Creek

Upon completion of the general data development activities described in Chapter 2, the following procedures were implemented at the Castleman Creek watershed to define the floodplains resulting from six SCS Type 2 storm events.

5.1.1 SITE SPECIFIC TERRAIN DATA DEVELOPMENT

Site-specific terrain data development is comprised of defining the terrain adequately to derive the hydrologic and hydraulic parameters necessary for modeling with HEC-HMS and HEC-RAS, respectively.

5.1.1.1 Terrain Development for Hydrologic Analysis

Terrain development for hydrologic analysis was accomplished with CRWR-PrePro. Figure 5-1 presents a summary of this procedure; some steps have been left out for clarity. The NHD stream network was burned (*Burned1*) into the clipped and projected DEM and the sinks filled (*Fill*). A flow direction grid (*Fdr*) was generated next, which was followed by a flow accumulation grid (*Facc*). A stream segment grid was also derived (*Strmgrd*), along with a link grid (*Link*) to identify the unique links along the stream centerline.

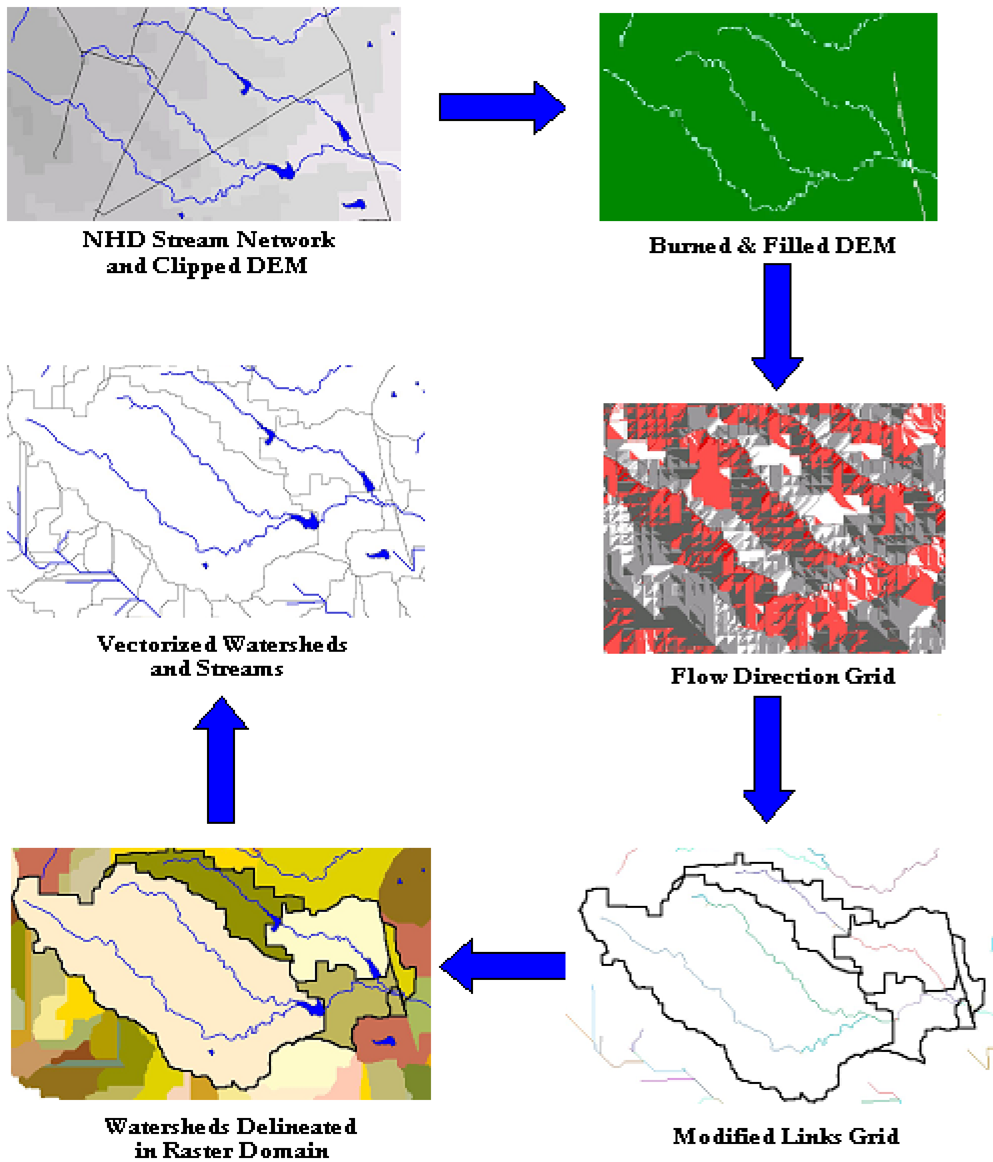


Figure 5-1 Summary of CRWR-PrePro Terrain Development for Hydrologic Analysis at Castleman Creek Watershed

The outlets to each link were identified (*Out*) in the raster domain, at which point additional outlets were identified, as a point shapefile, to represent the location of each of the three SCS flood control structures in the watershed and the upstream and downstream limits of the cross-sections provided in HEC-RAS (*AddAsCentrdOutlets.shp*). These outlets are depicted as red dots in Figure 5-2. Modified grids were then created for the new links (*Modlnk*) and outlets (*Modout*). From this data, subbasins were delineated in the raster domain (*Watgr*). The last step in this process included the creation of a polygon theme to represent the subbasins (*Watpoly2.shp*) and stream segments (*Riv2.shp*). Watersheds were then merged to attempt to duplicate the hydrologic network defined by TxDOT engineers in their HEC-1 model.

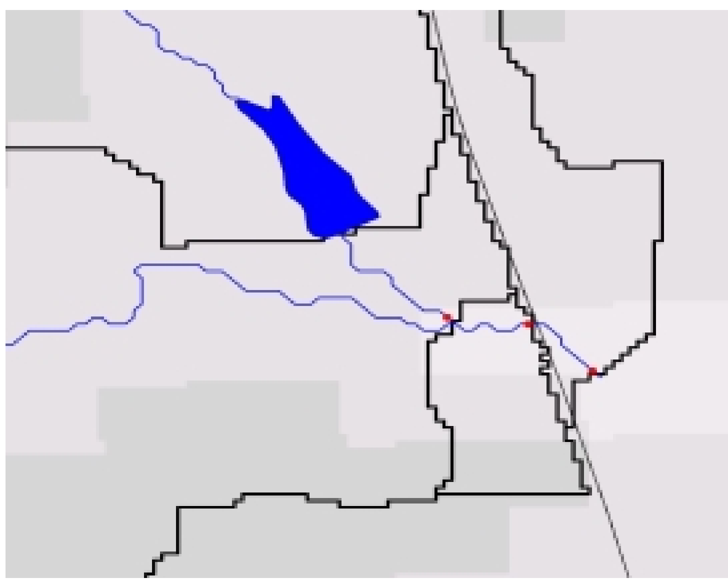


Figure 5-2 Additional Outlets Selected to Define Extents of HEC-RAS Cross-Section Data

5.1.1.2 Terrain Development for Floodplain Delineation

The TIN developed for floodplain delineation at this site was derived from HEC-RAS cross-sections and digital terrain data in the form of a DEM and photogrammetric survey data.

An initial analysis of the HEC-RAS cross-section data yielded cross-sections that were entered backwards (this was determined by analyzing the cross-section data at the US 77 bridge and finding that the slopes of the terrain in each floodway did not match the photogrammetric survey data in these areas). Cross-section geometry is defined looking downstream; the cross-sections provided by TxDOT were provided looking upstream and therefore needed to be reversed (Figure 5-3). The right side of the figure depicts the orientation of the original cross-sections, while the left side presents the reversed cross-sections.

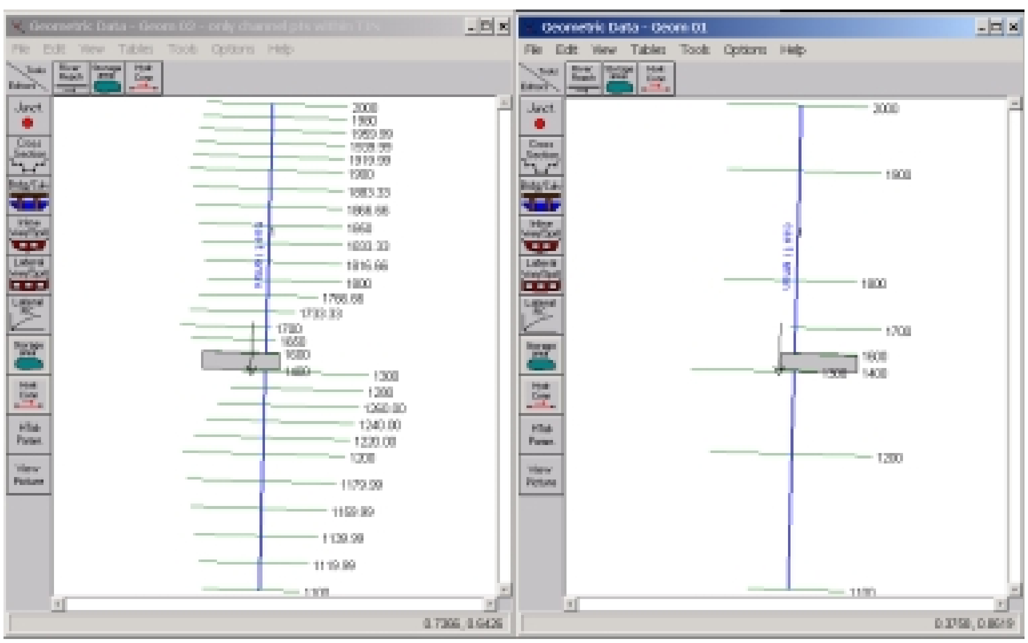


Figure 5-3 Reversed and Interpolated HEC-RAS Cross-Sections

In addition, to further define the terrain in between each cross-section, several interpolated cross-sections were added to the model; Figure 5-4 presents a typical interpolated cross-section. When interpolated cross-sections are generated in

HEC-RAS, the river station is appended with an asterisk (i.e., 1980*) that must be removed for the CRWR-FloodMap scripts to read the data correctly (since the script reads survey stationing as a number and not as a text string). The River Station field was modified for each interpolated cross-section but was documented as an interpolated section in the Description field.

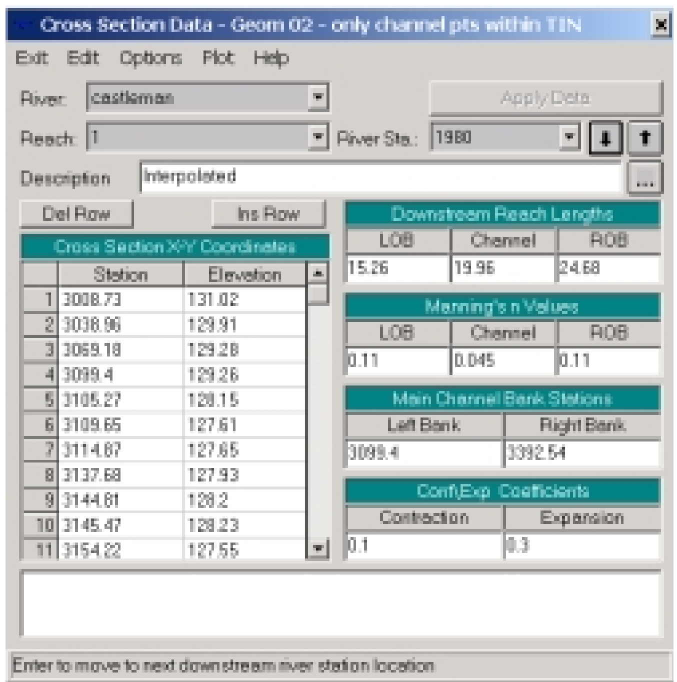


Figure 5-4 Interpolated Cross-Sections in HEC-RAS

Once the cross-sections were corrected, they were imported into ArcView GIS with the CRWR-FloodMap script *FloodRasRead*, resulting in the following table (Figure 5-5).

Table2

Station	Description	Type	LBankX	LBankZ	ChannelY	ChannelZ	RBankX	RBankZ
2000.000	Section D Upstream		115.6	129.4	20.0	126.2	167.1	128.9
1980.000	Interpolated		131.2	129.3	39.9	126.0	162.0	128.9
1959.990	Interpolated		146.7	129.1	59.9	125.9	156.9	128.8
1939.990	Interpolated		162.3	129.0	79.8	125.8	151.8	128.7
1919.990	Interpolated		177.9	128.8	99.8	125.7	146.7	128.7
1900.000	Section C Upstream		193.4	128.7	127.5	125.6	141.6	128.6
1883.330	Interpolated		193.6	128.6	155.1	125.6	132.6	128.5
1866.660	Interpolated		193.7	128.5	182.8	125.5	123.6	128.4
1850.000	Interpolated		193.9	128.4	210.4	125.5	114.6	128.4
1833.330	Interpolated		194.1	128.3	238.1	125.5	105.6	128.3
1816.660	Interpolated		194.2	128.2	265.7	125.5	96.7	128.2
1800.000	Section B Upstream		194.4	128.0	289.4	125.4	87.7	128.2
1766.660	Interpolated		133.8	128.2	313.0	125.5	136.4	128.2
1733.330	Interpolated		73.3	128.4	336.7	125.5	185.2	128.3
1700.000	Section A upstream		12.8	128.6	356.3	125.5	234.0	128.3

Figure 5-5 CRWR-FloodMap Import Table

CRWR-FloodMap was then used to create the formatted digital stream (*C1.shp*) – which was derived from the NHD stream network file – as well as 3D cross-sections (*terrain3d.shp*) that corresponded to the locations of the imported HEC-RAS cross-sections. The cross-sections were georeferenced using the *Bounds.shp* theme, which corresponded to the upstream, US 77 Bridge, and downstream outlets specified initially in CRWR-PrePro. The cross-sections were oriented using the modified *Terrain3D* script, and the orientation of each cross-section entered manually based on a sketch of the original cross-sections provided by TxDOT. A 3D stream centerline theme was then created (*Stream3d.shp*) to define the three-dimensional characteristics of the channel centerline based on the HEC-RAS cross-sections. Figure 5-6 presents the *Terrain3d* and *Stream3d* themes. The dark blue line represents the 3D stream centerline, and the maroon lines the cross-sections.

The *Terrain3d* theme was then re-sampled to provide a smooth transition from the banks of Castleman Creek to the surrounding DEM (*3dxsects.shp*). Because highly accurate photogrammetrical survey data was available in the immediate vicinity of US 77, this theme was edited manually to remove cross-section points falling within the limits of the photogrammetric survey bounding polygon (*Tinbound19.shp*), resulting in the *3dxsects(edit).shp* theme.

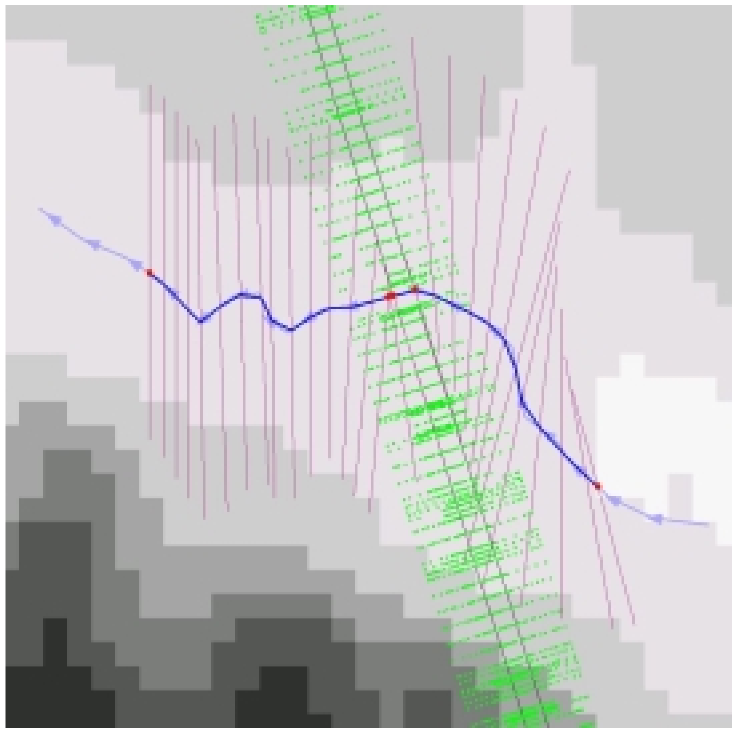


Figure 5-6 3D Cross-Section and Stream Centerline Themes

Figure 5-7 depicts the ArcView tools necessary for editing a 3D shapefile by deleting only the points of each cross-section that fall within the limits of the more accurately defined terrain.

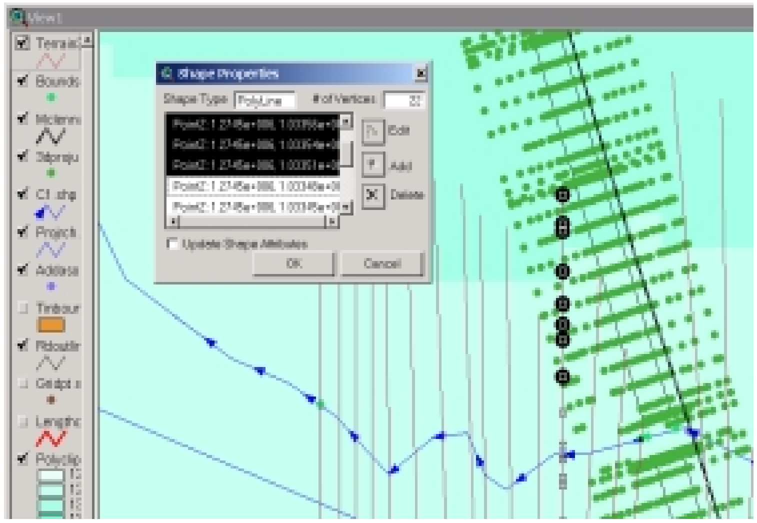


Figure 5-7 Procedure for Editing 3D Shapefiles

Once editing was completed, the necessary data was available for creating the most accurate TIN possible from the resolution of the data provided. Figure 5-8 shows the different resolutions of each type of data.

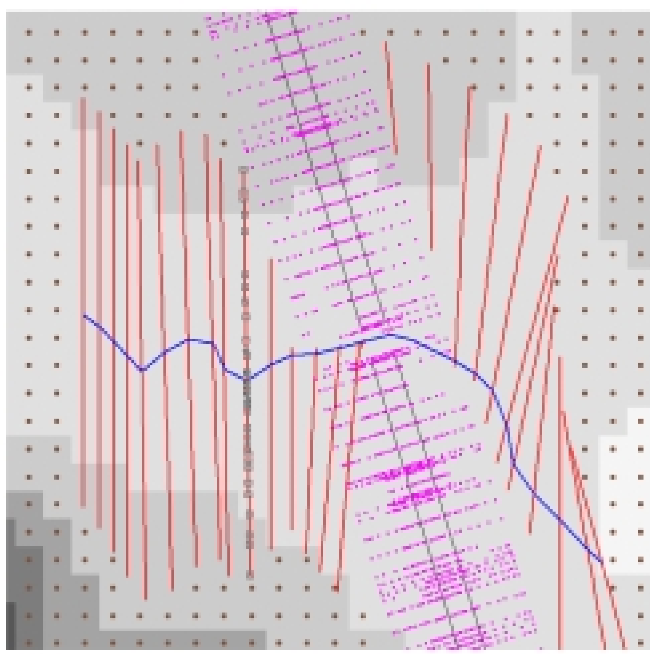


Figure 5-8 3D Point and PolylineZ Data for TIN Construction

Figure 5-9 depicts the TIN (*Landtin*) created from the above data. The *Stream3d.shp* theme was specified as a hard breakline, and the *3dxsects(edit).shp*, DEM points (*Gridpt.shp*), and photogrammetric survey data (*3dprojus77tin.shp*) themes as mass points. It is evident from this figure that US 77 and areas immediately to the left and right of the roadway are well defined, while the banks between, and the exterior limits of, each cross-section are jagged and require additional data for an adequate representation of the terrain. Unfortunately, this may be a function of the orientation of the original and interpolated cross-sections.

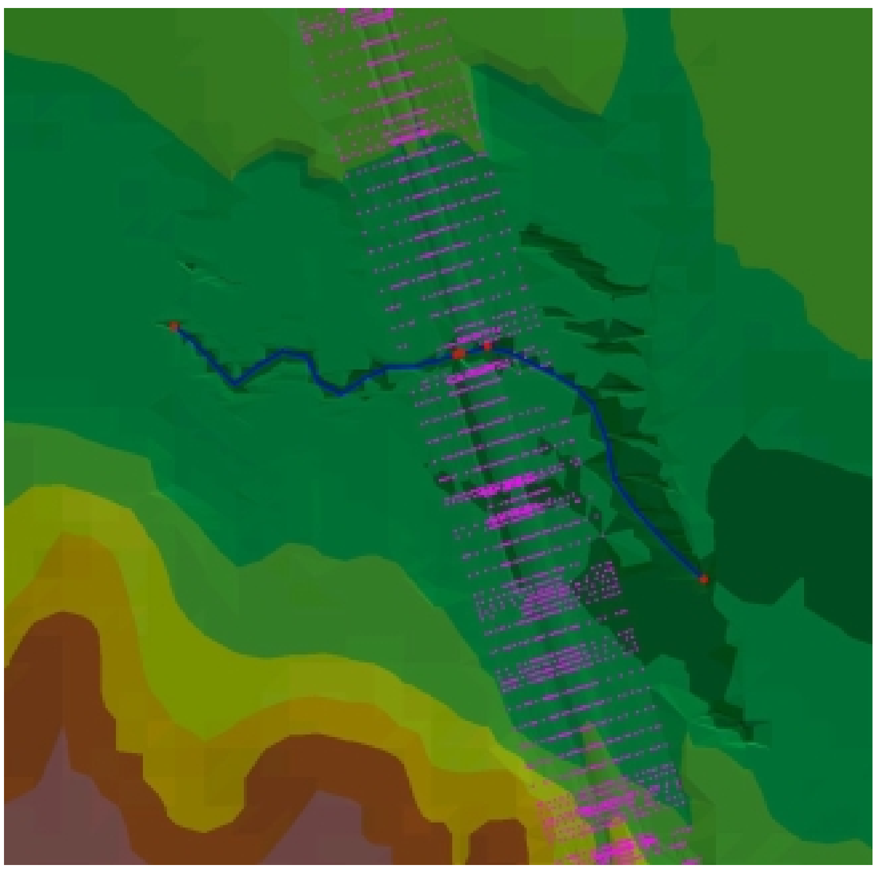


Figure 5-9 TIN Created from CRWR-FloodMap Georeferencing

5.1.2 GIS-BASED HYDROLOGIC PARAMETER EXTRACTION

Because there were no flow gauges available for data calibration in the Castleman Creek watershed, uncontrolled flows (flows modeled without considering the presence of the SCS flood control structures) were to be evaluated prior to generating a hydrologic model with the SCS flood control structures included. Calibration of these uncontrolled flows to the regional regression equations required specifying several different hydrologic parameters and generating a HEC-HMS export file for each scenario. Table 6-8 (Chapter 6) presents a summary of the scenarios evaluated for Castleman Creek.

The SCS curve number method was selected to model rainfall/runoff relationships using a curve number grid (*clipcn*) for the watershed (Figure 5-10) and the SCS unit hydrograph was selected to model routing of the storm through each subbasin.

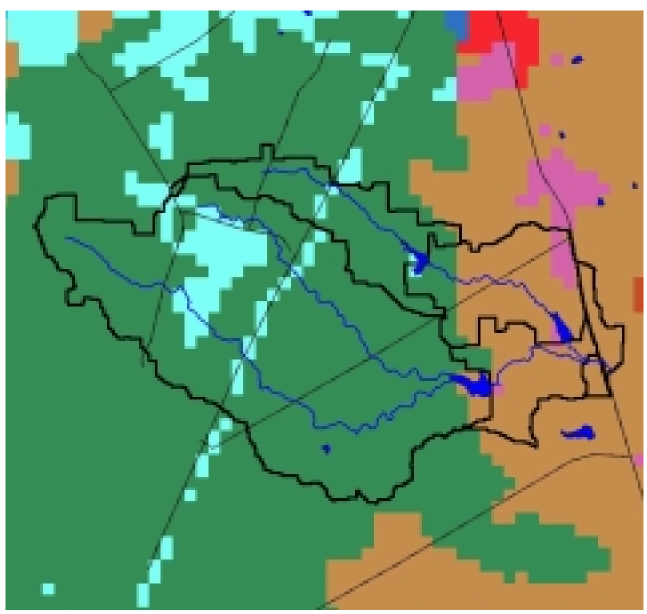


Figure 5-10 Curve Number Grid

In order to calculate the lag time associated with the runoff, a table was created and imported in ArcView GIS that specified average channel flow velocities and Muskingum X parameters for each watershed (Figure 5-11).

vel0_1.txt

Grid_code	Velocity	X
1	0.1	0.2
2	0.1	0.2
3	0.1	0.2
4	0.1	0.2
5	0.1	0.2
6	0.1	0.2
7	0.1	0.2
8	0.1	0.2
9	0.1	0.2
10	0.1	0.2

Figure 5-11 CRWR-PrePro Parameter Table

CRWR-PrePro then calculated a grid for each subbasin defining the downstream flow length (*FldsX*), upstream flow length (*FlusX*), flow length downstream to the watershed outlet (*FldswoX*), flow length upstream to the watershed boundary (*FluswbX*), and longest flow path (*LngfpX*), where X is a sequential number assigned to represent the different modeling scenarios. Figure 5-12 presents the longest flow path calculated for each watershed. The red lines overlaying the dark blue stream network lines represent the longest flow path in each watershed.

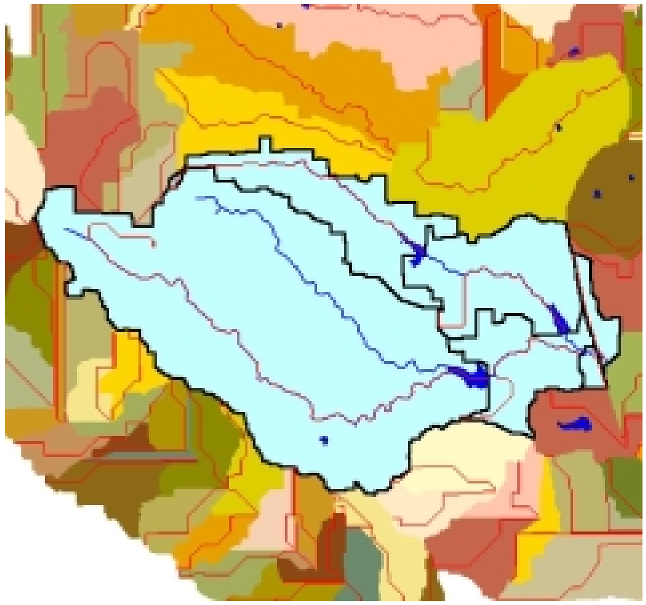


Figure 5-12 Longest Flow Path Grid

Hydrologic parameters were then calculated for each watershed and stream reach, and the following tables were created (Figure 5-13).

Attributes of Wshclp9.shp

Shape	Id	Gridcode	Area	Perimeter	Lngflwpth	Slope	Baseflow	Transform	Lossrate	Curvenum	Initloss	Closrate	Wshvel	Lagtime
Polygon	795	725	6580800.000	23640.000	6879.2544	0.0061	None	SCS	SCS	85.0438	0.0000	0.0000	0.0000	250.0680
Polygon	803	726	6807600.000	15720.000	5096.4678	0.0060	None	SCS	SCS	75.0009	0.0000	0.0000	0.0000	272.0863
Polygon	807	729	932400.000	7320.000	2595.8074	0.0083	None	SCS	SCS	70.0000	0.0000	0.0000	0.0000	154.9723
Polygon	808	728	367200.000	3240.000	1024.2640	0.0189	None	SCS	SCS	70.0000	0.0000	0.0000	0.0000	48.8061
Polygon	815	673	4245300.000	15180.000	4606.1743	0.0078	None	SCS	SCS	71.7157	0.0000	0.0000	0.0000	241.3678
Polygon	825	730	34282800.000	37020.000	14454.0547	0.0052	None	SCS	SCS	85.3981	0.0000	0.0000	0.0000	484.4576

Attributes of Rivclp9.shp

Shape	Arcid	Grid_code	From_node	To_node	Length	Wshcode	Streamvel	Muskx	Route	Muskk	Numreachn	Lagtime	Id
PolyLine	641	647	683	689	701.985	730	0.1	0.2	Muskingum	1.9500	10	0.0000	1
PolyLine	643	653	691	689	178.492	730	0.1	0.2	Muskingum	0.4958	3	0.0000	2
PolyLine	651	637	672	697	4130.879	725	0.1	0.2	Muskingum	11.4747	56	0.0000	3
PolyLine	652	657	698	697	136.066	725	0.1	0.2	Muskingum	0.3780	2	0.0000	4
PolyLine	654	725	697	700	544.264	725	0.1	0.2	Muskingum	1.5118	8	0.0000	5
PolyLine	667	726	700	717	4262.864	726	0.1	0.2	Muskingum	11.8413	57	0.0000	6
PolyLine	669	662	717	719	651.838	673	0.1	0.2	Muskingum	1.8107	9	0.0000	7
PolyLine	670	728	719	720	349.706	728	0.1	0.2	Muskingum	0.9714	5	0.0000	8
PolyLine	675	729	720	725	356.985	729	0.1	0.2	Muskingum	0.9916	5	0.0000	9
PolyLine	676	654	689	726	7694.773	730	0.1	0.2	Muskingum	21.3744	103	0.0000	10
PolyLine	677	673	727	719	2610.366	673	0.1	0.2	Muskingum	7.2510	35	0.0000	11
PolyLine	678	685	728	727	93.640	673	0.1	0.2	Muskingum	0.2601	2	0.0000	12
PolyLine	679	684	729	727	174.853	673	0.1	0.2	Muskingum	0.4857	3	0.0000	13
PolyLine	680	730	726	729	866.985	730	0.1	0.2	Muskingum	2.4083	12	0.0000	14
PolyLine	689	666	694	739	9038.301	730	0.1	0.2	Muskingum	25.1064	121	0.0000	15
PolyLine	690	683	739	726	3264.335	730	0.1	0.2	Muskingum	9.0676	44	0.0000	16
PolyLine	693	694	741	739	75.000	730	0.1	0.2	Muskingum	0.2083	2	0.0000	17

Figure 5-13 CRWR-PrePro Attribute Table for Each Hydrologic Element

These parameters were calculated for the entire watershed and its associated reaches, after which the subbasins and reaches of interest were clipped out to minimize the size of the HEC-HMS basin export file. CRWR-PrePro then created four themes (*HydrolX.shp*, *HydropX.shp*, *SymlX.shp*, and *SympX.shp*) that defined the connectivity of each hydrologic element for export to HEC-HMS as a *.basin* file (Figure 5-14).

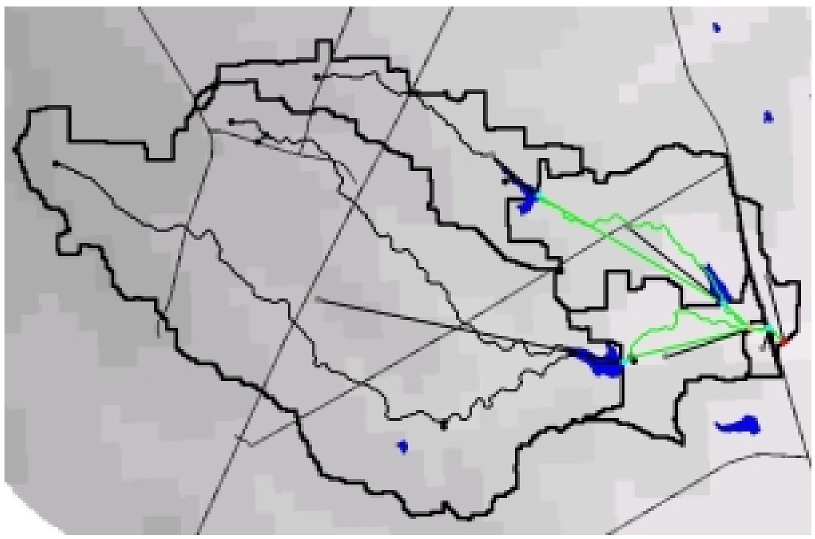


Figure 5-14 CRWR-PrePro HEC-HMS Schematic

5.1.3 GIS-BASED HYDRAULIC GEOMETRY EXTRACTION

The HEC-GeoRAS *preRAS* menu was used to extract hydraulic cross-section geometry data from the TIN created using CRWR-FloodMap methodology. A stream centerline theme was defined using existing NHD network files (*Stream.shp*) and the river and reach names identified using the *River ID* tool. The bankline and flowpath themes (*Banks.shp* and *Flowpath.shp*) were then created manually by estimating the location of the right and left banks and overbank flowlines based on the TIN. The orientation of each flowline was specified by using the *Flowpath ID* tool. Finally, cross-section cut lines were manually added to the model (*xscutlines.shp*) and the direction verified to ensure they proceeded from the left bank to the right bank looking downstream. Figure 5-15 presents these themes.

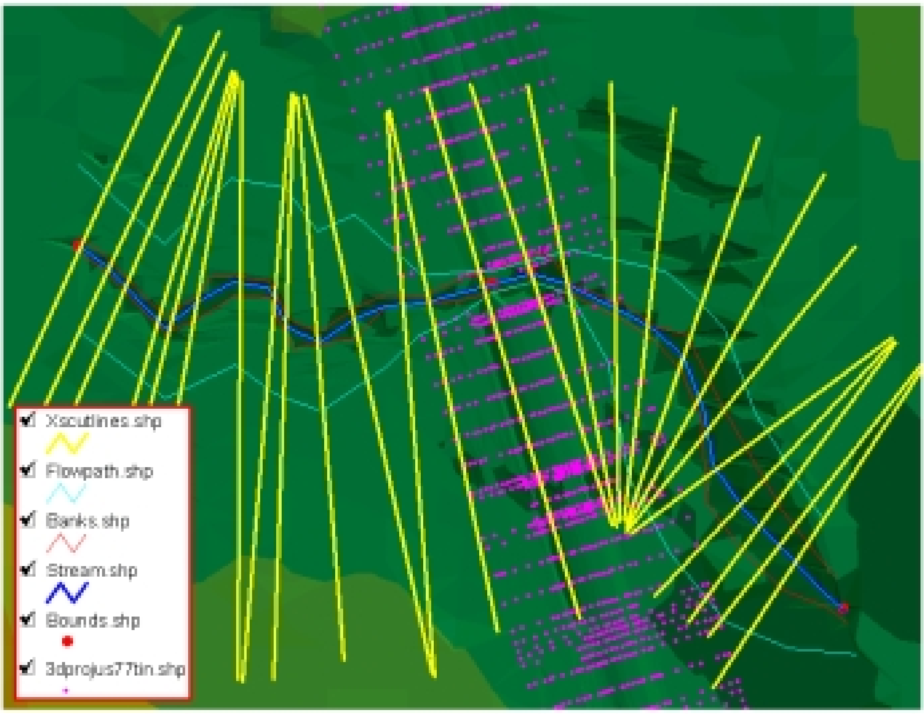


Figure 5-15 HEC-GeoRAS preRAS Themes

Geometric data was then extracted from each theme to adequately define a hydraulically correct model for export to HEC-RAS – a 3D stream centerline was created (*Stream3dgeo.shp*) along with a 3D cross-section cut line theme (*Xscutlines3dgeo.shp*). Once processing was finished, the RAS GIS Import file was specified. Figure 5-16 presents a summary of the themes and files created from the HEC-GeoRAS *preRAS* menu.

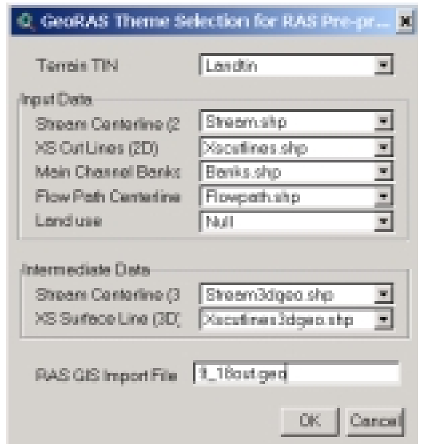


Figure 5-16 HEC-GeoRAS Theme Selection Menu

5.1.4 Hydrologic Modeling

The first step in HEC-HMS is the import of the *.basin* file created by CRWR-PrePro. As discussed previously, several scenarios were imported into HEC-HMS for hydrologic modeling. Figure 5-17 presents a summary of the basin models utilized, as well as the six different precipitation events modeled.

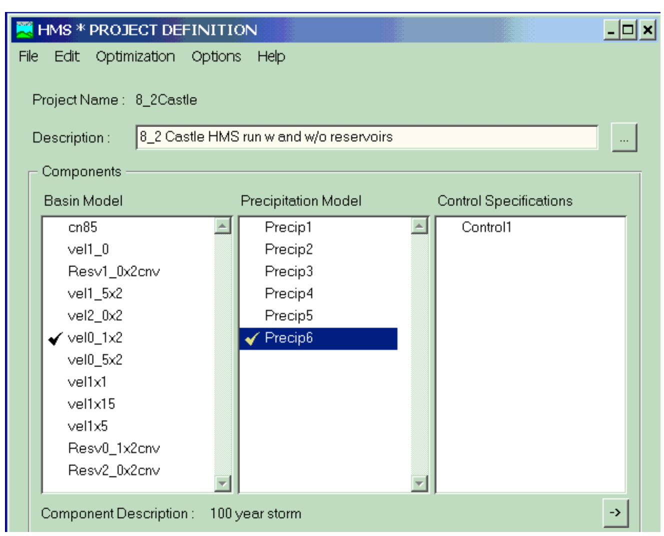


Figure 5-17 HEC-HMS Project Definition

The HEC-HMS *Subbasin Editor* was then activated to depict a schematic of the watershed for each scenario (Figure 5-18). This editor permitted the user to edit the selected loss rate, transform, and baseflow parameters.

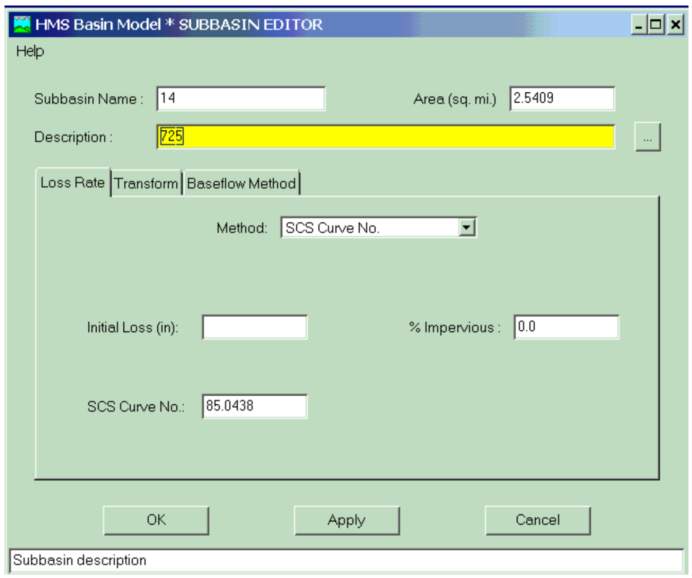


Figure 5-18 HEC-HMS Subbasin Editor

Figure 5-19 presents an example of the HEC-HMS schematic developed for a channel velocity of 0.1 m/s and a Muskingum X of 0.2.

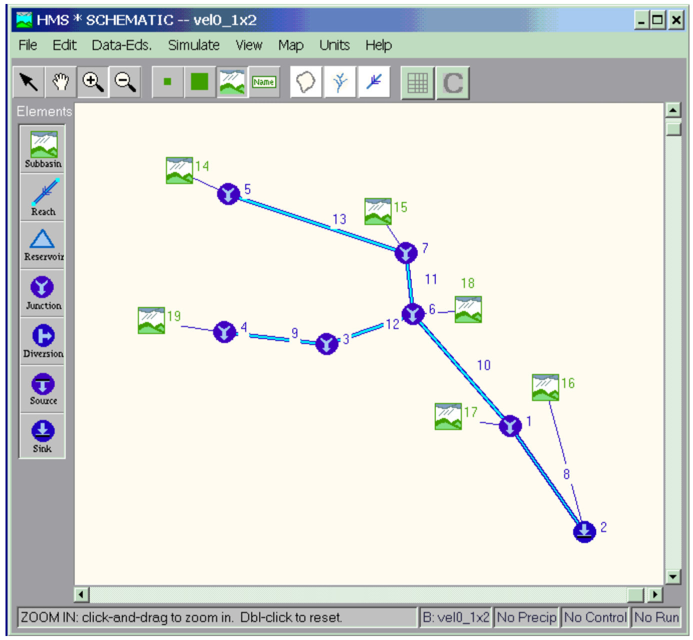


Figure 5-19 HEC-HMS Schematic

CRWR-PrePro defines the minimum Muskingum K as the time step (in this case 5 minutes), while HEC-HMS defines the minimum Muskingum K as 0.1 hrs, so any values of **K** falling between 5 and 6 minutes caused errors in two reaches in HEC-HMS. These reaches were edited to transform the hydrograph based on a lag time of:

$$\text{Lag time (min)} = (K(\text{hrs}) * 60) \qquad \textbf{Equation 5-1}$$

This editing was accomplished in the *Subbasin Editor* under the *Transform* tab (Figure 5-20).

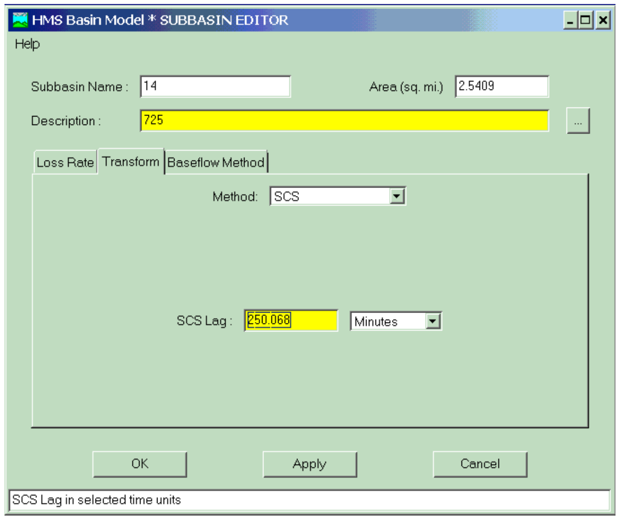


Figure 5-20 HEC-HMS Transform Parameter Editor

The precipitation data used in this model was derived from an existing HEC-1 model developed by TxDOT. Six SCS Type 2 storms were modeled: 2, 5, 10, 25, 50, and 100-year precipitation events. The data was entered as a *User-Specified Hyetograph* under the *Precipitation Model* component of the HEC-HMS *Project Definition* view. Cumulative precipitation depths were entered manually as shown in Figure 5-21. Each hyetograph was then specified for each subbasin, dictating a uniform rainfall over the entire watershed. This assumption was deemed valid due to the size of the Castleman Creek watershed. Figure 5-22 shows the application of a unique hyetograph for each subbasin.

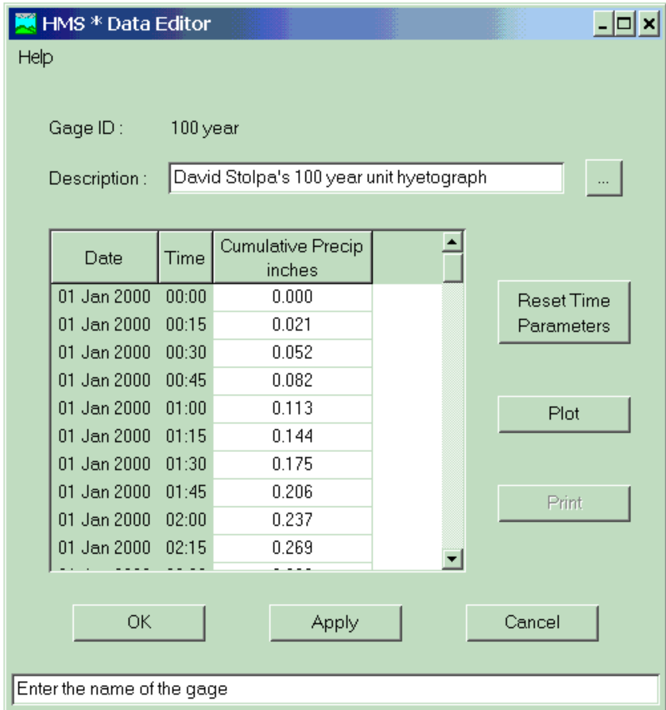


Figure 5-21 HEC-HMS User-Specified Hyetograph Data

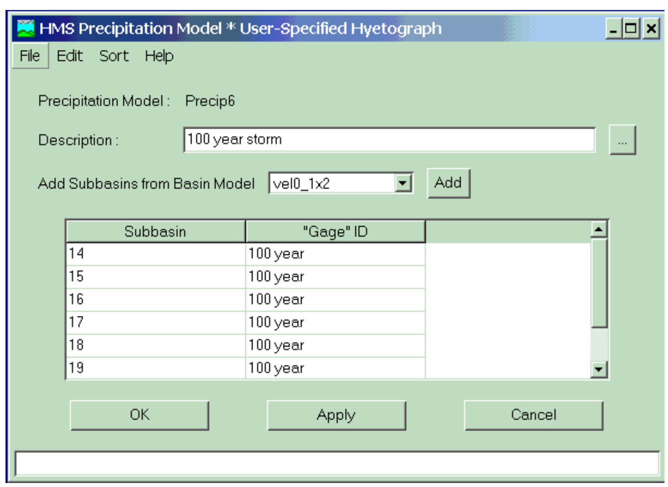


Figure 5-22 Application of Unique Hyetograph for Each Subbasin

The last step in the preparation of the model was the definition of the control specifications (Figure 5-23). For Castleman Creek, all precipitation data was synthetic, so the only items of interest are the selection of the time interval (specified as 10 minutes to match the precipitation data) and the duration of the storm. A duration of 5 days was selected to ensure that the peak flows from the 100-yr design storm would be recorded.

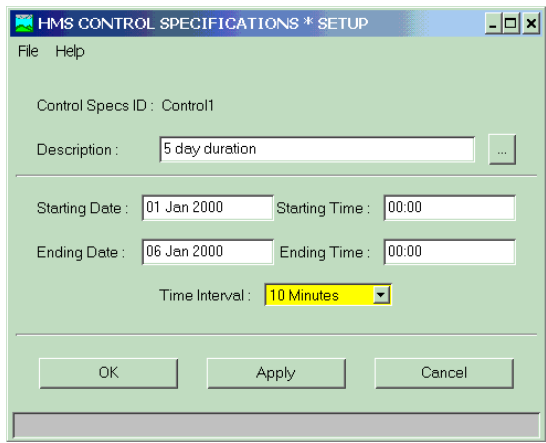


Figure 5-23 HEC-HMS Control Specifications

The *Simulation Manager* was then utilized to select the scenario to be modeled. In Figure 5-24, the 100-yr storm event is selected, with a channel velocity of 0.1 m/s, Muskingum X of 0.2, spatially averaged curve number (based on the curve number grid), and no reservoirs specified.

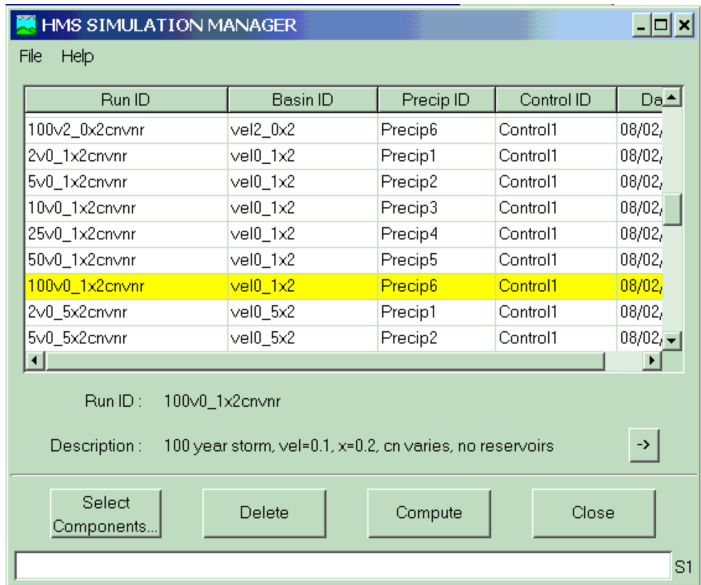


Figure 5-24 HEC-HMS Simulation Manager

Once the computations were complete, a flow hydrograph was generated for the US 77 Bridge (Figure 5-25).

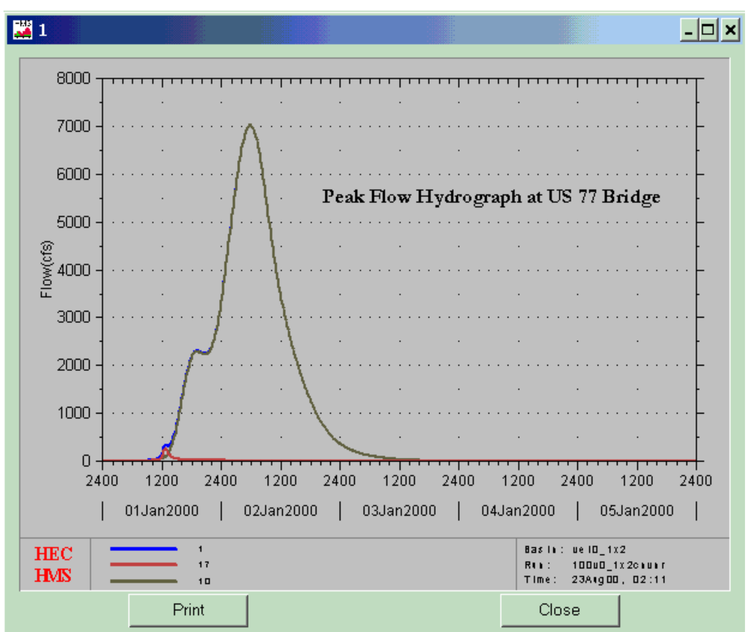


Figure 5-25 Example of Discharge Hydrograph at US 77 Bridge

5.1.5 HYDRAULIC MODELING

The *9_18out.geo* file created in ArcView using the HEC-GeoRAS *preRAS* menu was imported into HEC-RAS as shown in Figure 5-26.

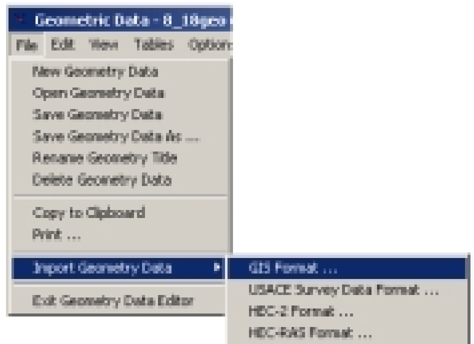


Figure 5-26 Importing GIS Data into HEC-RAS

Unfortunately, the import process does not import any hydraulic structure data, so the bridge data available in the original TxDOT HEC-RAS model was copied to the new HEC-RAS model. Because the original cross-sections had different lengths than the cross-sections derived from HEC-GeoRAS, the upstream and downstream bounding cross-sections for the US 77 Bridge were edited manually to reflect the original data within each channel. Elevation data outside of the banks was maintained to reflect the HEC-GeoRAS terrain data. The location of each bank was also manually edited in HEC-RAS (Figure 5-27) to more accurately reflect the limits of the channel.

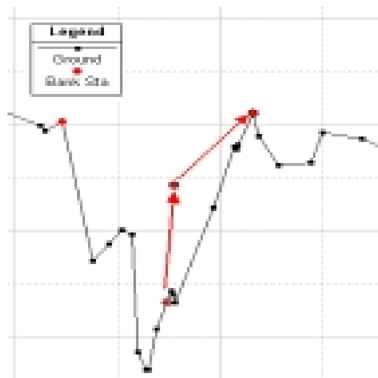


Figure 5-27 Bank Relocation in HEC-RAS

Although HEC-GeoRAS allows the user to define a land use theme to define spatially variable Manning's roughness coefficients, this data was entered manually in HEC-RAS to reflect the values provided with the original TxDOT HEC-1 project files. Manning's *n* values of 0.045 were provided by TxDOT in the channel area, and values of 0.11 for the floodplains on either side of the channel. Figure 5-28 presents a schematic of the imported HEC-GeoRAS cross-sections.

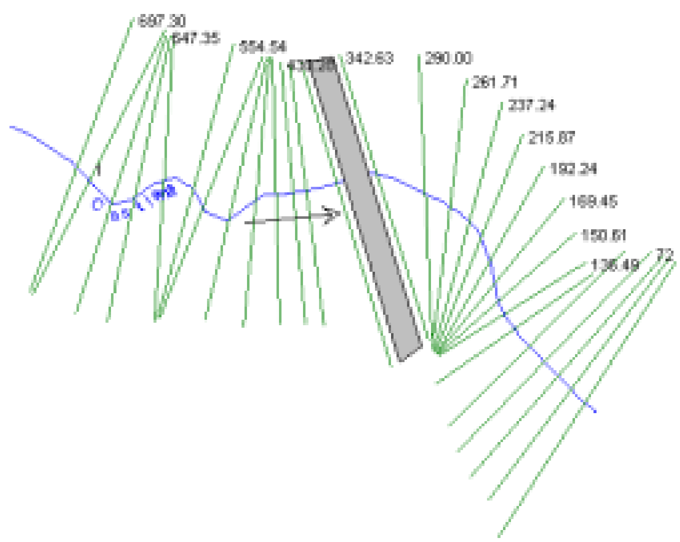


Figure 5-28 HEC-RAS Cross-Section Schematic

Steady flow conditions for the peak flows generated by the HEC-HMS model for each design storm were then specified as shown in Figure 5-29. Boundary conditions were specified to reflect original project conditions.

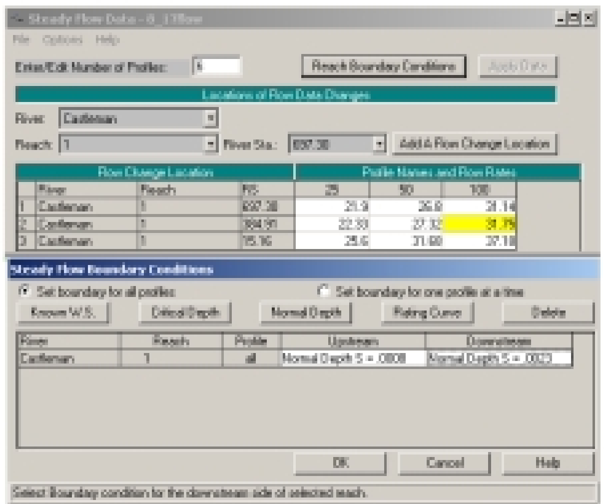


Figure 5-29 HEC-RAS Flow Data Editor

In addition, the peak flows calculated by the TxDOT HEC-1 model were also modeled under the same boundary conditions.At this time, the water surface profiles were generated and an export file created to transfer the data back to GIS (*9_18georas.gis*). These results are presented in Chapter 6.

5.1.6 FLOODPLAIN DELINEATION

Floodplain delineation was accomplished in ArcView GIS with the HEC-GeoRAS *postRAS* menu. The input themes were identified as depicted in Figure 5-30.

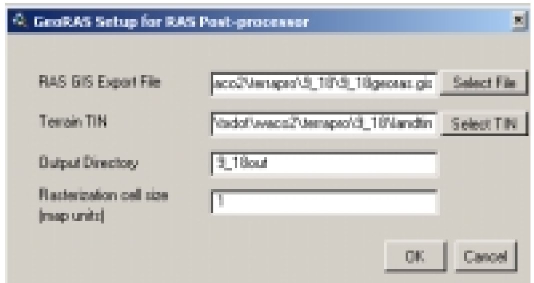


Figure 5-30 HEC-GeoRAS Setup for RAS Post-processor

The rasterization cell size was specified as 1 meter to obtain the best resolution possible in the resulting flood grid. A new view was created in ArcView named *9_18out*, with stream centerline (*9_19out_SN.shp*), cross-section (*9_18outXS.shp*), 3D cross-section (*9_18out_XS3D.shp*), bank (*9_18out_Banks.shp*), and bounding polygon (*BpwXXX.shp*) themes, where XXX is equal to the profiles modeled in HEC-RAS.

Seven water surface TINs (*wstinwXXX*) and floodplain grids (*gdwXXX*), and floodplain polygons (*fdwXXX*) were created in GIS, one for each of the design storm events and one for the peak flow calculated in the TxDOT HEC-1 model. Figure 5-31 presents the floodplain associated with the 100-yr design storm calculated by HEC-HMS. Figure 5-32 presents a three-dimensional representation of the same floodplain.

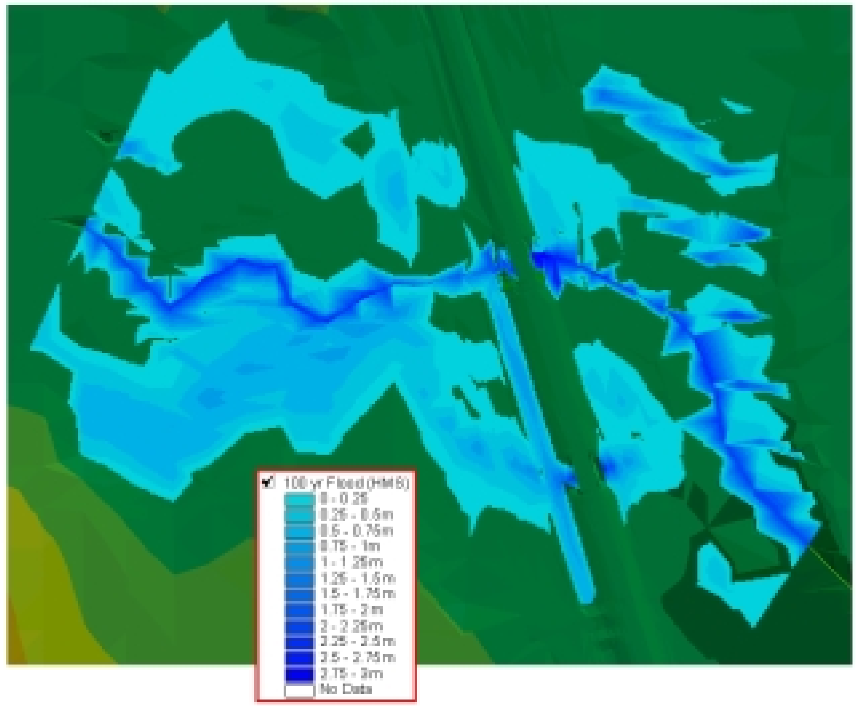


Figure 5-31 Floodplain Grid for 100-year Storm with SCS Flood Control Structures

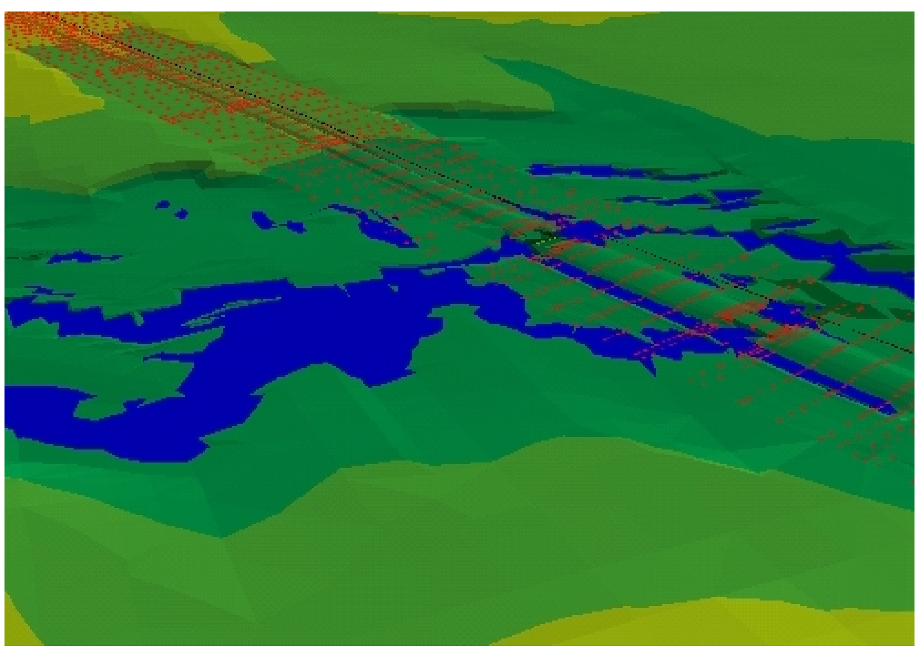


Figure 5-32 3D Representation of 100-year storm event at Castleman Creek

A discussion of the repercussions of the discontinuous nature of the resulting floodplain is presented in Chapter 6.

5.2 Pecan Bayou

The following procedures were implemented at the Pecan Bayou watershed to define the floodplain resulting from an extreme precipitation event in December 1991.

5.2.1 Site Specific Terrain Data Development

The site-specific terrain data development procedure at Pecan Bayou consisted of similar methodology to that presented for the Castleman Creek watershed.

5.2.1.1 Terrain Development for Hydrologic Analysis

Figure 5-33 presents a summary of the terrain development procedure at Pecan Bayou; some steps have been left out for clarity. The edited NHD stream network was burned (*Burned_Bufgrid*) into the clipped and projected DEM and the sinks filled (*Fill*). This was followed by the creation of a flow direction grid (*Fdr*), which was followed by a flow accumulation grid (*Facc*). A stream segment grid was derived (*Strm*) next, followed by the creation of an additional stream polyline (*Addlines.shp*). A modified stream grid was then created (*modstrm*), along with a link grid (*Link*) to identify the unique links along the stream centerline. The outlets to each link were identified (*Out*) in the raster domain, at which point additional outlets were identified, as a point shapefile, to represent the location of three bridges in the watershed (US 183, Hawkins St., and FM 2126) (*AddAsCentrdOutlets.shp*). Modified grids were then created for the new links (*Modlnk*) and outlets (*Modout*). From this data, subbasins were delineated in the raster domain (*Shedgrid*). The last step in this process involved the creation of a polygon theme to represent the subbasins (***Watpoly.shp***) and stream segments (***Rivline.shp***). Watershed polygons were then merged to minimize the number of subbasins to be exported to HEC-HMS.

5.2.1.2 Terrain Development for Floodplain Delineation

The TIN developed for floodplain delineation at this site was derived from HEC-RAS cross-sections and digital terrain data in the form of a elevation contour data supplied by the City of Brownwood in Microstation® format along with DEM data.

The HEC-RAS cross-sections provided by the Corps Ft. Worth district included cross-sections from Lake Brownwood to the confluence of Pecan Bayou with the Colorado River. The first step was to remove the cross-sections lying outside the limits of the study area. Once this was accomplished, cross-sections were interpolated using the methodology described previously.

Figure 5-34 presents a comparison of the original HEC-RAS project cross-sections to those interpolated in this model. The right side of the figure is the original cross-sections and the left depicts the significant number of interpolated cross-sections necessary to adequately define the stream centerline in the GIS domain.

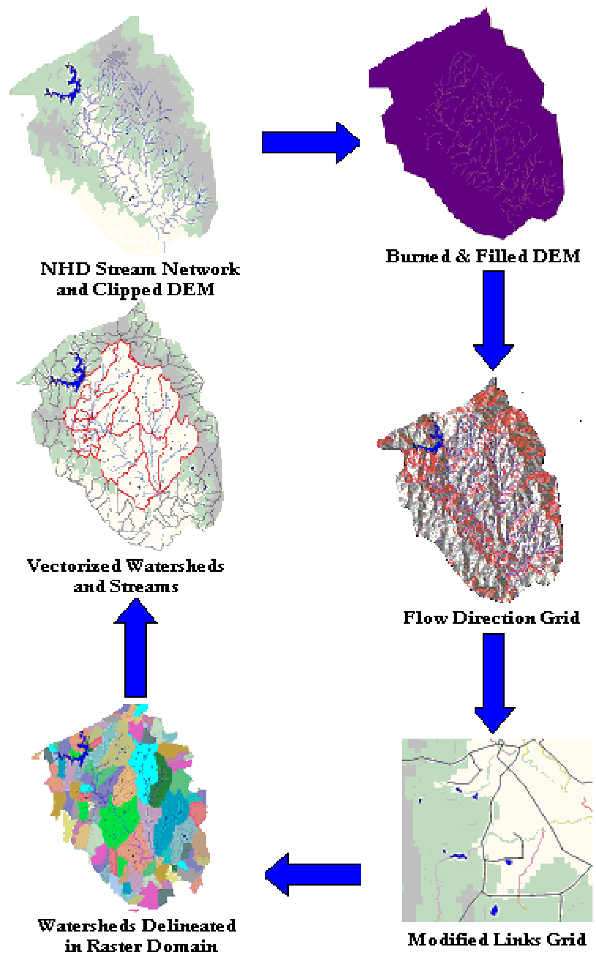


Figure 5-33 Summary of CRWR-PrePro Terrain Development for Hydrologic Analysis at Pecan Bayou

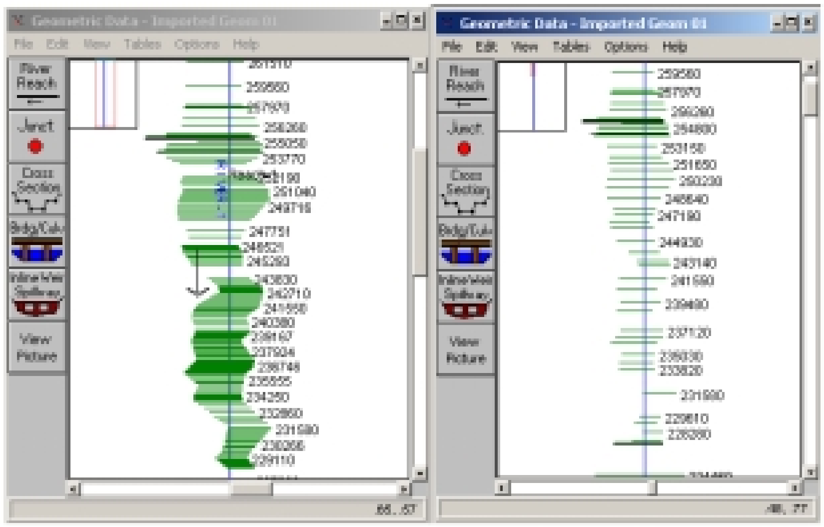


Figure 5-34 Addition of Interpolated Cross-Sections to Pecan Bayou Model

Once the cross-sections were developed, the geometric data was exported to a text file where it was imported into GIS using CRWR-FloodMap. A digital stream was derived (*Pecan.shp*) from a stream centerline digitized from the Microstation® contours (the NHD network files were not detailed enough to represent the tortuous nature of Pecan Bayou as it proceeds through the east side of the City of Brownwood). The bounding locations were specified (*bounds.shp*) and the cross-sections imported into the view (*terrain3d9_19.shp*) (Figure 5-35). The orientation of each cross-section was entered manually to attempt to define the channel adequately. Fortunately, the Microstation® contours provided excellent topographic relief almost down to the stream centerline. Therefore, once the 3D stream centerline (*Stream3d9_19.shp*) was created, it was the only data needed to finalize the channel geometry. In this figure, the red lines represent the cross-section data, the dark blue line the 3D stream theme, and the light blue lines the contour data.

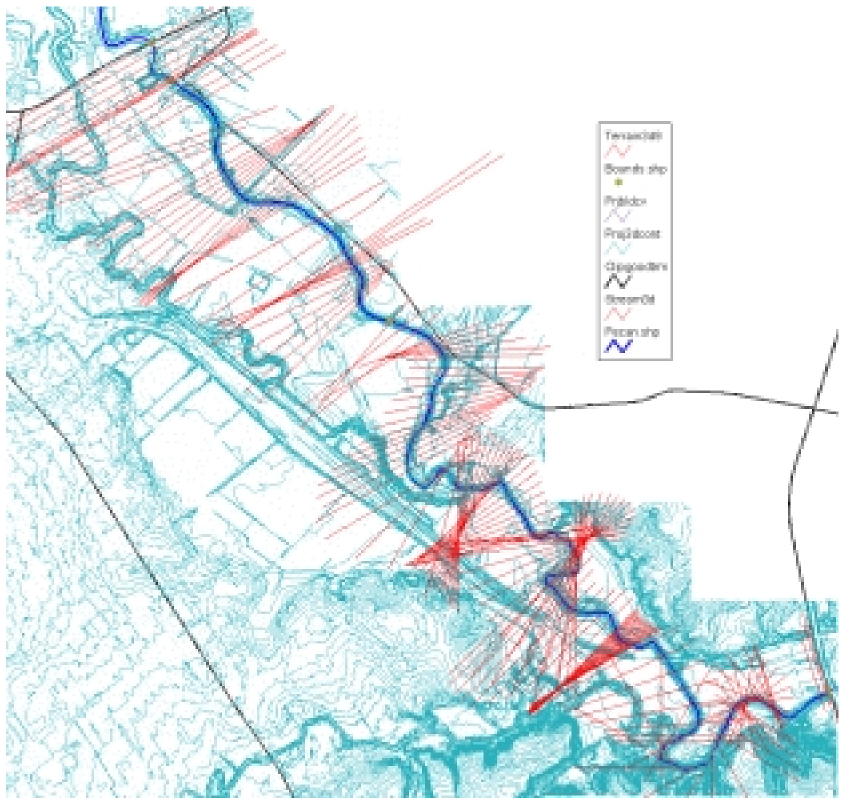


Figure 5-35 Cross-Sections Imported in Pecan Bayou GIS Model Using CRWR-FloodMap

The surrounding terrain was developed from the 152 Microstation® drawings provided by the City of Brownwood. Each drawing was imported into ArcView, where it appeared as a coverage with point, line, polygon, and annotation themes (Figure 5-36).

Figure 5-36 Microstation® Drawing Coverage

All of the line themes associated with each drawing were extracted as a separate theme in ArcView and then queried by elevation to remove any lines with elevation attributes equal to zero. Similarly, each polygon theme was added to ArcView and queried by the *Layer* attribute to select the polygons identified as buildings. A standard color scheme (which was specified in the *Layer* attribute) was provided by the City of Brownwood that differentiated the different types of lines and polygons in each drawing. New themes were then created for each of the drawings comprised of the desired lines and polygons. The *mrgthmcl* script, available as a sample script with ESRI ArcView GIS software, was used to merge all 152 line and polygon themes to create one contour theme (*contour*) and one building (*Theme6*) coverage.

The contour theme was projected in ArcInfo from the Texas State Mapping System Central zone to the projection specified in Chapter 2 (*projcont*). The building coverage required additional processing in ArcInfo:

```
Shapearc Theme6.shp Bldgcov
Project Bldgcov Prjbldcv
Regionclass Prjbldcv prjbldrg sub elevation
Clean Prjbldrg Prjbldrg # # Poly
```

The contour data was converted to a 3D shapefile in ArcView using the *Elevation* attribute (converted from English to Metric units) as the source of the three-dimensional data. Although the extents of these contours defined the main Pecan Bayou channel sufficiently, they did not provide adequate data for the overbanks east of the channel (see Figure 5-35 above). A NED DEM was clipped (*clipdem*) to cover the areas not defined (Figure 5-37), and the two data sets mosaiced to minimize discontinuity between the two data sources.

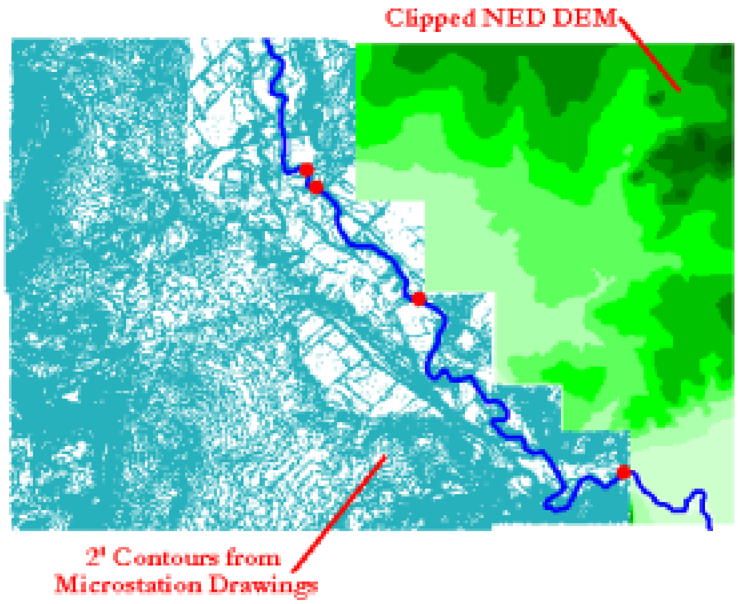


Figure 5-37 NED DEM Appended to Contour Data

Elevation contours were derived from *clipdem* and, with a 3D stream centerline defined, a preliminary TIN was generated. Once this preliminary TIN was developed, the last step in the development of the terrain data for Pecan Bayou was the integration of the building themes into the TIN. The building theme (*prjbldrg*) was converted to a 3D theme using the surface of the preliminary TIN to define the three-dimensional data (*9_193dbldg.shp*). The *BuffElev* script was then used to create the roof of each building. The script duplicates the shape of the original building footprint, but decreases the size of the footprint to create a surface that can be represented as a TIN (a vertical surface cannot be represented as a TIN) as shown in Figure 5-38.

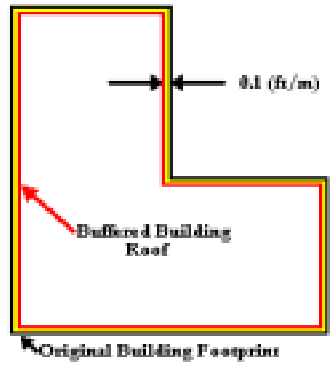


Figure 5-38 BuffElev Script Methodology

The elevation of this buffered theme (*Buffer.shp*) was manually entered as a value greater than every point in the TIN. This created unrealistically tall buildings, but was sufficient to integrate the building theme into the TIN. Figure 5-39 provides a summary of the data used to generate the Pecan Bayou terrain TIN.

Figure 5-39 Terrain Data Utilized to Generate Pecan Bayou TIN

The resulting TIN is depicted in Figure 5-40 – note the building integrated into the TIN surface west of Pecan Bayou. The blue line depicts the 3D stream centerline theme used to define the channel elevation.

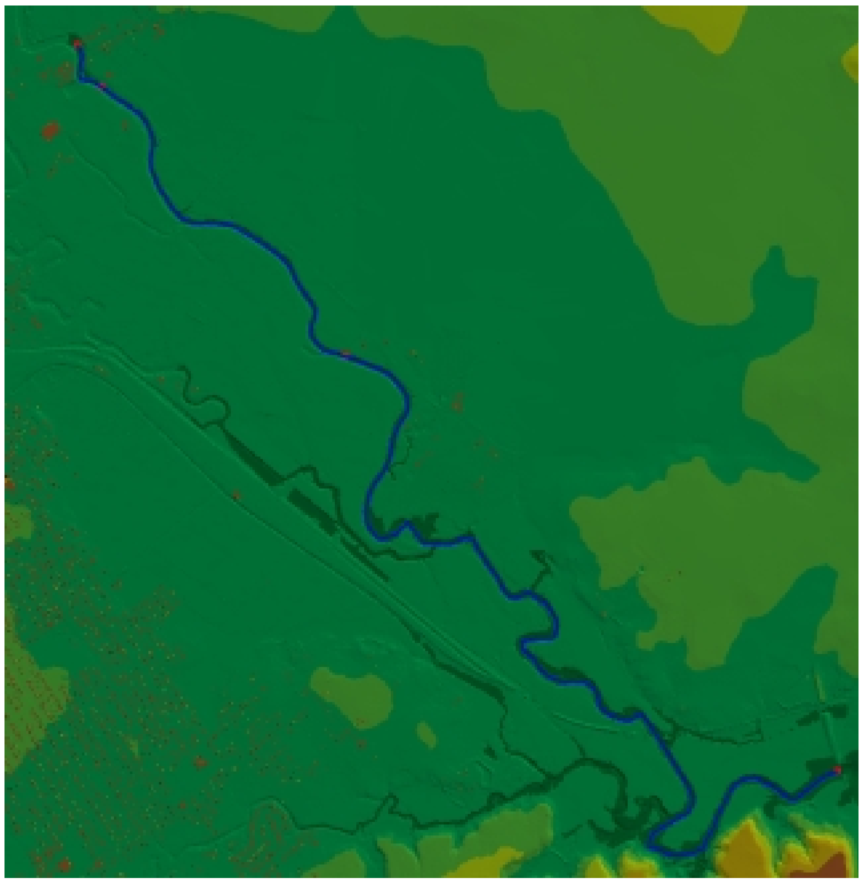


Figure 5-40 Pecan Bayou Terrain TIN

5.2.2 GIS-BASED HYDROLOGIC PARAMETER EXTRACTION

Hydrologic parameters at the Pecan Bayou site were extracted using the same methodology implemented at Castleman Creek. However, because of the presence of the USGS gage site, only one event was modeled, so only one set of parameters was extracted from GIS for use in HEC-HMS.

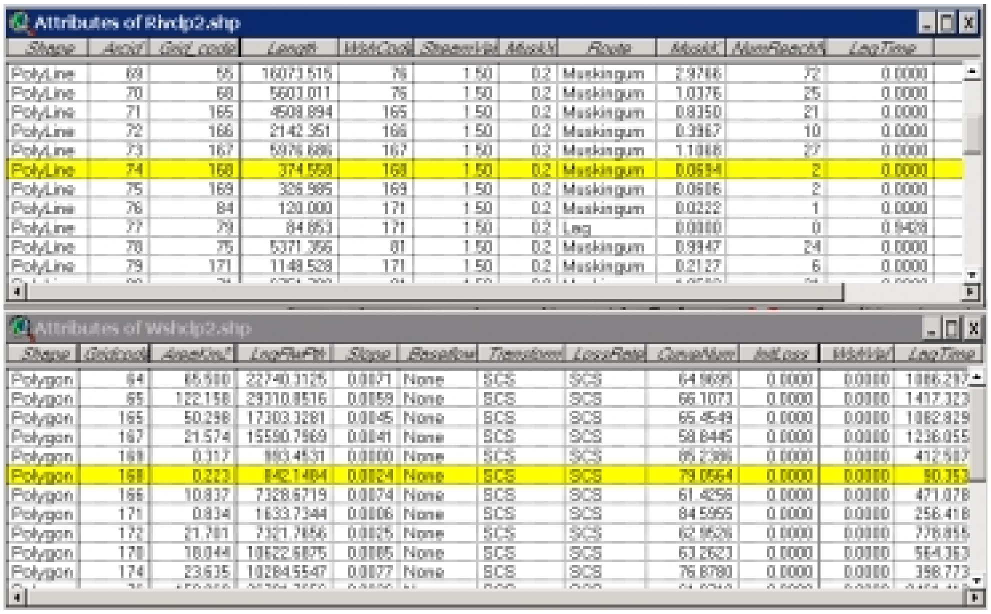
The SCS curve number method was also selected at this site to model rainfall/runoff relationships using a curve number grid (*TX_cngrid*) for the watershed and the SCS unit hydrograph was selected to model routing of the storm through each subbasin. In order to calculate the lag time associated with the runoff, a table was created and imported in ArcView GIS that specified average channel flow velocities and Muskingum X parameters for each watershed (Figure 5-41).

streamp(7_30).txt

Grid_code	Velocit	X
1	1.00	0.2
2	1.00	0.2
3	1.00	0.2
4	1.00	0.2
5	1.00	0.2
6	1.00	0.2
7	1.00	0.2
8	1.00	0.2
9	1.00	0.2
10	1.00	0.2
11	1.00	0.2

Figure 5-41 CRWR-PrePro Parameter Table for Pecan Bayou

Here, the channel velocity was assumed to be 1 m/s and the Muskingum X equal to 0.2. CRWR-PrePro then calculated a grid for each subbasin defining the downstream flow length (*Flds*), upstream flow length (*Flus*), flow length downstream to the watershed outlet (*Fldswo*), flow length upstream to the watershed boundary (*Fluswb*), and longest flow path (*Lfp*). Hydrologic parameters were then calculated for each watershed and stream reach, and the following tables were created (Figure 5-42).



Attributes of Rivdp2.shp

Shape	Arcid	Grid_code	Length	WshCode	StreamVel	MuskX	Route	MuskK	NumReach	LagTime
PolyLine	69	55	16073.515	76	1.50	0.2	Muskingum	2.9766	72	0.0000
PolyLine	70	68	5603.011	76	1.50	0.2	Muskingum	1.0376	25	0.0000
PolyLine	71	165	4508.894	165	1.50	0.2	Muskingum	0.8350	21	0.0000
PolyLine	72	166	2142.351	166	1.50	0.2	Muskingum	0.3967	10	0.0000
PolyLine	73	167	5976.686	167	1.50	0.2	Muskingum	1.1068	27	0.0000
PolyLine	74	168	374.558	168	1.50	0.2	Muskingum	0.0694	2	0.0000
PolyLine	75	169	326.985	169	1.50	0.2	Muskingum	0.0606	2	0.0000
PolyLine	76	84	120.000	171	1.50	0.2	Muskingum	0.0222	1	0.0000
PolyLine	77	79	84.853	171	1.50	0.2	Lag	0.0000	0	0.9428
PolyLine	78	75	5371.356	81	1.50	0.2	Muskingum	0.9947	24	0.0000
PolyLine	79	171	1148.528	171	1.50	0.2	Muskingum	0.2127	6	0.0000

Attributes of Wshdp2.shp

Shape	Gridcode	AreaKm2	LngFlwPth	Slope	Baseflow	Transform	LossRate	CurveNum	InitLoss	WshVel	LagTime
Polygon	64	65.500	22740.3125	0.0071	None	SCS	SCS	64.9695	0.0000	0.0000	1086.217
Polygon	65	122.158	29310.8516	0.0059	None	SCS	SCS	66.1073	0.0000	0.0000	1417.323
Polygon	165	50.298	17303.3281	0.0045	None	SCS	SCS	65.4549	0.0000	0.0000	1082.829
Polygon	167	21.574	15590.7969	0.0041	None	SCS	SCS	58.8445	0.0000	0.0000	1236.055
Polygon	169	0.317	993.4531	0.0000	None	SCS	SCS	85.2386	0.0000	0.0000	412.507
Polygon	168	0.223	842.1484	0.0024	None	SCS	SCS	79.0564	0.0000	0.0000	90.353
Polygon	166	10.837	7328.6719	0.0074	None	SCS	SCS	61.4256	0.0000	0.0000	471.078
Polygon	171	0.834	1633.7344	0.0006	None	SCS	SCS	84.5965	0.0000	0.0000	256.418
Polygon	172	21.701	7321.7656	0.0025	None	SCS	SCS	62.9526	0.0000	0.0000	778.855
Polygon	170	18.044	10622.6875	0.0085	None	SCS	SCS	63.2623	0.0000	0.0000	564.363
Polygon	174	23.635	10284.5547	0.0077	None	SCS	SCS	76.8780	0.0000	0.0000	398.773

Figure 5-42 CRWR-PrePro Attribute Table for Each Hydrologic Element in Pecan Bayou

These parameters were calculated for the entire watershed and its associated reaches, after which the subbasins and reaches of interest were clipped out to minimize the size of the HEC-HMS basin export file. CRWR-PrePro then created four themes (*Hydrol.shp*, *Hydrop.shp*, *Syml.shp*, and *Symp.shp*) that defined the connectivity of each hydrologic element for export to HEC-HMS as a *.basin* file (Figure 5-43).

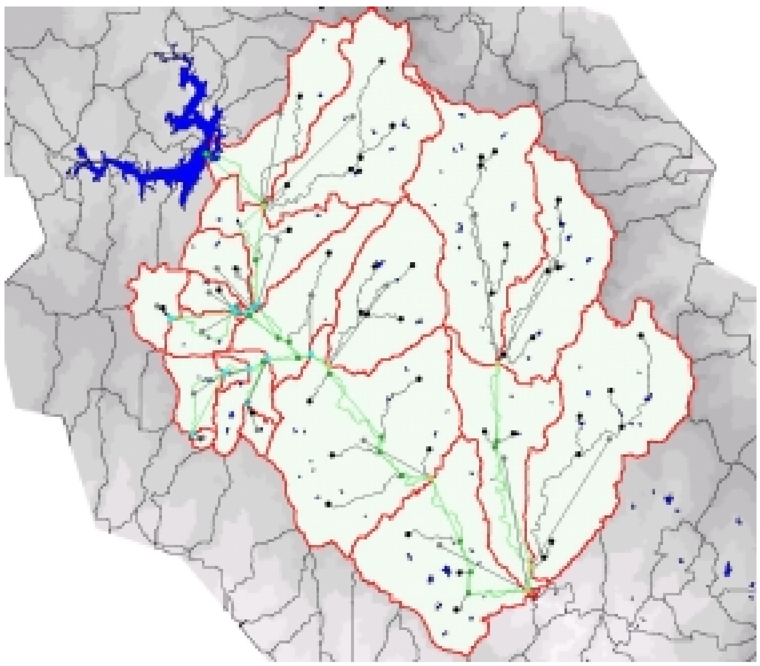


Figure 5-43 CRWR-PrePro HEC-HMS Schematic

5.2.3 GIS-BASED HYDRAULIC GEOMETRY EXTRACTION

The HEC-GeoRAS *preRAS* menu was used to extract hydraulic cross-section geometry data from the Pecan Bayou TIN. A stream centerline theme was defined using digitized stream centerline (*Stream.shp*) and the river and reach names identified using the *River ID* tool. The bankline and flowpath themes (*Banks.shp* and *Flowpath.shp*) were created manually by estimating the location of the right and left banks and overbank flowlines based on the TIN. The orientation of each flowline was specified by using the *Flowpath ID* tool. Cross-section cut lines were then manually added to the model (*xscutlines.shp*) (Figure 5-44).

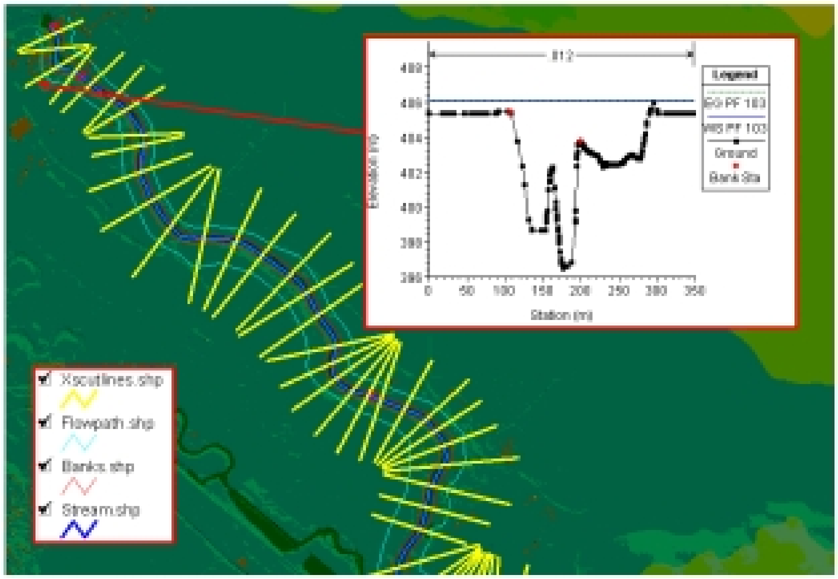


Figure 5-44 Original Pecan Bayou HEC-GeoRAS Cross-Sections

However, after preliminary analysis of the expected water surface profiles generated from existing HEC-RAS runs, wider cross-sections were selected instead of the detailed cross-sections shown in Figure 5-44 above. These cross-sections were placed on areas where there were significant terrain changes, but fewer cross-sections were necessary because the effects of terrain changes were reduced due to the width of the floodplain. The model used the original stream centerline, banklines, and flowpath lines, but new 3D streamlines and cross-sections (*Stream3dwide.shp* and *Xswide3D.shp*) were generated as shown in Figure 5-45.

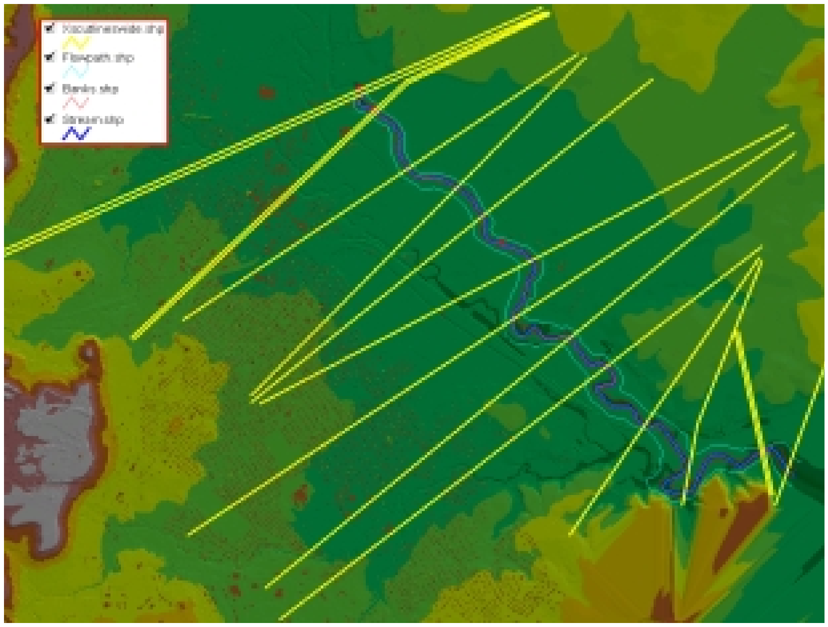


Figure 5-45 Revised HEC-GeoRAS Cross-Sections for Pecan Bayou

A land use theme was also used in this model to determine spatially variable Manning's roughness coefficients. The land use theme (*l_brodtx.shp*) was imported into GIS and a table relating the Anderson Land Use Classification to Manning's *n* was created (Figure 5-46) called *LuManning.dbf*.

lumanning.dbf

Lucode	N_value
33	0.050
31	0.050
43	0.080
21	0.030
42	0.070
32	0.050
22	0.035

Figure 5-46 Pecan Bayou Table Relating Manning's n to Land Use

At this point, the *RAS GIS Import File* was created. The themes exported to HEC-RAS are presented in Figure 5-47.

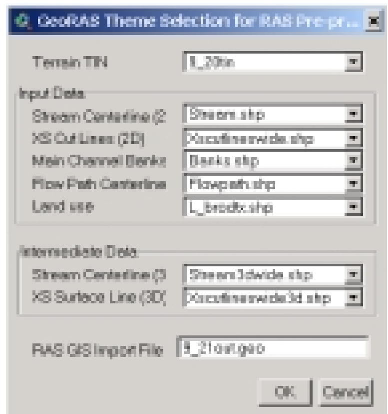


Figure 5-47 HEC-GeoRAS Theme Selection Menu for Pecan Bayou

5.2.4 HYDROLOGIC MODELING

The basic components in HEC-HMS have been discussed in Section 5.1 but the data relevant to each component in Pecan Bayou is much different due to the presence of observed flow at the USGS gage site. Figure 5-48 presents an annotated schematic of the Pecan Bayou watershed, with the major tributaries contributing flow to the watershed identified.

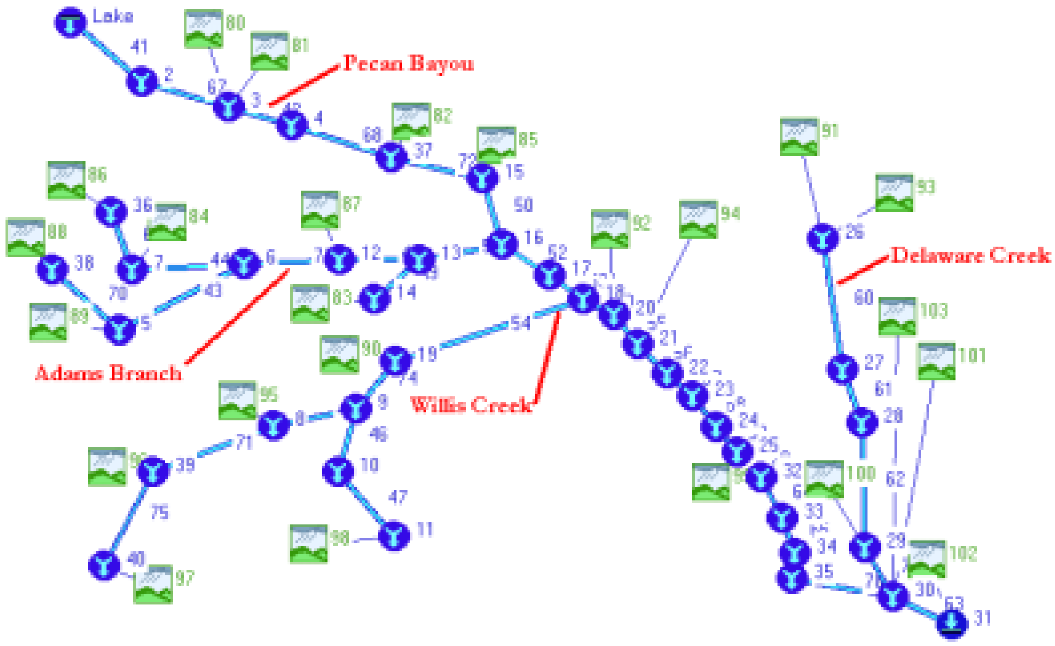


Figure 5-48 HEC-HMS Basin Schematic for Pecan Bayou

Although floodplain delineation activities will only occur between Junctions 37 and 20, the entire watershed was modeled to calibrate the calculated peak flow to the flow data observed at Sink 31 (USGS Gage 08143600).

The precipitation data used in this model was recorded at a NOAA site located southwest of the watershed and was corrected using the aerial reduction factors discussed in Chapter 2. Figure 5-49 presents the *User-Specified Hyetograph* precipitation data used in the Pecan Bayou HEC-HMS model.

Recorded lake elevation data also enabled the calculation of a discharge hydrograph from the Lake Brownwood spillway during the storm period. The peak flow from Lake Brownwood occurred on December 21 at 0900 and measured approximately 30,600 cfs (Figure 5-50).

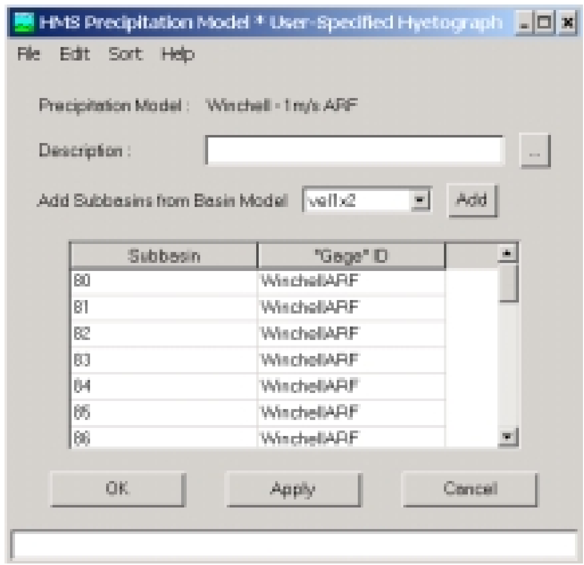


Figure 5-49 User-Specified Hyetograph Precipitation Data

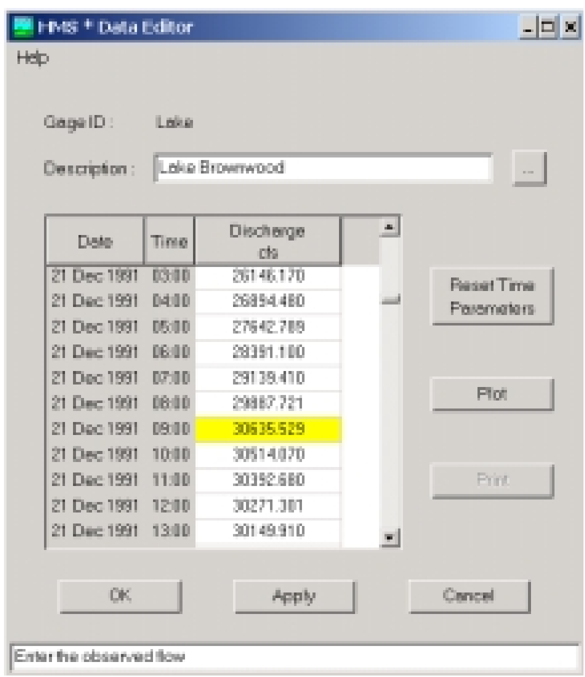


Figure 5-50 Lake Brownwood Spillway Discharge Data

The USGS flow gage data used for calibration is shown in Figure 5-51. The peak flow at this gage occurred on December 22 at 1600 and measured approximately 33,300 cfs. It is evident from this data that the hydrologic response of the Pecan Bayou watershed was largely dictated by the discharge from Lake Brownwood during the Christmas 1991 storm event.

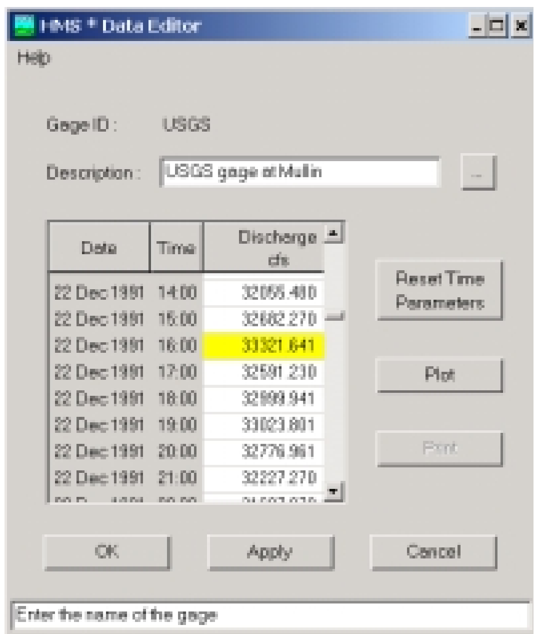


Figure 5-51 USGS Gage 08143600 Recorded Flow Data

The control specifications (Figure 5-52) were selected to span approximately two weeks, with a time interval of one hour selected based on the flow and precipitation available.

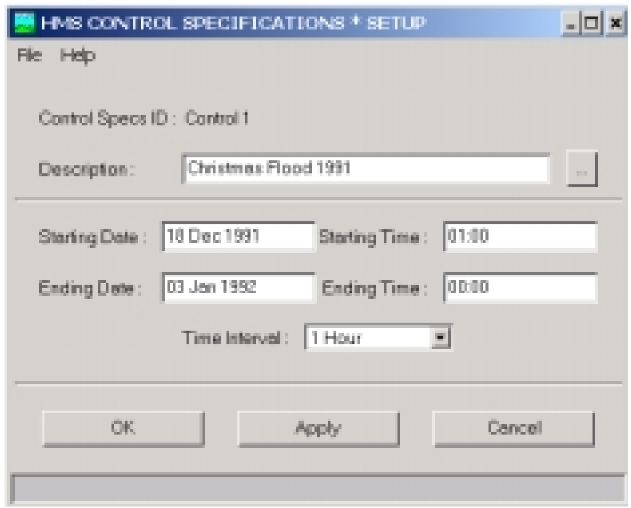


Figure 5-52 Pecan Bayou Control Specifications

Figure 5-53 presents a comparison of the calculated hydrograph at the USGS gage to the observed flow data (the observed data is shown in red).

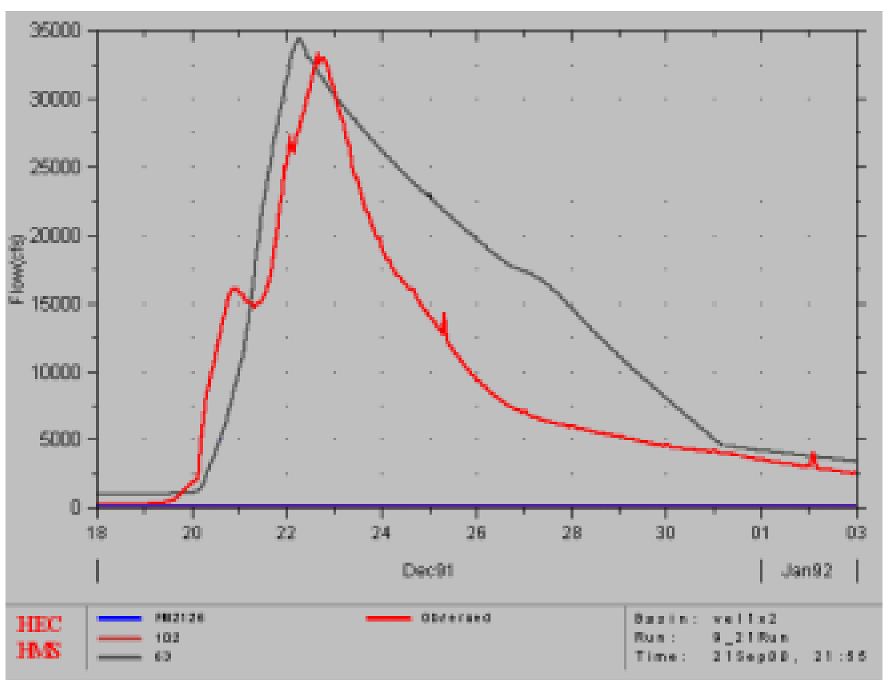


Figure 5-53 Comparison of Calculated and Observed Flow Data at USGS Gage 08143600

The peak flow and time-to-peak data is reasonable considering the quantity of non-continuous data used to model the system. The discrepancy between the flows on the tail of the hydrograph is discussed in Chapter 6. Figure 5-54 presents a tabular summary of the discharge hydrograph at the FM 2126 Bridge (Junction 20).

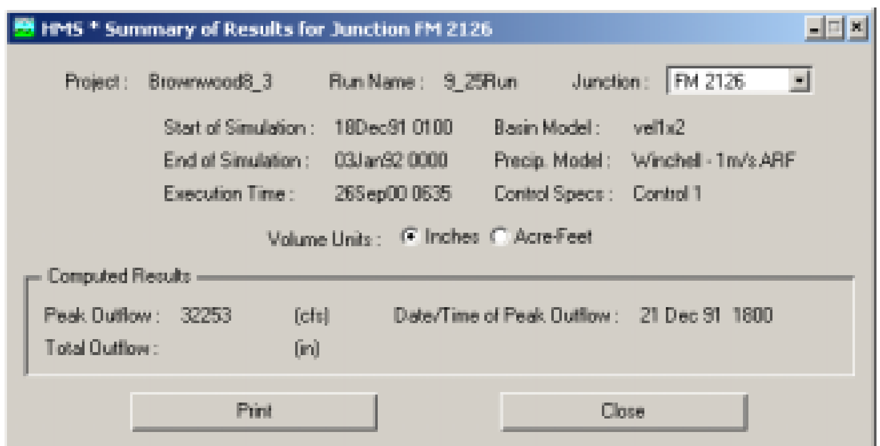


Figure 5-54 Summary Table of Discharge Hydrograph at FM 2126 Bridge

5.2.5 HYDRAULIC MODELING

The *9_21out.geo* file created in ArcView using the HEC-GeoRAS *preRAS* menu was imported into HEC-RAS and the hydraulic structure data copied from the existing HEC-RAS model created by the Corps Ft. Worth district. Difficulties arose in determining the elevation of the road surface at each bridge since many of the cross-sections had building data incorporated into the TIN (Figure 5-55).

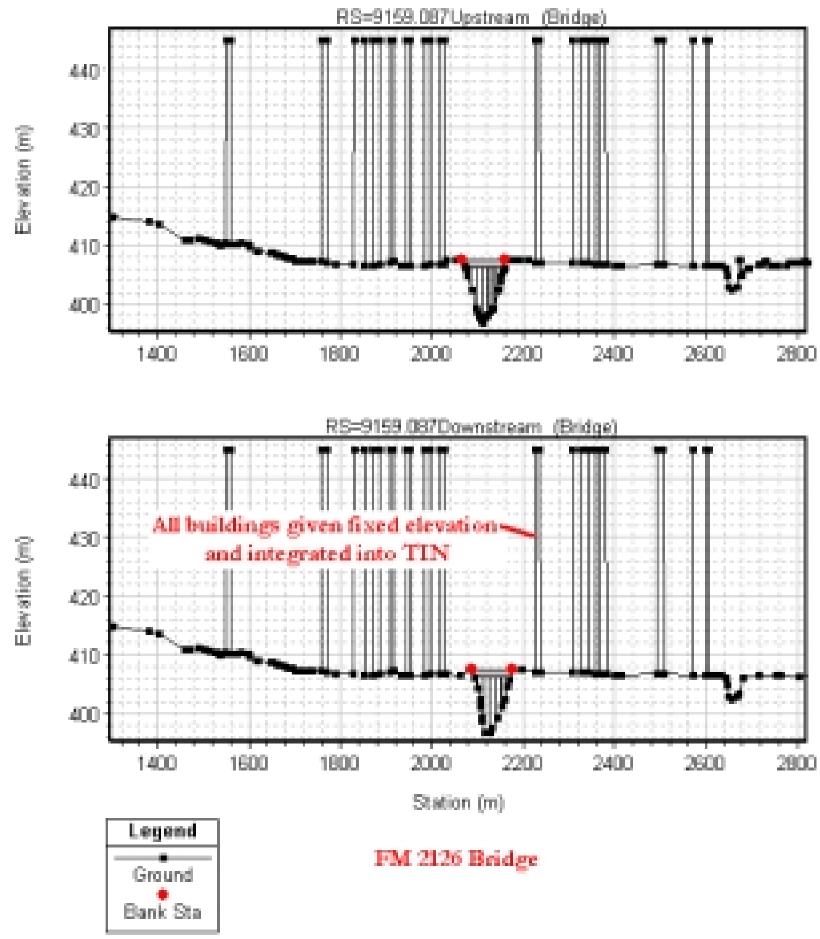


Figure 5-55 HEC-RAS Bridge Cross-Sections with Building Data Incorporated into the TIN

The road surface elevations extracted from the original HEC-RAS model were extended outside of the channel until they intersected a building, at which point the terrain TIN cross-section data became the controlling elevation data. Fortunately, no bridges were overtopped by the flows generated, and this decision did not affect the outcome of the hydraulic modeling. All bridge cross-section data was verified with bridge as-built drawings and scour inspection data. Figure 5-56 presents a schematic of the cross-sections extracted from GIS using the HEC-GeoRAS *preRAS* menu.

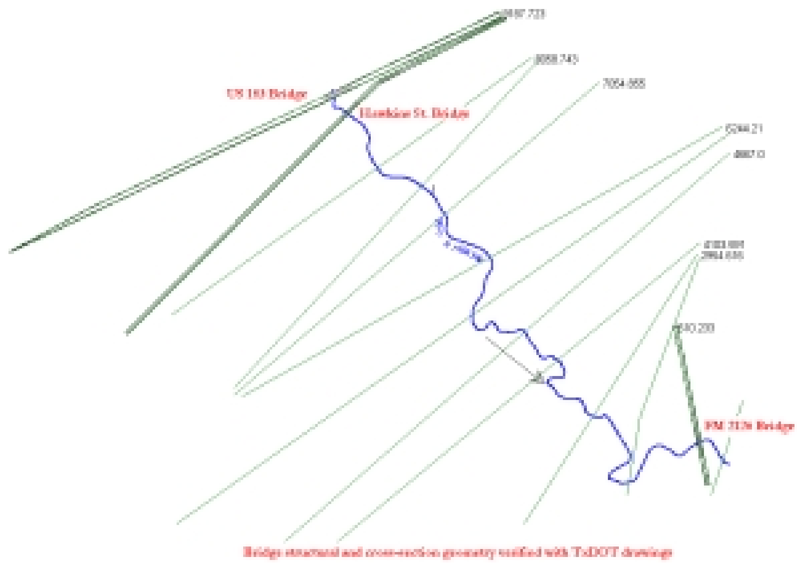


Figure 5-56 HEC-RAS Cross-Section Schematic for Pecan Bayou

Flow data was extracted from the HEC Data Storage System (HEC-DSS) file generated during hydrologic modeling (Figure 5-57).

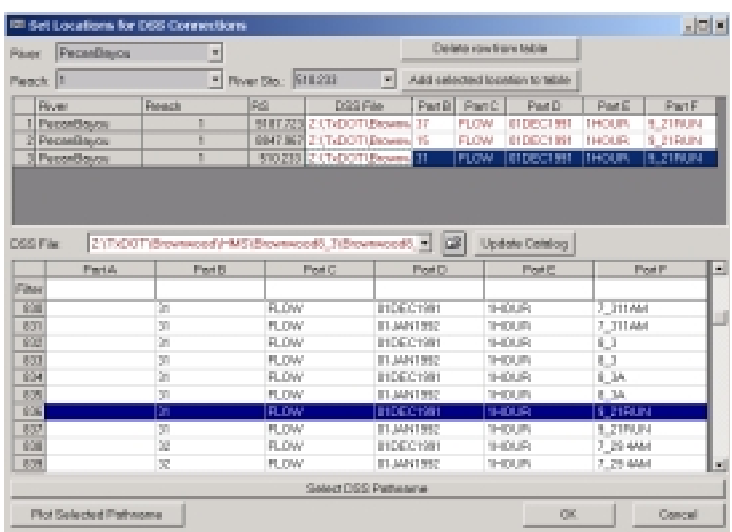


Figure 5-57 Extraction of Flow Data from HEC-DSS for Pecan Bayou

Hourly flow profiles were created for the two weeks modeled, resulting in a total of 323 flow profiles (Figure 5-58).

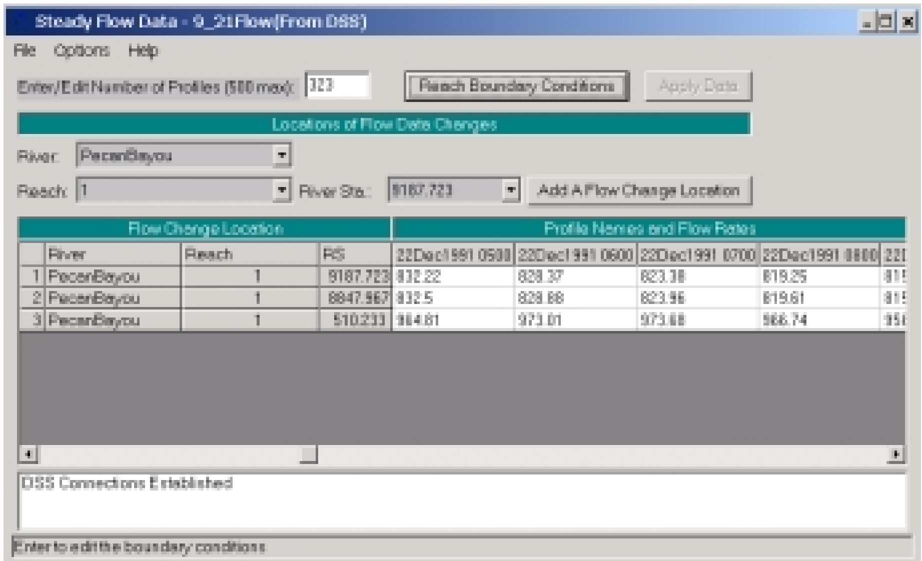


Figure 5-58 Hourly Flow Data for Pecan Bayou

The reach boundary conditions were set at *critical depth* for the upstream boundary and *normal depth* for the downstream boundary, with a slope of 0.003. HEC-RAS performed a steady flow analysis for the peak stage (Profile 90) associated with the storm event and the export file *9_25geo.gis* was created.

5.2.6 FLOODPLAIN DELINEATION

The input themes identified in the HEC-GeoRAS *postRAS* menu are depicted in Figure 5-59.

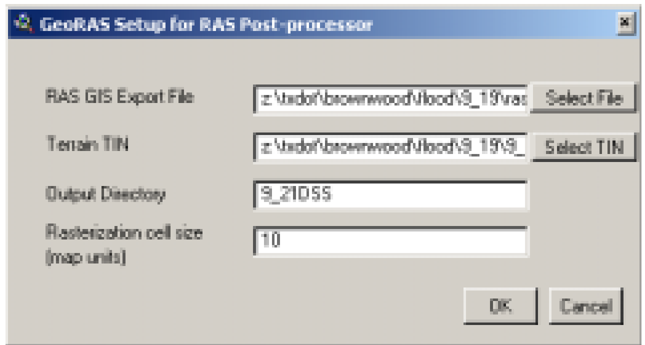


Figure 5-59 HEC-GeoRAS Setup for RAS Post-processor for Pecan Bayou

The rasterization cell size was specified as 10 meters since there are a maximum number of cells (10 million) that can be used by HEC-GeoRAS to create a flood grid. A new view was created in ArcView named *9_21DSS*, with stream centerline (*9_21DSS_SN.shp*), cross-section (*9_21DSSXS.shp*), 3D cross-section (*9_21DSS_XS3D.shp*), bank (*9_21DSS_Banks.shp*), and bounding polygon (*Bpw22dec199.shp*) themes.

One water surface TIN (*wstinw22dec199*), floodplain grid (*gdw22dec199*), and floodplain polygon (*fdw22dec199*) were created in GIS for the peak flow and stage modeled at the FM 2126 bridge. Figure 5-60 presents the floodplain associated with the Christmas 1991 flood.

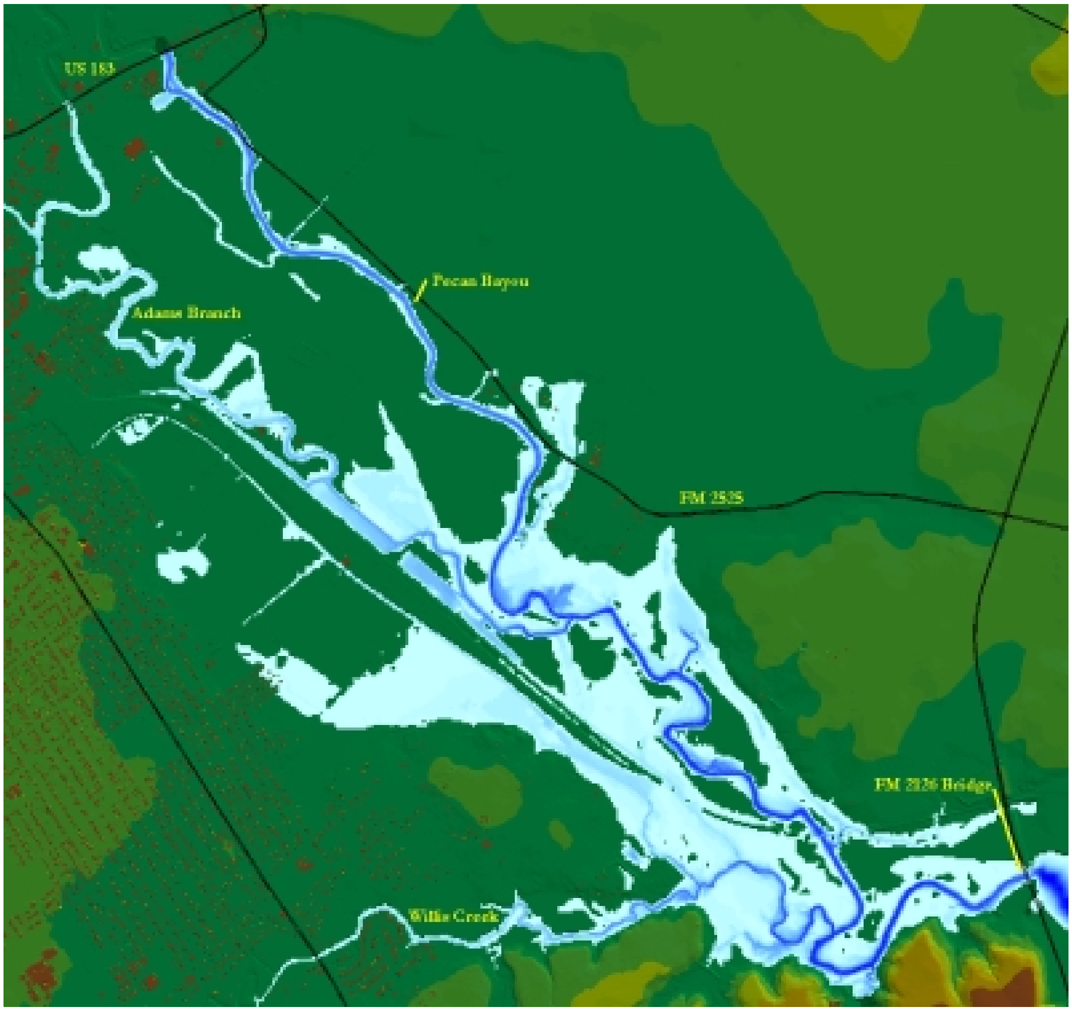


Figure 5-60 Christmas 1991 Flood at Pecan Bayou

6 RESULTS

The focus of this research project was to determine the effectiveness of floodplain modeling in the digital domain at highway river crossings. This chapter presents the results of the modeling at both the Castleman Creek and Pecan Bayou sites, and compares the results to existing data available at each site.

6.1 Castleman Creek

At the Castleman Creek site, existing HEC-1 and HEC-RAS models, developed by TxDOT, provided estimated flow and stage elevations for Castleman Creek at the US 77 Bridge resulting from a 100-year SCS Type 2 storm. To successfully evaluate the results of this research, three aspects of the model were compared to existing TxDOT data:

- The peak flows expected from the design storm as determined from hydrologic modeling;
- The hydraulic characteristics of the Castleman Creek channel developed using HEC-GeoRAS; and
- The floodplain delineated with the methodology presented in Chapter 4.

A discussion of each of these aspects is presented subsequently.

6.1.1 HYDROLOGIC MODELING

TxDOT engineers initially developed a HEC-1 model of the Castleman Creek watershed based on SCS TR-55 methodology in 1993. As discussed in

Chapter 3, two scenarios were evaluated: 1) no consideration of the SCS flood control structures; and 2) with consideration of these structures.

6.1.1.1 No Consideration of SCS Flood Control Structures

The model developed by TxDOT for this scenario did not match exactly with the model created using the methodology presented in this thesis - there were inherent differences between the schematic stream network diagram developed in HEC-1 and those developed using the methodology presented in this thesis. Figure 6-1 presents a comparison of these diagrams.

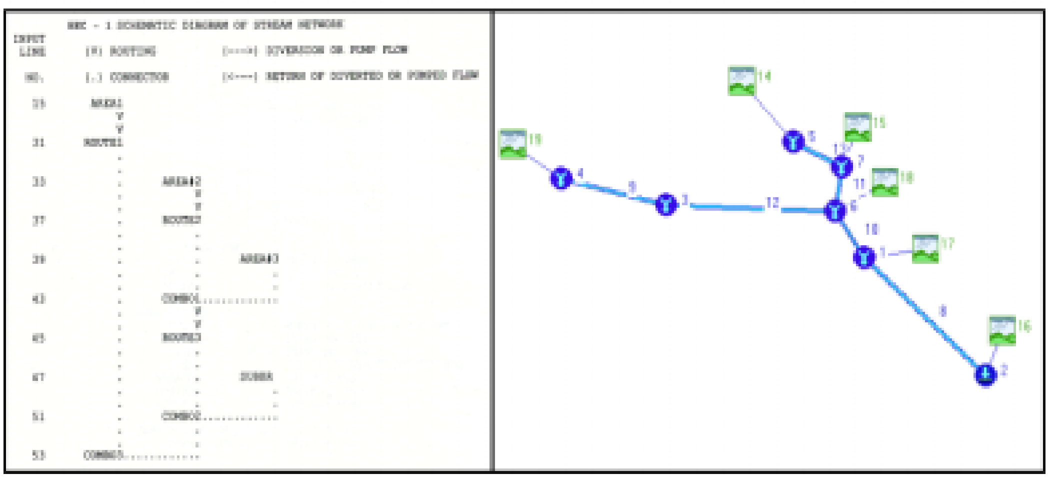


Figure 6-1 Comparison of HEC-1 and HEC-HMS Stream Network Schematic Diagrams without SCS Flood Control Structures

The left side of the figure presents the HEC-1 schematic diagram, while the right side depicts the same watershed delineated using HEC-HMS and CRWR-PrePro. The bridge over Castleman Creek at US 77 is shown as Junction 1 in the HMS schematic – the downstream subbasin (Subbasin 16) was modeled for floodplain delineation purposes only. The naming convention for each hydrologic element is presented in Table 6-1.

Table 6-1 Naming Conventions for Hydrologic Elements of Castleman Creek Watershed without SCS Flood Control Structures

HEC-1	HEC-HMS	Description of HEC-HMS Hydrologic Elements
Subbasins		
Area 1	19	Southwest Subbasin
Area 2	14	Northwest Subbasin
Area 3	15	Northeast Subbasin
Subbr	18	Southeast Subbasin
n/a	17	Small Subbasin Contributing to Outlet at Bridge
Reaches		
Route 1	9, 12	Main Castleman Creek Reaches
Route 2	13	Crow Creek Reach Between Subbasins 14 and 15
Route 3	11	Crow Creek Reach Between Subbasins 15 and 18
n/a	10	Short Reach after Junction of Castleman and Crow Creek
Junctions		
Combo 1	7	Junction of Reach 13 and Subbasin 15
Combo 2	6	Junction of Reaches 11 and 12 and Subbasin 18
Combo 3	n/a	Not applicable in HEC-HMS model
n/a	1	Outlet of Watershed at Bridge on US 77

It is evident from the figure and table that the location of the junction of the two main reaches of Castleman Creek is slightly different in the two models, which yielded an additional small subbasin in the HEC-HMS model (Subbasin 17). In the HEC-1 model, the two main reaches converge at the outlet; in the HEC-HMS model, there is a short reach before the bridge at US 77. Junction 13 was added to the HEC-HMS model to note the location of SCS flood control structure 1, which necessitated breaking the reach into two sub-reaches.

Although the watershed areas determined based on delineation of the DTM with CRWR-PrePro varied slightly when compared with the HEC-1 watershed areas (for comparison purposes, the areas of Subbasins 17 and 18 were combined), the major differences can be found in the use of spatially variable curve numbers (and the corresponding lag times for each watershed), along with different Muskingum K and X variables. Table 6-2 presents a comparison of the different subbasin areas. The characteristics developed using the methodology presented in this thesis can be found under the *HMS* heading, while those determined by TxDOT are listed under the *HEC-1* heading.

Table 6-2 Comparisons of Watershed Areas for Castleman Creek without SCS Flood Control Structures

SubBasin			HMS	HEC-1	Percent
Location	HMS Code	HEC-1 Code	Area (sq km)	Area (sq km)	Difference
NW	14	Area 2	6.58	6.06	7.90
NE	15	Area 3	6.81	5.83	14.41
SW	19	Area 1	34.28	33.15	3.30
SE	17,18	Subbr	4.61	4.45	3.42
Bridge	1	n/a	52.28	49.50	5.33

Table 6-3 presents a comparison of the loss rates calculated for each subbasin. It is evident from the table that there was no variability in the curve number selected for the HEC-1 model, whereas in the HEC-HMS model, the curve numbers were derived from the curve number grid developed by the Blacklands Research Center. The initial losses for both models were calculated using the Initial Abstraction equation presented in Chapter 4.

Table 6-3 Comparisons of Loss Rates for Castleman Creek without SCS Flood Control Structures

SubBasin			HMS			HEC-1		
Location	HMS Code	HEC-1 Code	Initial Loss	SCS Curve No.	% Impervious	Initial Loss	SCS Curve No.	% Impervious
NW	14	Area 2	0.35	85.1043	0	0.35	85	n/a
NE	15	Area 3	0.64	75.6163	0	0.35	85	n/a
SW	19	Area 1	0.34	85.4507	0	0.35	85	n/a
Junction	17,18	Subbr	0.78	71.953	0	0.35	85	n/a
Outlet	1	n/a	0.86	70.000	0	n/a	n/a	n/a

Table 6-4 provides a comparison of the lag times calculated for each watershed. As presented in Chapter 4, this was determined using the SCS Lag Equation and was influenced greatly by the length of the flow path within each subbasin. Because CRWR-PrePro calculates the flowpath from the watershed boundary, and TR-55 guidance recommends calculation of the flowpath from the end of the stream as shown on USGS 7.5' quads, there were significant differences in the lag time associated with each subbasin, and therefore, significant differences in the peak flows at the outlet of the watershed at the US 77 Bridge.

Table 6-4 Comparisons of Lag Times for Castleman Creek without SCS Flood Control Structures

SubBasin			HMS		HEC-1	
Location	HMS Code	HEC-1 Code	Lag (min)	Lag (hrs)	Lag (min)	Lag (hrs)
NW	14	Area 2	250.068	4.17	51.60	0.86
NE	15	Area 3	272.086	4.53	53.40	0.89
SW	19	Area 1	484.458	8.07	144.00	2.4
SE	17,18	Subbr	241.368	4.02	41.40	0.69
Bridge	1	Combo3	48.806	0.81	n/a	n/a

Figure 6-2 presents a graphical representation of the difference in the flowpath used in the CRWR-PrePro calculations and those that may have been used by TxDOT engineers. The light blue streams are RF3 files that match well with USGS 7.5' quad data, while the dark blue lines are the flowpaths calculated by CRWR-PrePro to the watershed outlet.

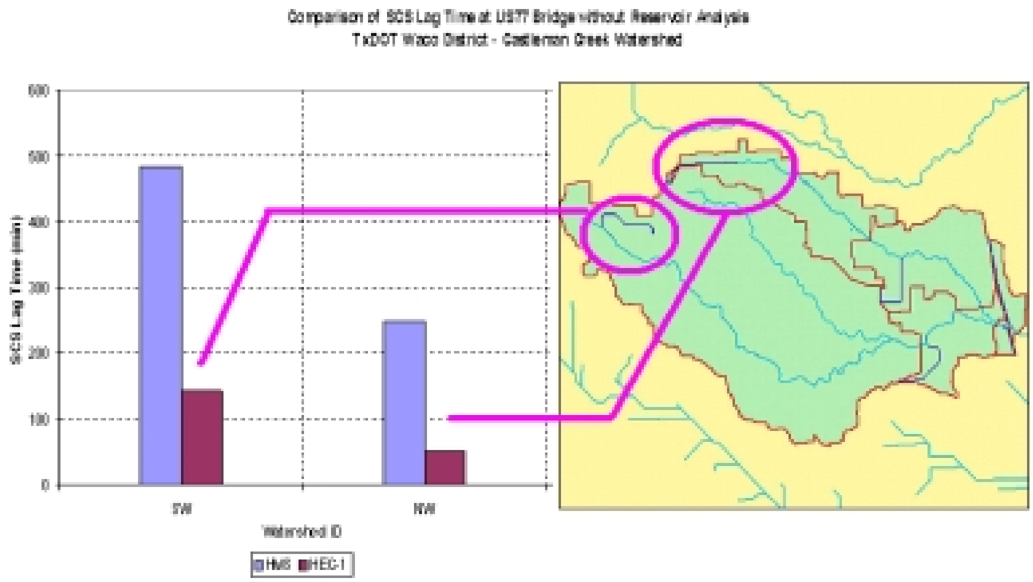


Figure 6-2 Comparisons of Flowpath Lengths for Selected Subbasins in Castleman Creek without SCS Flood Control Structures

The Muskingum K and X values were provided manually by TxDOT engineers for the HEC-1 model. Muskingum K was calculated in CRWR-PrePro as the time of travel in the reach of interest, and the Muskingum X was provided manually. In reaches where the time of travel was shorter than the calculated Muskingum K, pure lag routing was assumed. Table 6-5 presents a comparison of the Muskingum K and X values for the Castleman Creek reaches.

Table 6-5 Comparisons of Routing Parameters for Castleman Creek without SCS Flood Control Structures

Reaches		HMS			HEC-1		
HMS Code	HEC-1 Code	Lag (min)	K (hrs)	X	Lag (min)	K (hrs)	X
9	n/a	2.91	n/a	n/a	n/a	n/a	n/a
12	Route 1	n/a	0.73	0.20	n/a	0.90	0.30
13	Route 2	n/a	1.18	0.20	n/a	0.90	0.30
11	Route 3	n/a	0.18	0.20	n/a	0.13	0.30
10	n/a	5.8	n/a	n/a	n/a	n/a	n/a

The HEC-HMS values were calculated using an assumed stream velocity of 1.0 m/s. Combining the time of flow in Reaches 9 and 12 yielded a lag time of approximately 0.78 hrs, while combining Reaches 10 and 11 produced a lag time of 0.28 hrs.

Using the parameters specified above, peak flows were calculated for the 100-year SCS Type 2 design storm using both HEC-1 and HEC-HMS and compared to the USGS regional regression equations developed for this region of Texas. Figure 6-3 presents a comparison of these flows for a stream velocity of 1.0 m/s and a Muskingum X of 0.2.

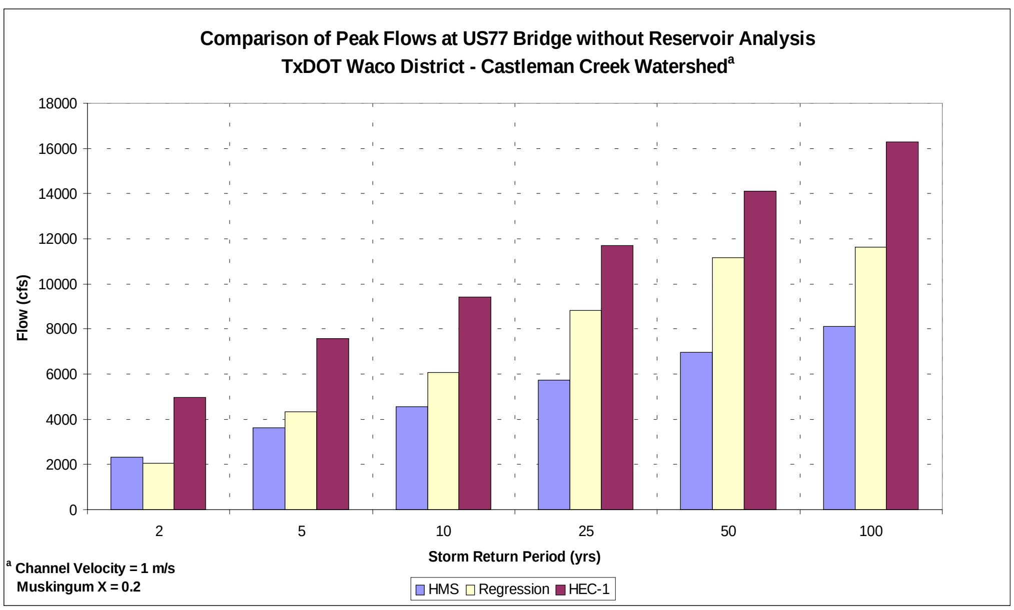


Figure 6-3 Comparisons of Peak Flows for Various Storm Return Periods for Castleman Creek without SCS Flood Control Structures

For return periods less than 10 years, the peak flows calculated using the methodology presented in this thesis matches well with the regional regression equations. For return periods greater than 10 years, this methodology calculated peak flows less than the regression equations. The HEC-1 model produced peak flows greater than the regression equations for all return periods. Table 6-6 presents a summary of the peak flows (in cfs) for selected storm return periods.

Table 6-6 Comparisons of Peak Flow Values for Various Storm Return Periods for Castleman Creek without SCS Flood Control Structures

	Storm Return Period					
Method	**2**	**5**	**10**	**25**	**50**	**100**
HMS	2316.4	3608.9	4544.5	5720.4	6980	8111.8
HEC-1	4950	7573	9413	11699	14113	16276
Regression	2034.32	4316.56	6072.76	8812.03	11172.38	11624.71
% Diff (HMS/Regression)	13.87	16.39	25.17	35.08	37.52	30.22
% Diff (HEC-1/Regression)	143.32	75.44	55.00	32.76	26.32	40.01

The highlighted values depict the minimum percent difference between the applicable model and the regional regression equations.

Another comparison was also made between the time-to-peak (in hours) for each return period at the watershed outlet (Table 6-7). This table highlights the impact of the watershed lag times on the time-to-peak for each storm event.

Table 6-7 Comparison of Time-to-Peak for Various Storm Return Period for Castleman Creek without SCS Flood Control Structures

	Storm Return Period					
Method	**2**	**5**	**10**	**25**	**50**	**100**
HMS	19.5	19.33	19.17	19	19	19
HEC-1	14.83	14.83	14.83	14.83	14.83	14.67

To fully understand the impacts of the manually inputted stream velocities and Muskingum X values on the HEC-HMS results, numerous scenarios were modeled to produce a range of peak flows (in cfs) for the same range of storm return periods (Figure 6-8). The code for the scenarios follows the format of **vA_AxB**, where **A_A** equals the stream velocity in meters per second, and **B** equals the

Muskingum X. For example, v1_0x15 represents a scenario where the stream velocity was assumed to be 1.0 m/s and the Muskingum X was estimated to be 0.15.

Table 6-8 Range of Peak Flows for Differing Stream Velocities and Muskingum X Values

	Storm Return Period					
Method	**2**	**5**	**10**	**25**	**50**	**100**
HEC-HMS						
v2_0x2	2319.6	3625.2	4571.2	5761.3	7036	8182
v1_5x2	2318.9	3620.3	4563.2	5749.1	7018.9	8160.4
v1_0x2	2316.4	3608.9	4544.5	5720.4	6980	8111.8
v0_5x2	2311.7	3580.7	4494.1	5641.7	6865.7	7966.5
v0_1x2	2126	3240.8	4035	5027	6079.8	7022.4
v1_0x1	2312	3601.7	4535	5708.6	6965.7	8095.4
v1_0x15	2313.3	3603.9	4537.9	5712.4	6970.3	8100.6
v1_0x5	2323.2	3621	4559.8	5739.2	7000.2	8135.1
cn85	2491.8	3821.3	4774	5966	7234.1	8371.3
HEC-1	4950	7573	9413	11699	14113	16276
Regression	**2034.32**	**4316.56**	**6072.76**	**8812.03**	**11172.38**	**11624.71**

The values listed in the table provide the basis for the selection of the parameters used to model the watershed while considering the effects of the SCS flood control structures. The highlighted values represent the scenarios used to model the watershed with the flood control structures in Section 6.1.1.2. Although velocities greater than 1.0 m/s yielded peak flows closer to the regional regression equation values, these velocities did not increase the peak flows significantly.

6.1.1.2 Consideration of SCS Flood Control Structures

The addition of the three SCS flood control structures in both models produced dramatic effects on the peak flows calculated at the watershed outlet. Figure 6-4 presents a comparison of the schematic stream network diagrams for this modeling scenario.

The differences in the watershed and routing parameters presented in the previous section are applicable to this modeling scenario as well. Significant differences in watershed lag times greatly affect the peak flow and time-to-peak values calculated at the watershed outlet. Figure 6-5 presents a comparison of the peak flows at the watershed outlet (in cfs) calculated using the methodology presented in this thesis to that produced by the existing HEC-1 model developed by TxDOT engineers. The stream velocity was assumed to be 1.0 m/s and the Muskingum X was estimated at 0.2.

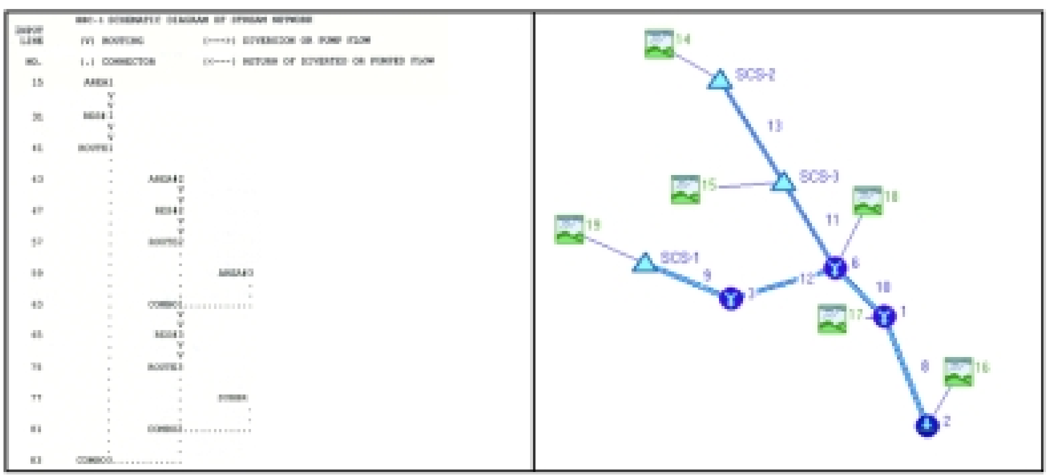


Figure 6-4 Comparison of HEC-1 and HEC-HMS Stream Network Schematic Diagrams with SCS Flood Control Structures

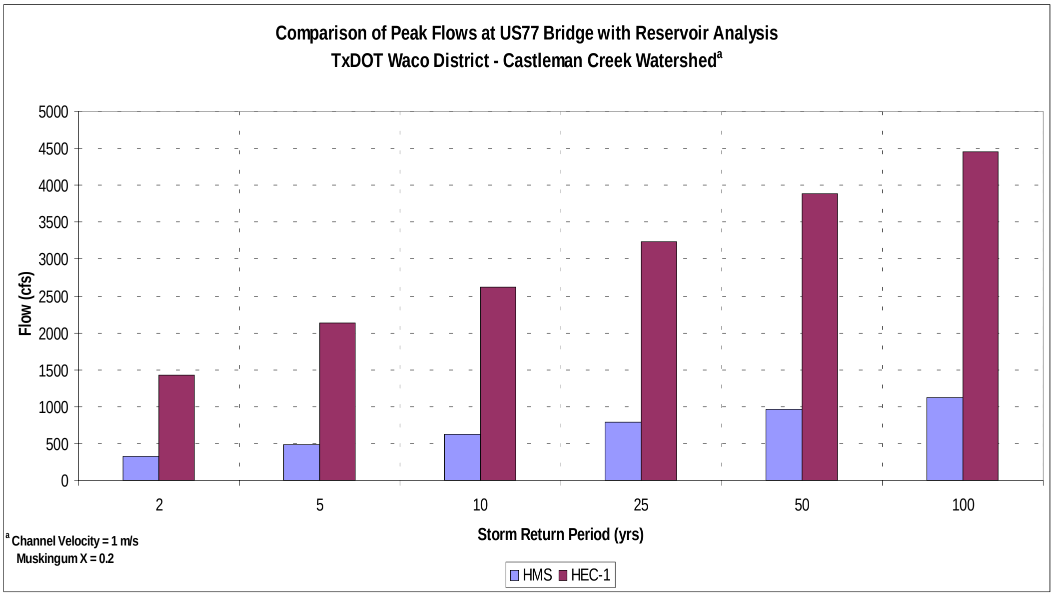


Figure 6-5 Comparisons of Peak Flows for Various Storm Return Periods for Castleman Creek with SCS Flood Control Structures

Table 6-9 presents a summary of the peak flows (in cfs) for selected storm return periods. This table shows the major differences in calculated peak flows for each storm event – for the 100-year storm, the HEC-HMS model predicted maximum flows equal to only 25% of those produced by the HEC-1 model.

Table 6-9 Comparisons of Peak Flow Values for Various Storm Return Periods for Castleman Creek with SCS Flood Control Structures

	Storm Return Period					
Method	**2**	**5**	**10**	**25**	**50**	**100**
HMS	324.48	492.88	621.36	788.7	964.83	1121.5
HEC-1	1424	2130	2626	3239	3882	4450

Additionally, the time-to-peak (in hours) varies in this scenario as well (Table 6-10).

Table 6-10 Comparison of Time-to-Peak for Various Storm Return Period for Castleman Creek with SCS Flood Control Structures

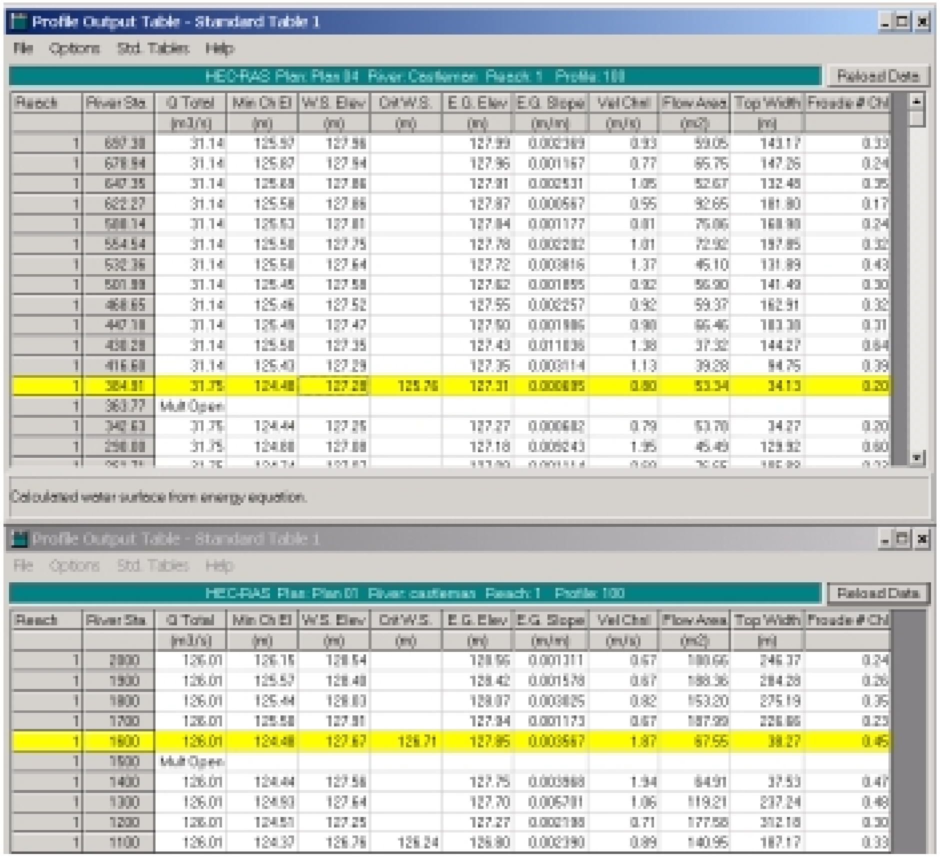
	Storm Return Period					
Method	2	5	10	25	50	100
HMS	16.83	16.67	16.5	16.5	16.33	16.33
HEC-1	12.5	12.5	12.5	12.5	12.5	12.5

The results of the hydrologic modeling presented in this section represent a portion of the input parameters for the subsequent hydraulic modeling necessary for stage determination and eventual floodplain mapping. The input and output from both the HEC-1 and HEC-HMS models is presented in Appendix C.1.

6.1.2 HYDRAULIC MODELING

The results of the hydraulic modeling were impacted by two major input parameters: 1) the flows calculated in the hydrologic model; and 2) the cross-sectional channel geometry. The channel geometry was provided by TxDOT upstream and downstream of the US 77 bridge (in the form of 11 field-surveyed cross-sections), and was used to model the stage at the watershed outlet for the 100-year SCS Type 2 design storm including the effects of the three SCS flood control structures.

Figure 6-6 presents a comparison of the calculated stage height at the US 77 bridge using the methodology presented in this thesis (the top table) to the HEC-RAS model provided by TxDOT for the proposed bridge structure (the bottom table).



Profile Output Table - Standard Table 1

HEC-RAS Plan: Plan 04 River: Castleman Reach: 1 Profile: 100

Reach	River Sta	Q Total (m3/s)	Min Ch El (m)	W.S. Elev (m)	Crit W.S. (m)	E.G. Elev (m)	E.G. Slope (m/m)	Vel Chnl (m/s)	Flow Area (m2)	Top Width (m)	Froude # Chl
1	687.38	31.14	125.97	127.96		127.99	0.002369	0.93	59.05	143.17	0.33
1	678.94	31.14	125.87	127.94		127.96	0.001167	0.77	65.75	147.26	0.24
1	647.35	31.14	125.68	127.86		127.91	0.002531	1.05	52.67	132.48	0.35
1	622.27	31.14	125.58	127.86		127.87	0.000567	0.55	92.65	181.80	0.17
1	588.14	31.14	125.53	127.81		127.84	0.001177	0.81	75.06	168.98	0.24
1	554.54	31.14	125.58	127.75		127.78	0.002282	1.01	72.92	197.85	0.32
1	532.36	31.14	125.58	127.64		127.72	0.003816	1.37	45.10	131.89	0.43
1	501.88	31.14	125.45	127.58		127.62	0.001855	0.92	56.90	141.49	0.30
1	468.65	31.14	125.46	127.52		127.55	0.002257	0.92	59.37	162.91	0.32
1	447.18	31.14	125.48	127.47		127.50	0.001986	0.90	66.46	183.38	0.31
1	438.28	31.14	125.58	127.35		127.43	0.011836	1.38	37.32	144.27	0.64
1	416.68	31.14	125.43	127.29		127.35	0.003114	1.13	39.28	94.75	0.39
1	384.81	31.75	124.48	127.28	125.76	127.31	0.000695	0.80	53.34	34.13	0.20
1	363.77	Mult Open									
1	342.63	31.75	124.44	127.25		127.27	0.000682	0.79	53.70	34.27	0.20
1	298.88	31.75	124.88	127.08		127.18	0.009243	1.95	45.49	129.92	0.60

Calculated water surface from energy equation.

Profile Output Table - Standard Table 1

HEC-RAS Plan: Plan 01 River: castleman Reach: 1 Profile: 100

Reach	River Sta	Q Total (m3/s)	Min Ch El (m)	W.S. Elev (m)	Crit W.S. (m)	E.G. Elev (m)	E.G. Slope (m/m)	Vel Chnl (m/s)	Flow Area (m2)	Top Width (m)	Froude # Chl
1	2000	126.01	126.15	128.54		128.56	0.001311	0.67	188.66	246.37	0.24
1	1900	126.01	125.57	128.40		128.42	0.001578	0.67	188.36	284.28	0.26
1	1800	126.01	125.44	128.03		128.07	0.003025	0.82	153.20	275.19	0.35
1	1700	126.01	125.58	127.91		127.94	0.001173	0.67	187.99	226.86	0.23
1	1600	126.01	124.48	127.67	126.71	127.85	0.003567	1.87	67.55	38.27	0.45
1	1500	Mult Open									
1	1400	126.01	124.44	127.56		127.75	0.003968	1.94	64.91	37.53	0.47
1	1300	126.01	124.93	127.64		127.70	0.005781	1.06	119.21	237.24	0.48
1	1200	126.01	124.51	127.25		127.27	0.002188	0.71	177.58	312.18	0.30
1	1100	126.01	124.37	126.76	126.24	126.80	0.002390	0.89	140.95	187.17	0.33

Figure 6-6 Comparison of Castleman Creek Stage for Proposed US 77 Bridge

The top portion of the figure presents a summary table of the water surface elevation resulting from the 100-year storm (among other parameters) for the HEC-RAS model developed as a result of the methodology presented in this thesis, while the lower portion presents the output from the existing HEC-RAS model provided by TxDOT. The cross-sections presented in the top portion of the figure were generated by HEC-GeoRAS – as expected, the minimum channel elevation is the same for both modeling scenarios, lending credence to the accuracy of implementing the terrain preprocessing methodology. The number of cross-sections in the top portion of the figure can also be considered accurate because they are based on the interpolation of cross-sections from the field-surveyed data provided by TxDOT.

The significant reduction in flow has yielded a reduction in stage height from 127.67 meters to 127.28 meters, which equates to approximately 1.28 feet – a significant reduction when evaluating the susceptibility of this bridge to potential overtopping due to extreme storm events. The reduction in flow has also yielded a decreased energy grade elevation, channel velocity, flow area, top width, and Froude number. All values can be considered reasonable for the flows estimated as a result of the hydrologic modeling.

6.1.3 FLOODPLAIN DELINEATION

To evaluate the impacts of the integration of DEM and photogrammetric data on the Castleman Creek field-surveyed cross-sections, and subsequently, the lateral extent of the floodplain, a comparison of the cross-sections derived from HEC-GeoRAS are compared to the existing TxDOT cross-sections. Additionally, the extent of the floodplain resulting from the 100-year storm is presented for both the flows calculated in HEC-1 by TxDOT and those calculated in HEC-HMS using the methodology presented in this thesis.

Figure 6-7 presents a comparison of the re-sampled cross-sections utilized during floodplain modeling.

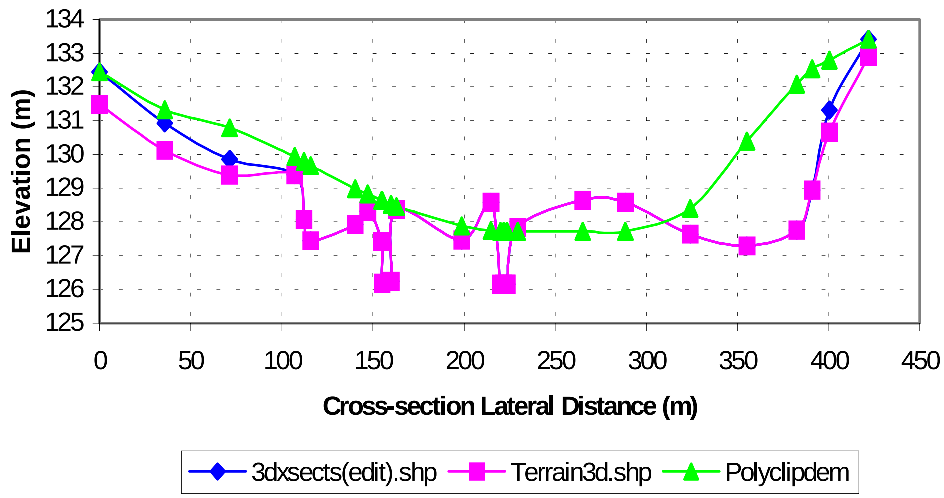


Figure 6-7 Comparisons of Cross-Sections at Station 2000 for Castleman Creek with SCS Flood Control Structures

The theme entitled *Polyclipdem* represents the land surface represented by the DEM, *Terrain3d* the cross-section data imported into GIS using CRWR-FloodMap, and *3dxsects(edit)* the re-sampled cross-sections interpolated outside of each bank station. The effects of this re-sampling can be seen in Figure 6-8. The reason the re-sampled cross-sections were used was due to the difficulty in determining the correct orientation of each cross-section.

The floodplain extent, along with the corresponding flood depth, delineated with the peak flows generated from HEC-HMS flows is depicted in Figure 6-9.

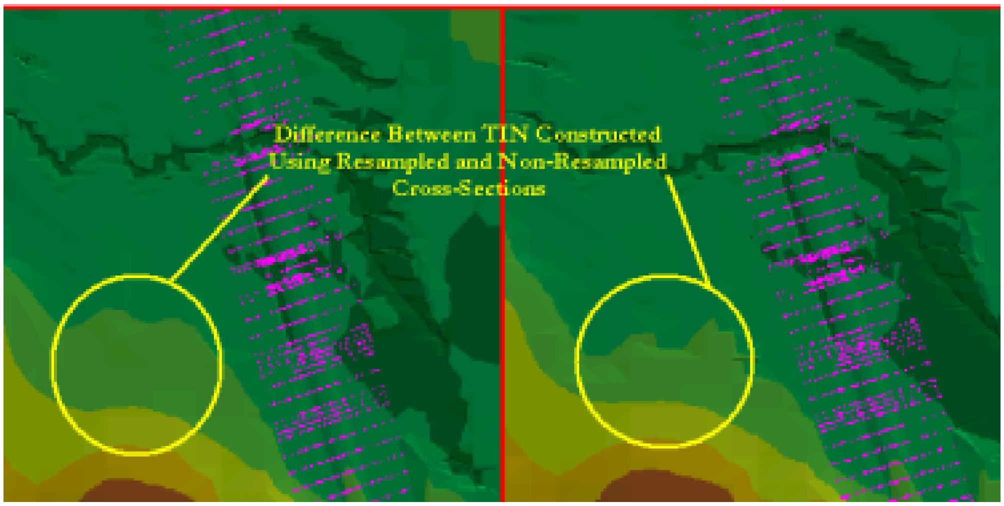


Figure 6-8 Comparison of TINs with and without Re-sampled Cross-Sections

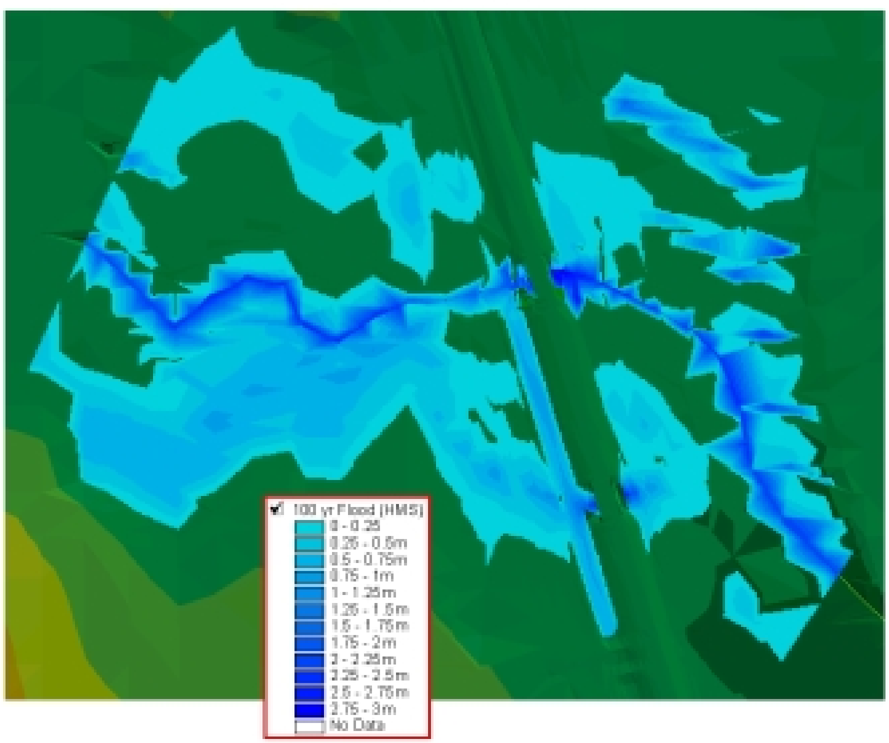


Figure 6-9 100-year Floodplain as Determined by HEC-HMS and HEC-RAS Hydrologic and Hydraulic modeling

Figure 6-10 presents a comparison between the flows calculated in HEC-1 by TxDOT and those calculated in HEC-HMS using the methodology presented in this thesis.

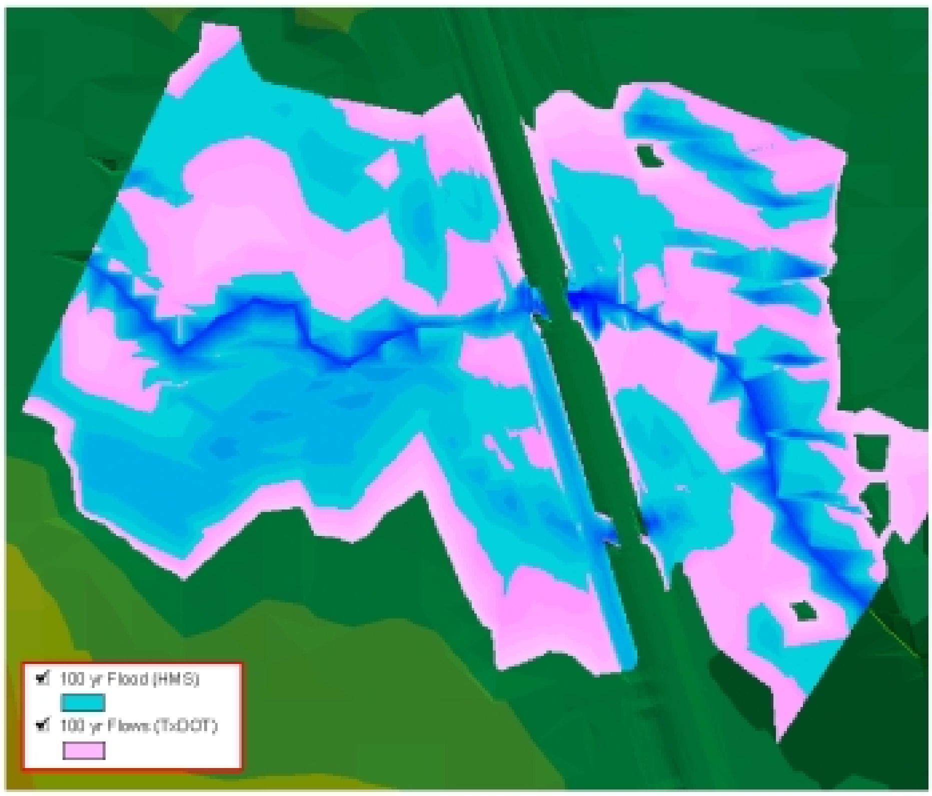


Figure 6-10 Comparison of Floodplain Generated from TxDOT and HEC-HMS Flow Data

The stage height calculated by TxDOT engineers is approximately 1.3 ft (0.39 m) higher than the height calculated using the methodology presented in this thesis.

6.2 Pecan Bayou

At the Pecan Bayou site, extreme storm event flows were generated from historical precipitation data, reservoir spillway release data, and rainfall/runoff modeling for the Christmas 1991 flood event. This flow data, modeled in HEC-

HMS, was imported into HEC-RAS for use with existing HEC-RAS cross-sections developed by the USACOE Ft. Worth District, and provided estimated stage elevations for Pecan Bayou at the bridge over Pecan Bayou on FM 2126.

To successfully evaluate the results of this research, three aspects of the model were compared to existing TxDOT data (where applicable):

- The modeled discharge hydrograph from the 1991 storm as compared to recorded stage and flow data at USGS Gage 08143600 near Mullin, TX;
- The hydraulic characteristics of the Pecan Bayou channel developed using HEC-GeoRAS; and
- The resulting floodplain map.

A discussion of each of these aspects is presented subsequently.

6.2.1 HYDROLOGIC MODELING

Prior to hydrologic modeling in HEC-HMS, CRWR-PrePro was used to extract the hydrologic parameters for the Pecan Bayou watershed contributing flow to USGS Gage 08143600 near Mullin, TX. Although the point of interest in this research was the bridge on FM 2126 over Pecan Bayou, the discharge hydrograph contained flows from additional watersheds located downstream of this bridge. Figure 6-11 presents a summary of the areas associated with each contributing subbasin.

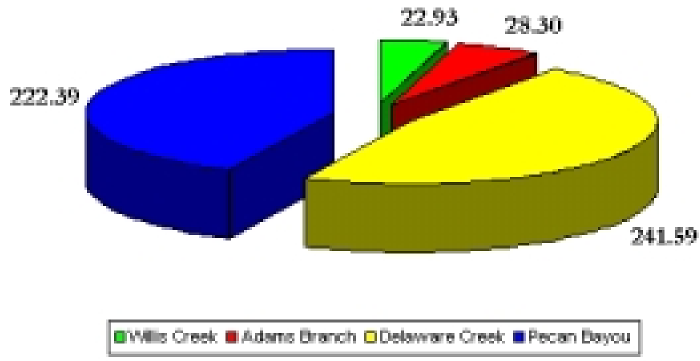


Figure 6-11 Area Summary (mi²)of Subbasins Contributing Flow to USGS Gage 08143600

Figure 6-12 depicts the relative contribution of flow from each watershed. It is evident from this figure that the response of the Pecan Bayou watershed to the Christmas 1991 storm event was based primarily on the spillway release from Lake Brownwood.

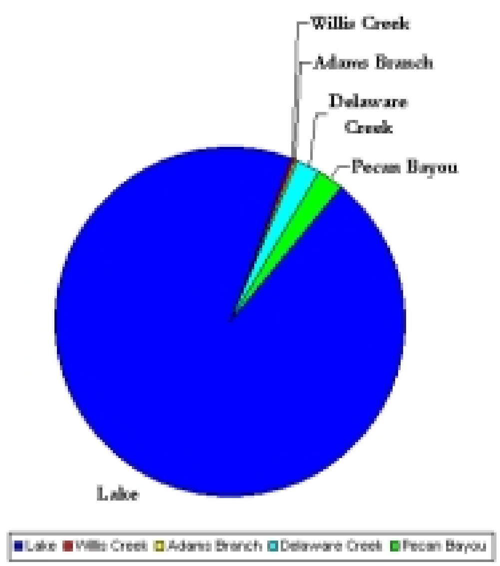


Figure 6-12 Cumulative Flow Summary of Subbasins Contributing Flow to USGS Gage 08143600

It is important to understand the time-to-peak associated with routing the storm through the watershed. Figure 6-13 presents a comparison of the recorded precipitation, a linearized discharge hydrograph from the Lake Brownwood spillway, and the recorded flows at the USGS gage site.

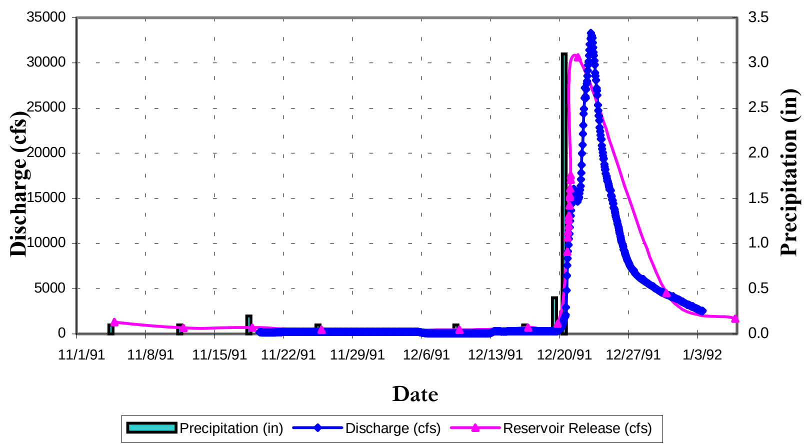


Figure 6-13 Comparison of Precipitation, Spillway Discharge, and Observed Flow at USGS Gage 08143600

With the contribution of each subbasin and the expected time of travel for the peak flow understood, HEC-HMS was used to model the rainfall/runoff relationships of the entire Pecan Bayou watershed, and yielded a maximum flow of approximately 32,280 cfs on December 21, 1991 at 1800 hours at the FM 2126 Bridge.

Because limited lake elevation data was available during the storm event, the tail of the spillway discharge hydrograph was estimated by linear interpolation. In reality, an exponential decay function may have been more appropriate to model the response effectively. Therefore, when the observed hydrograph at the USGS gage was compared to the modeled results, the peak flow and time-of-peak was estimated effectively, but the tail of the discharge hydrograph was over-estimated (Figure 6-14). This model was deemed adequate because the goal of the floodplain modeling was to obtain the maximum water surface elevation and extent of the floodplain at the FM 2126 Bridge, and did not consider the total quantity of flow through the system.

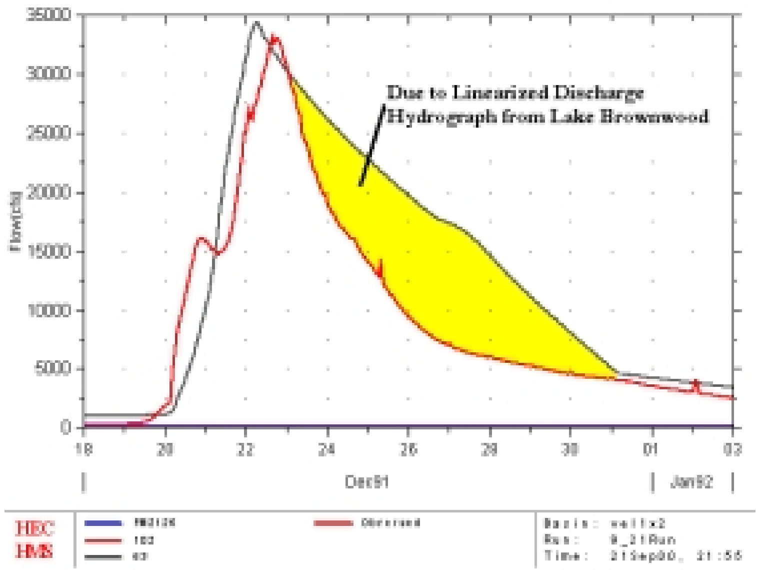


Figure 6-14 Observed and Modeled Discharge Hydrograph at USGS Gage 08143600

6.2.2 HYDRAULIC MODELING

An analysis of the hydraulic modeling results unfortunately yielded discrepancies between the surveyed cross-section data supplied by the Ft. Worth Corps and the contour data provided by the City of Brownwood. Because of the aforementioned difficulty of determining the optimum cross-section orientation in GIS, along with notations in most of the HEC-RAS cross-sections that documented the use of coarse elevation contour data (extracted from USGS 7.5' quads) to define the overbank areas, the contours provided by the City were deemed the most reliable data except within the channel itself. Figure 6-15 provides a comparison of one such cross-section, located immediately downstream of the Hawkins Street Bridge.

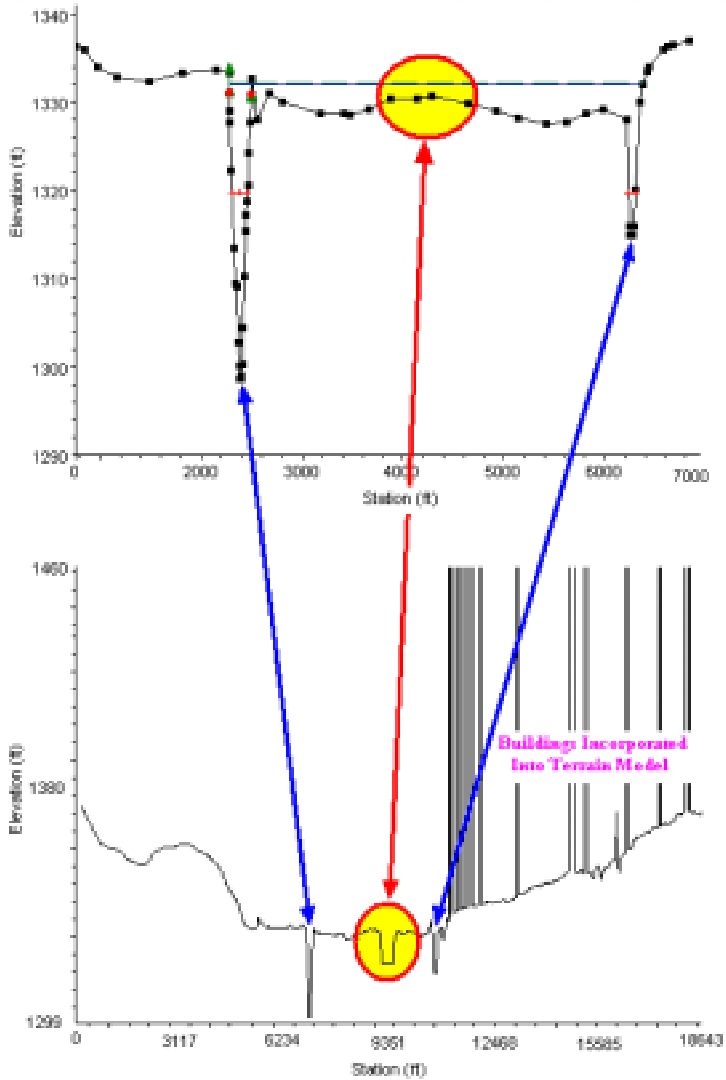


Figure 6-15 Comparison of HEC-RAS and HEC-GeoRAS Cross-Sections

HEC-RAS modeling yielded water surface profiles for each cross-section (Figure 6-16).

Profile Output Table - Standard Table 1
HEC-RAS Plan: 9_25DSS River: PecanBayou Reach: 1 Profile: 21Dec1991 1800

Rivers = 1
Hydraulic Reaches = 1

River Stations = 19
Plans = 1
Profiles = 1

Reach	River Sta	Q Total (m3/s)	Min Ch El (m)	W.S. Elev (m)	Crit W.S. (m)	E.G. Elev (m)	E.G. Slope (m/m)	Vel Chnl (m/s)	Flow Area (m2)	Top Width (m)	Froude # Chl
1	9187.723	879.10	396.78	404.49	401.79	404.76	0.000107	2.38	408.92	121.32	0.35
1	9159.087	Bridge									
1	9130.944	879.10	396.78	404.48		404.73	0.000107	2.37	447.52	184.28	0.35
1	8847.967	879.78	395.88	404.46	402.77	404.69	0.000150	2.39	479.28	199.70	0.39
1	8832.242	Bridge									
1	8816.516	879.78	395.88	404.53		404.65	0.000352	1.70	579.30	225.15	0.25
1	8058.743	879.78	396.57	403.92		404.25	0.000775	2.38	388.97	124.94	0.36
1	7482.381	879.78	396.58	403.63		403.78	0.000637	1.98	572.23	394.52	0.29
1	7054.855	879.78	396.58	403.35		403.49	0.000722	1.93	543.19	523.83	0.30
1	6244.215	879.78	394.01	403.15		403.19	0.000201	0.44	1146.87	763.96	0.07
1	5518.216	879.78	393.58	402.98		403.02	0.000326	0.59	1192.08	1076.83	0.09
1	4667.049	879.78	393.28	402.61		402.70	0.000565	0.68	903.11	894.86	0.11
1	4103.591	879.78	393.08	402.36		402.43	0.000397	0.61	907.97	806.73	0.10
1	2964.616	879.78	392.58	401.93		401.98	0.000553	1.21	1199.60	790.57	0.16
1	1626.235	879.78	391.34	401.00		401.11	0.000862	1.58	682.61	340.76	0.24
1	510.233	913.16	391.34	399.41	396.82	399.95	0.001200	3.27	278.86	52.79	0.45
1	492.259	Bridge									
1	474.188	913.16	391.34	399.37		399.74	0.000907	2.67	341.73	77.97	0.40
1	97.387	913.16	389.57	399.52	393.84	399.55	0.000100	0.81	1145.99	291.15	0.11

Figure 6-16 Summary of HEC-RAS Water Surface Profiles at each Cross-Section

Verbal communication with TxDOT personnel provided one means of evaluating the resulting water surface profile at the FM 2126 Bridge (highlighted in yellow above). According to TxDOT personnel, the maximum water elevation during the Christmas 1991 flood was observed to be at the base of the bottom chord of the bridge[15]. Figure 6-17 presents a comparison of the calculated water surface profile to the bottom chord elevation.

[15] Personal communication with Lynn Passmore, TxDOT, on March 12, 2000.

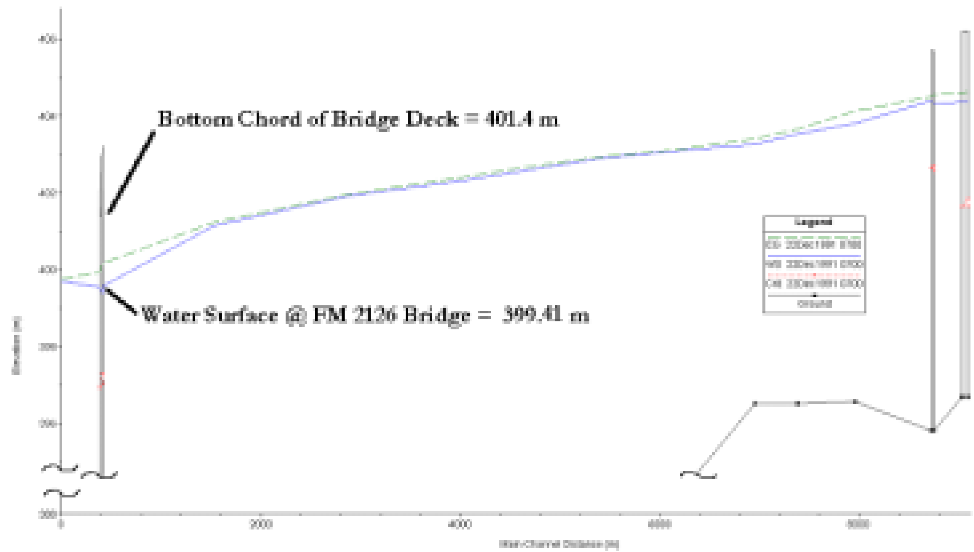


Figure 6-17 Water Surface Profile for Pecan Bayou at FM 2126 Bridge

6.2.3 FLOODPLAIN DELINEATION

The results of the floodplain delineation effectively communicated the effects of the surrounding terrain on water surface profiles near the FM 2126 Bridge. It is apparent from Figure 6-19 that the presence of a hill to the southwest of the bridge, along with the confluence of Pecan Bayou with Willis Creek and Adams Branch, creates backwater conditions that yield significant flooding in this area.

Unfortunately, cross-section data was not available for either Adams Branch or Willis Creek as they flow into Pecan Bayou, so the flow carried in this reach was not modeled as part of this research. The contributions of additional flows in this river may yield additional flooding to the east and west of these tributaries and inundate an even larger number of structures in the City of Brownwood.

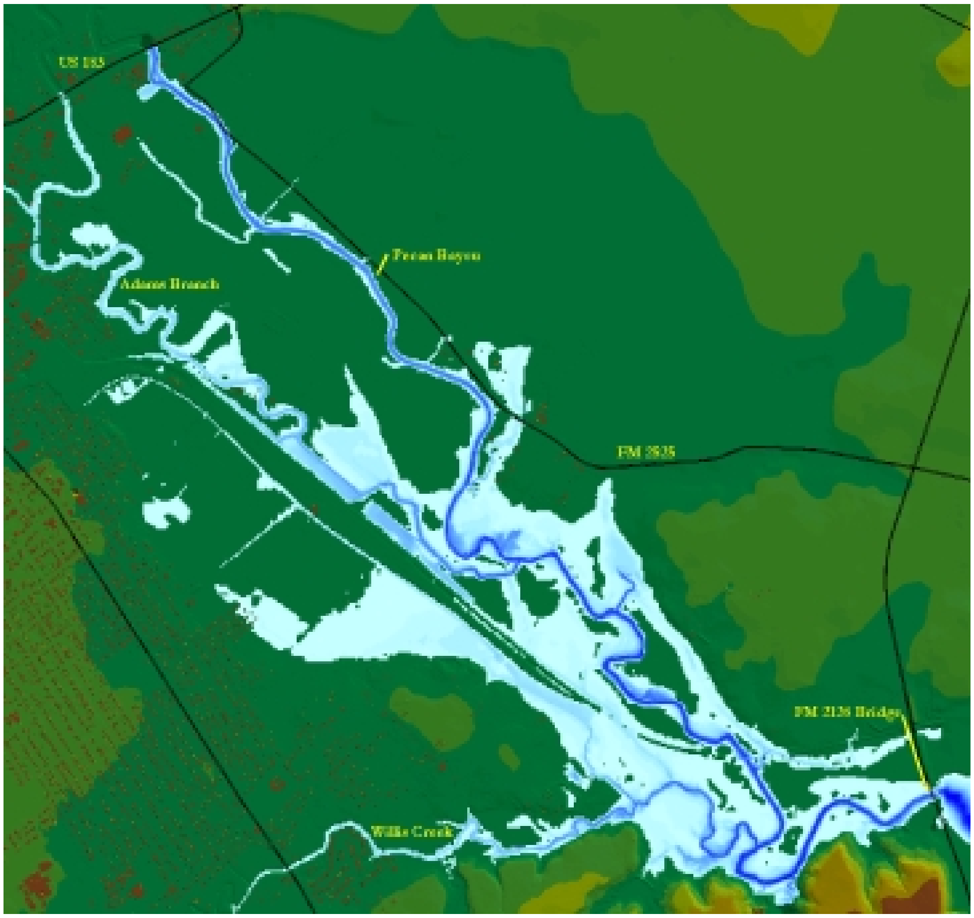


Figure 6-18 Christmas 1991 Floodplain on Pecan Bayou

7 CONCLUSIONS AND RECOMMENDATIONS

In this thesis, a methodology is presented for GIS-based hydrologic and hydraulic modeling to delineate floodplains at highway river crossings. This research provides a seamless integration of digital terrain development in GIS, hydrologic modeling using HEC-HMS, hydraulic modeling using HEC-RAS, and floodplain delineation using HEC-GeoRAS. Figure 7-1 provides a summary of this methodology.

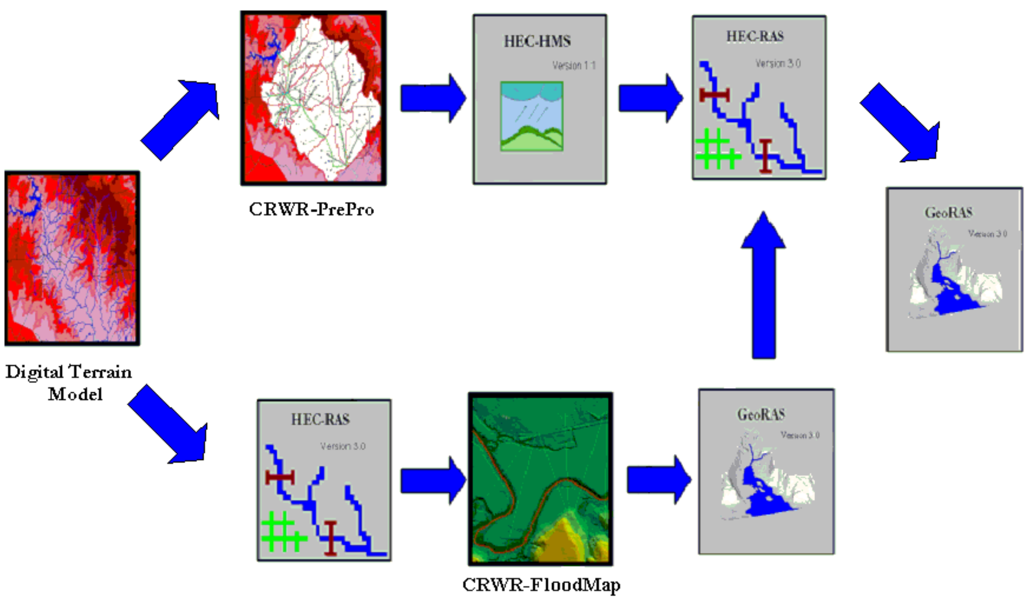


Figure 7-1 Schematic of Floodplain Delineation Methodology

The following sections of this chapter present conclusions drawn from the implementation of these tools at the Castleman Creek and Pecan Bayou watersheds, as well as recommendations for future work that should be undertaken to further refine the tools and ultimately yield more accurate floodplain maps.

7.1 Conclusions

The conclusions drawn from the research are best presented in terms of the methodology presented in Chapter 4.

7.1.1 Site-specific Terrain Data Development

Site-specific terrain data development is accomplished to meet two objectives:

1. Terrain development for hydrologic analysis.
2. Terrain development for floodplain delineation.

Excellent results were obtained from the portion of the methodology related to development of terrain data for hydrologic analysis. Proven algorithms have been developed in the GIS framework that can effectively define a hydrologically correct terrain model. The methodology contained in CRWR-PrePro is sound and is capable of defining a stream network in the digital domain effectively. Similarly, watersheds can be delineated accurately, and with the option of user-defined outlets, is flexible enough to meet most users' needs. As presented in Chapter 5, the watersheds delineated using CRWR-PrePro varied only slightly from those delineated by TxDOT engineers at Castleman Creek.

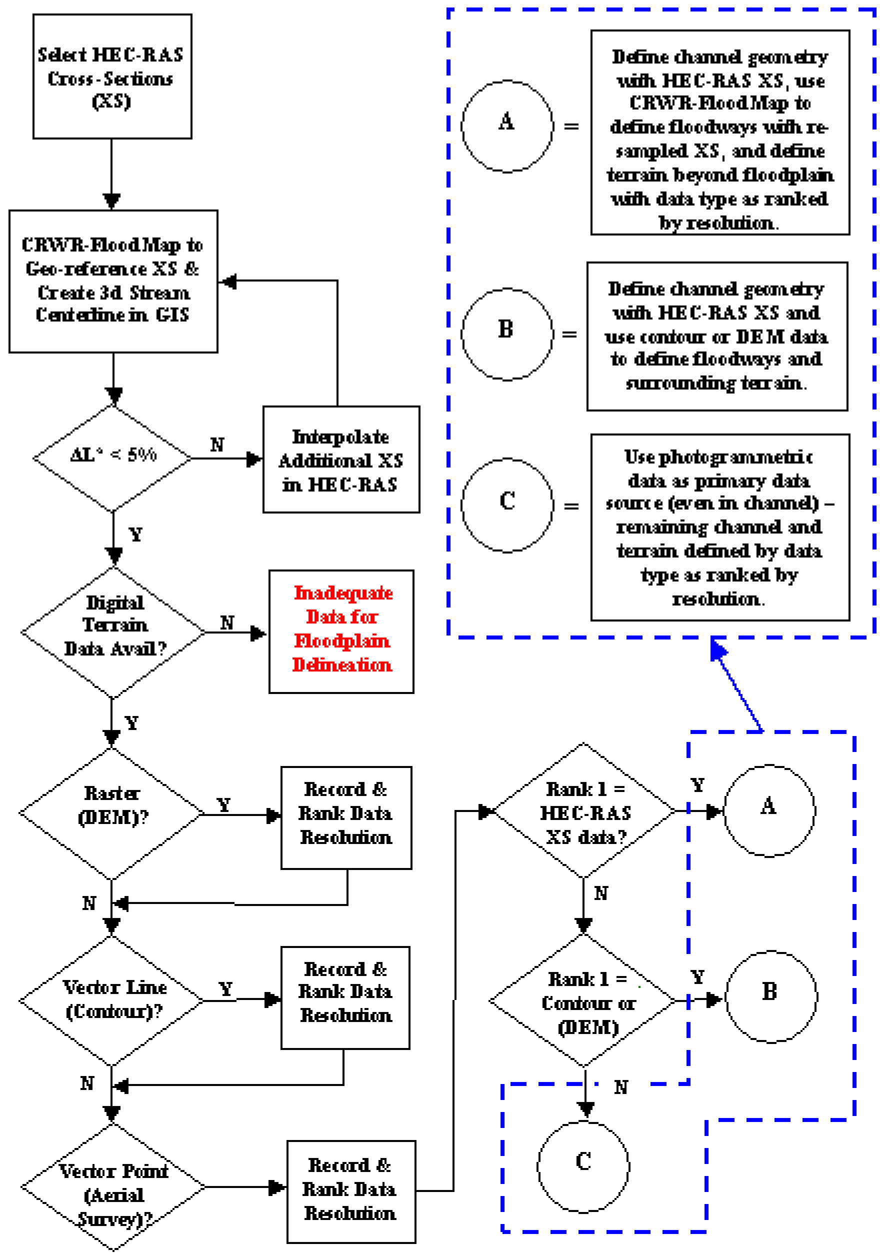
Conclusions that can be drawn from the implementation of terrain development tools for floodplain delineation can be summarized as follows:

1. The type and resolution of the data is the most important factor affecting accurate floodplain delineation activities.
2. The number of cross-sections necessary for the hydraulic modeling of a channel and its corresponding overbanks may not be equal to

the number of cross-sections necessary for floodplain delineation in GIS (due to the tortuosity of the stream of interest). For example, if only three cross-sections are necessary to adequately define the variability of the hydraulic properties of a very tortuous channel, many more may be necessary to represent the tortuosity of the stream thalweg. On the other hand, if the same stream segment is straight, only two cross-sections are needed to represent the stream thalweg, while the same three cross-sections are needed to model the hydraulic characteristics of the channel.

3. Intersecting cross-sections do not necessarily adversely affect floodplain delineation activities – in reality, the effects of intersecting cross-sections are based on the river stage determined by hydraulic modeling. This is evident from the exercise of reducing the number of cross-sections in the Pecan Bayou watershed due to the wide extent of the floodplain to the left and right of the main channel.

When developing a terrain model for floodplain delineation, it is apparent that the data with the best resolution should be prioritized. Figure 7-2 presents a flowchart to aid in prioritizing the data to be used when developing a terrain model for floodplain delineation. Depending on the resolution and accuracy of the data available, some data sources may be prioritized over others. At Castleman Creek, in the majority of the floodplain, the most accurate data was deemed to be the HEC-RAS cross-section information. However, near US 77, the photogrammetric data was more accurate, so in these regions, the cross-section information was edited out of the boundaries of the photogrammetric data.



* ΔL = Difference in Length Between Stream Centerline created by CRWR-FloodMap and Actual Stream Length

Figure 7-2 Data Prioritization Flow Chart for Digital Terrain Development for Floodplain Delineation

For river stages above the bank elevations, the goal of terrain development is to minimize reliance on orientation of the cross-sections. At Pecan Bayou, because of the limitations associated with orienting cross-sections extracted from HEC-RAS, it was advantageous to use elevation contour data in the overbank areas to define the terrain – cross-section data was only utilized within the channel. For small channels (or for large channels where a large portion of the banks are defined adequately by other terrain data), the exclusive use of a 3D stream centerline is adequate to define the 3D channel geometry if the channel can be considered a three-point, or "v-shaped", channel. If the channel cannot be defined as a three-point channel, this assumption is not valid.

Another conclusion that can be drawn from this portion of the research is that the number of cross-sections necessary for the hydraulic modeling of a channel and its corresponding overbanks may not be equal to the number of cross-sections necessary for terrain development for floodplain delineation in GIS. As described in the example presented previously in this chapter, if the stream of interest is extremely tortuous, the linear interpolation algorithms of CRWR-FloodMap (and HEC-GeoRAS) require an abundance of cross-sections to mimic the tortuous nature of the natural stream (the rationale behind this conclusion is presented in Chapter 4).

Finally, it can be concluded that the effects of intersecting cross-sections on terrain development activities may not be as significant as originally thought. For river stages below the bank elevations, the intersection of cross-sections is irrelevant since the cross-sections most likely cross in the overbank areas outside the limits of the channel. However, for river stages above the banks, intersecting cross-sections will yield an erroneous representation of the terrain. This concept is also addressed in Chapter 4.

7.1.2 GIS-based Hydrologic Parameter Extraction

CRWR-PrePro was used in this research to extract spatially variable hydrologic parameters from each watershed for export to HEC-HMS. Watershed areas, loss rate, and reach routing parameters were extracted successfully at both sites and matched well with the same parameters estimated by TxDOT engineers. The automated development of a HEC-HMS Basin file in CRWR-PrePro is a timesaving process that can significantly reduce the resources necessary to evaluate spatially variable hydrologic properties.

However, this research yielded significantly different transform parameters than those estimated by TxDOT at the Castleman Creek site. Lag times were calculated using this methodology that may be excessive for the watershed sizes and shapes encountered at highway drainage structures. Very small precipitation events may produce small quantities of runoff that follow tortuous paths to the outlet of the subbasin. However, as the storm increases in size, the velocity and quantity of the runoff will increase, and the flowpath to the watershed outlet may become more linear in nature. This can be supported by the fact that, for storm return periods of less than 10 years, CRWR-PrePro and HEC-HMS modeling yielded peak flows that matched well with the regional regression equations. However, as the storm return period increased, the peak flows estimated by this methodology were significantly less than the regional regression equation values. If the lag time for a watershed were decreased for a given quantity of runoff, the peak flow would have to be higher, which would better estimate peak flows according to the regression equations. In this study, however, increases in the channel velocity produced minimal results on the peak flows seen at the outlets of the watershed – this is due to the fact that overland flow velocities impacted the lag time greater than channel velocities. Unfortunately, the effects of overland flow on the lag time were not investigated, and are left for future research.

7.1.3 GIS-based Hydraulic Geometry Extraction

HEC-GeoRAS is an excellent tool for integrating hydraulic modeling tools in the GIS domain. The methodology is easy to follow, and allows the user flexibility in optimizing the location and orientation of channel cross-sections to obtain the most realistic hydraulic profile for a given stream.

The main conclusion to be drawn from this portion of the research is that the extent and number of cross-sections extracted from GIS varies with the size of the flow and subsequent river stage generated from a particular storm event. Initially, at Pecan Bayou, numerous cross-sections were created in HEC-GeoRAS because it was assumed that the river stage resulting from the Christmas 1991 flood would not extend much beyond the banks of the bayou. However, because this storm was so extreme, it yielded a floodplain that extended much further than originally anticipated. Therefore, it was necessary to create fewer cross-sections at major terrain changes, but these cross-sections extended much beyond the extents of the original cross-sections. This rationale was presented in Chapter 5.

7.1.4 FLOODPLAIN DELINEATION

HEC-GeoRAS was used to extract water surface profile data from HEC-RAS and incorporate it into a floodplain map in GIS. The *postRAS* menu in ArcView is user-friendly and is capable of processing multiple water surface profiles simultaneously, allowing the user to observe and compare the effects of different storm return periods on the surrounding terrain at one time. However, limitations do exist in the HEC-GeoRAS floodplain mapping algorithms. When converting the floodplain and terrain TINs to grid format, there is a maximum number of cells (10 million) that can be processed by the HEC-GeoRAS scripts. It is most advantageous to use the smallest cell size possible to display the floodplain grid but, for large floodplains, the total number of cells dictates the selection of the rasterization cell size to be used. Therefore, it is possible for large floodplains, such as Pecan Bayou, to have the resulting floodplain grid in a less-than-desirable cell size (in this case, 10 meters as opposed to 1 meter).

Additional conclusions to be drawn are best considered in light of the accuracy of the DTM. Terrain data is the most critical aspect of an accurate floodplain model, especially when considering small watersheds and floodplain areas such as those existing at Castleman Creek. Significant work was undertaken at this site to interpolate cross-sections that were, at most, 100 meters apart; however, this interpolation was based on linear algorithms and yielded erroneous results. Despite accurate data in some areas of the floodplain, inadequate data in other areas negatively impacted the resulting terrain data and subsequent floodplain map. This can be seen readily in Figure 7-3 as the jagged extents of the banks along the Castleman Creek channel.

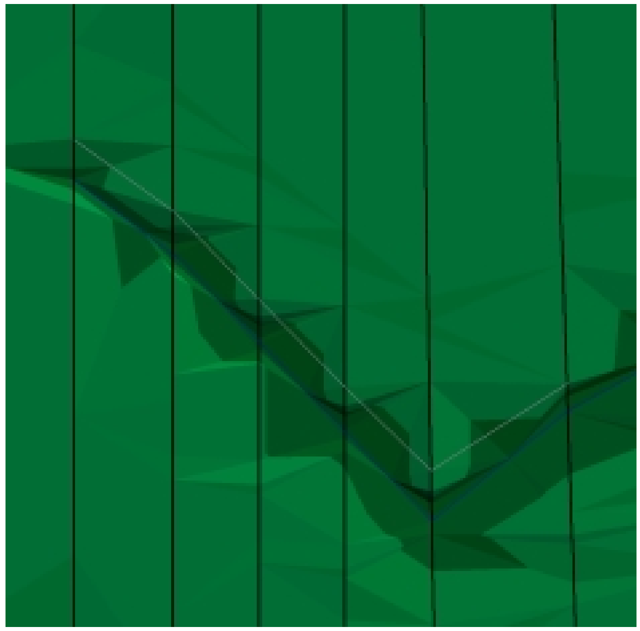


Figure 7-3 Detailed View of Castleman Creek Channel Defined by TIN

Higher resolution terrain data, or the ability to orient each cross-section perpendicular to the stream centerline, would provide a better representation of the channel banks and, ultimately, the extent of the floodplain.

7.2 Recommendations

The results of this implementation project indicate that performing terrain development, hydrologic and hydraulic modeling, and accurate floodplain delineation activities in the digital domain is becoming feasible. At the current time, the methodology for the development of a DTM for hydrologic purposes is a viable alternative to more dated manual procedures. Similarly, the integration of well-known one-dimensional hydrologic and hydraulic models (such as HEC-HMS and HEC-RAS) with GIS has become accepted in the engineering community, and can provide a more accurate representation of discharge and stage due to the consideration of spatially variable hydrologic and hydraulic parameters. In addition, the time and resource savings afforded by completing modeling in the digital domain are advantageous.

However, the results of the research and conclusions drawn from these results indicate that additional work must be accomplished in several areas of the methodology. Future research in these areas is necessary to move floodplain delineation in GIS from a general planning tool to a more accurate emergency management and response tool by providing floodplain-mapping capabilities at significantly higher resolutions (i.e., resolutions necessary for road closure evaluations and flood damage analyses).

7.2.1 DETERMINATION OF LONGEST FLOWPATH

The use of GIS for subbasin flowpath determinations (and the subsequent calculation of lag time) has yielded suspect results. Although other factors, such as spatially variable curve numbers and method of lag time calculation, also contributed to lag time discrepancies between the Castleman Creek model and that developed by TxDOT, further research into the effects of runoff quantity on the calculation of flowpath in the GIS domain would be invaluable in estimating the rainfall-runoff response of watersheds contributing flow to highway drainage structures.

7.2.2 UNCERTAINTY IN TERRAIN DATA

The lack of adequate terrain data for floodplain delineation greatly affects the outcome of the model. Research into the effects of the uncertainty involved with digital terrain data development, whether in raster or vector format, would give engineers and planners additional information on the applicability of floodplain mapping in GIS to real-world scenarios. There is a definite need to quantify this uncertainty in the terrain data before understanding the impacts of the water surface profiles generated by a hydraulic model.

7.2.3 CHANNEL CROSS-SECTION DEVELOPMENT IN GIS

Although CRWR-FloodMap is an effective tool for georeferencing cross-section data extracted from HEC-RAS, further research is warranted to develop non-linear interpolation algorithms for cross-sections that can be implemented within the GIS framework to temporarily forego the need for high-resolution elevation data within the floodplain. Similarly, the effects of tortuosity on the number of interpolated cross-sections should also deserve additional attention. By integrating cross-section interpolation into GIS, the correct orientation and location of cross-sections can be maintained, which is critical in developing an accurate representation of the topography of the overbanks and floodplain. This will also minimize the effects of cross-sections that may intersect in areas where the stream flowpath is tortuous.

7.2.4 SELECTION OF ADDITIONAL TERRAIN DATA

Figure 7-2 provides a summary of the data selection process for floodplain delineation. If deficiencies are observed during the data selection and prioritization process, a determination must be made of what additional data is needed and what resolution will be adequate for floodplain delineation activities. A solution to this problem is the use of aerial photogrammetric surveys at highway river crossings. Current TxDOT practices encourage aerial surveys that provide high-resolution elevation data along the road and adjacent terrain prior to detailed design. This procedure should be modified to include the expected extent of the floodplain for the design storm at a minimal cost to TxDOT. Preliminary hydraulic modeling should be conducted to determine the backwater effects of drainage structures, and the area impacted by the backwater included in the cost of aerial surveys prior to detailed hydraulic analyses. Further research is therefore necessary to determine the optimum resolution needed to achieve desired floodplain mapping objectives at the drainage structure prior to detailed design activities.