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Visual Floodplain Modeling with Geographic Information Systems (GIS)

by

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Abstract

Visual Floodplain Modeling with Geographical Information Systems (GIS)

by

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This research involves the integration of the HEC Hydrologic Modeling System (HEC-HMS) and HEC River Analysis System (HEC-RAS) with Geographic Information Systems (GIS) to develop a regional model for floodplain determination and representation.

The Corps of Engineers who have traditionally been the leaders in flood studies and research, using the HEC-HMS hydrologic model and the HEC-RAS hydraulic model developed at their Hydrologic Engineering Center (HEC). These models perform relatively well but lack the necessary visual representation aspect and still force many to plot computed elevations on paper maps- a tedious and time consuming task that has the potential for error. In addition, the data for these models requires a great deal of field

gathering of detailed terrain information. These shortcomings have ramifications that affect the timing and costs of studies.

Recent developments in Geographic Information Systems (GIS)–based tools can alleviate some of these shortcomings. Developments in GIS applications allow it to work in conjunction with hydrologic and hydraulic models thus reducing the need for field survey data and making the floodplain mapping process more automated and visual.

The Center for Research in Water Resources at the University of Texas at Austin is a leader in this area of floodplain modeling and mapping research. This ongoing research is applied to Mill Creek, a study currently being conducted by the Louisville Corps of Engineer District in Hamilton County in southwestern Ohio

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1 Introduction

"Around the world, unruly rivers have long driven a hard bargain. In exchange for rich soil, irrigated land and convenient transportation, they have forced floodplain dwellers to deal with an occasional washout. Engineers have labored for thousands of years to lessen the risk, but their attempts at managing Mother Nature have been mixed -- often resulting in as much failure as success" (NOVA Online Adventures) (http:www.pbs.org/wgbh/nova/flood/).

Although engineers continue to battle Mother Nature, the advance of technology is turning the tide of the struggle. However, limitations still exist. For example, the Corps of Engineers who have traditionally been the leaders in flood studies and research, using the *HEC Hydrologic Modeling System* (HEC-HMS) hydrologic model and the *HEC River Analysis System* (HEC-RAS) hydraulic model developed at their Hydrologic Engineering Center (HEC). These models perform relatively well but lack the necessary visual representation aspect and still force many to plot computed elevations on paper maps- a tedious and time consuming task that has the potential for error. In addition, the data for these models requires a great deal of field gathering of detailed terrain information. These shortcomings have ramifications that affect the timing and costs of studies. The data collection process is tedious and time consuming, while the lack of convincing visual results often causes difficulty when trying to sell a particular project where cost is shared 50/50 by local sponsors and the federal government.

Recent developments of Geographic Information Systems (GIS)–based tools can alleviate some of these shortcomings. The literature review in this report reveals how certain GIS applications can work in conjunction with hydrologic

and hydraulic models. This combination of GIS and modeling reduces the need for field survey data and makes the floodplain mapping process more automated and visual.

The Center for Research in Water Resources at the University of Texas at Austin is a leader in this area of floodplain modeling and mapping research. This research involves the integration of HEC-HMS and HEC-RAS with GIS to develop a regional model for floodplain determination and representation.

This ongoing research is applied to a study currently being conducted by the Louisville Corps of Engineer District in Hamilton County in southwestern Ohio.

1.1   Objectives

The purpose of this research is to validate existing floodplain determination and visualization tools developed at CRWR and apply them on a project scale in to assist the Louisville Corps of Engineer District and familiarize them with existing and emerging technologies. To accomplish this task, several goals must be met which include:

- Conduct Watershed Delineation Using Geographic Information Systems (GIS).

- Prepare Basin Model for Use in the Hydrologic Modeling System (HEC-HMS).

- Calibrate the HEC-HMS Hydrologic Model.

- Import HMS Results (Peak Discharges) into the River Analysis System (HEC-RAS).

- Generate RAS Water Surface Profiles.

- Create Triangular Irregular Network (TIN)

- Develop a Visual Floodplain Representation.

The figure below illustrates the use of GIS to obtain the schematic and the parameters required by HEC-HMS. The figure also shows how HEC-HMS uses the information imported from ArcView and generates the flow discharge values at time intervals that HEC-RAS needs. HEC-RAS generates water surface profiles from the flow discharges and the geometric data. RAS generates a file that allows the transfer of cross section data to include the parameters that delineate the water surface profile for use in GIS. Once imported into GIS, these profiles help define the flooded areas for floodplain visualization.
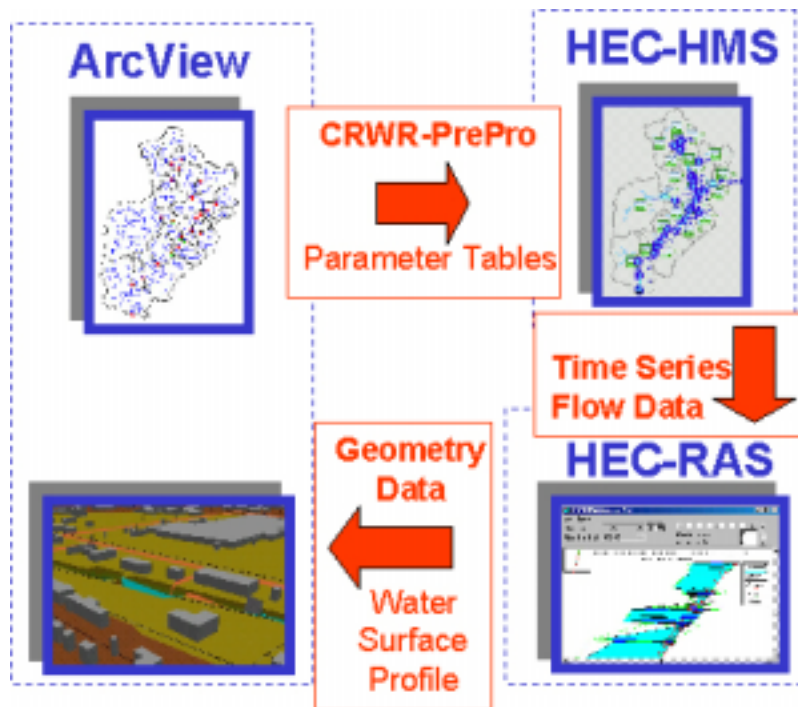
Figure 1-1. Floodplain Visualization Methodology.

1.2 Study Area

The study area is located in Hamilton County in southwestern Ohio. Mill Creek flows from the southeastern part of Butler County in a southerly direction across Hamilton County and through the City of Cincinnati to its confluence with the Ohio River at approximately river mile 472.5. The total fall in elevation of the thalweg from the headwaters of Mill Creek to the mouth, over a distance of approximately 28 stream miles, is about 250 feet, with an average gradient of 0.18%.
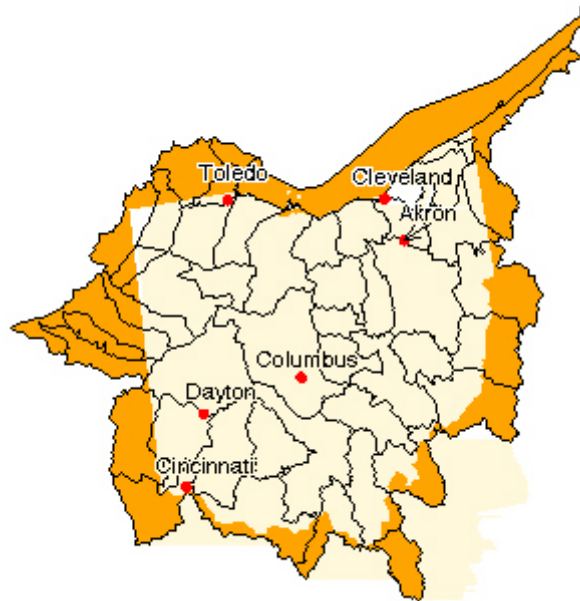
Figure 1-2. Ohio Watersheds.

Figure 1-3. HUC 05090203.
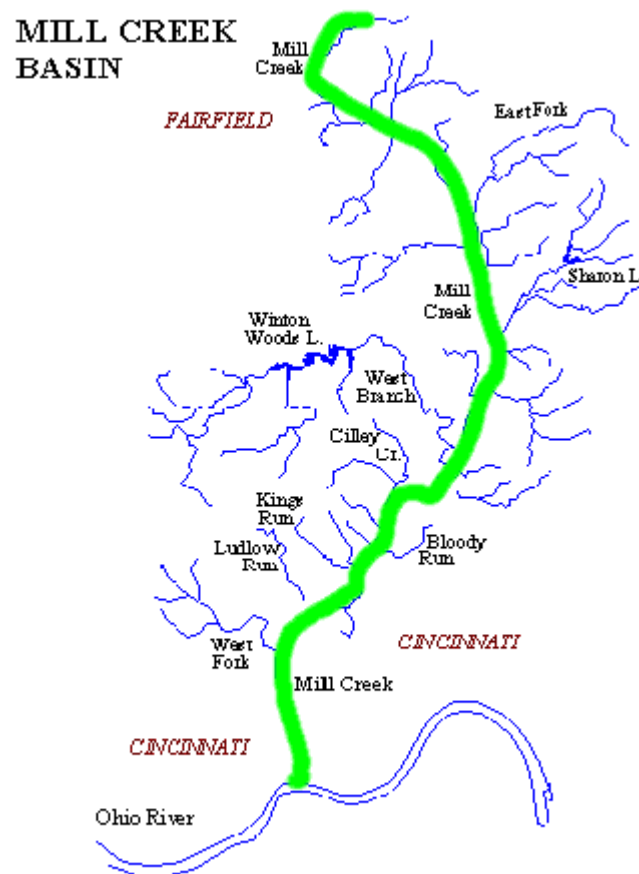
Figure 1-4. Mill Creek Location.

The Mill Creek watershed is approximately 165 square miles in area. In the upper half of the basin the valley bottom is wide, averaging 1-1/2 miles, but it narrows in the downstream reaches, averaging only ½ mile through the City of Cincinnati. In the lower portions of the basin, valley walls are steep, rising 200 to 300 feet above the valley floor, but are much less steep in the upstream areas. In 1996, the environmental interest group, American Rivers, designated Mill Creek as the most threatened urban stream in North America (Mill Creek Study, 1999).

1.3   Literature Review

Recent advances in GIS technology in the 1990s have improved the capabilities of existing hydrologic and hydraulic models. Jenson and Dominique (1988) and Jensen (1991) suggested an approach to delineate watershed boundaries and stream networks using geographic information extracted from digital elevation models (DEM). Later their work appeared in the form of ArcView extensions Spatial Analyst and Watershed Delineator distributed by ESRI.

Hellweger and Maidment (1997) accomplished an important advance in the integration of hydrologic models and GIS, with the development of a GIS-based tool named HECPrePro. HECPrePro is a compilation of Arc/Info Language scripts (AMLs) and Avenue to pre-process and export spatial data into HEC-HMS. Soon thereafter, Maidment, Olivera and Reed (1998) developed CRWR-PrePro.

The linking of hydraulic models and GIS has resulted in various tools, which allow for the display and analysis of floodplain maps in GIS. Beavers (1994) created ARC/HEC2 to connect the HEC-2 hydraulic model with Arc/Info. This

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interface is built on AML and C code and extracts terrain information from contour coverages and exports the data into HEC-2. Once the HEC-2 execution is complete it prepares an Arc/Info-based floodplain representation.

Hydraulic modeling requires stream channel detail that is not found in a digital elevation model (DEM). Although DEMs provide sufficient data for watershed delineation purposes, they lack the accuracy required within the stream channel. The degree of detail is available in a Triangular Irregular Network (TIN). TINs can be generated in ArcView from a DEM but will lack the necessary detail of the channel. Tate (1999) approached this problem by developing a methodology that integrates the existing hydraulic model (HEC-RAS) geometry data with GIS-based coverages to create TIN models.

The research presented in this report validates this evolution of floodplain mapping methodology.

Figure 1-5. Example Of Digital Terrain Representation.

1.4   Structure of Report

The research detailed in this report documents an approach for visual floodplain modeling. The report is divided into ten chapters. Chapter 1 provides an introduction to the study area and a review of the related literature. Chapter 2 is a discussion of the data used for the analysis. Chapter 3 outlines the technical capabilities of the computer programs used during the research. Chapters 4 through 9 detail the procedure of application of these data and programs to the study area. Chapter 10 includes a discussion of the results and conclusions and recommendations. Appendix A presents the Carthage USGS Gage data used for calibration of the hydrologic model. Appendix B describes the recording precipitation gages within the study area. Appendix C presents the stream parameter data used in calibration of the hydrologic model. Appendix D specifies the watershed parameters used in calibration of the hydrologic model. Appendix E details the cross section data used to refine stream velocity in the hydrologic model. Appendix F presents the Mill Creek Wastewater Treatment Plant flow data for April 15 and 16th 1998. Appendix G provides a data dictionary describing the digital data used in the project.

2 Data Discussion

Data models are central to the application of information technology because they are the means by which the real world is represented inside a computer. The following data discussion explains how we use different types of data in a logical sequence to replicate real world conditions as it is modeled in this research. The figure below shows the sequence. The first section focuses on the Geospatial Data that is used to represent the terrain and water in ArcView GIS to build a hydrologic model for use in HEC-HMS. This hydrologic representation imported into HMS is then combined with precipitation data and control specifications to create flow and time series data for use in a Hydraulic Data Model HEC-HMS. The flow and time series data from HMS is imported into the hydraulic model HEC-RAS along with its geometry data to develop water surface profiles. To close the loop, data is then once again used in ArcView from HEC-RAS to create a visual model. The use of the data presented here is described in Chapters 4 through 9.
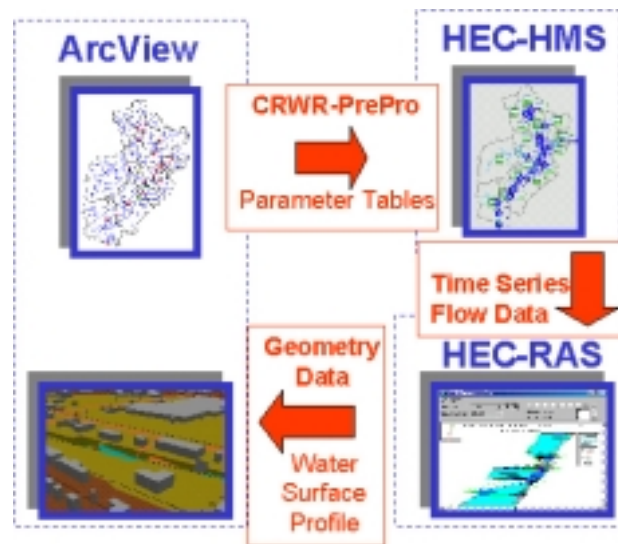
Figure 2-1. Flow of Data for Floodplain Mapping.

2.1   Geospatial Data (ArcView GIS)

Geospatial data is a collection of themes that represent information about the earth. ARC/INFO and ArcView GIS are built on a fundamental geographic data model that links the spatial representation of the location of geographic features with a tabular description of their attributes. The model can be implemented in a discrete space representation using vector objects (points, lines, and polygons), or continuous space representation as a raster grid.

2.1.1   Vector Objects

Vector objects include three types of elements: points, lines, and polygons. A point is defined by a single set of Cartesian coordinates [easting(x), northing(y)]. A line is defined by a string of points in which the beginning and end points are called nodes, and intermediate points are called vertices. A straight line consists of two nodes and no vertices whereas a curved line consists of two nodes and a varying number of vertices. Three or more lines that connect to form an enclosed area define a polygon.

Vector feature representation is typically used for linear feature modeling (roads, lakes, etc.), cartographic base maps, and time-varying process modeling (Tate, 1998).

2.1.2   Raster

The raster data structure consists of a rectangular mesh of points joined with lines, creating a grid of uniformly sized square cells. Each cell is assigned a numerical value that defines the condition of any desired spatially varied quantity. Grids are the basis of analysis in raster GIS and are typically used for steady-state spatial modeling and two-dimensional surface representation.

A land surface representation in the grid domain is called a digital elevation model (DEM) (Tate, 1998).

2.1.3 Raster-vector Data Model

The easiest way to understand the close association between different kinds of spatial objects is to use the hydrologic cycle where water moves through a network of connected flow systems.
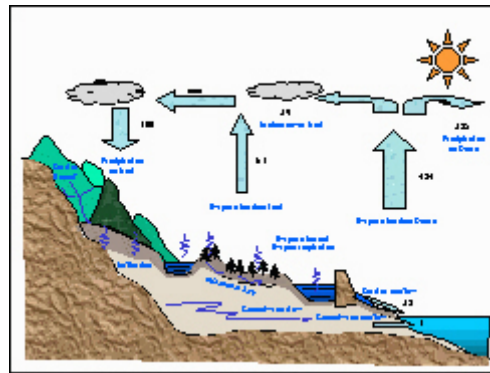
Figure 2-2. Hydrologic Cycle. Source http://campus.esri.com/index.cfm?theme=usa.

In this cycle, a watershed (polygon feature) has an associated stream segment (line feature) and drains to an outlet (point feature). These features are vector data models - establishing associations are difficult due to the different spatial formats. To establish an association, a grid format is used in a raster data model, which allows these objects to be overlaid cell by cell. The raster data model allows one to visualize the spatial object relationships and permits a cell-based calculation. Note that vector data models do have some advantages over raster data models. Vector data models are precise, have good analytic capability, and make storing and transferring data easier.

For complex hydrologic processes, an external hydrologic modeling system is required for a thorough characterization. Representation of hydrologic

features in GIS provides the spatial data support for external hydrologic models such as the Hydrologic Modeling System (HEC-HMS).

The relationship between raster and vector data models is extremely important. There is a one-to-one correspondence between the raster and vector representation of each hydrologic feature that allows users to switch back and forth between the two formats depending on what of analysis they want to perform. This is called a raster-vector data model which is defined as a set of related data structures in both raster and vector formats in which geographic features are represented for purposed of hydrologic modeling and analysis.
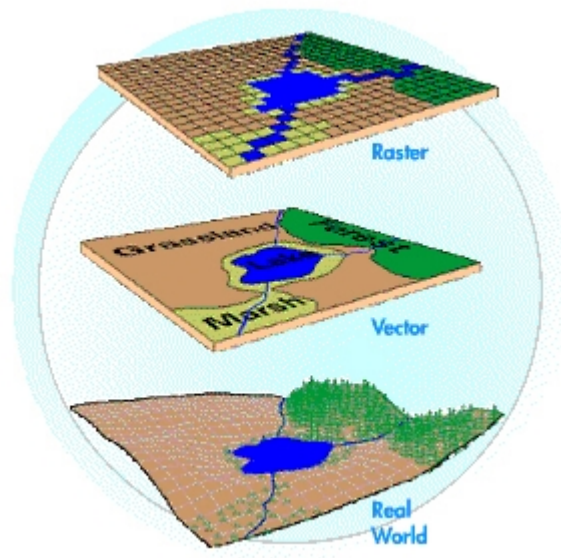
Figure 2-3. Raster-Vector Data Model. Source:
http://campus.esri.com/index.cfm?theme=usa.

2.1.4 Georeferencing the Data

Raster and vector data for use in GIS is readily available in the United States on the Internet at little or no cost to users. The data can be downloaded from

the USGS and EPA websites found below in section 2.1.6. The key to finding the required data is the knowing the required hydrologic unit.

The United States is divided and sub-divided into successively smaller hydrologic units which are classified into four levels: regions, sub-regions, accounting units, and cataloging units. The hydrologic units are arranged within each other, from the smallest (cataloging units) to the largest (regions). Each hydrologic unit is identified by a unique hydrologic unit code (HUC) consisting of two to eight digits based on the four levels of classification in the hydrologic unit system.

The first level of classification divides the Nation into 21 major geographic areas or regions. These geographic areas contain either the drainage area of a major river, such as the Ohio region, or the combined drainage areas of a series of rivers. Eighteen of the regions occupy the land area of the conterminous United States. Alaska is region 19, the Hawaii Islands constitute region 20, and Puerto Rico and other outlying Caribbean areas are region 21.

The second level of classification divides the 21 regions into 222 subregions. A subregion includes the area drained by a river system, a reach of a river and its tributaries in that reach, a closed basin(s), or a group of streams forming a coastal drainage area.

The third level of classification subdivides many of the subregions into accounting units. These 352 hydrologic accounting units nest within, or are equivalent to, the subregions.

The fourth level of classification is the cataloging unit, the smallest element in the hierarchy of hydrologic units. A cataloging unit is a geographic area representing part of all of a surface drainage basin, a combination of drainage

basins, or a distinct hydrologic feature. These units subdivide the subregions and accounting units into smaller areas. There are 2150 Cataloging Units in the Nation. More detals on hydrologic can be found at the followoing link http://water.usgs.gov/GIS/huc.html. Mill Creek falls within HUC 05090203.

2.1.5 Preparing Files For Data Storage

Before beginning a download, two folders must be created. For practical purposed, the two folders in this work were named Data and Millcreek. The Data folder is used to store all downloaded files and .zip files. This folder ensures that a clean copy of the data remains preserved in case it is needed later. The Millcreek folder is the project-working directory. All necessary project files are copied or extracted to this folder from the Data folder. Within the Millcreek folder a tmp folder must also be created as required by CRWR-PrePro. Once the data is downloaded in zip format to the data folder, it should then be extracted to the project-working directory.

2.1.6 Data Available For Download

The EPS's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) website at http://www.epa.gov/OST/BASINS/ is mainly for using GIS to assess point and nonpoint pollution sources, but it is a great source of GIS data for download. At the site, go to **Download/Basins GIS Data**. From the United States map, select Ohio. The next page displays the HUCs of Ohio, where the general location of Mill Creek can be selected. The Middle Ohio-Laughery HUC 05090203 page links to three data downloads including:

BASINS Core Data (05090203_core)

The following is a list of shapefiles that come bundled in the Data file. The files that were used have an asterisk at the end of the entry. Additional shapefiles were received from the Louisville district that included buildings, railroads, and levees.

- Land use/land cover*

- Urbanized areas*

- Populated place locations

- Soils (STATSGO)*

- Major roads*

- USGS hydrologic unit boundaries (accounting unit, cataloging unit) *

- Drinking water supply sites

- Dam sites*

- EPA regional, state, and county boundaries

- Federal and Indian Lands

- Ecoregions

- Environmental Monitoring Data

- Water quality monitoring station summaries

- Water quality observation data

- Bacteria monitoring station summaries

- Weather station sites

- USGS gaging stations*

- Fish and wildlife advisories

- National sediment inventory (NSI)

- Shellfish classified areas

- Clean Water Needs Survey

- Point Source Data

- Permit Compliance System (PCS) sites and computed loadings

- Industrial Facilities Discharge (IFD) sites

- Toxic Release Inventory (TRI) sites

- Superfund National Priority List (NPL) sites

- Resource Conservation and Recovery Act (RCRA) sites

Digital Elevation Model (DEM)(05090203_dem)

This DEM is suitable for this work, but does not provide the most recent data. The Louisville Corps of Engineer District provided the Digital Elevation Model (DEM) for this project. The DEM is a 1^0 by 1^0 seamless version made up of 30 meter by 30-meter cells.

Reach File Version 3 (RF3)(05090203_rf3)

The Rf3 files for neighboring HUCs 05090202 and 05080002 were also necessary for the procedure.

The Center for Research in Water Resources at the University of Texas at Austin produces a collection of exercises, data, reports and information designed to support the use of Geographic Information Systems in Hydrology and Water Resources annually. The data is produced in CD form and can be found at the following link.
http://internetcity.crwr.utexas.edu/gis/gishydro99/GisHyd99.htm

On the main page at the Watershed Characterization link, a number of resources can be found. Essential for watershed delineation is Prepro04.apr, which is found on this page. Prepro04.apr is an ArcView project file that contains the Scripts, Menus and Buttons for running CRWR-Prepro.

Another project file that is critical to this research is Floodmap.apr. This ArcView Project contains the scripts and menus needed for floodplain mapping. It can be retrieved at Eric Tate's website. The direct link to the file for download is:
http://www.ce.utexas.edu/prof/maidment/grad/tate/research/Floodmap/webfiles/floodmap.html The file to download is Floodmap1.zip. These project files must be downloaded and placed in the data file.

2.1.7 Setting Parameters

Raster and vector data must be projected prior to being used. Raster data requires ArcInfo to be projected while vector data can be easily projected in ArcView using the Projector extension.

A new DEM comes projected using the Geographic Coordinate System. Elevations were specified in meters. Chapter 6, Cartographic Guidelines, of

the Ohio Geographic Information Management Systems (GIMS) Program website was accessed at the following link: http://www.dnr.state.oh.us/odnr/occ/gims/hb_chpt6.as This chapter recommends Projection/Coordinate Systems that are in accordance with surveying law (ORC 157). The Ohio State Plane Coordinate System (OSPC) was chosen for this project. The OSPC System is a planer Cartesian coordinate system based on a Lambert Conformal Conic projection. Ohio has been divided into two zones, north and south, to restrict distortion to no greater than 1 in 10,000, or roughly one foot for every two miles. The input and output parameters were specified in ArcInfo by starting the program and specifying the working directory where the DEM is stored. The project command was then used, which identifies the input projection found below minus the text in parenthesis:

INPUT

PROJECTION GEOGRAPHIC

/*DATUM NAD83

ZUNITS METERS

UNITS DD

SPHEROID GRS1980

XSHIFT 0.0

YSHIFT 0.0

PARAMETERS

-85.000 (Standard Parallel 1)

-84.000 (Standard Parallel 2)

39.000 (Central Meridian)

40.000 (Reference Latitude)

Then inputting the following text into ArcInfo specified the output projection: project cover <DEM file name>

At this point, ArcInfo identified the projection above and prompted for input of the output parameters for the new file. The following text was then input minus the text in parenthesis:

OUTPUT

PROJECTION LAMBERT

/*DATUM NAD83

ZUNITS NO

UNITS METERS

SPHEROID GRS1980

XSHIFT 0.0

YSHIFT 0.0

PARAMETERS

38.733333 (Standard Parallel 1)

40.033333 (Standard Parallel 2)

-82.5 (Central Meridian)

38.0 (Reference Latitude)

600000 (False Easting)

END

This completed the projection of the DEM into the Ohio State Plane Coordinate System.

2.2   Hydrologic Data (HEC-HMS)

Each HEC-HMS project requires three data components: a Basin Model, a Precipitation Model, and Control Specifications.

2.2.1   Basin Model Data

The basin model contains data, which represents the physical system. The descriptive data is entered by the user or imported from GIS and can be edited. Such data includes specification of the hydrologic elements of which the basin model is comprised, information on how the hydrologic elements are connected, and values of parameters for the hydrologic elements. The capability to configure a basin model by "dragging-and-dropping" icons on a schematic display is provided. The element data can be edited with single-element or global editors.

A basin model consists of hydrologic elements, of which there are seven types: subbasin, routing reach, junction, reservoir, diversion, source, and sink. The development of a basin model requires the specification of such elements and data that controls their 'behavior'. Users can generally choose from alternative computational methods (e.g., routing methods for a river reach) to define such behavior (HEC-HMS Online Help, v 1.1).

For this research, the Basin Model was created using CRWR-PrePro. CRWR-PrePRo generates this information in ArcView and writes a file that is

importable into HEC-HMS. The Basin Model was built using the following spatial data:

- Digital Elevation Model representing terrain elevation for slope and area.

- River Reach Files for Stream network with junctions and diversions.

- Curve Number Grid developed from soils data and land cover/land use data for runoff determination.

- Point coverage of gage stations represented as junctions to link calibrations hydrographs.

- Stream parameters (flow velocity and Muskingum X) transferred in parameter tables.

2.2.2 Precipitation Model

The Precipitation Model is a set of information required to define historical or hypothetical precipitation to be used in conjunction with a basin model. Types of hypothetical storm include frequency-based and the Corps of Engineers' Standard Project Storm. Frequency-based storms require that the user provide rainfall depths for various durations.

	Duration							
Return Pd	5 min	15 min	1-hr	2-hr	3-hr	6-hr	12-hr	24-hr
	5	15	20	120	180	360	720	1440
2-yr	0.34	0.77	1.34	1.66	1.83	2.14	2.49	2.86
5-yr	0.42	0.94	1.64	2.02	2.23	2.62	3.04	3.49
10-yr	0.48	1.08	1.88	2.31	2.55	2.99	3.47	3.99
25-yr	0.56	1.27	2.21	2.73	3.01	3.52	4.09	4.70
50-yr	0.64	1.44	2.50	3.09	3.40	3.99	4.63	5.33
100-yr	0.72	1.63	2.84	3.50	3.87	4.53	5.25	6.04
Source: Rainfall frequency atlas of the Midwest Climate Center, Huff and Angel 1999.								

Table 2-1. Frequency-based Precipitation Data.

Several options exist for specifying historical precipitation: (1) utilize cell-
based precipitation as required for the Modified Clark method; (2) import
previously determined spatially-averaged precipitation; (3) specify gages and
their locations and weights and locations of index nodes, to be used in an
automated inverse distance-weighting; or (4) specify gages and associated
weights (e.g., from Thiessen polygons). The latter method is the method
used in this research. Below is an example of the incremental precipitation
plot that results from the input of recording gage data. The data for all 8
gages is in Appendix B.
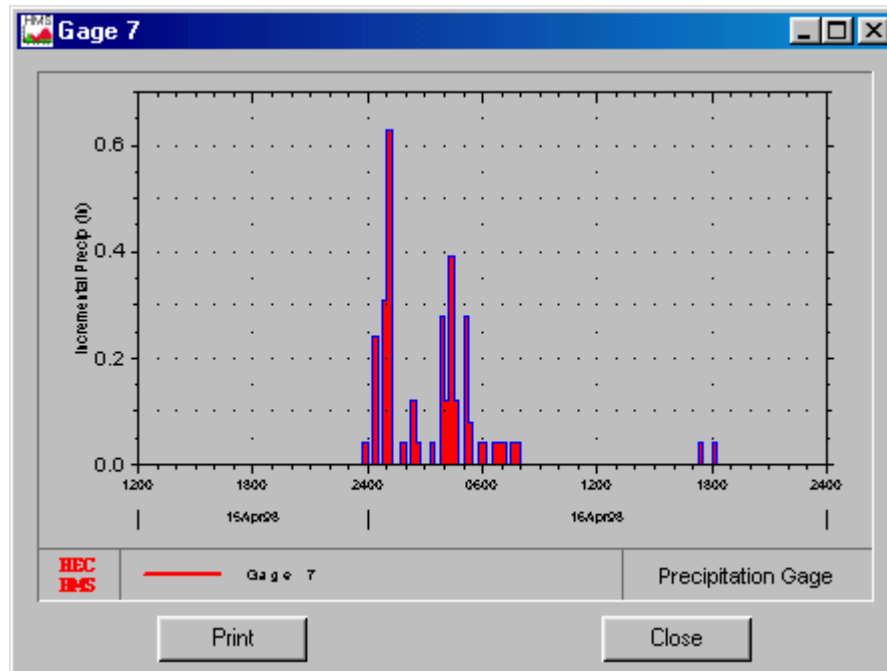
Figure 2-4. Mill Creek WWTP Precipitation Gage Data.

With this option, weighting factors (Thiessen-type) are specified to be applied to gaged precipitation to calculate spatially averaged precipitation for subbasins. The USER-SPECIFIED GAGE WEIGHTS screen contains a "notebook" with three tabs. The first tab, labeled Gages, provides for specification of a gage ID, gage type, total storm depth, and index precipitation for each precipitation gage (both recording and non-recording). The second tab, Subbasins, provides for the addition of subbasins to the precipitation model and allows for specification of index precipitation for each subbasin. The optional specification of index precipitation for subbasins and precipitation gages enables adjustment for bias in gage-precipitation values. The third tab, Weights, specifies both the total-storm weight and temporal-distribution weight for each gage (HEC-HMS Online Help, v 1.1). The precipitation model is complete when the data from all 8 gages is entered in the three tabs discussed above.

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2.2.3 Control Specifications

Lastly, the Control Specifications define time-related information for a simulation, including the starting and ending dates and the time interval for computations. The function of control specifications is to set the starting and ending dates and times and time (computation) interval (HEC-HMS Online Help, v 1.1).

A variety of styles are available for entering starting and ending dates. The month designation is not case sensitive. Months may be specified with the first three characters of the month name. The following are examples of valid entries for dates:

> 01MAR72

> 1 March 1972

> March 1, 1972

Time is specified as a four-digit number representing 24-hour clock time. A colon after the first two digits is optional. The following are examples of valid entries for times:

> 0100

> 13:30

(HEC-HMS Online Help, v 1.1)

2.3 Hydraulic Data (HEC-RAS)

The data files for a HEC-RAS project are categorized as follows: plan data, geometric data, steady flow data, unsteady flow data, sediment data, and

hydraulic design data. For the purposes of this research, only the first three data files were used.

2.3.1 Geometry Data

Cross section data represent the geometric boundary of the stream. Cross sections are located at relatively short intervals along the stream to characterize the flow carrying capacity of the stream and its adjacent floodplain. Cross sections are required at representative locations throughout the stream and at locations where changes occur in discharge, slope, shape, roughness; at locations where levees begin and end; and at hydraulic structures (bridges, culverts, and weirs).

The required information for a cross section consists of: the river, reach and river station identifiers; a description; X & Y coordinates (station and elevation points); downstream reach lengths; Manning's roughness coefficients; main channel bank stations; and contraction and expansion coefficients. The Louisville Corps of Engineer District provided the geometry data for this research. The cross-section information was gathered either from a physical survey or taken form topographic maps and then entered manually (HEC-RAS Online Help, v 2.2).

2.3.2 Flow Data

Once the geometric data is entered, the necessary flow data can be entered. Steady Flow Data consist of: the number of profiles to be computed; the flow data; and the river system boundary conditions. At least one flow must be entered for every reach within the system. Additionally, flow can be changed at any location within the river system. Flow values must be entered for all profiles. Flow values can be imported directly from the HEC-HMS run for different hypothetical design storms. The HMS flow data at the junctions is

referenced to a corresponding cross-section in RAS and then imported (HEC-RAS Online Help, v 2.2). The HMS flow data was used in RAS for this research. The flows were taken at the time of peak flow for the Carthage gage and imported into RAS.

Boundary conditions are necessary to establish the starting water surface at the ends of the river system (upstream and downstream). A starting water surface is necessary in order for the program to begin the calculations. In a subcritical flow regime, boundary conditions are only necessary at the downstream ends of the river system. If a supercritical flow regime is going to be calculated, boundary conditions are only necessary at the upstream ends of the river system. If a mixed flow regime calculation is going to be made, then boundary conditions must be entered at all ends of the river system.

The boundary conditions editor contains a table listing every reach. Each reach has an upstream and a downstream boundary condition. Connections to junctions are considered internal boundary conditions. Internal boundary conditions are automatically listed in the table, based on how the river system was defined in the geometric data editor. The user is only required to enter the necessary external boundary conditions (HEC-RAS Online Help, v 2.2). The boundary condition used was critical depth for the downstream boundary. This is explained in greater detail in section 4.6.4.

2.3.3 Plan Data

Usually the first step in performing a simulation is to put together a Plan. The Plan defines which geometry and flow data are to be used, as well as provide a description and short identifier for the run. If the geometry and flow data do not exist, then this action is performed after their creation. Also included in the plan information are the selected flow regime and the simulation options.

The user can select between subcritical, supercritical, or mixed flow regime calculations (HEC-RAS Online Help, v 2.2).

2.4   Floodplain Visualization Data (ArcView GIS)

The determination and visualization of flooded areas in ArcView requires a detailed representation of actual conditions to accurately identify the structures and facilities affected by the water within a floodplain.

To replicate a detailed floodplain, a digital representation of the terrain (DEM) is necessary to build a Triangular Irregular Network (TIN). Additionally, feature themes such as buildings, roads, railroads, and levees help to improve the visualization of the flooded areas. The most effective representation is the TIN with the above features added in a 3-D perspective view. To create a TIN with precise detail, RAS cross section data is required. Below is a detailed description of what makes up a TIN. The actual processing of a TIN is discussed in Chapter 4.

TIN is an efficient way for representing continuous surfaces as a series of linked triangles. Although both grids and TINs can be used for surface representation, TINs are especially useful for representing surface elevation, subsurface elevation and terrain modeling, especially when the represented surfaces are highly variable and contain discontinuities and breaklines.

TIN components are nodes, triangles and edges. Nodes are locations defined by x, y and z values from which a TIN is constructed. Triangles are formed by connecting each node with its neighbors according to the Delaunay criterion: all sample points are connected with two neighbors to form triangles (by using this method the triangles are as equi-angular as possible, any point on the surface is as close as possible to a node, and the triangulation results are

independent of the order the points are processed). Edges are the sides of triangles.

TINs are generated from points, polygons and lines. Points used in defining the TIN are called mass points. Areas of constant elevation, such as water surfaces, are called exclusion polygons. Finally, lines such as streams and shorelines are called breaklines. Breaklines can be either hard or soft. Hard breaklines are features like roads, streams, and shorelines, which indicate a significant break in elevation. Soft breaklines are features like ridgelines on rolling hills.

Ridges like these represent distinct breaks in slope but not elevation. But since they separate watersheds, maintaining triangulation is recommended. When a TIN is created, mass points become nodes of triangles, while breaklines and exclusion polygon boundaries become triangle edges.

3   Modeling

This chapter discusses the modeling capabilities of the computer programs used in the research. The analysis focuses first on the GIS-based applications with CRWR-PrePro, then the hydrologic model HEC-HMS, followed by the hydraulic model HEC-RAS. Finally, the analysis returns to GIS using Floodmap to create a visual model. Below is a schematic that shows the overall process. Chapter 4 documents the step-by-step application of the computer models presented in this chapter using the data described in Chapter 2.
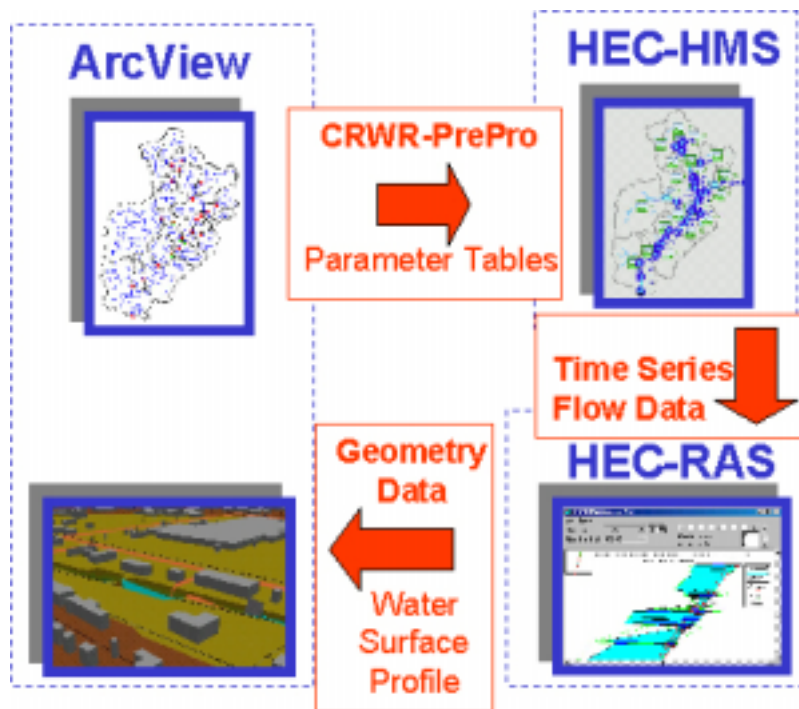
Figure 3-1. Floodplain Mapping Methodology.

3.1 HEC-HMS

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) provides a variety of options for simulating precipitation-runoff processes. In addition to unit hydrograph and hydrologic routing options similar to those in HEC-1, capabilities currently available include: a linear-distributed runoff transformation that can be applied with gridded (e.g., radar) rainfall data, a simple "moisture depletion" option that can be used for simulations over extended time periods, and a versatile parameter optimization option.

The basic framework for simulation of basin runoff is similar to that in HEC-1. Hydrologic elements are arranged in a dendritic network, and computations are performed in an upstream-to-downstream sequence.

Computations are performed with SI (Systeme International d`Unites) units. However data can be entered and viewed with units in the U.S. Customary system. The program is capable of convert input or results from one unit system to the other.

The execution of a simulation, called a "run", requires specification of three sets of data. The first, labeled Basin Model contains parameter and connectivity data for hydrologic elements. Types of elements are: subbasin, routing reach, junction, reservoir, source, sink, and diversion. The second set, labeled Precipitation Model consists of meteorological data and information required to process it. The model may represent historical or hypothetical conditions. The third set, labeled Control Specifications, and specifies time-related information for a simulation. A project is used to hold the different data sets and can contain many of each type. A project also contains at least one run and may contain many. HEC-HMS modeling results

can be used as input data for hydraulic modeling. HEC-HMS provides the following options for simulating precipitation-runoff processes:

- Several alternatives for loss determination.

- Lumped or linear distributed-runoff transformation methods.

- Hydrologic routing options.

- A powerful parameter optimization system (HEC, 1999).

3.1.1 Loss Determination

The term "losses" or "abstractions" refers to the amount of rainfall lost to the soil due to infiltration. Options for calculating losses for event simulation include initial/constant, SCS Curve Number, gridded SCS Curve Numbers, Green and Ampt, and no loss. For continuous simulation, a simple deficit/constant loss function can be used where the user specifies a soil moisture storage capacity, which must be filled before excess can occur. The capacity is filled by rainfall and depleted during rain-free periods at a user-specified monthly-average depletion rate. When the capacity is filled, loss occurs at the specified constant rate. It is planned to incorporate detailed soil moisture accounting options in future versions of HEC-HMS.

3.1.2 Runoff Transformation

Runoff transformations convert excess precipitation on a subbasin to direct runoff at the subbasin outlet. Subbasin runoff can be computed in either a lumped or linear-distributed mode. In a lumped mode, precipitation and "losses" are spatially averaged over a subbasin. In the linear-distributed mode, rainfall is specified on a gridded basis, and loss and excess are

tracked separately for each grid cell in a subbasin. Rainfall is transformed to direct runoff with the Modified Clark method.

Transformation of precipitation excess to direct runoff can be achieved with unit hydrograph or kinematic wave methods. A unit hydrograph may be specified in tabular form or in terms of parameters defined by Clark, Snyder, or SCS methods. The kinematic wave method permits definition of two rectangular overland flow planes. Runoff from an overland flow plane may be routed through one or two collector channels and a main channel with kinematic wave or Muskingum Cunge methods.

A quasi-distributed treatment of subbasin runoff can be achieved with the Modified Clark method, which is based on the Clark conceptual runoff model. In the Modified Clark method, grid cells are superposed on the basin and rainfall and losses are tracked uniquely for each cell. Rainfall excess from each cell is lagged to the basin outlet and routed through a linear reservoir. The outflows from the linear reservoir are summed and baseflow is added to obtain a total-runoff hydrograph.

3.1.3 Routing

Routing techniques replicate the conveyance of the runoff from the reaches within different subbasins to the end of the river basin. Routing options include Muskingum, Modified Puls, Kinematic Wave, and Muskingum-Cunge methods. The Kinematic Wave and Muskingum-Cunge methods may be invoked with standard geometric shapes (e.g., circle, trapezoid) or with cross sections defined with eight sets of X-Y coordinates and three Manning's n values. Capability is also provided for routing through an uncontrolled reservoir, for which a relation between outflow and storage is required. If more sophisticated routing methods are required because of complex

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boundary conditions, hydrographs may be imported for use from software such as UNET, which provides a numerical solution to the one-dimensional St. Venant equations.

3.1.4 Parameter Optimization

Once set up, a hydrologic model requires a calibration process accomplished by changing some user-defined parameters. The process can vary in difficulty depending on the number of parameters or the complexity of the network. If required, HEC-HMS provides the capability to enable automated estimation of values for calibrating purposes.

3.2 HEC-RAS

HEC-RAS is an integrated package of hydraulic analysis programs in which the user interacts with the system through the use of a Graphical User Interface (GUI). The system is capable of performing Steady Flow water surface profile calculations and will include Unsteady Flow, Sediment Transport, and several hydraulic design computations in the future. The results of the model can be applied in floodplain management and flood insurance studies.

3.2.1 Steady Flow

Steady flow describes conditions in which depth and velocity at a given channel location do not change with time. Gradually varied flow is characterized by minor changes in water depth and velocity from cross-section to cross-section. The primary procedure used by HEC-RAS to compute water surface profiles assumes a steady, gradually varied flow scenario and is called the direct step method. The basic computational procedure is based on an iterative solution of the energy equation,

$H = Z + Y + \dfrac{\alpha V^2}{2g}$, which states that the total energy (H) at any given

location along the stream is the sum of potential energy (Z + Y) and kinetic

energy $\left(\dfrac{\alpha V^2}{2g} \right)$. The change in energy between two cross-sections is called

head loss (h_L) (Tate, 1998). The energy equation parameters are illustrated

in the following graphic:
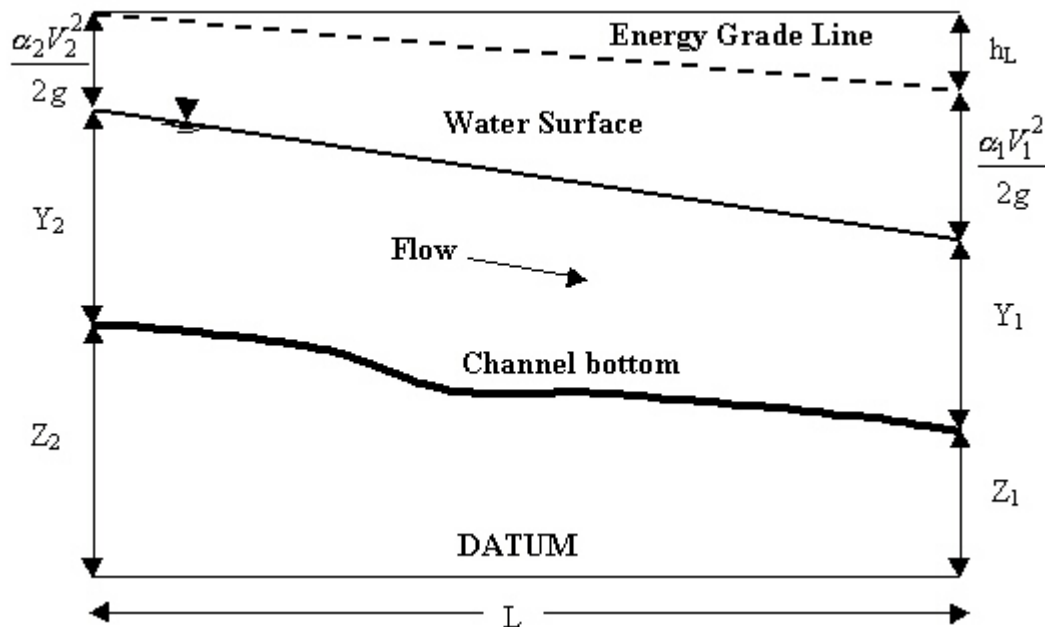
Figure 3-2. Energy Equation Parameters for Gradually Varied Flow. Source: Tate 1998.

Given the flow and water surface elevation at one cross-section, the goal of

the direct step method is to compute the water surface elevation at the

adjacent cross-section. Whether the computations proceed from upstream to

downstream or vice versa depends on the flow regime. The dimensionless

Froude number (Fr) = $\sqrt{\dfrac{V}{gY}}$ is used to characterize flow regime, where:

- Fr < 1 denotes subcritical flow

- Fr > 1 denotes supercritical flow

- Fr = 1 denotes critical flow

For a subcritical flow scenario, which is very common in natural and man-made channels, direct step computations would begin at the downstream end of the reach and progress upstream between adjacent cross-sections. For supercritical flow, the computations begin at the upstream end of the reach and proceed downstream (Tate, 1998).

3.2.2 Project Files

In HEC-RAS terminology, a Project is a set of data files associated with a particular river system. The modeler can perform any or all of the various types of analyses included in the HEC-RAS package as part of the project. The data files for a project are categorized as follows: plan data, geometric data, steady flow data, unsteady flow data, sediment data, and hydraulic design data.

3.2.3 Results

Once the model has finished all of the computations, the modeler can begin viewing the results. Several output features are available under the View option from the main window. These options include: cross section plots; profile plots; rating curve plots; X-Y-Z perspective plots; tabular output at

specific locations (Cross Section Table); tabular output for many locations (Profile Table); and the summary of errors, warnings, and notes.

3.2.3.1 Cross Section Plots

The user can plot any cross section to include bridges and culverts by simply selecting the appropriate River, Reach and River Station from the list boxes at the top of the plot. The user can also step through the plots by using the up and down arrow buttons. Several plotting features are available under the Options menu of the Cross Section plot. These options include: zoom in; zoom out; selecting which plans, profiles and variables to plot; and control over the lines, symbols, labels, scaling, and grid options.

Hardcopy outputs of the graphics can be accomplished in two different ways. Plots can be sent directly from HEC-RAS to whichever printer or plotter the user has defined under the Windows Print Manager. Plots can also be sent to the Windows clipboard. Once the plot is in the clipboard it can then be pasted into other programs, such as a word processor. Both of these options are available from the File menu on the various plot windows.

All of the options available in the cross section plot are also available in the profile plot. Additionally, the user can select which specific reaches to plot when a multiple-reach river system is being modeled.

3.2.3.2 X-Y-Z Perspective Plot

An X-Y-Z Perspective Plot is also available. The user has the option of defining the starting and ending location for the extent of the plot. The plot can be rotated left or right and up or down in order to get different perspectives of the river reach. The computed water surface profiles can be overlaid on top of the cross section data. The graphic can be sent to the

printer or plotter directly, or the plot can be sent through the Windows Clipboard to other programs.

3.2.3.3 Tabular Output

Tabular output is available in two different formats. The first type of tabular output provides detailed hydraulic results at a specific cross section location (cross section table). The second type of tabular output shows a limited number of hydraulic variables for several cross sections and multiple profiles. There are several standard tables that are pre-defined and provided to the user under the Tables menu from the profile output tables. Users can also define their own tables by specifying what variables they would like to have in a table. User specified table headings can be saved and then selected later as one of the standard tables available to the project.

Tabular output can be sent directly to the printer or passed through the clipboard in the same manner as the graphical output described previously. This option is also available under the File menu on each of the table forms.

3.3   GIS-based Applications

Geographic Information Systems are computer environments where users can create, manipulate, store, and display graphical elements with associated data. GIS applications support engineering analysis in very different fields, including hydrology and hydraulics. The GIS-based applications used in this research are CRWR-PrePro and Floodmap, both working under the ArcView GIS software.

CRWR-PrePro and Floodmap are ArcView extensions created by the Center for Research in Water Resources, at the University of Texas at Austin. CRWR PrePro generates the hydrologic elements required by HEC-HMS,

including the subbasins, reaches, sources, sinks and diversions. For more information about CRWR-PrePro, the reader is referred to Olivera (1999). Floodmap is a project containing the scripts and menus needed for floodplain visualization and analysis in GIS by post-processing HEC-RAS data. Floodmap can also develop a terrain model with a density of points in the channel sufficient for hydraulic modeling. (http://www.ce.utexas.edu/prof/maidment/g…research/Floodmap/webfiles/floodmap.htm).

4 Watershed Delineation with CRWR-PrePro

This chapter details the application of Watershed Delineation in ArcView with CRWR-PrePro.
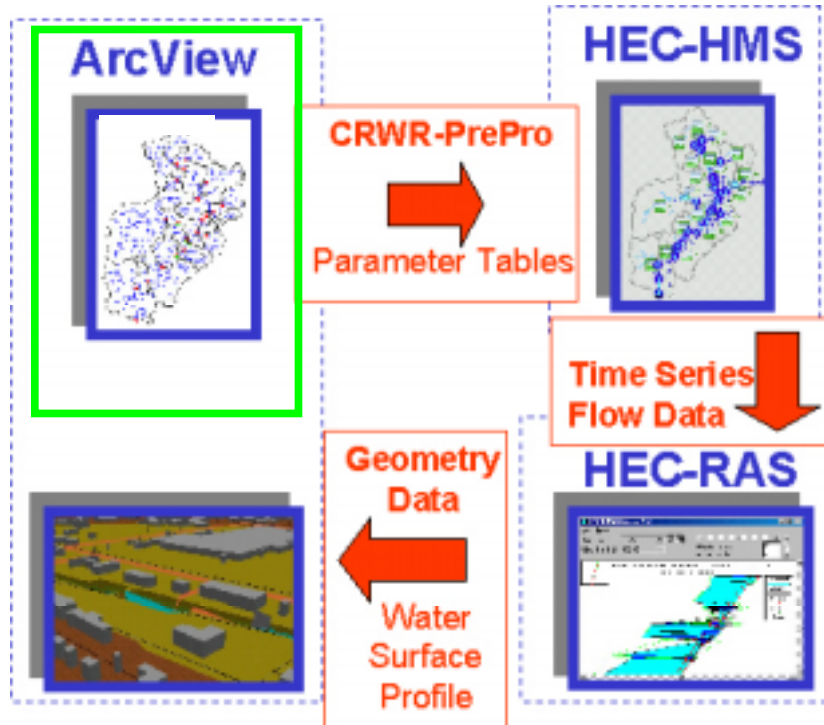
Figure 4-1. Watershed Delineation with CRWR-PrePro.

4.1 Starting ArcView

With ArcView operating, the project file prepro04.apr was opened. Two new dropdown main menus, CRWR-Prepro and CRWR-Utility are now visible. In addition, some new buttons are also visible; these new functions are implemented by Avenue Scripts. Clicking on the Scripts icon in the Project window shows the customized scripts used in this project. From the **File/Set Working Directory**, the working directory was set to **/Millcreek**. Also under

File/Extensions the following were selected: 3D Analyst, Spatial Analyst, CRWR Vector, CRWR Raster, Projector!, and Geoprocessing.

4.2   Viewing the DEM

In View1, using the Add Theme Button, Demgridp and Huc.shp were added from the **Millcreek** directory.   For Demgrip, the Data Source Type in the Add Theme Dialog box must be set to Grid Data Source and for Huc.shp it must be set to Feature Source Data.
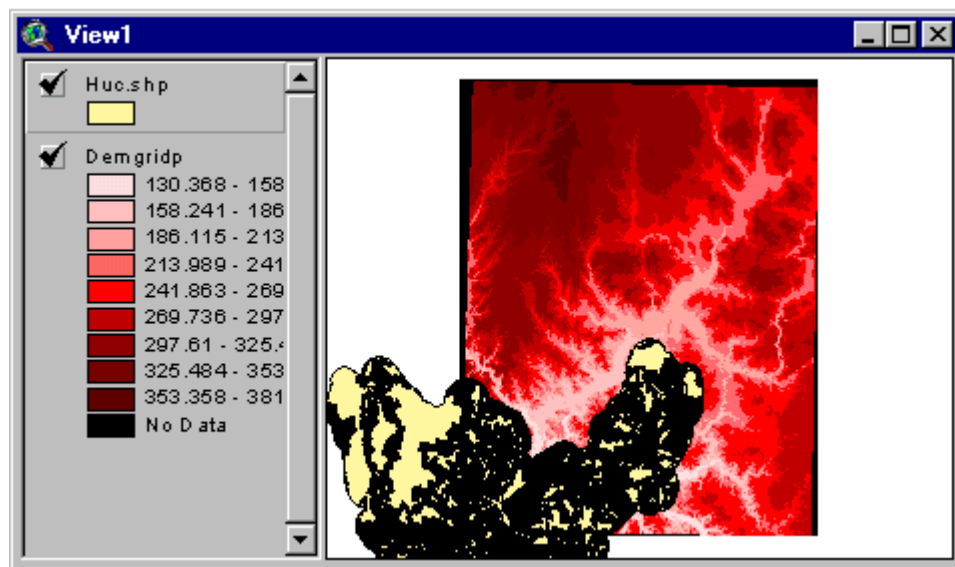
Figure 4-2. Digital Elevation Model and Hydrologic Unit Code.

From the view above, it is apparent that the HUC only covers a small portion of this DEM. Mill Creek is found in the upper right of the HUC so no other DEMs are necessary. There is no need to buffer the HUC to allow for error, the area under study is well within this HUC. It is recommended that DEMs used in CRWR-PrePro not exceed 1,000,000 cells due to the fact that certain procedures can take hours to process. The DEM above contains about 12,960,000 cells and must be reduced in size before continuing. Using CRWR-Raster and the Clip Grid by Polygon function, the necessary portion of

the DEM that matched the HUC can be clipped out. When Demgridp is the active theme, the Clip by Polygon function uses HUC.shp and performs the function. The new DEM will resemble the intersection between the DEM and polygon.

4.3 Set Analysis Extent

Before processing the DEM, the Analysis Extent must be set to tell ArcView what part of the view is to be analyzed. From **Analysis/Properties**, set the Analysis Extent at the top of the window to Same as Demgridp, and set the Analysis Cell Size in the middle of the window to Same as Demgridp. Setting the analysis extent and keeping it consistent ensures that the various grids generated in the analysis are locationally consistent with one another and their cells are the same size.

4.4 Preparing the River Reach Files

The River Reach Files must be refined before they can be used in CRWR Pre-Pro. The RF3 files from the Mill Creek HUC and two northern most HUCs must be added to the view. The purpose of adding the additional RF3 files is to ensure the watershed area for the Mill Creek Basin is reduced as much as possible to the actual area. The reaches from the neighboring HUCs must be burned in to the DEM to ensure that any runoff contributing to those reaches runs away from the Mill Creek Basin. In the view below, HUCs 05090203 (blue) and 05080002 (green) are visible. In the view, green stream segments can be seen running away from and to Mill Creek. If the segments running away are not considered, the area that contributes runoff to those segments may actually be included in the Mill Creek Watershed. Though the contribution may seem small, the aggregation across the watershed may be significant.

With the RF3 images in view, the Mill Creek segments must be inspected for larger bodies of water that are represented by their banks and not centerlines. The network should also be proofed for breaks in the streams. Shown below is an example of a lake in the upper portion of the basin. If the "Burn Streams" function were to be applied, it would burn in the banks and create two streams in the terrain. In CRWR Pre-Pro, the centerline must be drawn in lieu of the banks.
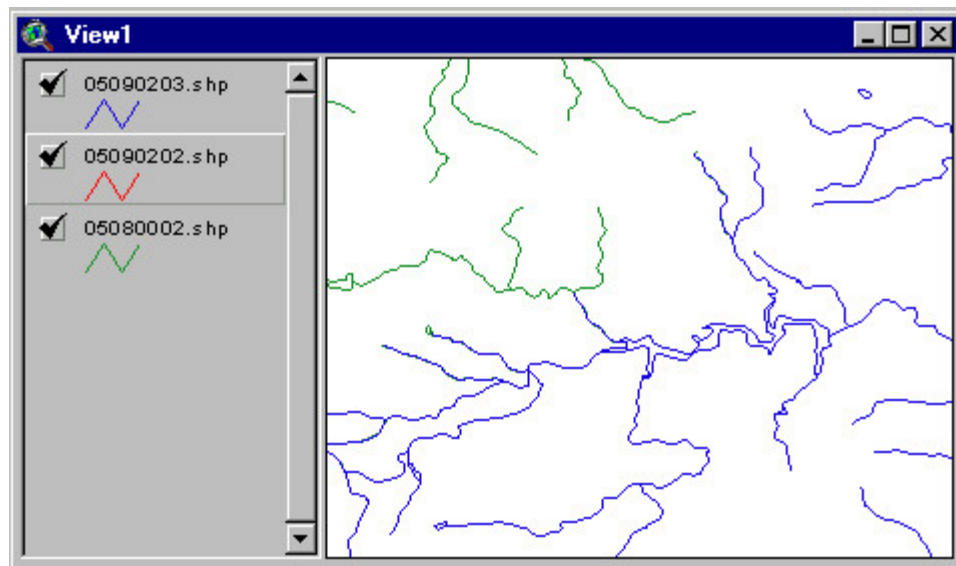
Figure 4-3. RF3 Shape File.

With the 05090203.shp theme highlighted, the query tool is accessed and the following entered. This highlights the "R" and "S" reaches as shown below so they can be saved as another shapefile for editing.
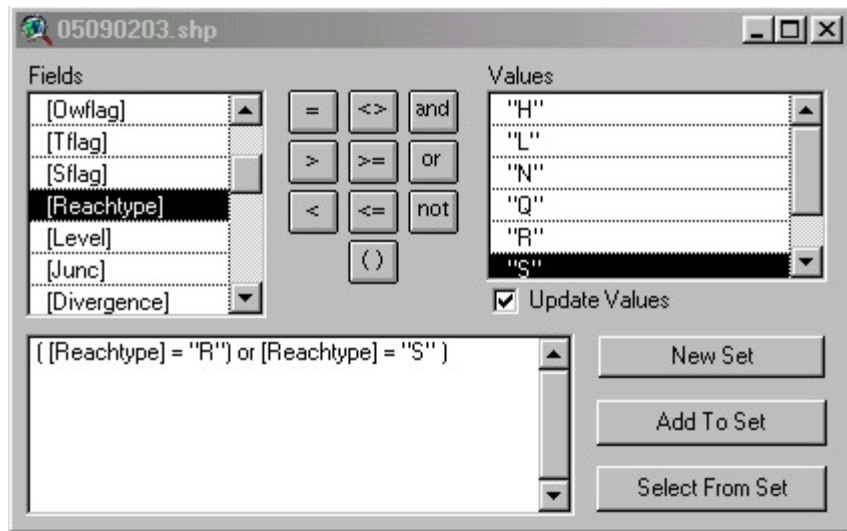
Figure 4-4. Map Calculator.
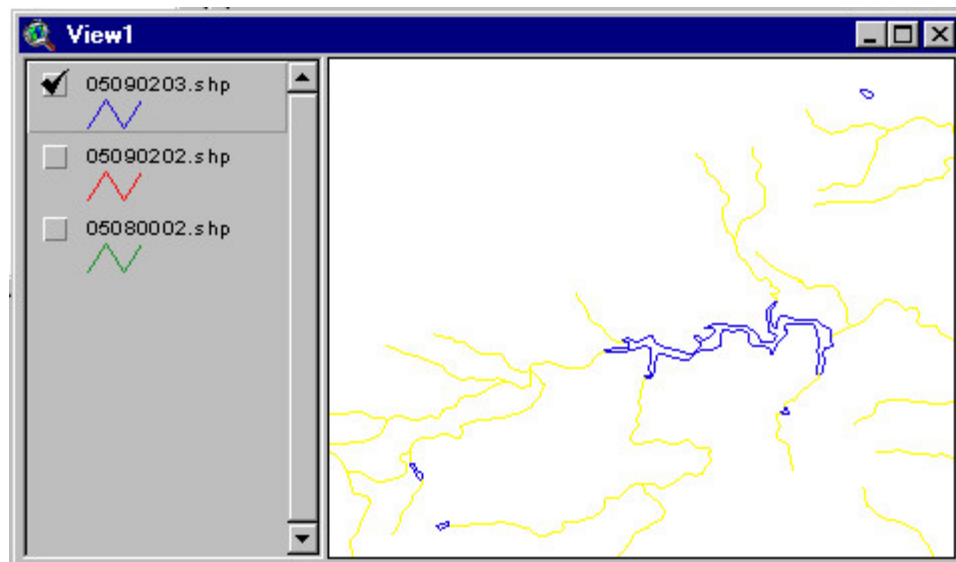
Figure 4-5. RF3 With "R", "S", and "T" Segments Selected.

Under **Theme/Convert to Shapefile,** a new RF3 theme was created called Cleanrf.shp. This theme is shown below in red on top of the original RF3 file. This is the view that was used to create the centerline of the lake. The original RF3 file was used as a guide to aid in drawing the centerline

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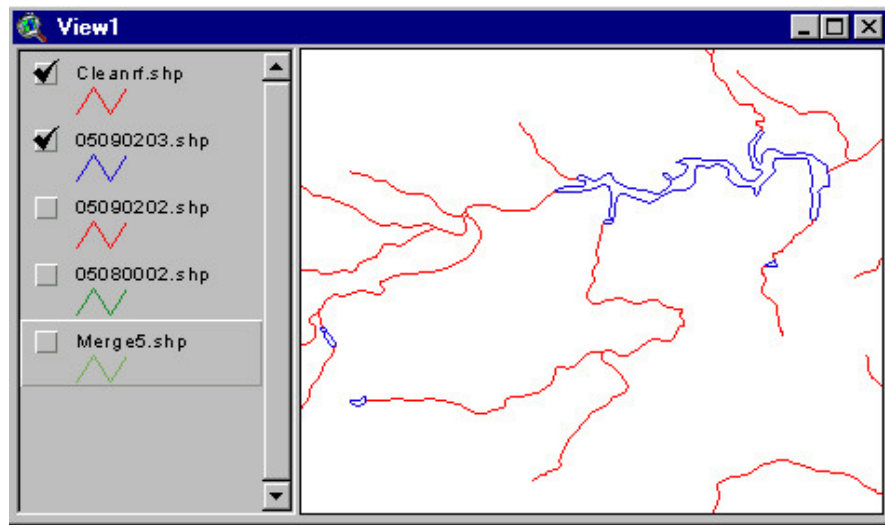
Figure 4-6. Queried RF3 File.

With the Cleanrf.shp file active, **Theme/Properties** was accessed and the **Edit** function was then accessed. General and interactive snapping were selected and set to .005 miles. After selecting **Theme/Start Editing,** the Cleanrf.shp file is ready for the stream centerlines to be added in those areas where required. Using the old RF3 file as a guide the centerline was added as shown below. Once all edits are complete, it is saved by choosing **Theme/Stop Edits**.
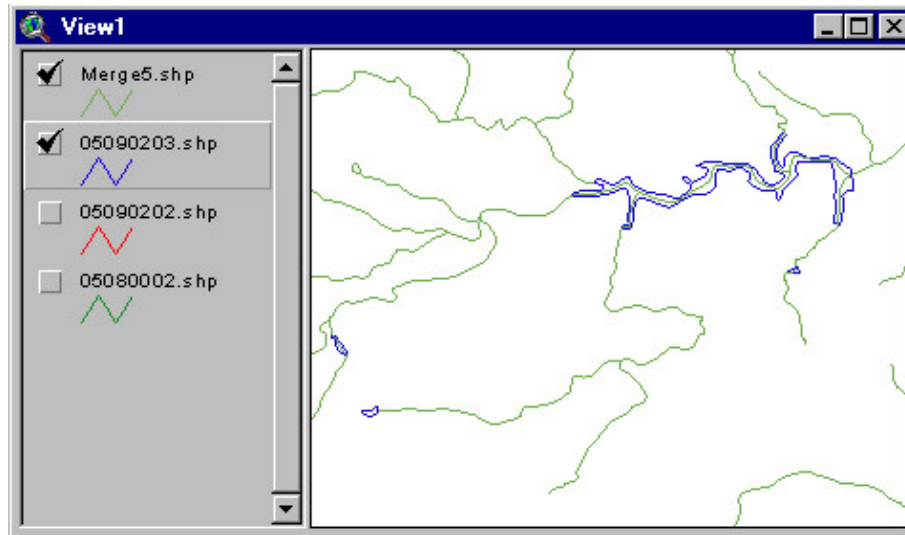
Figure 4-7. RF3 with Edited Centerline.

With the Mill Creek RF3 files clean and prepared for Stream Burning, all of the RF3 files must first be merged into one theme. After loading the Geoprocessing Wizard extension, **Edit/Geoprocessing** was chosen and the three files were merged.

4.5 Burn in the Streams

The next step is to perform "Burning Streams." Burning Streams entails raising the land surface cells that are off the streams by an arbitrary elevation amount so that the streams delineated from the DEM exactly match those in RF3.

With both Cleanrf.shp and Demgrid themes active, CRWR-PrePro/Burn Streams was selected. In the Elevation Rise dialog box, 1000 was chosen as the arbitrary elevation rise. Since this is the temporary grid, it was saved in the Millcreek\tmp directory. This allows one to rebuild the project easily should ArcView crash. Under **Theme/Save Data Set**, the grid was saved as millburn. Highlighting the Burned_Dem theme and using the Identify tool near

the streams, it is evident that the stream cell elevations remain as they were on the original DEM surface but the land surface elevations have been raised 1000m higher.

4.6   Fill Sinks in the DEM

Most of the DEM data are accurate; however, aberrations do occur in the DEM which cause pits to form in the terrain. These pits need to be filled; otherwise, they will result in the wrong flow direction. The **Fill Sinks** function raises pit cell elevations to the level of the lowest neighboring cell. Only tiny sinks will be filled, since large sinks, such as lakes, are real sinks that we do not want to remove from the DEM.

Under **CRWR-Prepro/Fill Sinks**, Burned_DEM is chosen from the prompted dialog box as the Input Theme. Burned_Dem is automatically populated in the Input Theme 1 field and millfill is chosen as the Output Theme 1. Once **OK** is selected, a blue bar can be seen running across the bottom of the View1 window to indicate that processing is occurring. When it is completed, the new grid millfill will be added to the View window. This process is the most time consuming of all the functions and may take some time to execute on a slower computer. Once the millfill theme is added, the project is saved to preserve the project in case ArcView crashes. This periodic saving should be common practice.

4.7   Compute the Flow Direction Grid

With the DEM grid filled, the flow direction grid can be calculated using **CRWR Pre-Pro/Flow Direction**. The Input Theme1 is automatically populated with the FilledDem (millfill). This is because the theme millfill has a theme tag of FilledDem. The theme tag helps ArcView to recognize the intrinsic properties of the grid, no matter what the given name of the theme.

All of the current theme tags by choosing menu **CRWR-Utility /Display Theme Tags**.

For Output Theme 1, millfdr was chosen and given and the Flow Direction Grid was calculated. After a short period, a flow direction grid was added to the View. For a better view of the flow direction Grid, the legend of millfdr was opened, and in the Legend Editor, a file titled fdr.avl was applied using the Load button. Shown below is the new flow direction grid with a 3-D-like appearance.
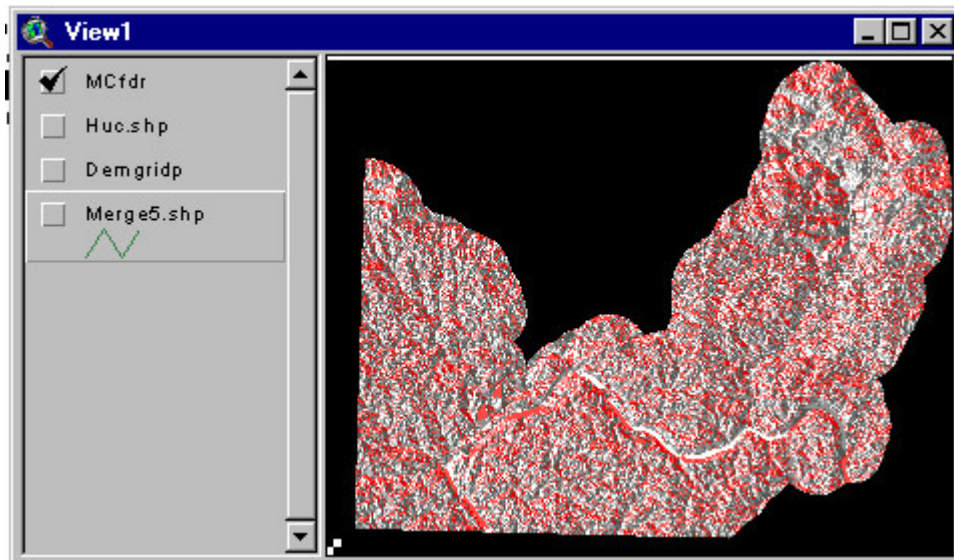
Figure 4-8. Flow Direction Grid.

4.8   Compute the Flow Accumulation Grid

From **CRWR-Prepro /Flow Accumulation**, the Input Theme1 is automatically populated with the flow direction grid, in this case, MCfdr. The Output Theme 1 is entered as Mcfag (Mill Creek Flow Accumulation Grid). After a short period, a flow accumulation grid will be added to the View. Some faint streams can be seen running from the upper right to lower left. The

change in color represents the accumulation of grid cells, where the darker color indicates that more grid cells have drained into that particular cell.

Using the Identify tool, the concept of flow accumulation can be seen. By clicking on the most down stream portion and working upstream, the number of cells will decrease. This is directly associated with the change in drainage area that is associated with the number of cells. Another location to look at is the confluence of tributaries. By first looking at the upstream portion and then the downstream portion, the contribution by the incoming tributary or branch can be seen.

4.9   Define the Basic Stream Network

Before constructing the stream network, the cell threshold or minimum stream drainage area must be designated. From **CRWR-PrePro /Stream Definition (Threshold)**, the Input Theme1 is automatically populated with the flow accumulation grid (Mcfag) and MCstr (Mill Creek stream Grid) is added as the Output Theme 1.

In the prompt dialog box, the stream threshold was changed from the default 10000 to 1000 cells (0.9 KM^2). After a short period, the stream grid MCstr was added to the View. The stream grid has a value of 1 in each cell with a flow accumulation value larger than 1000 and NODATA on all other cells.
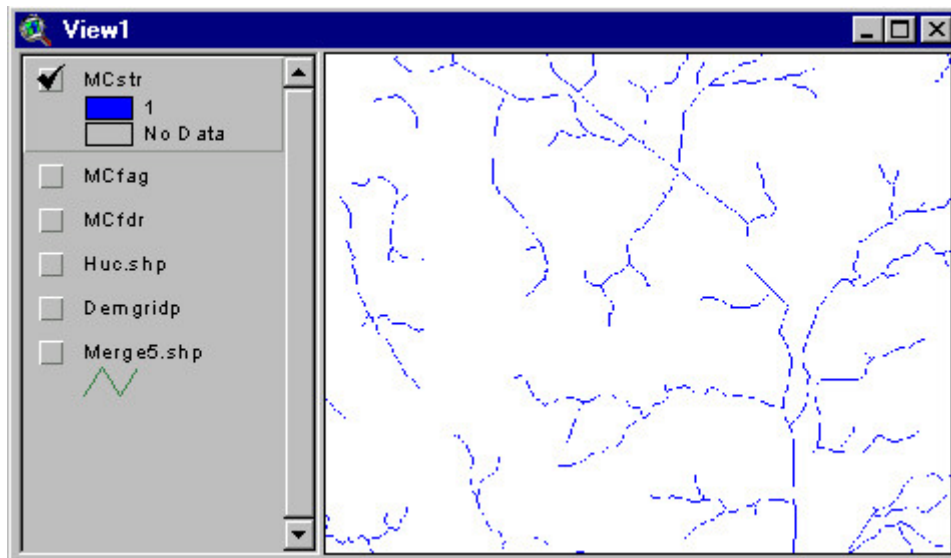
Figure 4-9. Stream Grid with 1000 Cell Threshold.

When viewing the Merge5.shp theme (red) just below MCstr (blue) (as shown below), some of the streams of Merge5.shp are not covered. This occurs because the 1000 cell threshold is too large to identify some of the smaller streams represented by Merge5.shp. Using this threshold eliminates some of the more insignificant sub-watersheds.
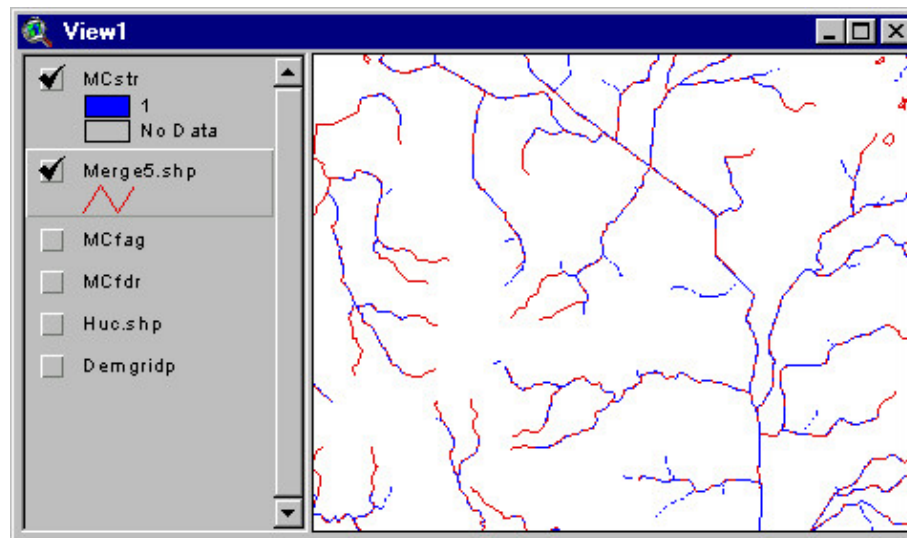
Figure 4-10. Stream Grid Over RF3 File.

4.10 Add a Stream to the Stream Network

Although we do not want to delineate all of the extra streams described by a Rf3 file, there will be a few streams that need to be kept for watershed delineation. In the view below, there is an example of a stream that must be added to MCstr. Segment #2 is a segment identified as significant to the watershed by the Ohio EPA. If the stream grid (MCstr) does not define these streams, streams can be added to the MCstr grid using the Edit Stream tool.

To include these segments, the Edit Stream Tool is selected and then each of the segments on Merge5.shp not defined by stream grid MCstr is selected. This adds a new theme named Addlines.shp. The stream traced using the Edit Stream Tool is added to the view.
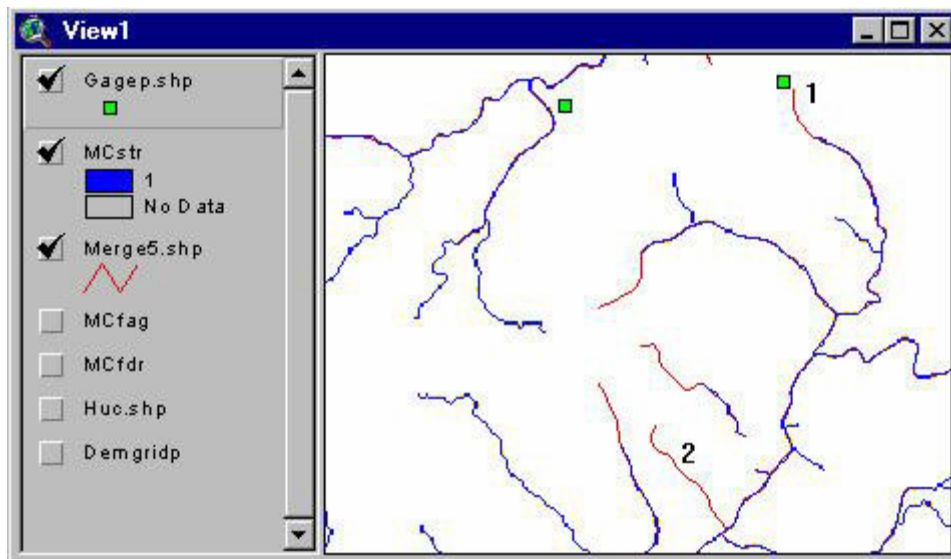
Figure 4-11. Add Stream Segments.

The new stream Addlines.shp needs to be added into the existing grid stream network. Using **CRWR-PrePro/Add Streams,** a prompt dialog box will show with the three Input Themes already populated with the proper grids. The Output Theme name was named MCmodstr (modified stream grid).

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Shortly after execution, a Yes/No dialog box appears. Yes is chosen to use traced and threshold streams. The modified stream grid MCmodstr includes both the original stream with a cell threshold 1000 and the traced stream added.

4.11 Segment Streams into Stream Links

The Stream Link function gives each stream segment a unique ID. From **CRWR-PrePro/Stream Segmentation** (Links), a dialog box pops-up, and ModifiedStreamGrid is chosen. The two Input Themes are automatically populated with the flow direction grid (MCfdr) and the modified stream grid (MCmodstr). The output grid name as MClnk. Shortly after execution, the stream link grid MClnk will be added in the view. To better view the stream link grid, the Legend Editor is accessed, and the Unique Value is chosen for Legend Type and Value for Values Field. For the color scheme, Fruit & Vegetables is chosen and applied. This will show the stream grid segmented to stream links, with each link having its own unique color and value as shown in the legend bar.
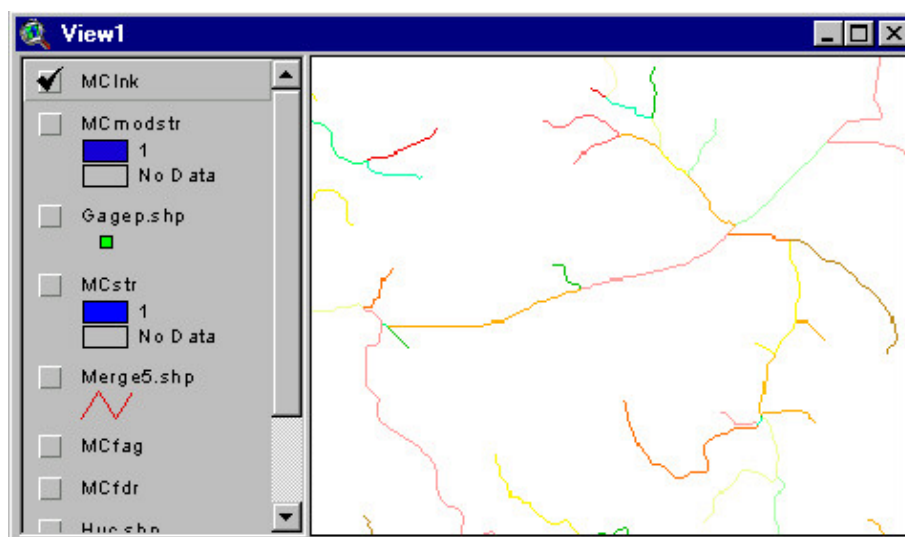
Figure 4-12. Stream Links Grid.

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4.12 Find Link Outlets

An outlet cell is the cell in each link that has the largest flow accumulation value. All of the cells upstream of the outlet cell flow into the outlet cell. From **CRWR-Prepro/Outlets from Links** LinkGrid is chosen to create the outlet grids. The two Input Themes are automatically populated with the flow accumulation grid (MCfag) and stream links grid (MClnk) and the output grid name is designated as MCout. After execution, the resulting grid is a scattered set of single cells, each the farthest downstream cell of a stream link.

For a better view of the outlets grid, access the Legend Editor. Double-click on the first color square and choose the color black in the Color Palette. Then, on the Legend Editor, double-click on the last color square above the No Data square. Choose the color black once again in the Color Palette. The Color Ramp button is then clicked resulting in all of the symbols becoming black. A view of what the outlets look like will be shown in the next section.
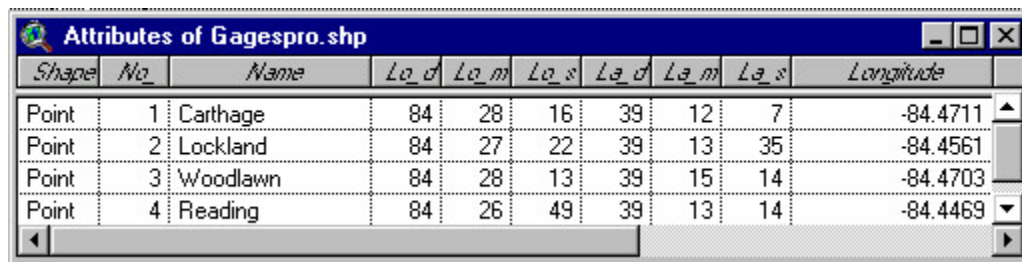
4.13 Creating a Point Coverage of Flow Gaging Locations

Gage locations are necessary in HEC-HMS to calibrate the flows from design storms. In the Basins Core Data, there is a point coverage of gage stations with attributes. This theme should be loaded, viewed, and reviewed. Using the gage numbers, the USGS website was accessed to verify if the gages were still active or if any others had been added or moved. It was found that many of the gages were not active or moved while the rest did not pertain to the Mill Creek Watershed.

All of the current gages were downloaded and the required data was entered into an Excel Spreadsheet and saved as gages.dbf. In the spreadsheet, several fields were entered. First was **Shape** followed by **No_** and **Name.**

These were followed by the fields **Lo_d, Lo_m** and **Lo_s** corresponding to the longitude degrees, minutes and seconds; while fields **La_d, La_m,** and **La_s** correspond to the latitude degrees, minutes, and seconds. Added next were **Longitude** and **Latitude** in decimal degrees. The last entry was **Station_,** which contained the station number. (Note that **Longitude** = - **Lo_d - Lo_m**/60 **- Lo_s**/3600 (negative signs because is West longitude) and **Latitude** = **La_d + La_m**/60 **+ La_s**/3600).

Once the file is created and placed in the working directory, it is added to the project file using the **Tables** icon of the **Project** window. When opened, the table will look as shown below.

Shape	No.	Name	Lo_d	Lo_m	Lo_s	La_d	La_m	La_s	Longitude
Point	1	Carthage	84	28	16	39	12	7	-84.4711
Point	2	Lockland	84	27	22	39	13	35	-84.4561
Point	3	Woodlawn	84	28	13	39	15	14	-84.4703
Point	4	Reading	84	26	49	39	13	14	-84.4469

Attributes of Gagespro.shp

Table 4-1. Stream Gages Attribute Table.

To create a point coverage, a new View window must be opened. Select **View/Add Event Theme,** and select Gages.dbf in the **Table** slot, **Longitude** in the **X Field** slot and **Latitude** in the **Y Field** slot. After clicking **OK,** a point theme called **Gages.dbf** is created. Before adding this to the working project, the theme must be put into the correct projection.

First, the View2 map units must be defined by clicking on **View/Properties** and selecting **decimal degrees** in the **Map Units** slot of the View Properties window. Second, the theme needs to be added to the view and Projected from Geographic into the Ohio State Plane Projection by clicking on **CRWR-Vector/Project.** Select meters the Output Units window; then select State

Plane in the Category slot and Ohio South in the Type slot of the Projection Properties window. Call the projected coverage **GagesPro.shp** and add it to View1 as shown below in purple. Also shown in red are the outlets defined by CRWR-PrePro.
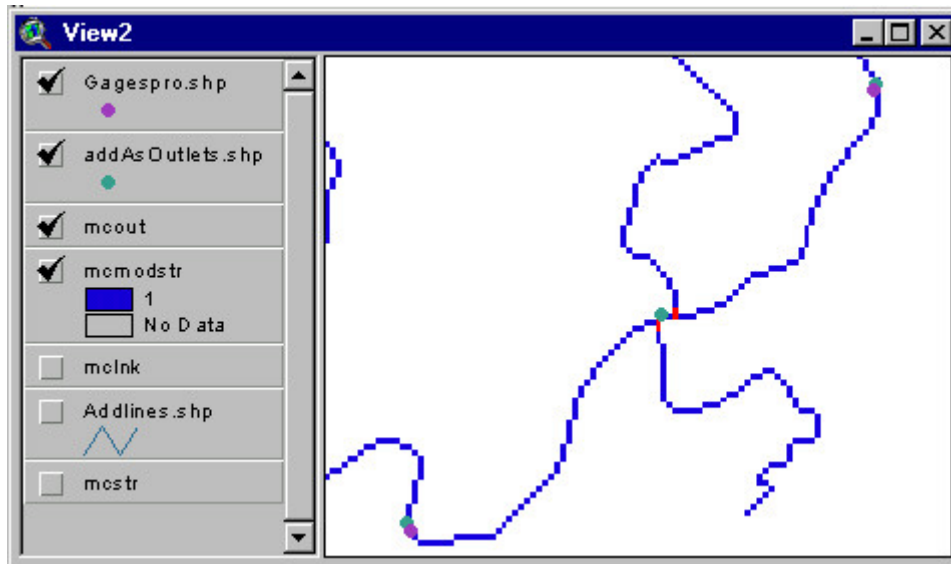
Figure 4-13. Adding Gages as Outlets.

To add these gages as outlets, zoom into the Mcmodstr theme to the individual cell level. Using the add outlets tool, click on the stream segment nearest the gage location. (When selecting a location, verify that it is not one of the defined outlets and not less than 2 cells from an outlet.) Once an outlet is added, a new point theme called Addasoutlets.shp is added to the view as shown in green.

4.14 Manually Defining Watershed Outlets

Watershed delineation can be executed with the data compiled up to this point. CRWR PrePro will use all of the outlets found in MCout and generate one watershed per outlet. In order to keep the project consistent with the Louisville District, outlets must be manually defined to generate the same

watersheds. To do this, the outlet locations must be given. Below is a digitized version of the watersheds that were delineated by hand at the Louisville Corps of Engineer District.
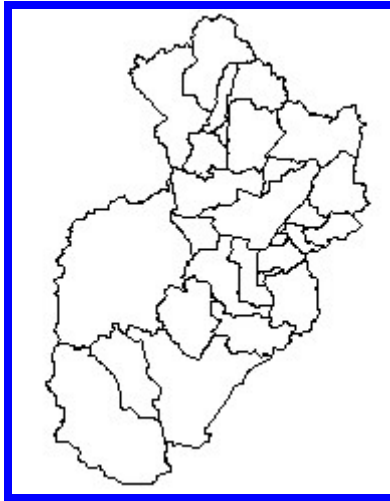
Figure 4-14. Louisville District's Manual Delineated Watershed Coverage.

Using this as a template, outlets were manually added in an effort to replicate the watersheds. The outlets that were selected were added to addasoutlets.shp with the gage locations. The following is a depiction of the outlets that were added on to the Mcmodstr theme. The breaks in the stream really do not exist; they are caused when adding the photo to the document.
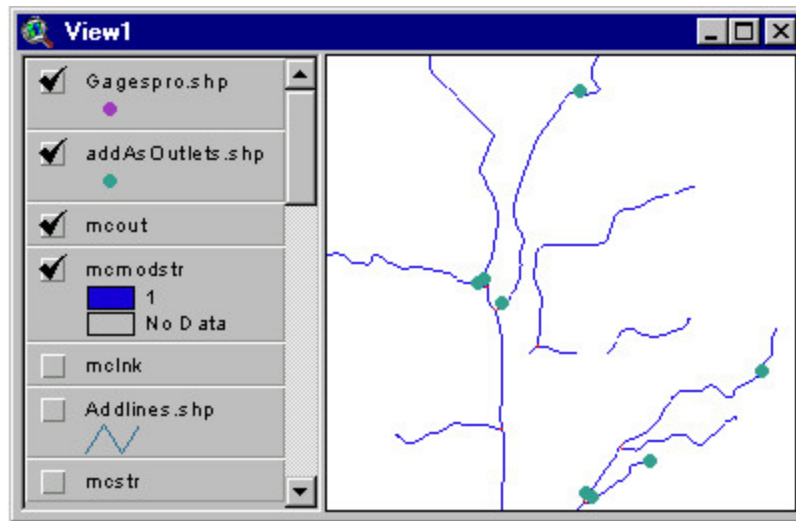
Figure 4-15. Refining Outlets for Watersheds.

After adding all the proposed outlets, **CRWR-Prepro/Add Outlets** was selected. ModifiedStreamGrid was chosen for outlets processing. In the prompted dialog box, five Input Themes were automatically populated. MCmod_out was designated as the modifiedoutletsgrid and MCmod_lnk for the modifiedlinksgrid.

A Yes/No dialog box appears, and **No** was chosen to use the manually selected outlets and PrePro-selected outlets. The modified outlets grid MCmod_out and stream links grid MCmod_lnk are added to the view.

4.15 Delineate the Watersheds

With the links and outlets finalized, the watersheds can be delineated. From the **CRWR-PrePro / Sub-Watershed Delineation** menu, select ModifiedOutletsGrid from the prompted dialog box. In the next dialog box, the two Input Themes are automatically populated with flow direction grid MCfdr and modified outlets grid MC_out. MCwshd is the name given to the output watershed grid.

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After clicking OK, the watershed grid MCwshd is added to the view. (A sub-watershed is a zone of cells with the same cell value as the first outlet cell they drain through.) With Mcmodstr added to the top layer in the legend, the correlation of the streams to the watershed can be seen. To view the watershed in a more contrasting view, the Legend Editor is accessed and Unique Value is chosen for Legend Type, Value for Values Field. The default Color Schemes Bountiful Harvest is applied. Notice that each of the stream segments has a watershed associated with it. By dragging the MC_out theme to the top of the legend bar, an outlet at the end of each stream segment is created. Using this process, outlets can be manually adjusted by editing addasoutlets.shp until the desired subwaterheds are achieved as found in the figure above submitted by the Louisville District.
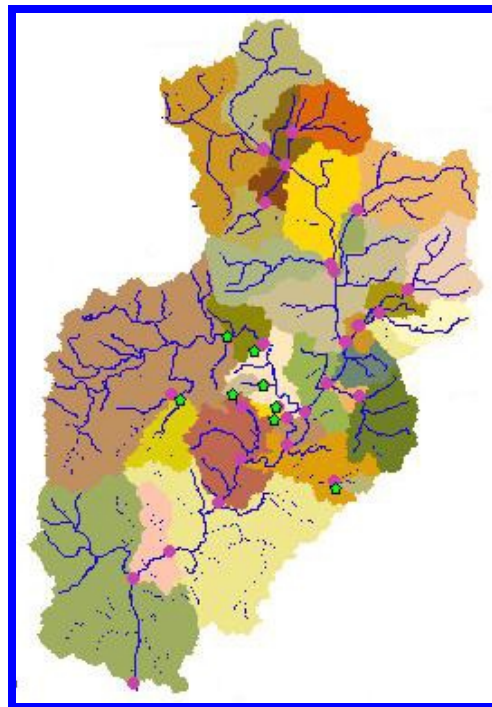
Figure 4-16. Watershed Grid.

4.16 Vectorize the Stream and Watershed Grids

Grids have been the primary data worked with to this point in the study. Grids are excellent for cell-based analysis; however, vector data is easier to use and store. To convert raster data to vector format, select **CRWR-Prepro /Vectorize Streams and Watersheds**. In the dialog box, the Input theme is automatically populated with the watershed grid MCwshd, and MCwshply is the name given as the output theme name.

In the Vectorize Streams dialog box, ModifiedlinksGrid is selected and the two input themes are already populated. MCrvr is selected as the Output Theme name. A Yes/No dialog box for backing up the MCwshply.shp appears – choose NO. A prompt will then indicate that a certain number of dangling polygons have been merged. Due to the fact that a vector polygon does not necessarily have a square shaped border like the grid, the conversion of the grid to a polygon sometimes creates a dangling polygon on the edge of an existing polygon. This dangling polygon is a tiny watershed that does not exist, and is dissolved into the parent watershed polygon to which it belongs. (Note that the blue running status bar will stay at 100% for quite some time before the process is complete. This should not be taken as a problem with the program.) Once complete, the watershed polygon MCwshply.shp and the river line MCrvr.shp are added to the view. The vectorized watershed with its stream segments is shown below.
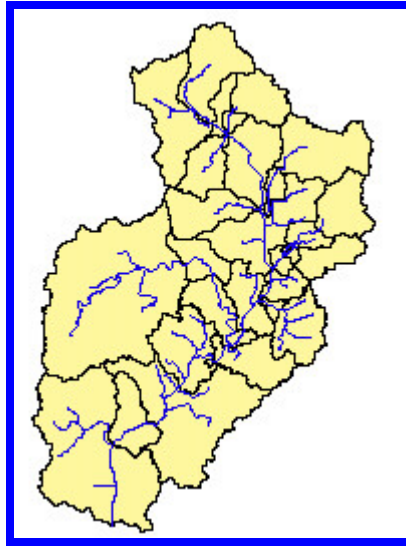
Figure 4-17. Vectorized Watershed.

Once the outlets are refined and appear to be the same as those used by the Louisville District then the process can continue. The series of delineations and outlet adjustments resulted in the vectorized watershed correlating to the Louisville District's outlets. Below on the left is the Louisville watershed and on the right is the final watershed developed in ArcView. The difference in area is about three square miles. The district's figure is 165 mi^2 and the ArcView watershed is 168mi^2.
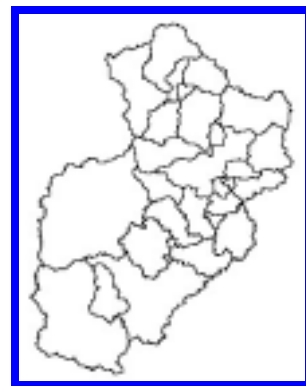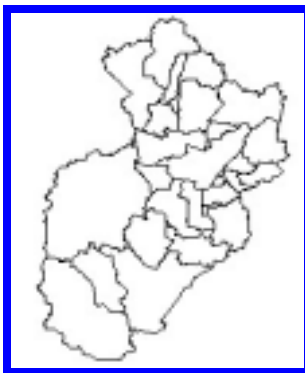
Figure 4-18. Watershed Comparison.

4.17 STATSGO Soils and Land Cover/Land Use Data

To add soils themes to the view, select a new view and add the statsgo.shp from the core data folder in the working directory. This view reveals a large number of Statsgo polygons, which are needed to describe the soils of the HUC. Highlighting statsgo.shp and using the legend editor, the field Muid is used to label the mapunits. Muid is the mapunit identification number for each unique combination soil components depicted in Statsgo.

From the Tables icon in the Project window, the mapunit.dbf and comp.dbf tables are added from the working directory. Each of these tables has a number of fields that are not necessary for the project. With the mapunit.dbf table highlighted, use **Table/Properties** to click off all of the checked boxes except for Muid and Muname In the Comp.dbf table, clicked off all fields except for Muid, Seqnum, Compname, Comppct, Slopel, Slopeh, Surftex, and Hydgrp. The percentage of each hydrologic soil group in each map unit is necessary for the calculation of the curve number theme. Using **CRWR PrePro/Soil Group Percentages**, along with the required responses for the map unit (mapunit.dbf) and component tables (comp.dbf) when asked, a table called muidjoin.dbf will be created.

To clip off the excess soils coverage, use the Geoprocessing Wizard extension found in **View.** With Mcwshply as the template, a new theme as shown below will result.
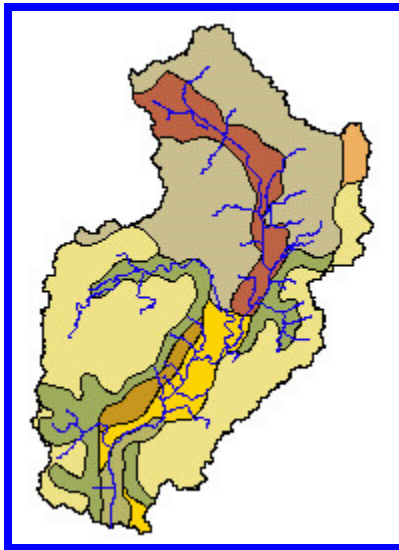
Figure 4-19. STATSGO Soils Coverage.
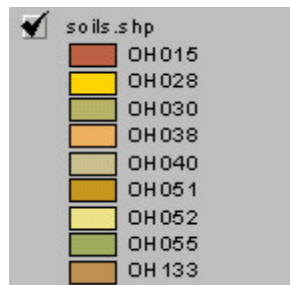
Figure 4-20. STATSGO Soils Legend.

4.17.1 Working with Land Cover and Land Use Data

Land use/land cover files use the Anderson Land Use Code classification system, in which major land use types are broken out into 9 categories including:

1 = urban

2 = agriculture

3 = rangeland

4 = forest

5 = water

6 = wetlands

7 = barren land

8 = tundra

9 = ice and snow.

The second number describes subcategories of these principal categories such as:

11 = urban residential

12 = urban commercial

13 = urban industrial, etc.

This land use classification of the United States was developed in the late 1970s and land use has changed since then particularly in and around cities. Regardless, the LU/LC files are still the standard land use classification of the United States, but are now being replaced by MRLC.

With the theme lulc.shp added to the view, the individual land uses can be seen by accessing the Legend Editor and changing the Legend Type to Graduated Color and the Classification Field to lulc_code. First, on the Classify button, the number of classes was changed to 8. Second, the Value buttons were used to change the values of each category and the Label buttons were used to change the labels of each category. The Fill Palette was then used to color-code each of the symbols into land use categories as seen below. The Geoprocessing Wizard was used to clip the theme to the Mill Creek Basin as seen below.

Value	Label	Symbol Color
0-9	Unknown	White
10-19	Urban	Red
20-29	Agriculture	Yellow
30-39	Range Land	Green
40-49	Forest	Dark Green
50-59	Water	Blue
60-69	Wetlands	Light Blue
70-79	Barren	Grey

Table 4-2. Land Use and Land Cover.
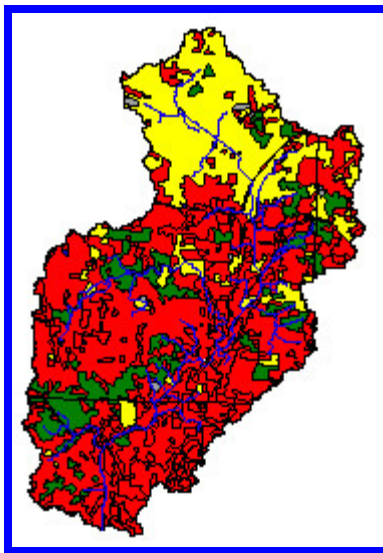
Figure 4-21. Land Use/Land Cover.
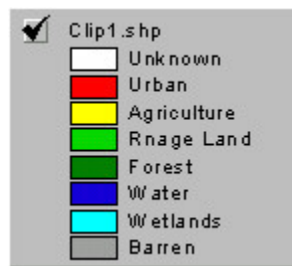
Figure 4-22. Land Use/Land Cover Legend.

4.17.2 Curve Number Calculation

By combining the land use and soils data, a curve number grid can be
generated. Soil Conservation Service (SCS) curve numbers are parameters

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for calculating abstractions. With the soil theme and land use theme active, select **CRWR PrePro/Curve Number Grid**. When prompted for the name of the lookup table, select rcn.txt. It may be necessary to add this table to the working directory. It can be found on the GIS Hydro '99 website under Watershed Characterization. When prompted for the name of table with soil group percentages, select muidjoin.dbf. The name given to the theme is Curvenumber. Below is a depiction of the Curve Number Grid that is calculated after various color schemes are selected.
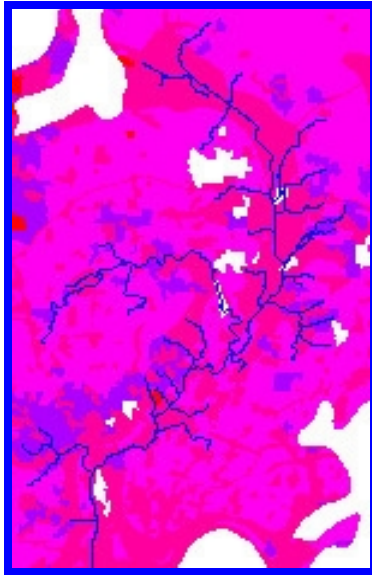
Figure 4-23. Curve Number Grid.
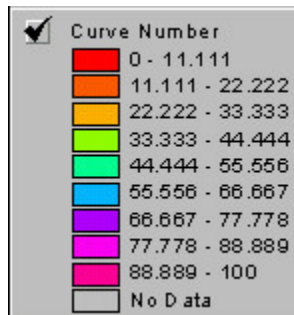
Figure 4-24. Curve Number Legend.

4.17.3 Soil Water Storage

Using the Curve Number coverage found above, the SCS equation for Soil Water Storage (S) is applied. The value (**S**) for soil storage is calculated in inches. Once the soil water storage coverage is found, the SCS equation for initial abstractions (**I$_a$**) can be applied and the theme statistics accessed to find the mean across the watershed. The equations are found below.

$$S = \frac{1000}{CN} - 10$$

Equation 4-1. Soil Storage.
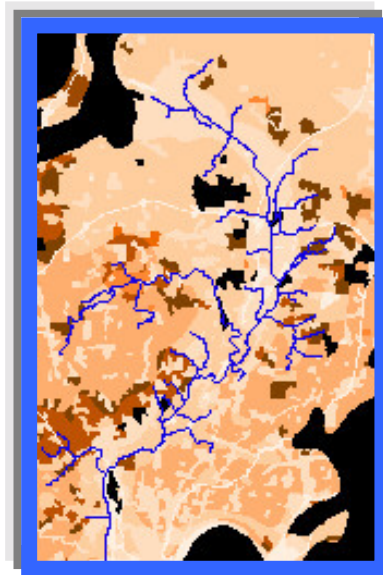
Figure 4-25. Soil Storage Grid.
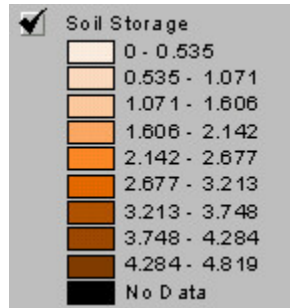
Figure 4-26. Soils Storage Legend.

$$I_a = 0.2S$$

Equation 4-2. Initial Abstractions.

The mean was converted to (mm) which is the required units for HEC-HMS. A value of 6 mm was found to be the mean across the basin. This differs from the 12.7 mm used by the Louisville District.

5   Developing A Hydrologic Model

This chapter details the application of Developing a Hydrologic Model.
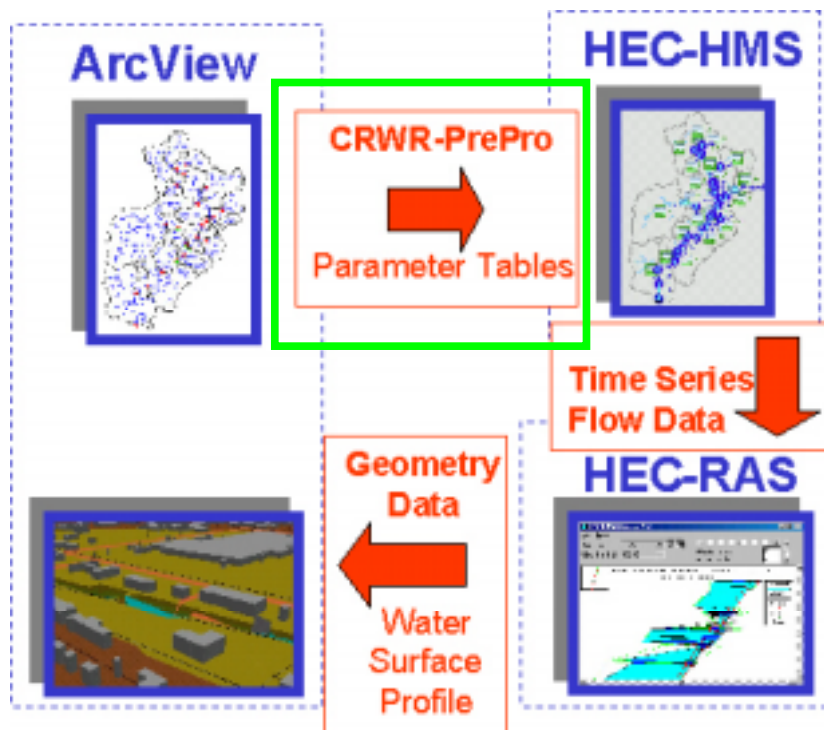
Figure 5-1. Developing a Hydrologic Model.
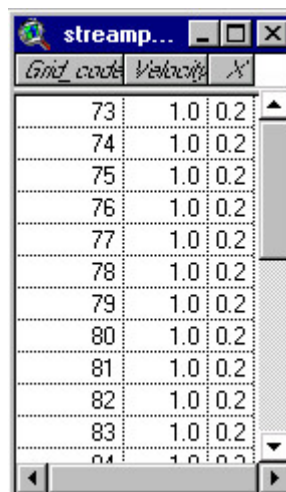
5.1   Calculating Hydrologic Attributes

To calculate the attributes, use **CRWR-PrePro/DEM Based Parameters**.
From the Choose an Outlets Grid window, select ModifiedOutletsGrid. In the
DEM Pre-processing: Calc. Watershed and Stream Parameters window, fill
the blanks with the following theme names: Demgridp, MCfdr, MCout,
MCWshd, MCwshply.shp, MCrvr.shp and LFP. In the first Calculation Method
window, SCS is selected for the abstractions method, and in the second

Calculation Method window, SCS is selected for the lag-time method. Yes is selected in both Input Warning windows. The Curve Number theme is selected for the Curve Number Grid.

In the Time-Step window, 1-30 minutes is selected and in the Time-Step [minutes] window, 15 is selected. For Select Stream Input File (Grid_code) window, select StreamP.txt from the working directory. This table can be found on the GIS Hydro '99 Website under Watershed Characterization. This table will require modification for each project. This particular one was developed for the Guadalupe basin in Texas. The main field that must be adjusted is Grid-code. Using the vectorized stream theme for the watershed, access the attributes table to view the Grid-code numbers assigned. These numbers must be the same ones used for the StreamP.txt. A sample table is shown below with the stream parameters: flow velocity = 1 m/s and Muskingum X = 0.2.

Grid_code	Velocity	X
73	1.0	0.2
74	1.0	0.2
75	1.0	0.2
76	1.0	0.2
77	1.0	0.2
78	1.0	0.2
79	1.0	0.2
80	1.0	0.2
81	1.0	0.2
82	1.0	0.2
83	1.0	0.2

Table 5-1. Stream Parameter Table.

This process has added fields to the attribute tables of MCwshply and MCrvr and populated them with values that represent the hydrologic parameters of the feature elements.

The fields added to the MCwshply table are: LngFlwPth (length of longest flow-path), Slope (slope of longest flow-path), Baseflow (baseflow method), Transform (unit hydrograph model), LossRate (loss rate method), CurveNum (average curve number), InitLoss (initial loss for the initial plus constant rate loss method), CLossRate (constant rate loss for the initial plus constant rate loss method), WVel (average velocity of longest flow-path), and LagTime (lag time for the SCS unit hydrograph). The fields added to the MCrvr table are: StreamVel (flow velocity), MuskX (Muskingum X), Route (flow routing method), MuskK (Muskingum K), NumReachN (number of subreaches for Muskingum flow routing method),and LagTime (lag time for pure lag flow routing method).

5.2   Determining the schematic and writing a basin file for HMS

The HMS schematic is a conceptual model that captures the connectivity between the different elements of the hydrologic system. The HMS basin file is an ASCII file, readable by HMS, which includes all the information stored in the schematic.

To transfer the hydrologic attributes calculated in 4.3.2 to the schematic and basin file, it is necessary to add to the project the following tables from the working directory: hecsub.dbf, hecjunct.dbf, hecreach.dbf, hecres.dbf, hecsink.dbf, hecsource.dbf and hecdiv.dbf. This is done in the project window under **Tables/Add.**

To determine the schematic and write the basin file for HMS, the AddAsOutlets.shp, MCwshply.shp and MCrvr.shp themes must be active prior

to using **CRWR-PrePro/HMS Schematic**. In the HECPREPRO window fill the six blanks with the following strings or values: yes, default, 23, 2, MCBasinSCSv1 and Mill Creek BasinSCSv1. The Hydrol#.shp and Hydrop#.shp as well as Syml#.shp and Symp#.shp store all the relevant information of the hydrologic system necessary for HMS. Additionally, Syml#.shp and Symp#.shp are the stick diagrams of the system. A text file called MCbasinSCSv1.basin has also been created in the process, which is the basin file for HMS. Below is the view that will be generated in the process.
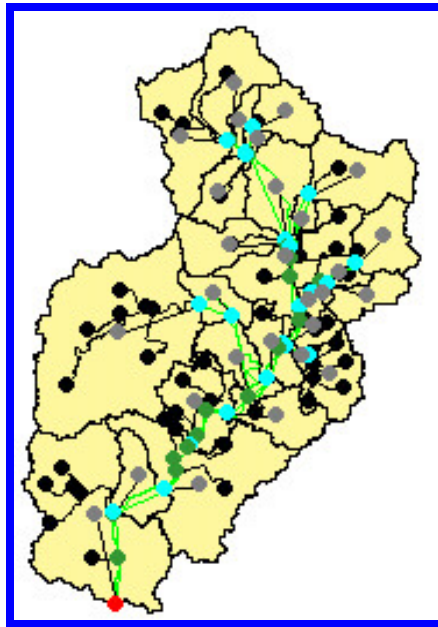
Figure 5-2. HMS Schematic.

6   Modeling with HMS

This chapter details the application of Modeling with HMS.
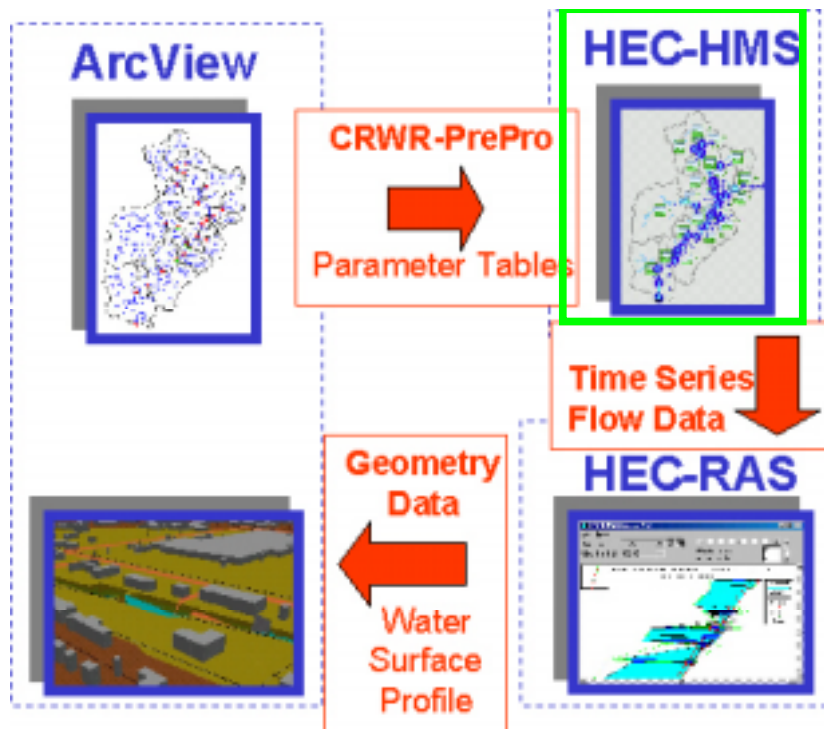
Figure 6-1. Modeling with HEC-HMS.

6.1   Creating the HMS components

When HMS 1.1 is opened, a HMS Project Definition window will appear. A new HMS project is created using **File/New Project**. In the HMS * NEW PROJECT window, enter a name in the Project slot such as Mill Creek Basin.

To import the MCbasinSCSv1.basin file created in GIS, **Edit/Basin Model/Import** is accessed. In the HMS Basin Model * IMPORT BASIN

MODEL window, basin file is selected from the working directory under tmp. The file description Mill Creek BasinSCSv1 will appear but not the file name.

With the basin Model opened, some editing is required. Earlier in the project lakes were taken out of the river reach file and replaced by centerlines. These lakes were manmade and created by dams. In HMS, dams are replicated by reservoirs. This is made easy in HMS by simply adding the new element. In this case, outlets were used where the dams were located earlier in the project so they only need to be replaced. Outlets become junctions in HMS. Find the junction that corresponds to the dam location, and replace using **Edit/Delete Element(s).** Then using **Edit/New Element/Reservoir** a reservoir is added to the view.

The new element must be moved into place then connected to its respective neighboring elements. To do this, the up stream basin is connected by right clicking and selecting **Connect Down Stream**. Using the cross hair, the reservoir is selected and connected. The same process is used to connect the reservoir to the downstream reach. This process is done for West Fork Mill Creek Lake (Reservoir-1) and Sharon Lake (Reservoir-2) as shown below. After opening the Reservoir icon, parameters must be entered for its use. In both reservoirs, a storage/discharge relationship was used with a given initial discharge. The Louisville District provided the values used in the model. The other parameter that must be added to the basin file is the initial losses for each basin. Double-click on each basin to add the initial losses. The value of 6mm was used on each basin; this was calculated using the soil storage grid developed above.
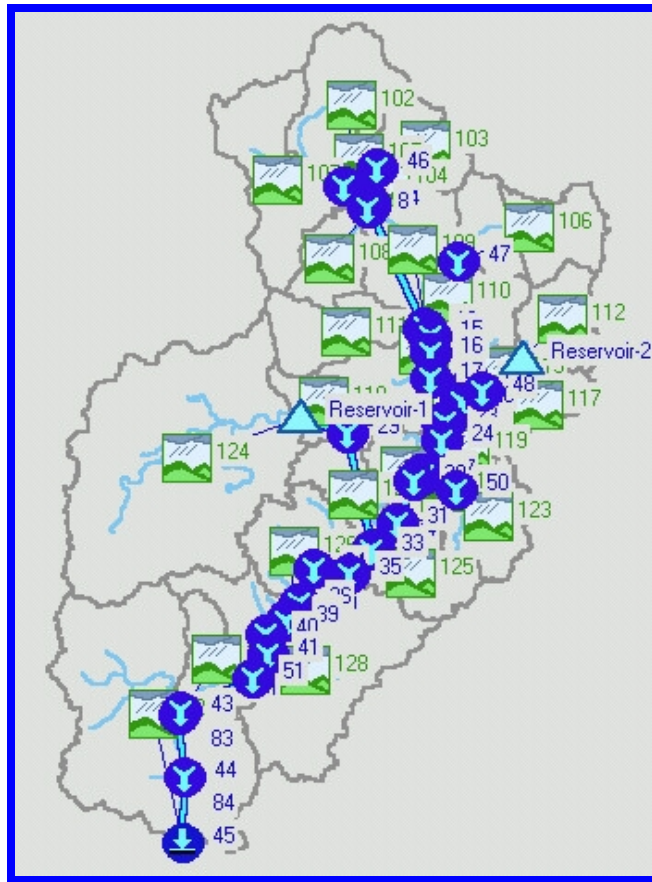
Figure 6-2. HMS Basin Model.

6.2 Creating a Precipitation Model

To create a precipitation model, click on **Edit/Precipitation Model/New**, and then write Thiessen8 in the Precipitation Model and Description slots and click OK. The next view is the HMS Precipitation Model - Method Select Window, select **User Specified Gage Weighting**.

With this option, you specify weighting factors (Thiessen-type) to be applied to gaged precipitation to calculate spatially averaged precipitation for subbasins. The User-Specified Gage Weights Screen contains a "notebook" with three tabbed sections as shown below. The first, labeled Gages, provides for specification of a gage ID, gage type, total storm depth, and

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index precipitation for each precipitation gage (both recording and non-recording). The second section, Subbasins, provides for the addition of subbasins to the precipitation model, and allows for specification of index precipitation for each subbasin. The optional specification of index precipitation for subbasins and precipitation gages enables adjustment for bias in gage-precipitation values. The third section, Weights, specifies both the total-storm weight and temporal-distribution weight for each gage.

Figure 6-3. Precipitation Model.

The first tab is Gages. On this sheet, you specify the gages that are to be used for the design storm. Two gage types can be used with the method - recording and non-recording gages.

Gages for total storm precipitation (i.e., non-recording gages) can be entered in the Gages section by using **Edit/Gage Data/Precipitation** and selecting the **Add Total-Storm (NR) Gage** button and entering a gage name and appropriate storm depth. Non-Recording gages that are entered in this manner can only be accessed by the current precipitation model. Recording gage IDs are obtained by selecting them from the Gage Selection List, which is accessed by clicking the Gage Select button. A total-storm depth is not normally entered for recording gages but can optionally be added. When total-storm depth is specified for recording gages, the individual precipitation values will be scaled so that the total-storm rainfall will equal the specified amount.

Recording precipitation gage data must have been previously entered before it can be referenced from the Gage Select button. The gage type for both recording and non-recording gages is entered automatically. Using **Edit/Gage Data/Precipitation,** recording gage data for an actual storm can be entered. The storm used for this project can be found in the Control Specifications section. The gage data for this design storm was received from the Cincinnati Municipal Sewer District (MSD). Mike Heitz from the MSD provided eight recording gages located in the basin. The precipitation data is found in Appendix B. After entering values, the gages are stored for use in other projects as well and added to the model. Below is an example of the incremental hyetograph associated with a gage that HMS produces once the data is saved.
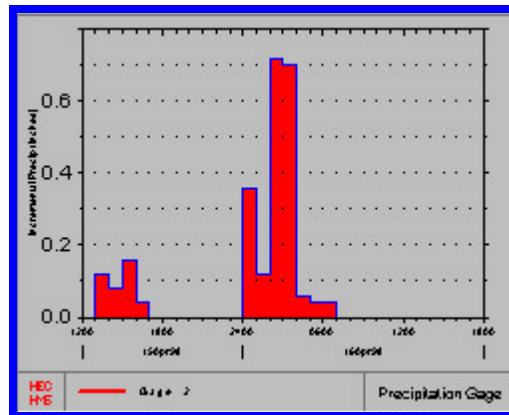
Figure 6-4. Hyetograph.

In the Subbasins section the subbasin names are entered and the number of
gages associated with each subbasin is shown. Subbasins are added from
the basin model by clicking the **Add** button. The addition of subbasins from a
basin model must be done before the subbasins can be referenced in the
Weights section. Index precipitation (e.g., normal annual) amounts can be
entered for both precipitation gages and subbasins. If such data is entered, it
will be used to apply a bias adjustment to gage precipitation.

The Weights section displays information for a single subbasin at a time. A
droplist allows selection of a subbasin that has previously been specified in
the Subbasins section. Gage ID, type, and associated weight are entered in
the table. When a gage ID field is selected, a drop list appears that shows
the gages previously entered in the Gages Section. The gage type is either
"R" for recording, or "NR" for non-recording, and is entered automatically.
The Total Storm Gage Weight is applicable to both recording and non-
recording gages, whereas the Temporal Distribution Gage Weight applies
only to recording gages. The weights of each type are normalized to sum to 1
if the entered values do not sum to 1.

Weights were assigned using the Thiessen diagram below. It was created in GIS using **CRWR PrePro/Precipitation Gage Weights**. First, a point coverage had to be created similar to the section on flow gages (section 4.1.13). Once created, the eight Precipitation gages were added to the view. The ArcView script creates a Thiessen Diagram found below. This diagram shows the sub basins with the eight gage locations and the mid point between each of the eight points. The visible lines represent the mid-point between two neighboring gages that are perpendicular to a line that would connect the two gages. The lines between all neighboring gages connect to form polygons, which represent the areas to which each rain gages contributes precipitation. Each polygon contains a basin or a portion of the basin. Where polygon boundaries contain an entire basin, the assigned weight is 1 representing 100% of the basin precipitation is applied by that gage. Bisected basins are assigned weights depending on the percentage of the basin area that each gage contributes to. Below, is the Thiessen Polygon generated in ArcView. The values in blue were entered in the weights section in the HMS precipitation model.
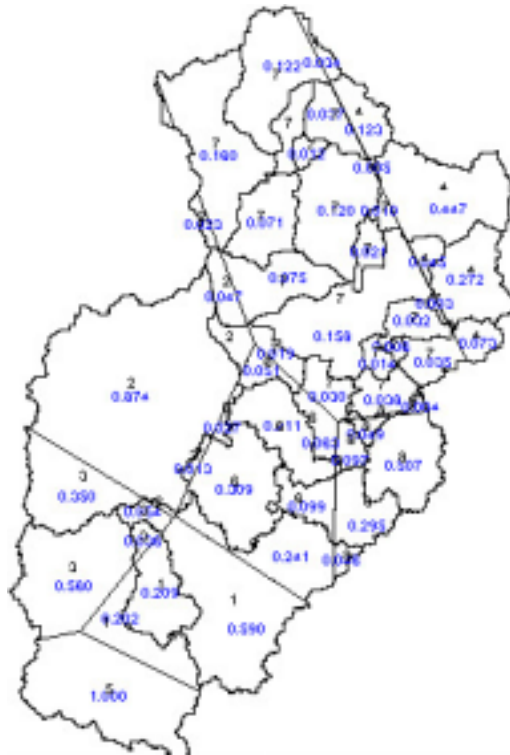
Figure 6-5. Thiessen Polygon.

6.3   Create Control Specifications.

To create the control specifications, the third component of HMS, click on
Edit/Control Specifications/New in the HMS * PROJECT DEFINITION
window. Write Control in the Control Specs ID and in the Description slots of
the HMS * NEW CONTROL SPECIFICATIONS window and click OK. In the
HMS CONTROL SPECIFICATIONS *SETUP window fill in the blanks as
shown in the figure below with the exception of the time interval which should
be 10 minutes. These dates correspond to the storm the Louisville District
chose to use for model calibration.
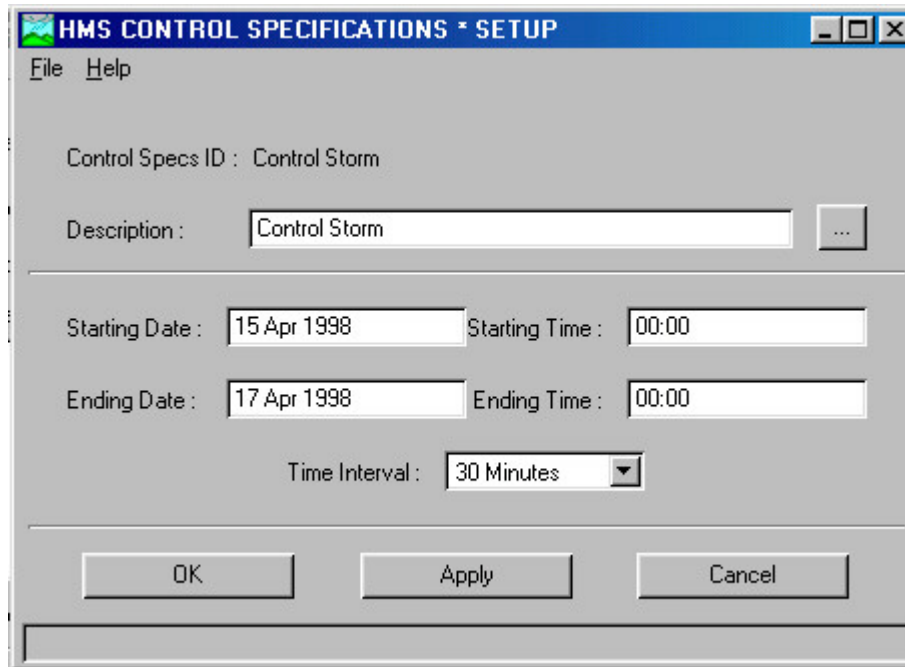
Figure 6-6. Control Specifications Setup.

6.4 Running a Design Storm for Calibration

To calibrate the derived model, a USGS gage is necessary. For Mill Creek, a gage at Carthage(03259000) (junction 35 in HMS) was used. The time series data for the gage was provided by Tim Raines, from the USGS. This data was entered using **Edit/Gage Data/Discharge**. In the NEW GAGE RECORD screen, the name Carthage was given for the gage. Selection of the data type and units is required when the data will be entered manually. Latitude and longitude data is not required. Select whether the data will be referenced in an external DSS file or entered manually.

Once the data is entered for the gage, the graph can be attached to its correct location in the basin file. At junction 35, the right-click was used and observed flow was selected. In the next window, the Carthage Gage is selected. When HMS is run and the results at Junction are viewed, the observed hydrograph will be present for comparison.

To run the design storm for model calibration, the basin model is accessed from the HMS - SCHEMATIC window. First, **Simulate/Run Configuration** must be selected. Then, the components created above must be highlighted and the **Add** button selected.   In the HMS-SCHEMATIC window, clicking on **Simulate/ Compute <Run 1>** will begin the simulation. Once the run is complete, the HMS Compute window must be closed unless there is an error – if an error occurs, view the run log. To see the hydrograph at any junction, watershed or stream, click on the arrow located on the upper-left corner of the HMS-Schematic window and right-click on the applicable element. In the pop-up menu, choose **View Results/Graph**. The following figure is the hydrograph for the Carthage Gage.
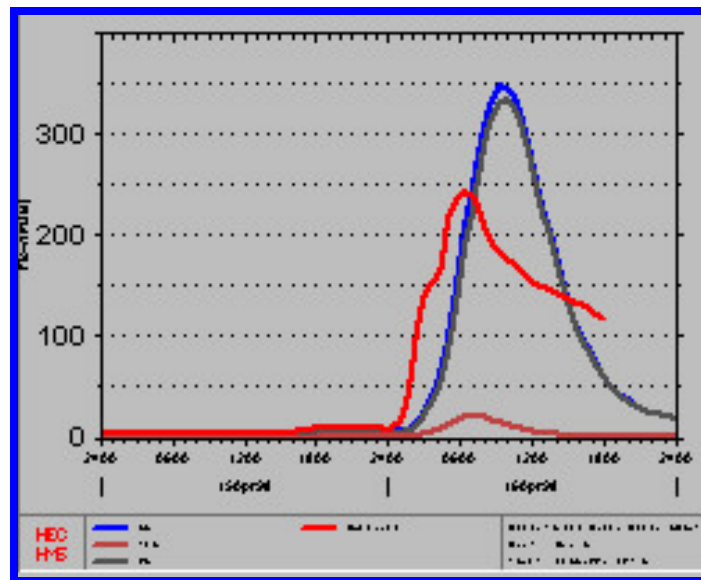
Figure 6-7. Carthage Gage Hydrograph (Velocity 1 m/s).

To calibrate this model, parameters must be identified and isolated. In the initial basin model, the StreamP.txt file designated initial estimated values for the velocity and Muskingum X of 1 m/s and 0.2 respectively. In viewing the gage hydrograph, it is evident from the curves that the observed (red) flow

and the model (blue) flow are not similar. Both curves indicate a steep climb to the peak on the approach of the flood wave but the peaks and time of peak do not correlate.

In choosing the parameters that could be adjusted in calibration, velocity and Muskingum X were chosen arbitrarily. Muskingum X is a storage constant and has a range of 0-0.5. It is well known that changing this value slightly has little to no effect on the flows. The value of 0.2 is pretty common in natural streams. The only other parameter is the velocity. By using the StreamP.txt file and manually changing the velocities to 0.5 m/s and 1.5 m/s two more basin files were created using CRWR PrePro. It is evident from the hydrograph below that the desired end state is not achieved. At V = 0.5 m/s, the peak flow drops just below the desired level, but the time of peak moves to the right which in contrary to the desired effect. It is also apparent that the shape of the curve is not consistent with the observed data. The rising portion is characteristic, but the peak and falling portion are not characteristic.
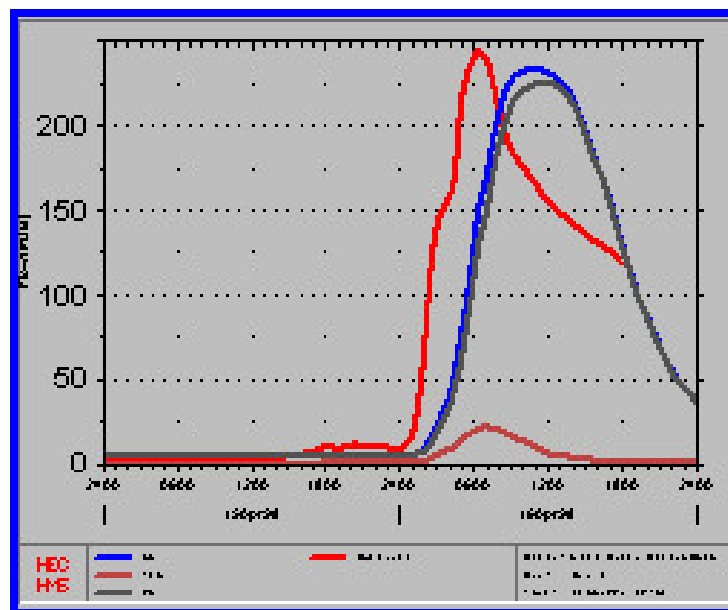
Figure 6-8. Carthage Gage Hydrograph (Velocity 0.5m/s).

In the second hydrograph, the desired end state is not achieved as well. Using V = 1.5 m/s the peak is almost 150 cms higher than the observed peak but the time of peak has moved to the left in the desired direction.
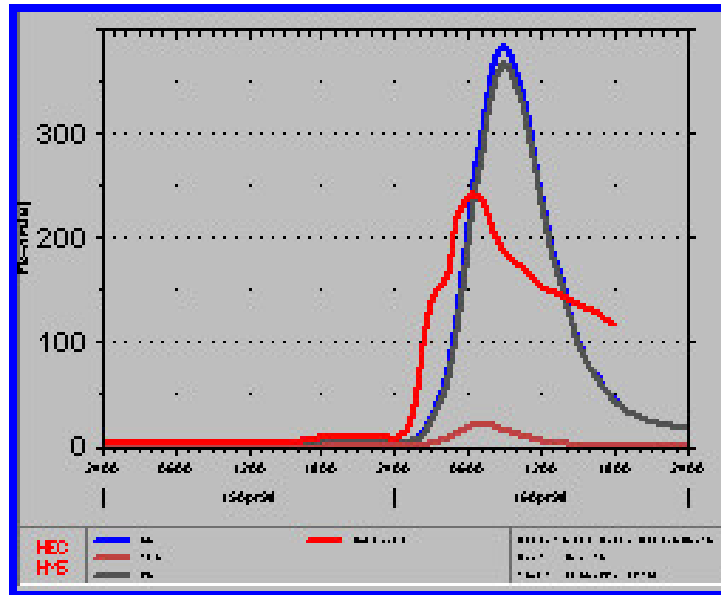
Figure 6-9. Carthage Gage Hydrograph (Velocity 1.5m/s).

7 Calibration

All models and their parameters are approximations to reality, as such there is a general need for calibration or checking with observed data. If data are not available at the site, this can only be accomplished using a regional relationship between parameter values and physical characteristics. Records at nearby basins can be used to recalibrate a relation of this type.

Where flood records are available at a site, one or more model parameters should be adjusted to give the best possible fit of the calculated and observed hydrographs for at least one flood. Where two or more parameters are adjusted, interaction of the value's frequency occurs, so that different combinations of parameter values give very similar computed hydrographs for an observed flood but may give quite different results with design floods of larger magnitude. It is often desirable to select the values of all but the most important parameter from physical considerations or by judgment and to adjust the remaining parameter to give the best fit to the observed data.

Manual trial-and-error adjustment of parameters is often of sufficient accuracy for practical flood estimation and allows examination of the effects of changing parameter values. Alternatively, automatic optimization programs, such as the one found in HEC-HMS can be used (Maidment, 1993). Common calibration methods include judging the fit of a calculated to an observed hydrograph and split sample testing.

Various criteria may be used for judging the fit of a calculated to an observed hydrograph. Common measures are the differences between peak magnitudes, a measure of overall fit (such as the sum of absolute values), or squares of the differences between lags or other time measures. The first

two are the most common and satisfactory. There is no one uniquely correct criterion, and the choice must be made by judgment, taking into consideration the objectives of the analysis, noting that use of different criteria will usually lead to different derived parameter values. Even when a single fitting criterion is used, parameter values derived from different floods will generally be different as a result of the data errors and the fact that all models are only approximations of reality. The possibility of trends in derived values should always be examined (Maidment, 1993).

If sufficient data are available, it is desirable to use split sample testing. The model calibrated with about two-thirds of the data is tested by its ability to reproduce the remaining data, considering the effects of any trends. If the test results lie within acceptable limits, the data and model are accepted, and recalibration is carried out using all of the data. If the test results lie outside acceptable limits, the basic assumptions and data used in the calibration should be thoroughly checked. If the test results are still outside acceptable limits, resort must be made to recalibrating with all of the data, but confidence in the results is then reduced (Maidment, 1993).

7.1   The Original Basin Model

As discussed in the HEC-HMS chapter of this report, the program was run using the basin model created with CRWR PrePro using common parameters for watersheds. Using the Carthage USGS Gage Station identified as (Control), the following hydrograph was generated after the run. The red curve represents the observed data and the blue curve is the HMS generated hydrograph. It is evident that the model requires calibration.
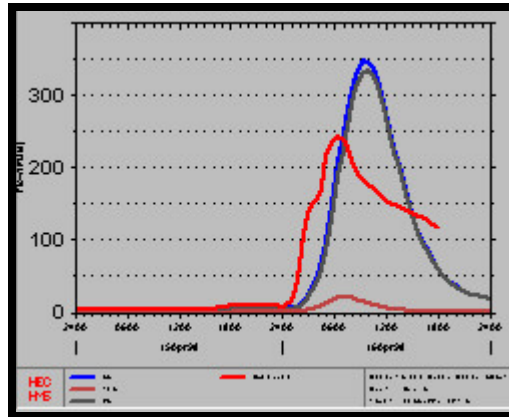
Figure 7-1. Carthage Gage Hydrograph (Velocity 1 m/s).

Method	Flow (ft3/s)	Time of Peak
Control	8616.7	0630
Run 1	12218.88	0930

Table 7-1. Run 1 Data Versus Carthage Gage.

7.2   Calibration of the HMS Basin Model

Within a basin model in HMS, there are three sections in which to edit parameters or to refine the model. The method in which these variables were defined is found in the chapter dealing with developing a hydrologic model. The following three areas are defined in the model with the respective parameters and are discussed below:

1. Loss Rates Soil Conservation Service (SCS) Method

2. Curve Number

3. Initial Abstractions (mm)

4. Percent Impervious Cover (%)

5. Reach Routing

6. Muskingum

7. K (hours)

8. X-Storage Coefficient

9. n-Number of Sub-reaches

10. Lag

11. Lag time through reach (minutes)

12. Transform SCS

13. Basin Lag Time (minutes)

7.2.1 Loss Rates

Loss Rate adjustments are discussed first because there is little room for refinement in this area. In the loss rates tab of the basin folder, the parameters that can be adjusted include Curve Number (CN), Initial Losses, and Percent Impervious cover. A detailed discussion of how all the Loss Rate values were derived can be found in Chapter 4. A brief discussion of each value and how it plays in calibration is found below.

Curve Numbers were initially derived in ArcView and CRWR PrePro using soils and land cover/land use data. The only way to refine these values is to use more recent land cover/land use data, which is not currently available at this time. An initial look reveals that there would be little change because most of the basin is urbanized and only the northern portions of the basin will show small changes due to urban sprawl.

The parameter of initial losses was derived in ArcView using the generated Curve Number grid. Generalized values were initially added to HMS using transfer tables, but once the basin model was built, the values were adjusted with the ArcView values. These values were used in Run 1 shown above.

Initial values for percent impervious cover were added manually based on personal observations and Digital Ortho Photos. Throughout the basin, a majority of the area is urbanized while the remainder is agricultural. The urban areas were given a value of 60% and the agricultural areas were assigned a value of 30%. All of these values are adjusted in HMS using the Loss Rate tab of each basin folder.

7.2.2 Reach Routing

The routing parameters for the basin model were derived in CRWR PrePro using the capabilities of ArcView and CRWR PrePro. The parameters were added to the model using transfer tables. These transfer tables have some parameters that are generalized due to the fact that ArcView is not capable of generating them with precision. For reach routing, the reach length was defined by ArcView while the stream velocity (1 m/s) and Muskingum X (0.2) were defined in the transfer tables.

In this HMS model, the runoff is routed using one of two methods as defined by CRWR PrePro. The routing method determines the time of travel of the flood wave through each reach in the HMS model. The particular method to be used is a function of the stream velocities (V) used and the length of the flow path (L_S). As shown below, the L_S/V value will determine the type of routing method to use. The term Delta t that the fraction is compared against is the analysis time step. For this basin model the time-step is 15 minutes. If the resulting value is less than the time step (15 min), the pure lag equation (t_{lag}) is used. This equation is typically used in shorter reaches, and the units for the lag time are minutes.

$$\frac{L_s}{V_s} < \Delta t$$

$$t_{lag} = \frac{L_s}{60\,V_s}$$

Equation 7-1. Pure Lag.

When the resulting value is greater than the time step, the Muskingum method (K) is used. The units of this equation are hours. In looking at the two equations, it is readily apparent what variable has the greatest effect on the outcome due to the fact that the length of flow path, which is calculated in PrePro, is not subject to change.

$$\frac{L_s}{V_s} > \Delta t$$

$$K = \frac{L_s}{3600\,V_s}$$

Equation 7-2. Muskingum Method.

Velocity is not only important in determining the routing method used, but also the flood wave time of travel. Knowing this, the next task is to determine the approximate velocities of the channel in hopes of calibrating the model.

Before looking at the velocities, a more in depth look at the Muskingum Method is necessary to eliminate two of the parameters that are used in the method. The two parameters are the number of sub reaches (n) and Muskingum (X).

The number of sub-reaches is just a method of solving an algorithm numerical instability issue. The value of (n) is an integer value defined by the equation below. As a result, this is a parameter that will not be refined for the

calibration. If a different time step is used, the value of n must be
recalculated to account for the change. If CRWR PrePro is not used with the
parameter tables, the values of n must be calculated manually and entered in
HEC-HMS accordingly.

$$n = \frac{L}{3 \times \Delta t \times V} + 1$$

Equation 7-3. Number of Subreaches.

The Muskingum method models the storage volume of flooding in a river
channel by a combination of wedge and prism storage. During the advance
of a flood wave, inflow exceeds outflow, producing a wedge of storage.
During the recession flow, outflow exceeds inflow, resulting in a negative
wedge. In addition to this, there is a prism of storage, which is formed by a
volume of constant cross section along the length of prismatic channel. This
is illustrated in the figure below (Maidment, 1993).
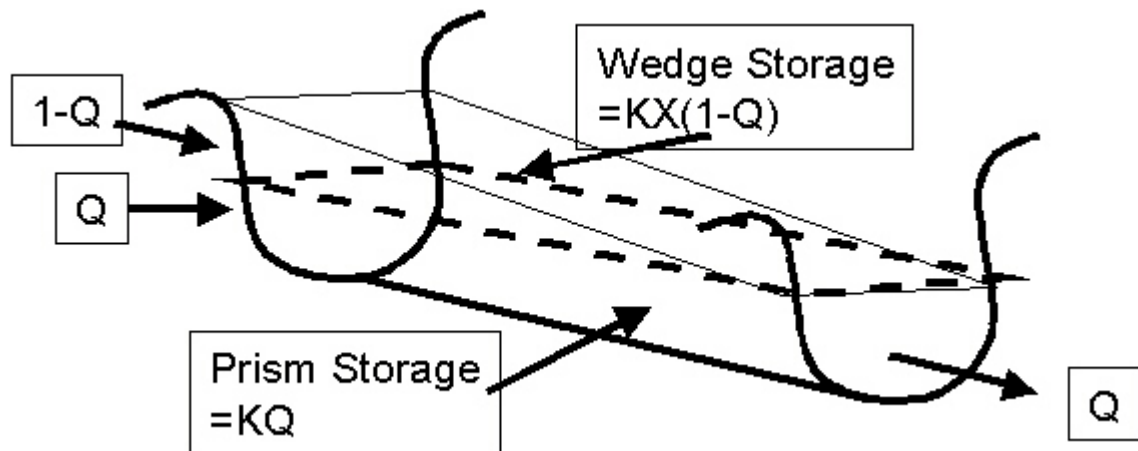
Figure 7-2. Channel Storage. Source Tate 1998.

The Muskingum X (storage constant) ranges from 0 to 0.5 with the mean near
0.2. For this model, the mean was used for calibration purposes and the

value was not changed because results are relatively insensitive to the changing of this value (Maidment, 1993).

To refine the routing method for calibration, the stream velocity is the only parameter that will need to be considered. A simple sensitivity test was conducted to see the effects of lower and higher velocities. Using two new parameter tables with velocities of 0.5 and 1.5 m/s, the following results were found at the Carthage gage.

	Control	V=0.5 m/s	V=1.0 m/s	V=1.5 m/s
Flow (ft3/s)	8616.8	8193.0	12218.9	13560.8
Qdelta vs. Control		-423.8	3602.1	4944.1
Peak (24-hr)	6:30	11:00	9:30	9:00
TpDelta vs. Control		4:30	3:00	2:30
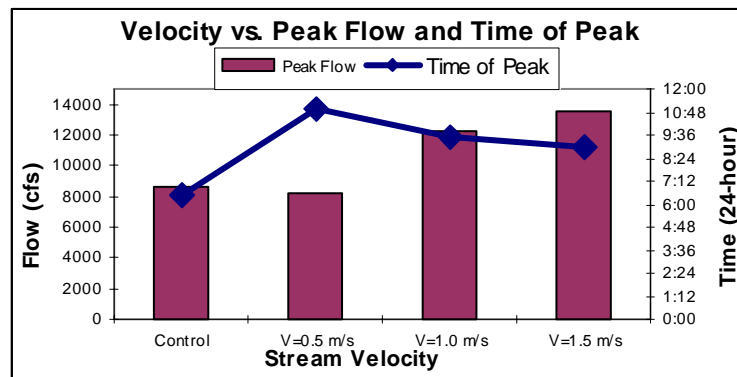
Figure 7-3. Velocity Effects on Flow and Time of Peak.

It is apparent from the graph above, that as the stream velocity increases, the flows increase while the time of peak decreases. This graph does show that the flows and time of peak discharge are sensitive to the stream velocities.

In the parameter tables, the velocities are entered as constant throughout the entire model. It is rather obvious that velocities vary in streams due to the varying physical characteristics of the channel and floodplain. The following photos show some of those aspects affecting stream velocity. Mill Creek has

sections of concrete lined channel, improved natural channel and numerous bridges. Due to poor maintenance, sediment has deposited in these channels as well.

Figure 7-4. Channel Characteristics.

Figure 7-5. Channel Characteristics.

All of these characteristics affect stream velocity. The easiest way to depict this is using Manning's equation for English units as shown below.

$$V = \frac{1.49}{n} R^{\frac{2}{3}} S_f^{\frac{2}{3}}$$

Equation 7-4. Mannings.

The variable in the equation are the Manning roughness coefficient (n), hydraulic radius (R), and the friction slope (S_f). When viewing the results in a portion of a channel where the hydraulic radius and slope remain constant, it

is apparent that the velocity is sensitive to the roughness coefficient. This is illustrated below using the various values for (n).

Width=	200	P= 210	
Depth=	5	Slope=0.03	
Roughness	**Velocity**		
Coef	**(ft/s)**		
0.012	6.09	Concrete	
0.02	3.65	Gravel w/conc sides	
0.033	2.21	Gravel w/riprap sides	
0.03	2.44	Clean Natural	
0.05	1.46	Winding w/weeds	

Table 7-2 . Effect of Manning's n on Stream Velocity.
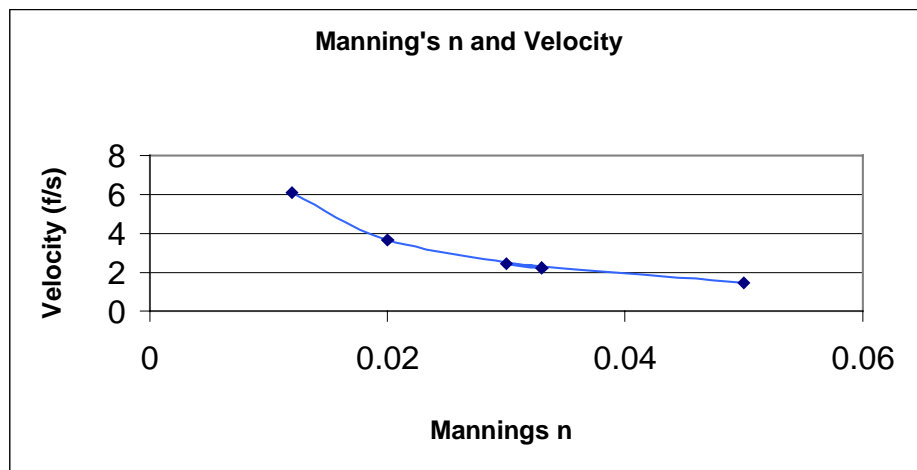
Figure 7-6. Effect of Manning's n on Stream Velocity.

Velocities vary from 1.4 f/s to 6.0 f/s depending on the channel type. This change in velocities is indicative of the range within the Mill Creek Basin as the flood wave passes through the different sections that are natural or altered.

Cross section characteristics can be found in HEC-RAS when provided with a geometry file. A table can be generated in RAS when specifying the parameters required. In this case, all of the variables applicable to the

Manning's equation were generated and put into an Excel spreadsheet. This
spreadsheet can be found in Appendix E. Then the series of cross sections
that make up each reach in HMS were grouped accordingly to determine
average values for that reach. An extract of that product is shown below.
The reaches are numbered according to the HMS basin they pass through
numbered from 102 to 129. First all the variables in the Manning's Equation
were averaged and then applied to the equation to yield an average velocity
for each reach. These values are shown below in column 1 (Velocity of
Averages). Then, Manning's equation was applied to each cross section in
the reach and the resulting velocities were averaged. These values are
shown below in column 3 (Average of Velocities). Note the term RAS in the
source row, this means that the slopes used in the velocity determination
were derived from the generated RAS data.

Source	RAS	ArcView	RAS	ArcView
	Velocity of Averages	Velocity of Averages	Average of Velocities	Average of Velocities
Basin	Velocity	Velocity	Velocity	Velocity
(HMS)	(ft/s)	(ft/s)	(ft/s)	(ft/s)
102	0.92	1.48	1.13	1.85
105	0.69	2.90	0.53	2.92
109	1.77	3.18	1.71	3.56
115	3.88	6.04	3.66	6.35
119	4.27	6.92	3.82	7.19
121	3.97	4.73	3.71	5.16
122	4.08	6.34	3.89	6.81
125	10.35	8.28	9.38	10.11
126	4.10	5.36	5.09	7.17
128	13.60	17.63	13.67	19.44
127	5.30	14.20	5.29	14.73
129	11.17	15.77	8.81	21.51

Table 7-3. Basin Velocity Calculation.

In RAS the slope (S_f) is determined by the using the channel bottom between
adjacent cross sections. If there is a long distance between two cross

sections this slope may no be indicative of the actual slope. In columns 2 and 4 the same procedure of averages was used as discussed above with the exception of the slope value. Using ArcView, reach slopes were determined and used to see if there was any difference. The average of velocities method (columns 3 and 4) appeared to yield data with the smallest deviation. The slopes in ArcView also revealed more realistic velocities that would be representative of the channel. As a result, the column 4 values were used to compare results. The graph below shows the velocity profiles for the various methods in the 4 columns above. There is a definite trend in the rise and fall of the velocity as the flood wave moves down the channel.
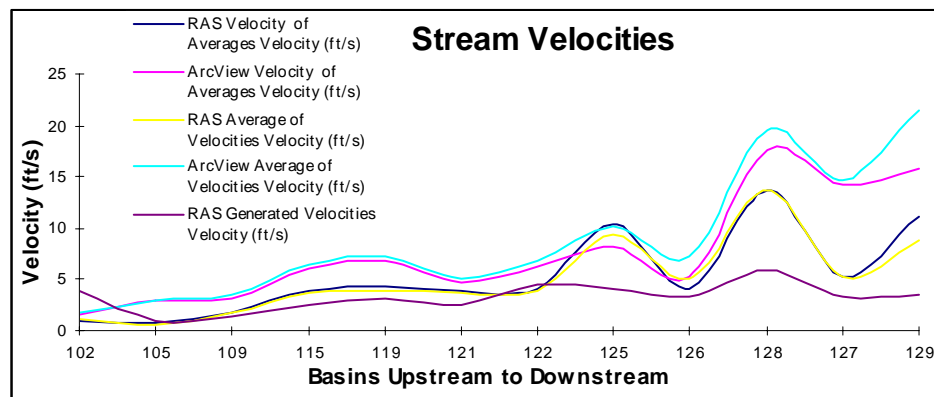
Figure 7-7. Velocity Profile Using Manning's Equation.

Geometry data was not provided for all of the tributaries contributing to Mill Creek. Data was provided for the West Fork branch and to simplify things, the RAS velocities were used. This average velocity of approximately 5 f/s was used for all branches and the respective routing methods were determined. The complete spreadsheet of routing methods can be found in Appendix C.

The velocities in column 4 were used to attempt to calibrate the model with the exception of the value for basin 129. The velocity used in Basin 129 was the value in column 2. As stated above, 5 f/s was used for all tributaries and

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the HMS reach parameters were recalculated in Excel and entered in HMS. The following is the new hydrograph produced at the Carthage Gage.
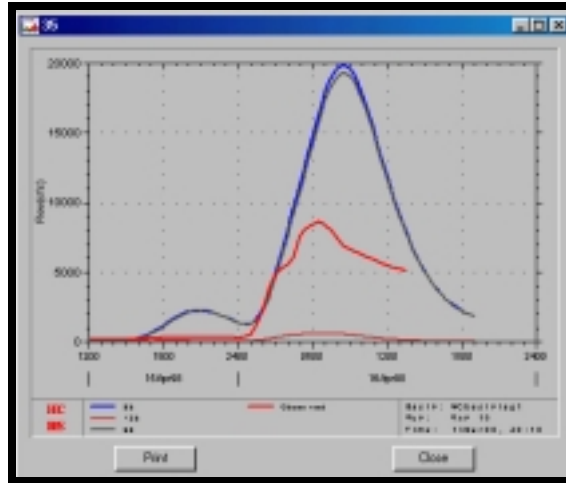
Figure 7-8. Hydrograph at Carthage Gage with Adjusted Velocities.

Method	Flow (ft3/s)	Time of Peak
Control	8616.7	0630
Adjusted Velocities SCS Lag Equation With initial Losses Average % Impervious Cover	19785	0830
Adjusted Velocities SCS Lag Equation With initial Losses 0 % Impervious Cover	17902	0845
Adjusted Velocities SCS Lag Equation With initial Losses 75 % Impervious Cover	20503	0830

Table 7-4. Impervious Cover Sensitivity Analysis.

The resulting discharge from velocity calibration increased considerably from the first run. These results are contrary to the desired results for calibration, but this step is necessary and more representative of actual channel conditions. Given the fact that the new channel velocities are not enough to calibrate the model, other parameters must be considered. The table above

shows the same run of the basin model changing the percent of impervious cover. A simple tolerance test showing the effects of increased and decreased impervious cover showed that the adjustment of this variable has minimal effect.

7.2.3 Transform: Soil Conservation Service (SCS)

The sub-basin lag-time is calculated with the SCS formula and is given below. In the formula, (t_p) is in minutes and is the basin lag time, which is measured from the centroid of the hyetograph to the peak time of the hydrograph. Other parameters are the longest flow path (**L$_w$**), slope of the longest flow path (**S**), and Curve Number (**CN**). All of these values are found in CRWR PrePro and transferred to HMS.

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

Equation 7-5. SCS Lag-time.

The only parameter that can be adjusted is the CN, but as discussed above, recent Land Cover/Land Use data is not available. In addition, due to the fact that the basin is predominately urban, the increase will be minimal because max development of the area has peaked.

7.3 Additional Basin Characteristics Contributing to Hydrograph Changes

Thus far, a simplistic approach has been taken to adjust the parameters in an attempt to calibrate the model. The main parameter was the reach velocities

that affect the time of travel of the flood wave. The results still yield peak flows that are too high with a time of peak that is still late.

A closer look at the basin must be taken to account for some of the oddities that are characteristic of a heavily urbanized basin in an older city such as Cincinnati. Below are some of the characteristics that contribute to its complexity as found on the ORSANCO website (http://www.orsanco.org/wwdemo/wwd_trib.html). This site is broken into two sections, one is Land Use and the other is Combined Sewer Overflows (CSOs). The Land Use information is to reiterate the extent to which the basin is urbanized. The CSO facts appear to make the model calibration difficult. A more detailed discussion of CSOs follows.

1. Land Use: Predominately urbanized (Cincinnati Municipal Sewer District, 1994)

   a. residential 46%

   b. commercial 13%

   c. undeveloped 12%

   d. industrial 11%

   e. public and recreational 10%

   f. agriculture 8%

2. Two reservoirs associated with Hamilton County Park District

   a. Sharon Lake: 36 acres

   b. Winton Lake: 188 acres

3. Population - 453,800 (2,130 people/sq. mile)

4. Combined Sewer Overflows (CSO): 57 on the Mill Creek; 45 on Mill
   Creek tributaries. The red circles in the diagram below represent the
   approximate locations of the CSO outfalls.
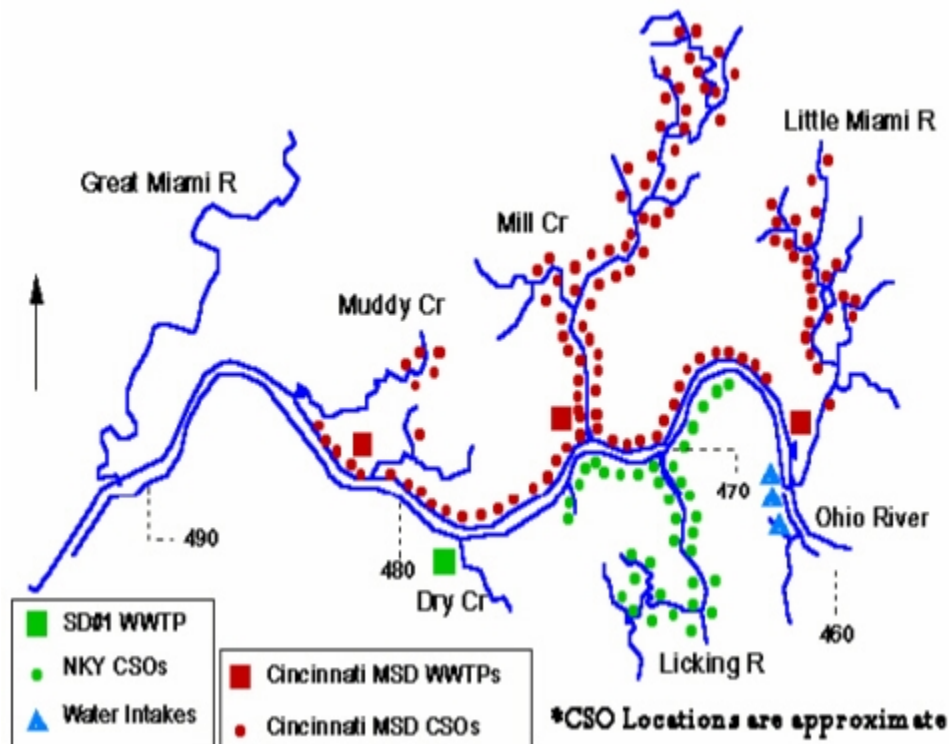
Figure 7-9. CSO Locations. Source: http://www.orsanco.org/wwdemo.html.

A combined sewer carries both sanitary wastewater and storm water runoff.
The characteristics of wastewater in a combined sewer will vary depending
upon dry and wet weather conditions and characteristics of surface runoff.
The impact upon wastewater treatment facilities and receiving water may be
significant during wet weather conditions (Qasim, 1999).

On normal days, the combined sewers carry all of Cincinnati's wastewater
through one of the Metropolitan Sewer District (MSD) treatment plants before

being released into the Ohio River or one of several creeks and rivers that feed into the Ohio. But after heavy rains, storm water surges overwhelm the system's treatment capacity. When flow is too strong, the plants are designed to allow water to pass by straight into the river (http://enquirer.com/editions/1998/08/04/loc_river04.html). The diagram below illustrates how CSOs such as those in the Mill Creek Basin operate.
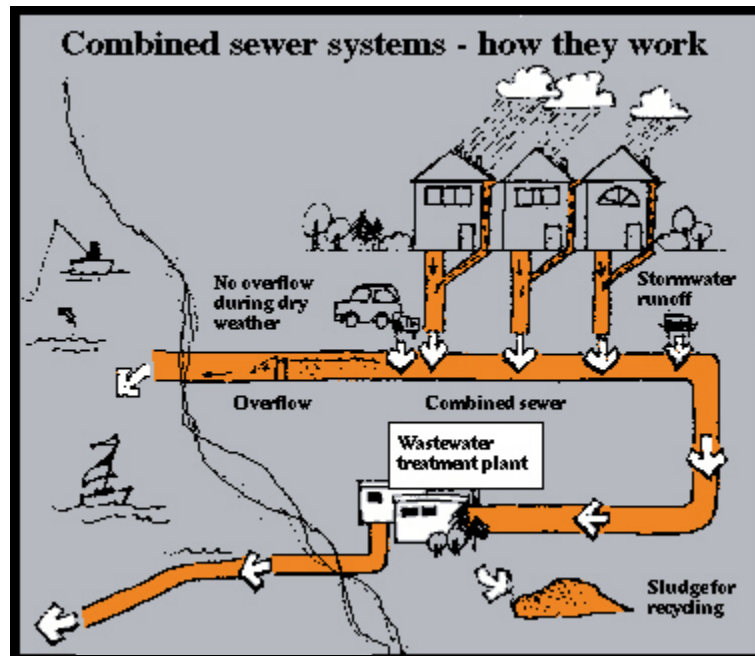
Figure 7-10. CSO Schematic. Source: http://www.orsanco.org/wwdemo.html.

In looking at the diagram above, one can see that there are two points of discharge as a result of the CSO system. The overflow drains to the basin during extreme wet weather conditions. During these times, storm water runoff as well as raw sewage from the basin runoff. The facility discharges treated wastewater to stream as well. This creates difficulties in the system because the overflow discharge is dependent on the time of day and severity of the storm event. Below is what a CSO outfall looks like in Mill Creek.

Figure 7-11. CSO Outfall on Mill Creek.

The best way to illustrate what happens with CSOs when it rains is by looking at a simple diurnal inflow/infiltration curve for a treatment plant. This curve was taken from Qasim (1999).
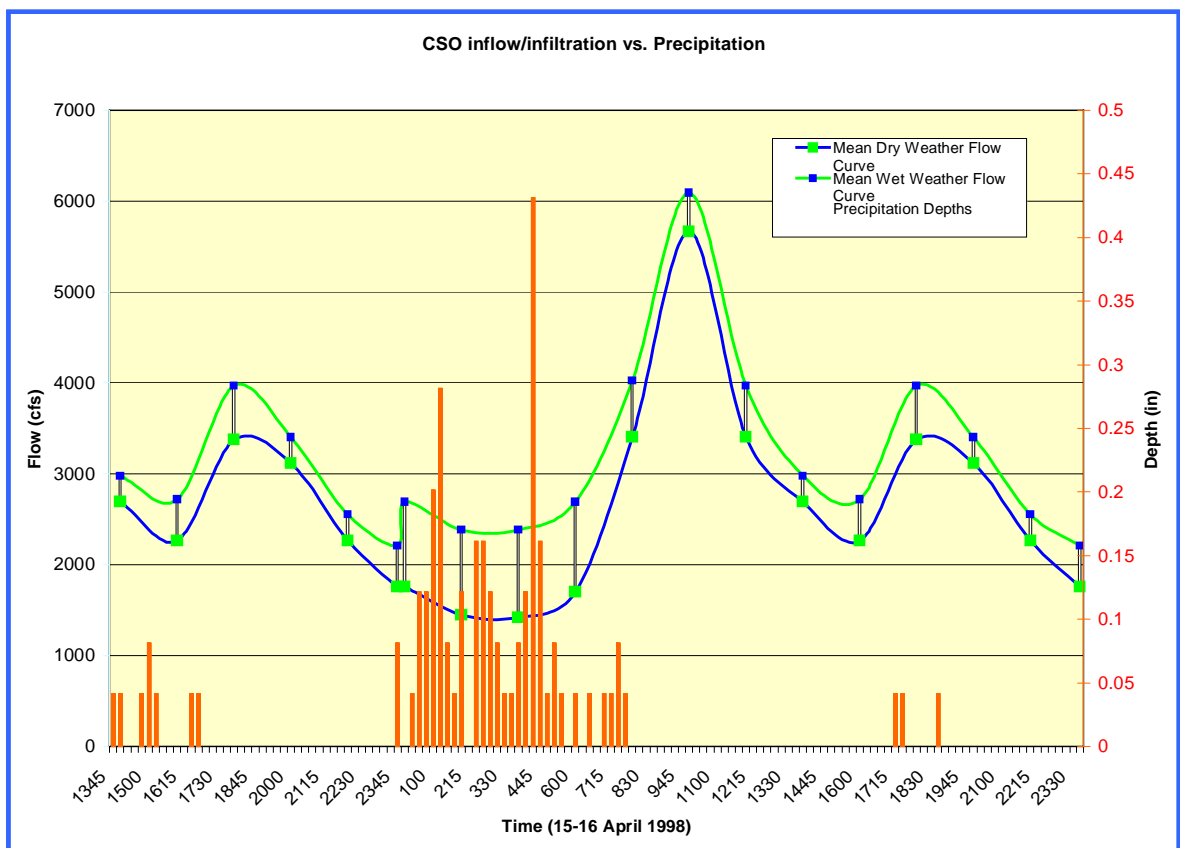
Figure 7-12. Inflow/Inflitration Curve with Precipitation.

This sample inflow/infiltration curve shows the diurnal effects of wastewater flows for a typical treatment plant. This is for wastewater only and does not consider the effects of how a combined system works. Two curves depict the dry weather flows and wet weather flows. The wet weather flows increase into the treatment facility as a result of infiltration into the sewer lines. Considering how a combined system works, it is likely that the wet weather flows will increase because storm water is routed through the same conveyance system. During dry conditions, the treatment facility flows peak around 1000 hours as a result of the morning "first flush" created by morning showers and toilet usage.

Assuming the above curve represents a combined system during dry periods, the facility probably reaches peak storage capacity at 1000 hours as a result of diurnal flows. The wet weather curve will fluctuate as a result of precipitation events depending on time, duration, and intensity. For an event that began the evening before when the facility is at the lowest inflow, the facility would capture the storm water and treat it accordingly. If the event occurred in the early morning hours during the rise of wastewater flows, the plant will reach peak capacity earlier than 1000 hours. When this early peak occurs, the continuing flows of wastewater and storm water will then overflow the combined system and discharge to the nearby stream. In this case, the flows going to the stream can be much greater than would be expected from the expected runoff. These two examples illustrate how the typical rainfall/runoff values depicted in HMS may not be indicative of actual conditions in Mill Creek.

To replicate these conditions in HMS, some simple assumptions must be made to account for CSO effects. The assumptions are as follows:

(1) Precipitation occurring prior to the facility reaching full capacity will be captured.

(2) Precipitation occurring during and after the facility reaching full capacity will overflow the combined sewer with raw wastewater.

(3) Periods of extended precipitation will cause the treatment facility to reach capacity earlier than the diurnal dry weather flows.

These assumptions can be visualized plotting precipitation data on the inflow/infiltration curve as seen above. The above precipitation data was taken from one of the rain gages in the Mill Creek Basin. In this example, a majority of the precipitation occurs during early morning hours prior to the introduction of wastewater flows shown in the rising portion of the curve. Theoretically, some of the precipitation would be captured by the treatment facility and the actual peak would occur sooner than 1000 hours. These assumptions can be validated with Figure 4-44 below.

This is the actual flow data for the Mill Creek Wastewater Treatment Plant on the 15th and 16th of April 1998. The red squares indicate the time when the plant reached capacity and overflow began. The time frame is 0103 hours to 1101 hours on 16 April. This is due to the rainfall that occurred in the early evening. From 0000 hours to 0200 hours, 1.26 inches of rain fell on the basin around the Mill Creek WWTP. Remembering how diurnal municipal wastes flow, the plant should have been at its lowest flow period during dry weather. The reason it peaked was the capture of the runoff from the 1.26 inches that fell and was captured by the combined sewers. This lends validity to the assumptions made above.
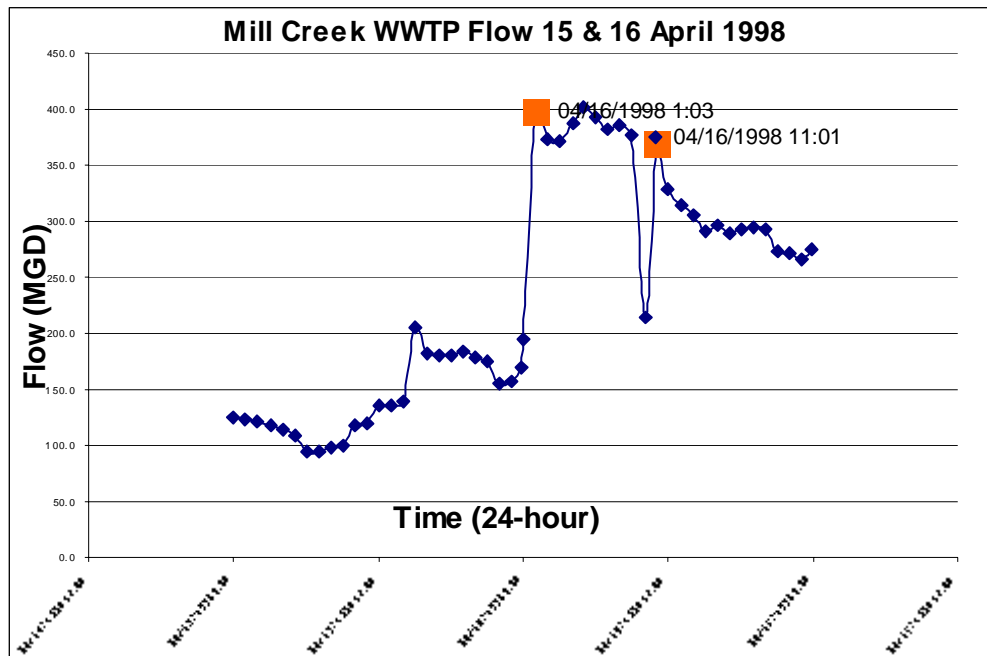
Figure 7-13. Mill Creek WWTP Flow Data on 15 and 16 April 1998.

During this 10-hour time frame when the plant reached capacity, the inflow was 398 MGD. The plant design capacity is 130 MGD for the municipal flow. The fact that the plant was able to accept 398 MGD shows that there is a significant storage capacity in the plant. Over a 12-hour period this storage capacity translates to 135 million gallons. In addition to this storage capacity, there is additional storage in the interceptor pipes. Rough estimates from Mike Heitz show that the interceptors are about 12 feet in diameter and run in excess of 30 miles. There are two such interceptors along Mill Creek. Keeping in mind how the combined system works, once the plant reaches capacity, the interceptors begin to store water until a point in which it flows over a weir and to an outfall. Calculations reveal that these interceptors with the dimensions above can hold around an additional 266.6 million gallons. There is another unknown amount that is stored in the lines bringing water

and municipal waste to the interceptors. These rough estimates alone show how a combined sewer systems affects the natural state of a basin.

To get a realistic look at how this works, some data will be necessary. The treatment facilities in the basin would need to be identified and their location plotted in ArcView. A coverage of the actual sewer lines and where they drain from would form a CSO shed that would show what areas are contributing to each treatment facility. In addition, the time that each facility peaked during the event used for calibration yields the time that overflow occurred.

This data is critical to another assumption, which was not considered in the earlier parameter calibration. In this case, the precipitation model would have to be adjusted to account for the capture of runoff that went to the treatment facility. In simplest terms, when the plant reaches capacity, all precipitation data prior to that time is deleted and assumed to not contribute to stream flows. The last item needed to conduct a thorough analysis would be the discharge locations of the plant treated discharges and CSO outfalls. In some cases, the outfalls may be out of the basin to other water bodies such as the Ohio River. This translates to a portion of the basin that does not contribute to Mill Creek Flows.

To verify these assumptions, the HMS model was copied and altered to see the effects on the hydrograph at the Carthage gage. The following are a series of runs that were conducted in which a portion of the precipitation data was removed replicating a time when overflow occurs.
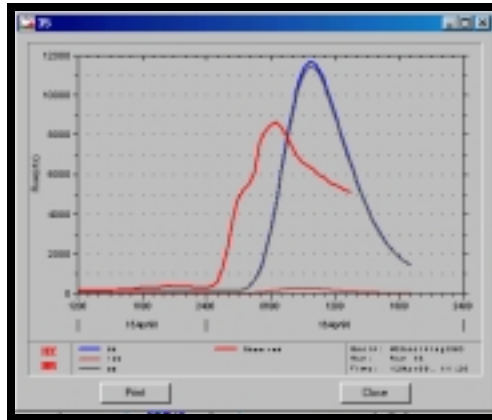
Figure 7-14. Hydrograph with Precipitation Beginning at 0200 hours.

Method	Flow (ft3/s)	Time of Peak
Control	8616.7	0630
Precip 0200 hours	11650	0945

Table 7-5. Results of Adjusted Precipitation at 0200 hours.
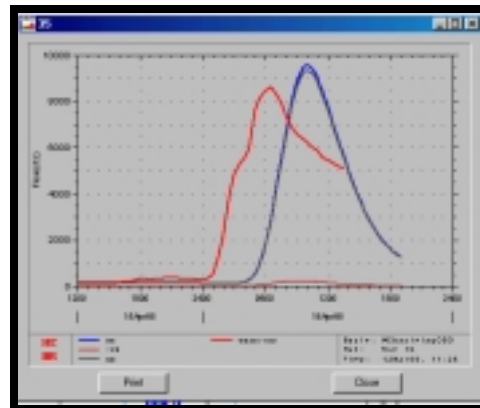
Figure 7-15. Hydrograph with Precipitation Beginning at 0300 hours.

Method	Flow (ft3/s)	Time of Peak
Control	8616.7	0630
Precip 0300 hours	9537.9	1000

Table 7-6. Results of Adjusted Precipitation at 0300 hours.

These runs show how the peak discharge drops dramatically after assuming
that the precipitation in the earlier portion of the event goes straight to the
treatment facility. It appears that this assumption is correct in order to

calibrate the peak flows. Though this is generalized throughout the basin, refined times of when the treatment facilities reached capacity will continue to bring the flows into tolerance.

The next parameter that needs calibration is the time that the peak discharge occurs. In both examples above, the flood wave is still over three hours late. This means that the wave must hit sooner. After having adjusted all of the possible parameters as discussed earlier another in depth look at the basin is still required.

This urban environment in littered with conveyance systems to carry wastewater and storm water. This forces one to look at the method in which basin lag times were calculated. The SCS Lag equation below uses the longest flow path of the watershed, the average watershed slope, and the runoff curve number. The equation was adapted to small urban basins and found to be generally good where the area is completely paved but tends to overestimate in mixed basins (Maidment, 501). The fact that it tends to over estimate reveals that the basin lag times are too long and thus cause the time of peak to occur later.

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

Equation 7-6. SCS Lag-time Using Curve Number.

In considering the makeup of the basin and the numerous conveyance systems, it appears that in most cases the water runs off pavement to nearby combined sewers and flows to the treatment plant or creek by way of pipe flow which is much quicker than the overland flow replicated in the SCS Lag

Equation. A more realistic representation would be the longest flow path and average pipe flow through a combined sewer system.

$$Tp = \frac{L}{60x1.67xV}, 3.5\Delta t$$

Equation 7-7. SCS Lag.

Using the basin model that replicated the flows above with the adjusted precipitation model the lag times were adjusted using the above equation. The following hydrographs were produced at the Carthage gage.
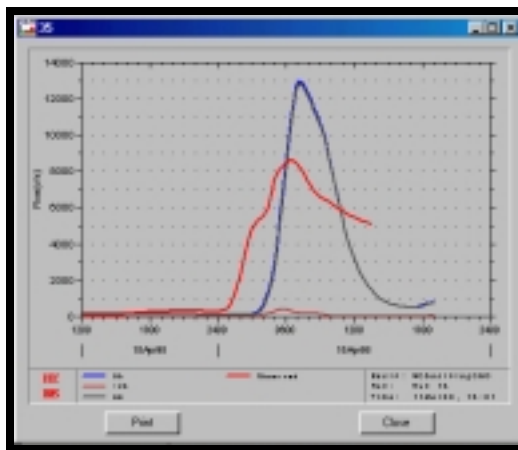
Figure 7-16. Hydrograph with Precipitation Beginning at 0300 hours and Adjusted Lag Times.

Method	Flow (ft3/s)	Time of Peak
Control	8616.7	0630
Precip 0300 hours L/V Lag time w/ V=1.5 m/s	12,959	0715

Table 7-7. Results of Adjusted Lag Time and Precipitation at 0300 hours.
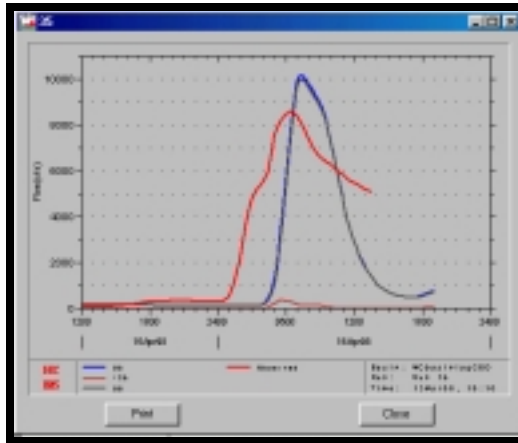
Figure 7-17. Hydrograph with Precipitation Beginning at 0330 hours and Adjusted Lag Times.

Method	Flow (ft3/s)	Time of Peak
Control	8616.7	0630
Precip 0330 hours L/V Lag time w/ V=1.5 m/s	10,107	0730

Table 7-8. Results of Adjusted Precipitation at 0330 hours.

The results above show how the adjusting of basin lag times brings the time of peak within one hour of the actual time and the flows within 1500 cfs verifying the assumptions made about the effects of the combined sewer system. Given more detailed information about the treatments facilities within the basin, this model can be calibrated to this particular storm event. This requires a great deal of work due to the complexities of the basin and the effects of wet weather on the sewer system.

The problem that arises from the calibration of this system is the calibrated model cannot be used to replicate the frequency events necessary for planning flood control measures. This model is calibrated to a particular event, and the precipitation model is adjusted using assumptions about how much runoff is actually flowing to the river and how much is captured for

treatment. A worst-case method will have to be established for planning

purposes in order to use this model for flood control planning.

8   Hydraulic Modeling with HEC-RAS

This chapter details the application of Hydraulic Modeling with HEC-RAS.
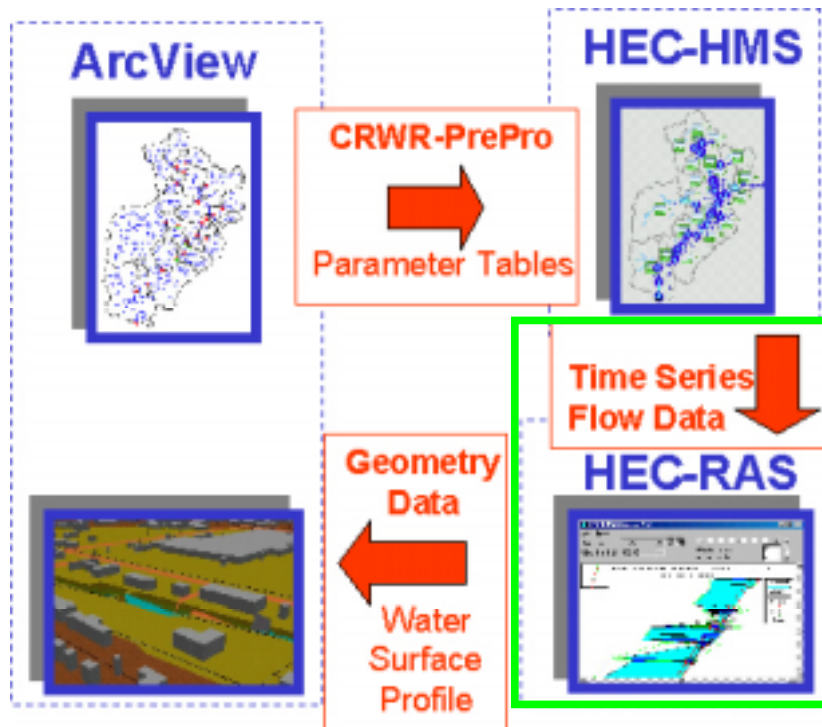
Figure 8-1. Hydraulic Modeling with HEC-RAS.

8.1   Data Requirements.

The data required for this section is the output time series data from the HMS model in the previous section titled, MillCreek_CSO_lag2.dss. Additional requirements are the cross section geometry data titled Mill Creek, Upstream at Barrier Dam; Mill Creek, Middle Sections; West Fork Mill Creek; and Mill Creek in Hamilton County. The Louisville Corps of Engineer District provided this information. With a working directory selected, these files were downloaded for use.

8.2   Starting the Project

HEC-RAS is started by clicking, **Start/Programs/Hec/HEC-RAS 2.2**. The
following window (Main Project Window) will subsequently appear.
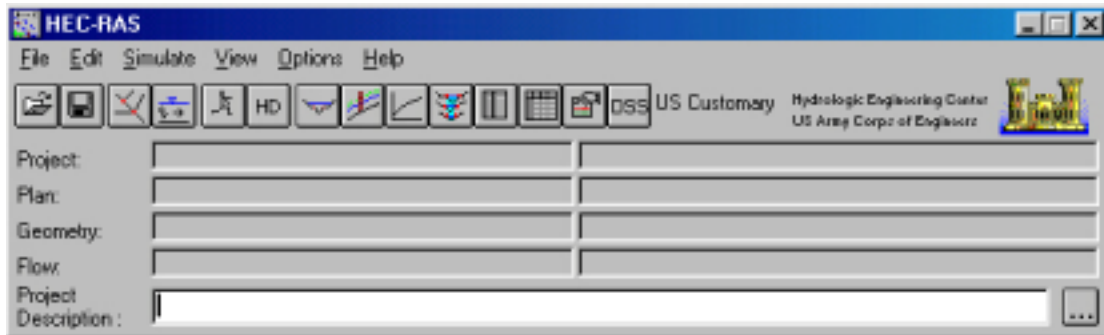
Figure 8-2. RAS Program Screen.

A Project in RAS refers to all of the data sets associated with a particular river
system. To define a new project, **File/New Project** is selected to bring up the
main project window.
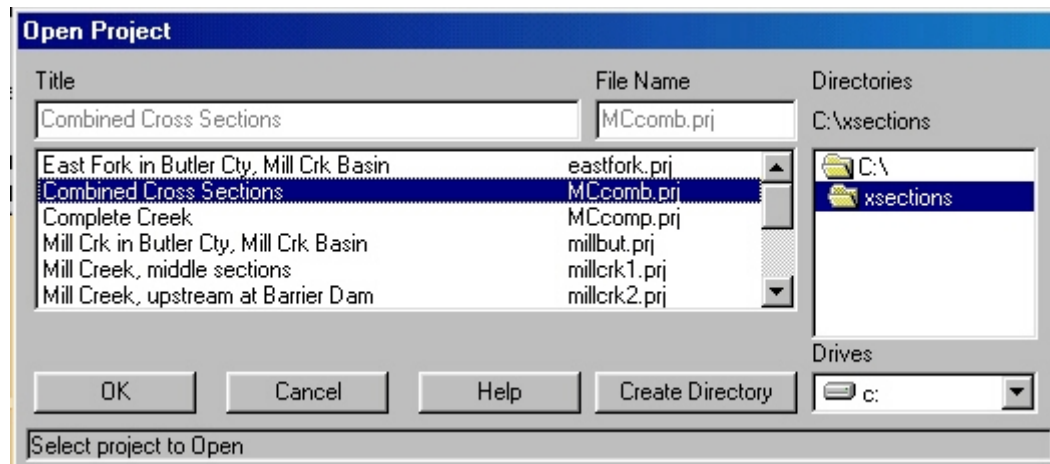
Figure 8-3. New Project Window.

The working directory in this case was set to C:\xsections where the geometry
data provided by the Louisville District was stored. The title "Combined Cross

Sections" was designated in the title block and the file name was Mcomb.prj. All project filenames for HEC-RAS are assigned the extension ".prj".

After clicking the OK button, a window opens confirming the information just entered. Click the OK button. The project line in the main project window will now be filled in. The **Project Description** line at the bottom of the main project window allows a detailed name for the actual short **Project** name. If desired, the button to the right of the **Description** bar can be clicked for additional space to type a lengthy description.

Each HEC-RAS project requires three components - Geometry Data, Flow Data, and Plan Data. The Geometry Data consists of a description of the size, shape, and connectivity of stream cross-sections. The Flow Data contains discharge rates, and the Plan Data contains information pertinent to the run specifications of the model, including a description of the flow regime. Each of these components is discussed in detail below.

8.3   Importing and Editing Geometric Data

The first of the components considered is channel geometry. To analyze stream flow, HEC-RAS represents a stream channel and floodplain as a series of cross-sections along the channel. To create a geometric model of Mill Creek it is necessary to import the geometry files provided by the Louisville District. In HEC-RAS main project window, select **File/Import HEC-RAS Data** and the most downstream set of cross-sections (millcrk2.g01). This HEC-RAS geometry file contains physical parameters describing Mill Creek cross-sections. To view the data, select **Edit/Geometric Data** from the project window.
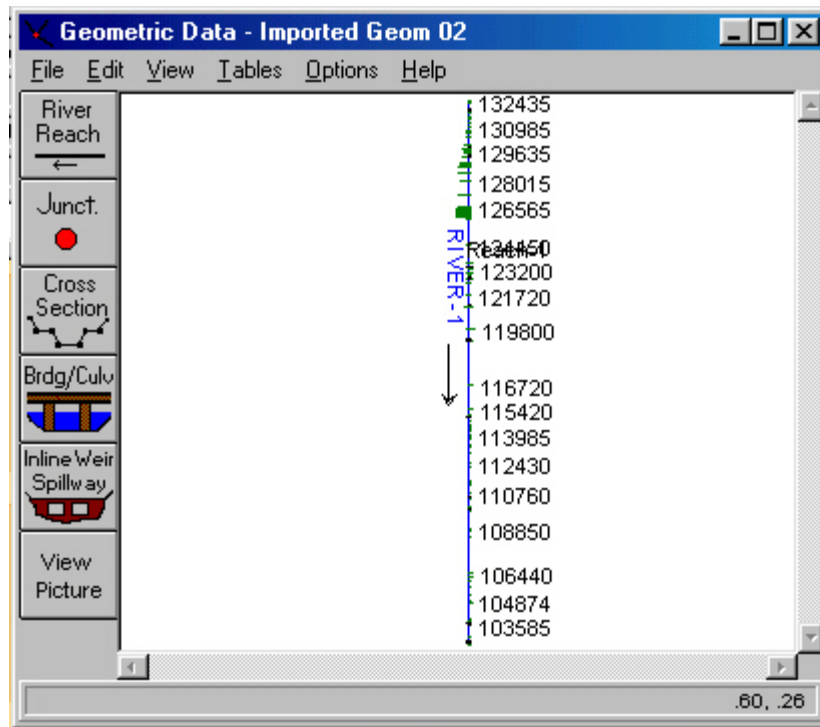
Figure 8-4. Geometric Data for Lower Portion of Mill Creek.

To complete the main channel, the remainder of the cross-sections must be added to the current set. Select **File/Import Geometry Data/HEC-RAS Format;** then select the radio button stating **add data to current geometry**. In the next view, select the geometry file for the cross-sections upstream titled "Middle Sections; West Fork Mill Creek." The Geometric Data View will show the added cross-sections. The same process is used for the final set titled "Creek in Hamilton County." The following figure will be in the view that contains all of the cross-sections.
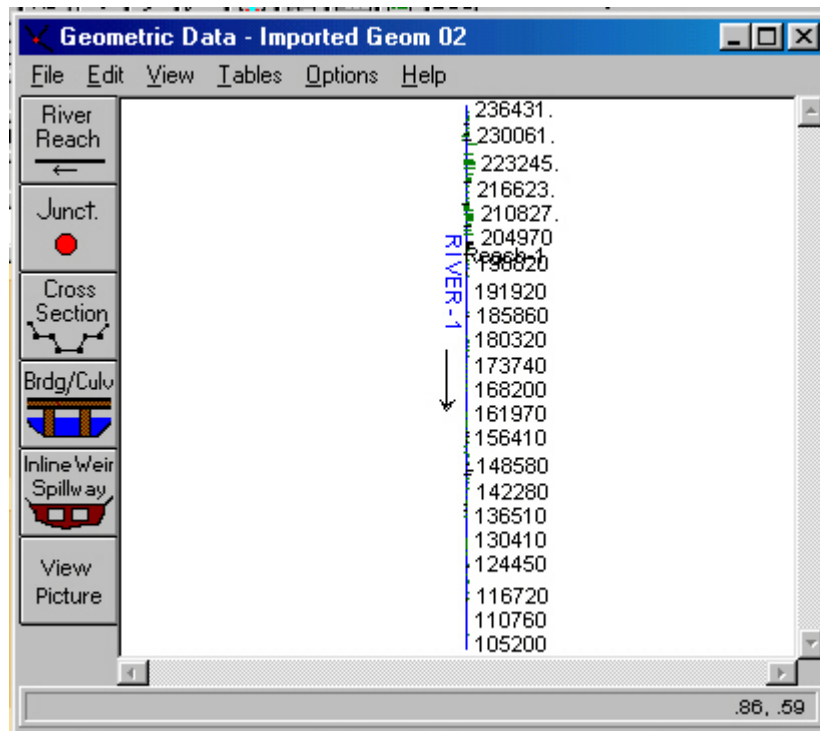
Figure 8-5. RAS Geometric Data.

The tick marks and corresponding station numbers denote individual cross-sections. Choices under the **View** menu provide for zoom and pan tools. The six buttons on the left side of the screen are used to input and edit geometric data. The **River Reach** and **Junct** buttons are used to create the reach schematic. (A reach is simply a subsection of a river, and a junction occurs at the confluence of two rivers.) Since the reach schematic is already defined, there is no need to use these buttons.

The **Cross Section**, **Brdg/Culv**, and **Incline Weir Spillway** buttons are used to input and edit geometric descriptions for cross-sections and hydraulic structures such as bridges, culverts, and weirs. The **View Picture** allows association of an image file (photograph) with a particular cross-section. Click on the **Cross Section** button to open the cross-section data window.

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Figure 8-6. RAS Cross Section Data.

The data used to describe the cross-sections include the river station/cross-section number 236431 in the figure, lateral and elevation coordinates for each terrain point (station and elevation columns), Manning's roughness coefficients (n), reach lengths between adjacent cross-sections, left and right bank station, and channel contraction and expansion coefficients. This data is typically obtained by field surveys. The **up and down arrow** buttons can be used to toggle between different cross-sections. Data is edited by double-clicking on the field of interest and manually changing the value. When performing this action, all of the data fields turn red and the "Apply Data"

button is enabled. Input data colored red indicates that the application is in
edit mode. To leave edit mode:

1.Click the **Apply Data** button. The data fields will turn black, indicating that
one is out of edit mode, and the data changes are applied.

2.Select **Edit/Undo Editing**. This allows users to leave the edit mode without
changing any of the data.

To actually see what the cross-sections look like, select the **Plot/Plot Cross-
Section** menu item.

Figure 8-7. RAS Cross Section.

The cross-section points appear black and bank stations are denoted with
red. Manning roughness coefficients appear across the top of the plot. The

up and down arrow buttons can be used to maneuver between different cross-sections. Any solid black areas occurring in a cross-section represent blocked obstructions. These are areas in the cross-section through which no flow can occur. Some cross-sections contain green arrows and gray areas. This symbolism is indicative of the presence of a bridge or culvert. Input data and plots specifically associated with bridges and culverts can be accessed from the main geometric data editor window by clicking on the **Brdg/Culv** button.

8.4   Importing and Editing Flow Data

To enter the flow editor, **Edit/Steady Flow Data** is selected from the main project window. At this point, stream flow output from the HEC-HMS model run in the HMS section is used. The resulting flows are based on the 10-year design storm taken from the Rainfall Frequency Atlas of the Midwest.

Output data from HEC-HMS models are stored in files with a .dss extension. DSS stands for Data Storage System, which is essentially a database for storing time-series information. To use these data, **File/Set Locations for DSS Connections** is selected from the main flow data window. To open the DSS file, File Folder Button is accessed and the MillCreek_CSO_lag2.dss file is selected from the working directory. The window should now look like this.

Figure 8-8. Set Locations for DSS Connections.

The DSS data are stored in table records, each one representing a 24-hour increment of time-series flow data. Each record is described by several parameters; some are shown below.

Column	Description
A	??????
B	HMS hydrologic element (subbasin, junctions, etc.) identifier
C	Flow Type (baseflow, floodflow)

D	Date
E	Model Time Step
F	HMS Run ID

Table 8-1. DSS Data Records.

HEC-RAS allows one to view the hydrograph of any DSS record. The highest flows for this model run occur on 12 December. After selecting a record with Column C = FLOW and Column D = 12DEC1999, **Plot Selected Pathname** is selected to yield the associated hydrograph shown below.
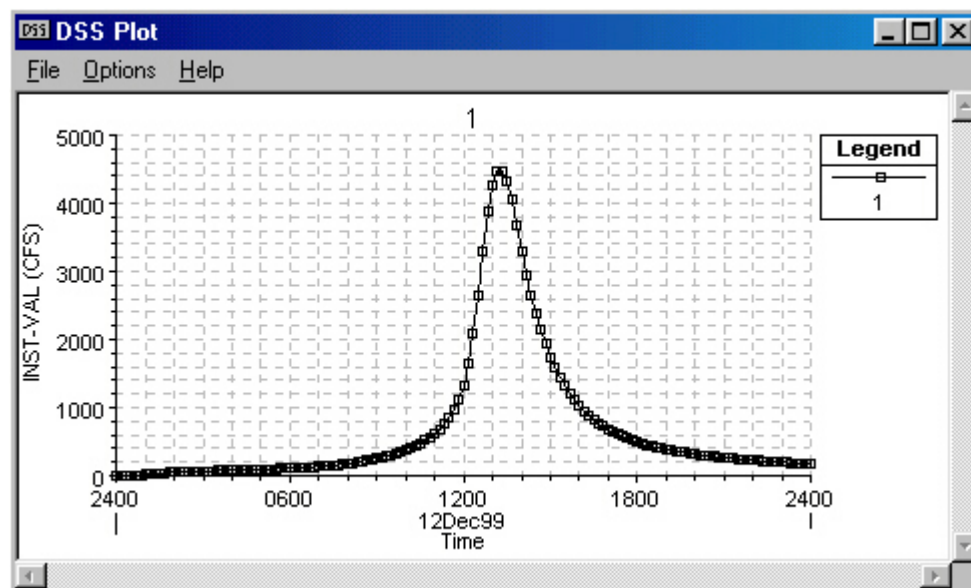
Figure 8-9. DSS Plot.

The coordinates of the cursor (time, flow rate) are displayed in the bottom right corner of the plot. The **Options/Grid** menu item can be selected to plot gridlines.

Returning to the **Set Locations for DSS Connections** window, the HEC-RAS cross-sections can be linked with their calculated DSS flows from HEC-HMS. The following table shows the relationship between the junctions in the HEC-HMS basin model and cross-sections in the HEC-RAS geometry file.

HEC-HMS Basin Outlet	HEC-RAS Cross-Section
102	223245
105	219460
109	198820
115	183710
119	176850
121	167500
122 (Confluence with West Fork)	161750
125	154880
126	142190
128	129015
127	121130
129 (Barier Dam)	102400

Table 8-2. HMS Basin Links to RAS Cross Sections.

The procedure for linking the DSS records with their associated cross-sections is as follows.

1.Choose the river station from the drop-down list

2.Click on the button "Add selected location to table"

3.Click on the DSS record in which the Part B corresponds to the selected cross-section. Ensure that Part B column reads "FLOW" and Part C says "12DEC1999". Click on "Select DSS Pathname" to link the data.

4.Repeat for each of the junctions. Below is the view as one works through the process. Once complete, select OK to save the associated links.

Table 8-3. Set Locations for DSS Connections.

Once the DSS records for the 12 junctions have been set, the DSS data must be imported. Returning to the main steady flow data window and selecting **File/DSS Import** brings up the following view. The fields are filled out as shown below.
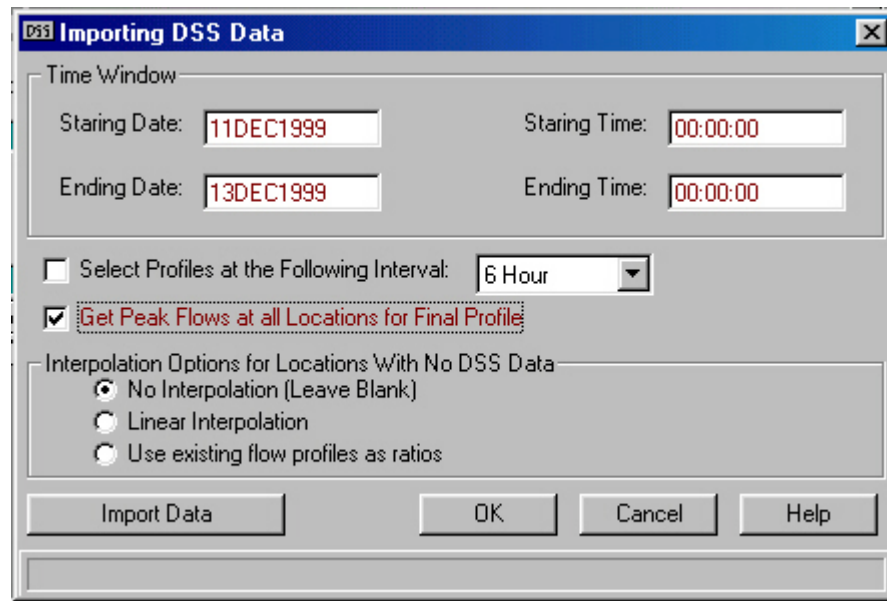
Figure 8-10. Importing DSS Data.
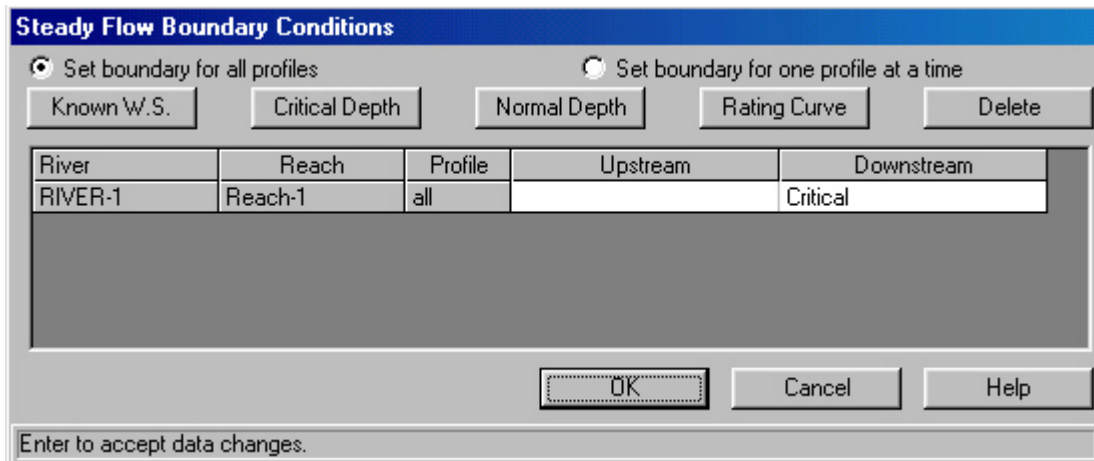
To complete the process, the **Import Data** button is selected and the flows from HEC-HMS are imported into the HEC-RAS model.

As discussed earlier, the direct step method uses a known water surface elevation and several hydraulic parameters to calculate the water surface elevation at an adjacent cross-section. Assuming that a subcritical flow regime exists for this model the computations will begin downstream. As such, the water surface elevation at the downstream boundary must be known. To establish this value, the **Reach Boundary Condition** button from the steady flow data window is selected. This allows one to set the water surface elevation boundary condition to be set by one of four methods:

1. Known water surface - based on observed data

2. Critical depth - the program will calculate critical depth

3. Normal depth - the program will calculate normal depth

4.Rating curve - elevation determined from an existing stage-discharge relationship curve

In this case, the critical depth option is selected in the **Downstream** column as shown below.

Figure 8-11. Steady Flow Boundary Conditions.

Once OK is clicked, the main steady flow window will come up and each of the junctions will have assigned peak flow values from the HMS DSS output. For cross-sections falling between HMS junctions, the flow value of the upstream junction is applied. Note that the most upstream cross-section has not been assigned a flow value, which is normal. Before running the program, a number will have to be input but its magnitude is inconsequential because the computations will proceed from downstream to upstream as is the case with subcritical flow. A value of 2000 was used in this case. To this point, all of the required flow parameters are present and the model can be run. The data is saved using **File\Save Flow Data** and named **10-year flows**. Finally use **File/Exit Flow Data Editor** to return to the HEC-RAS project window.

8.5   Executing the Model

Selecting **Simulate/ Steady Flow Analysis** from the project window brings
up the window below. However, before running the model, a plan definition is
needed. The plan specifies the geometry (Imported Geom 01) and flow files
(10 year flows) to be used in the simulation. To define a plan, File/New Plan is
selected and a plan title and a 12 character short identifier are entered.
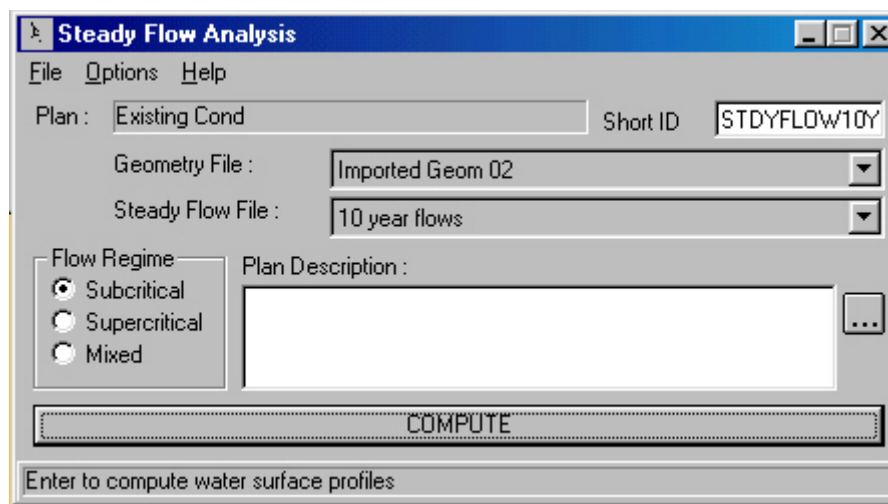
Figure 8-12. Steady Flow Analysis Compute Window.

To execute the model, one must ensure that the flow regime radio button is
set to **Subcritical** before clicking the compute button. The computations are
performed by a FORTRAN program named SNET. Clicking the compute
button starts SNET and opens a DOS window that shows the progress of the
simulation. When the computations are complete, the **PROGRAM FINISHED
NORMALLY** message appears as shown below.
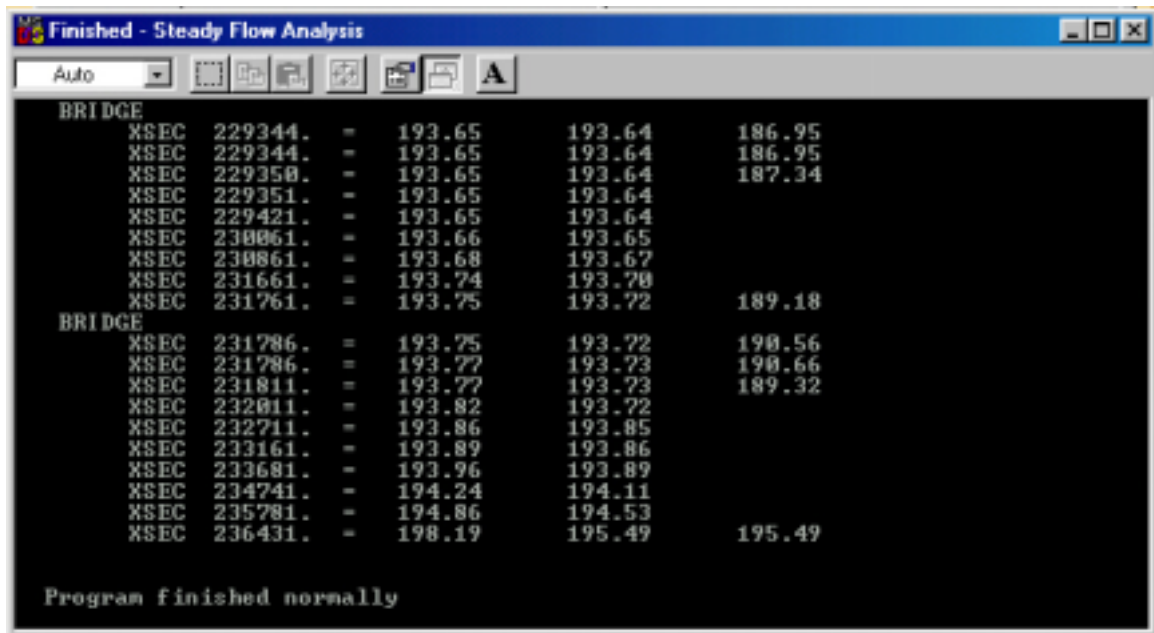
Figure 8-13. DOS Finished – Steady Flow Analysis.

8.6 Viewing the Results

There are several methods available with which to view HEC-RAS output including: cross-section profiles, perspective plots, and data tables. From the project window, select **View/Cross-Sections**.
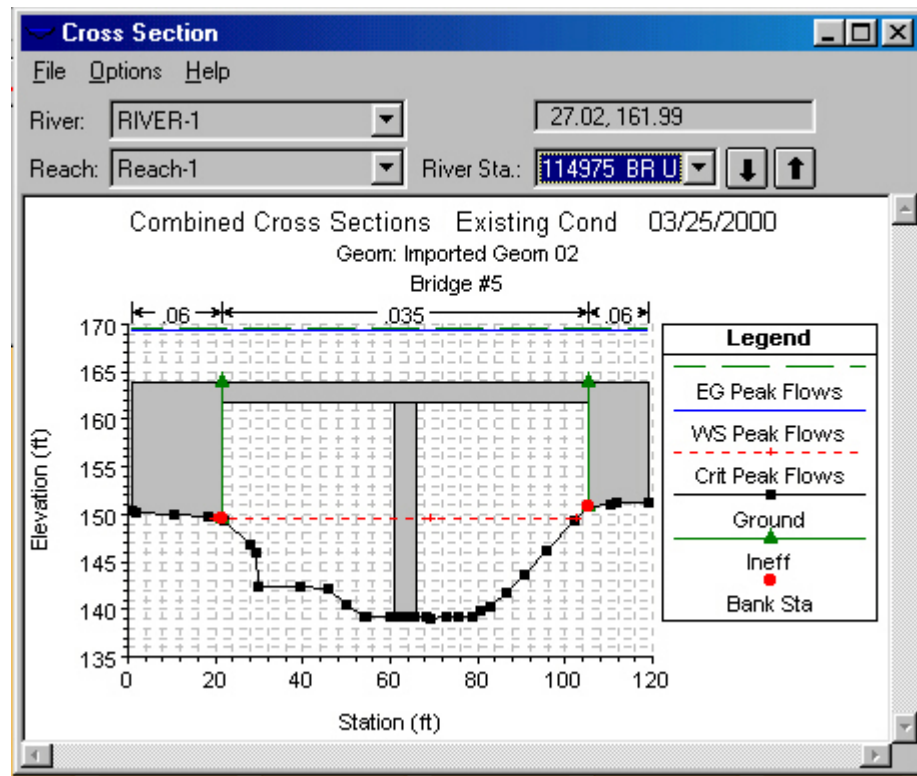
Figure 8-14. Bridge Cross-Section.

The cross-section view after running the program is similar to the one shown earlier in the document with the exception that the output view also shows the elevation of the total energy head line (EG Peak Flows), the water surface (WS Peak Flows), and critical depth (Crit Peak Flows). As with the cross-section geometry editor, use the **up and down arrows** to scroll to other cross-sections. For a profile of the entire reach, select **View/Water Surface Profiles** from the project window.
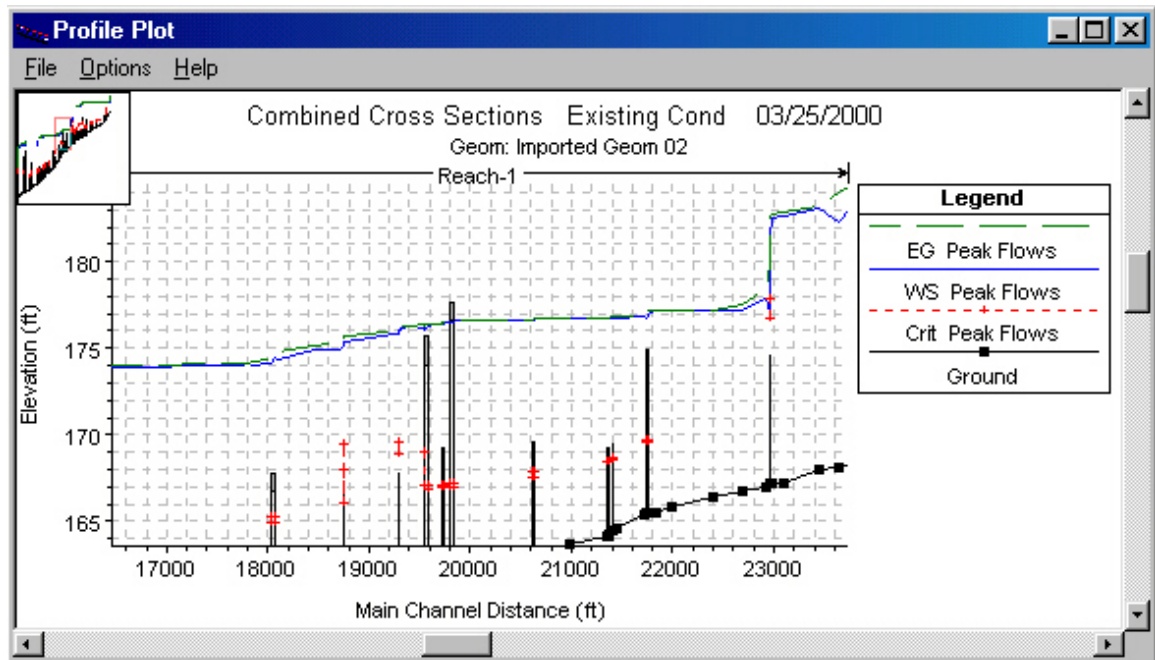
Figure 8-15. Water Surface Profile Plot.

Use the **Options/Zoom In** menu option, to focus on a particular stretch of reach to see how the water surface relates to structures in the channel such as bridges. Other available options for graphical display of output data include plots of velocity distribution (**View/Cross-Sections/Options/Velocity Distribution)** and pseudo 3D plots (**View/X-Y-Z Perspective Plots**) as shown below.
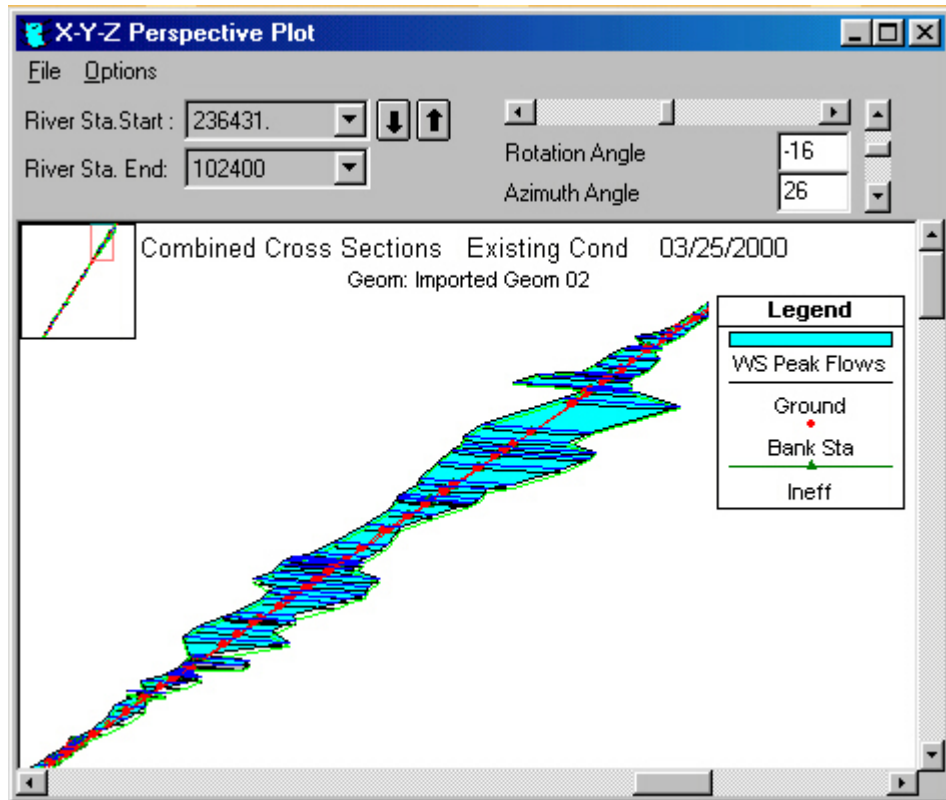
Figure 8-16. X-Y-Z Perspective Plot.

For hydraulic design, it is often useful to know the calculated values of various hydraulic parameters. HEC-RAS offers numerous options for tabular output data display. From the project window, select **View/ Cross Section Table**.
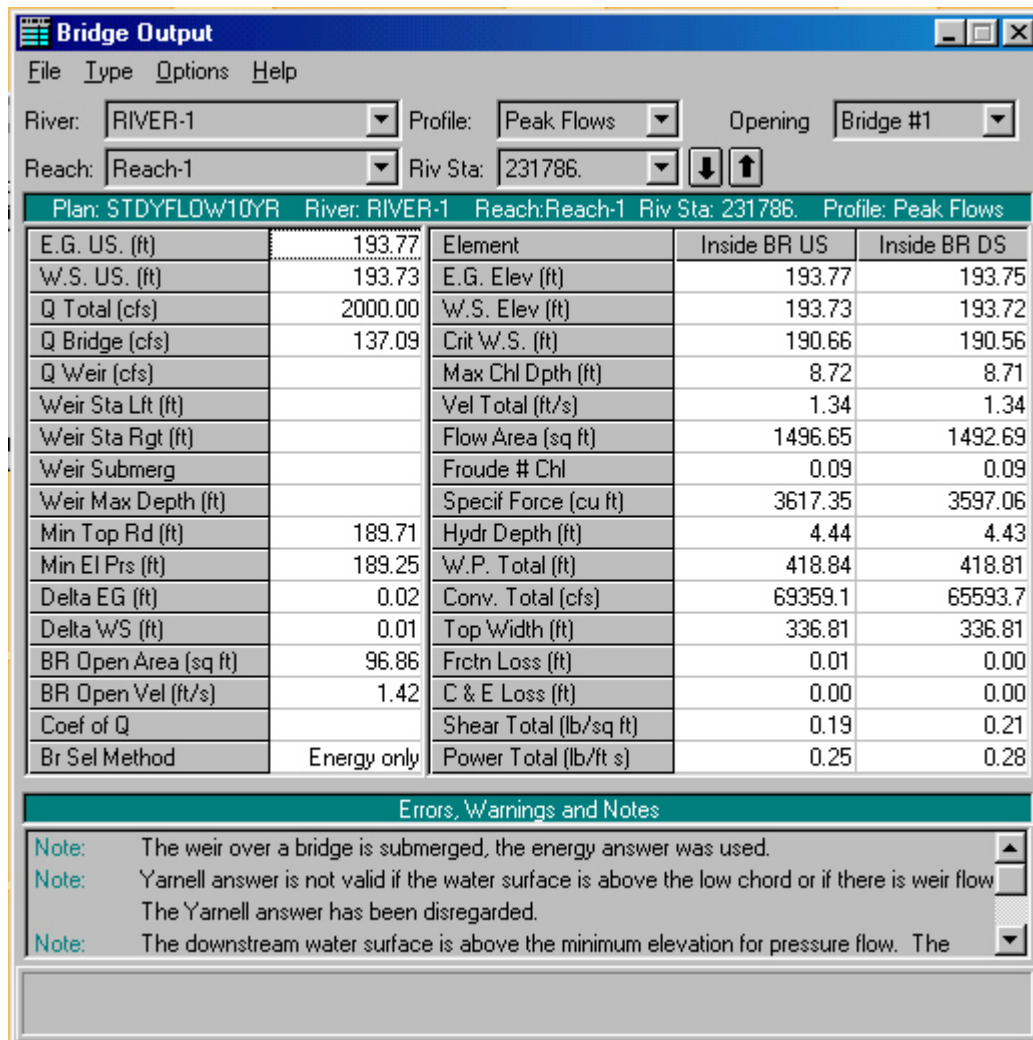
Figure 8-17. Cross Section Output for Bridge Cross-Section.

The resulting table includes a number of hydraulic parameters, including water surface elevation, head losses, and cross-sectional area. At the bottom of the window, **Errors, Warnings and Notes** resulting from the steady flow computations are shown. Additional tabular output data can be viewed by selecting **View/Profile Table** from the main project window. Below is an example of the output by cross-section.

Table 8-4. Profile Output Table.

This data can be copied to the clipboard for use in other applications. Other formats and data types can be viewed by selecting different tables from the **Standard Tables** Menu.

9   Floodplain Mapping

This chapter details the application of Floodplain Representation with Floodmap.
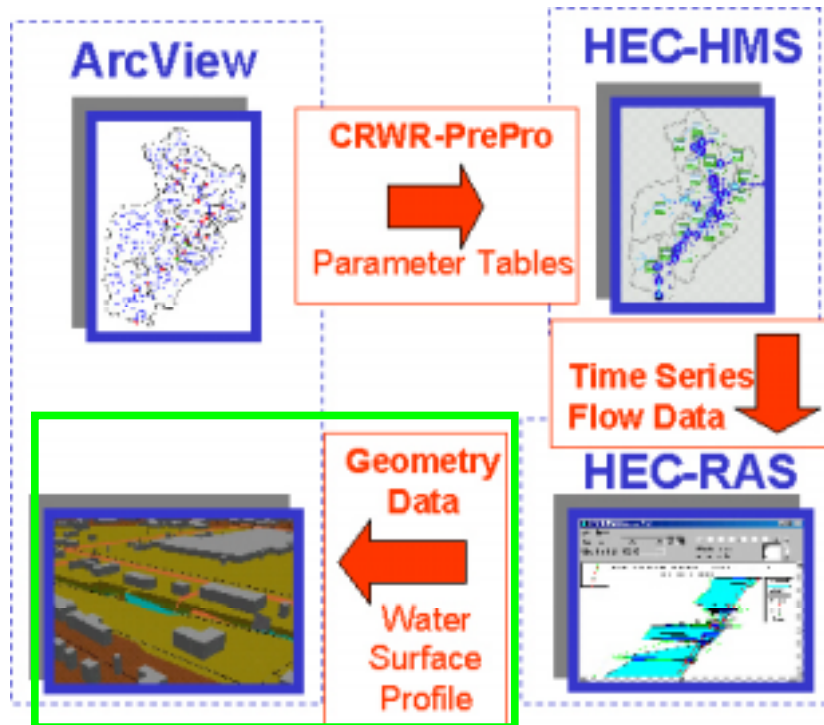
Figure 9-1. Floodplain Mapping.

HEC-RAS models have proven themselves floodplain analysis, but the X-Y-Z Prospective Plots are not sufficient for floodplain visualization. The following is a method to quickly post-process HEC-RAS output and provide an avenue for floodplain visualization and analysis in ArcView GIS. This method can also be used to develop a terrain model that accounts for the high density of points that define a channel while a low density of points is used to define the surrounding terrain. These properties make this single terrain model applicable for both hydrologic and hydraulic modeling.

This section demonstrates automated floodplain mapping using HEC-RAS and ArcView GIS using the following procedure:

1. Import HEC-RAS output into ArcView.

2. Create a digital stream representation.

3. Combine HEC-RAS and DEM data to develop a three-dimensional terrain model.

4. Delineate and analyze the HEC-RAS floodplain.

9.1   Data Requirements

The data required for this exercise consists of a HEC-RAS output data file, ArcView shapefiles, and the Floodmap ArcView project file (Floodmap.apr) that can be found in Eric Tate's website as shown in 2.4. A working directory titles Flood was established and the appropriate files were added to this location. The Floodmap.apr file was downloaded and the remainder of the files was copied using the ArcView Data Source Manager.

9.2   Procedure

With ArcView running, the Floodplain Mapping Project (floodmap.apr) is opened by selecting **File/ Open New Project**. The working project is now called floodmap.apr. It is imperative that the working directory be set to the Flood folder that was created earlier. Within this folder a Tmp folder must be created in the same manner as earlier ArcView projects. The Flood Mapping Project is customized with special menu options to help in the floodplain mapping process. The primary menus of interest are the **Floodmap** and **Flood-Utility** selections, located on the main-menu bar of ArcView.

A summary description of the **Floodmap** and **Flood-Utility** menu items are provided as follows.

1. Floodmap

   - Import HEC-RAS Data - Translates HEC-RAS output data from text file to ArcView format.

   - Format Digital Stream - The digital stream centerline shapefile must be formatted in order to be used in the subsequent steps.

   - Map HEC-RAS Cross-Sections - Map coordinates are assigned to HEC-RAS cross-sections.

   - Resample Cross-Section Elevations - Resamples cross-section elevations to incorporate digital elevation model (DEM) elevations data.

   - Stream Centerline and Banklines - Forms a three-dimensional line theme of the stream centerline, right banks, and left banks.

   - Convert Grid to Points - Performs a raster to vector conversion on a DEM.

   - Cross-Section Bounding Polygon - Forms a polygon representing the outer boundary of the mapped cross-sections.

   - Map Water Surface Profiles - HEC-RAS computed water surface profile at each cross-section is assigned map coordinates.

- Delineate Floodplain - Areas inundated by flooding are determined.

2. Flood-Utility

- Flip Polyline - Reverses the direction of a line theme.

- Compare Cross-Section Profiles - Creates a text file containing cross-section coordinate data that can be used to create profile plots.

- Clip Grid by Theme - Clips a DEM based on a given polygon theme.

9.3   Importing HEC-RAS Output

To move into the GIS environment, the HEC-RAS output information must first be extracted. Once a model is executed in HEC-RAS, an output text file can be created selecting **File/Generate Report** from the main project window. When the selection window comes up, **Plan Data** and **Geometric Data** is selected as the General Input Data, **Reach Lengths** is selected under the Summary Input Data, and **Cross Section Table** is selected under the Specific Table (Detailed Output) option. Additionally, only one profile is selected for the report and the modeled stream has only one branch. Only one branch can be used due to a level of complexity that cannot be currently handled by the ArcView scripts. If modeling more than one flow profile, the specific profile used for the output report can be selected using the **Set**

Profiles button. The Report Generator window will look somewhat like the
following graphic.
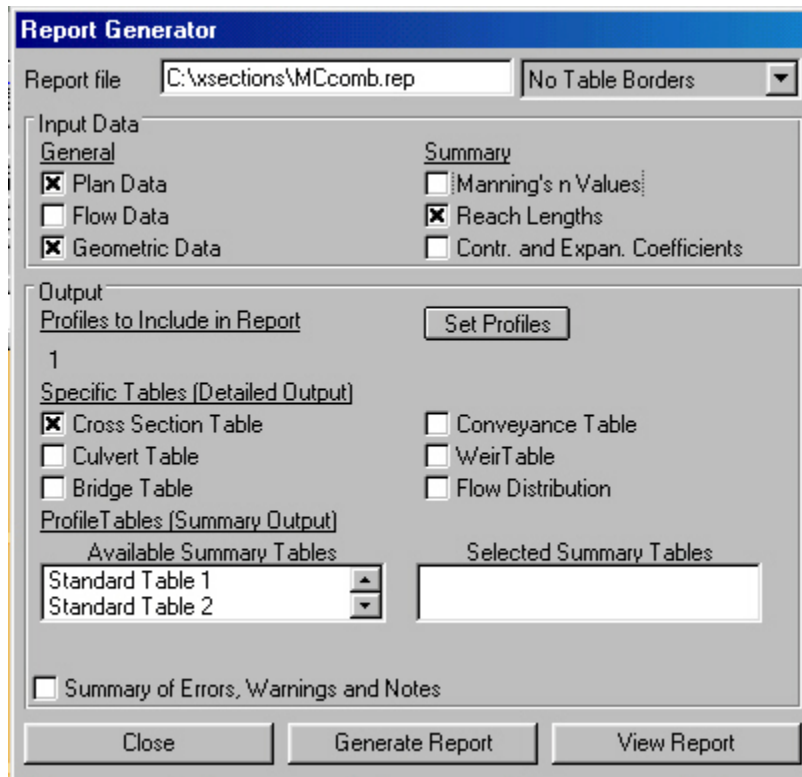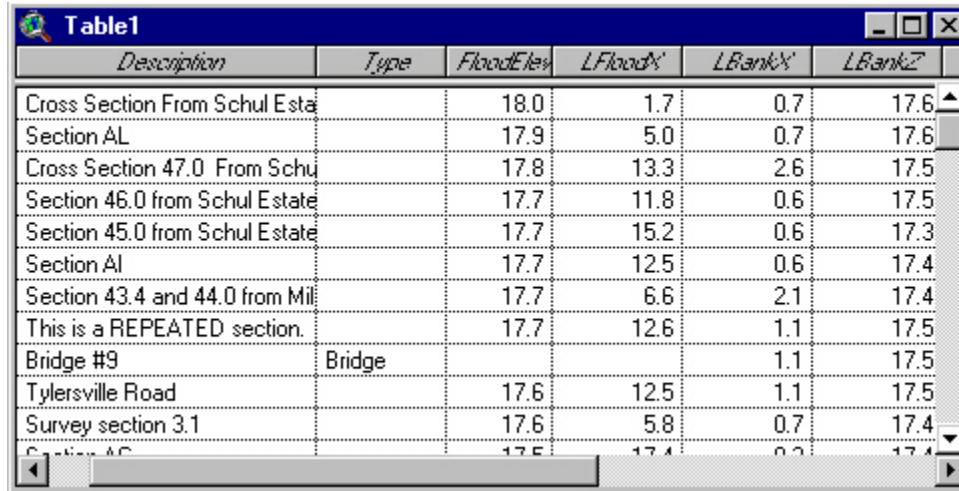
Figure 9-2. Report Generator.

Once the window looks similar to the above figure, click on the **Generate
Report** button. HEC-RAS will create an output file and save it in the location
designated. The resulting output file can be viewed in any text editor. The
data must then be imported into the ArcView project by selecting
Floodmap/Import HEC-RAS Data. Prior to continuing, the correct units must
be designated. The HEC-RAS model has units of feet, while the GIS data are
in units of meters. When queried by ArcView for the units, meters must be
selected.

The time to import the data will vary depending on the file size. The progress is shown at the bottom of the view window. When the processing is complete, a file name and location must be selected at the prompt. In actuality what is happening here is the data is being transformed from a text file format into a dBase format to be read by ArcView.

To view the data in ArcView, the **Tables** icon must be selected in the main project window. The table selection window should now show a **Table1**. Once opened, the table should appear as below.

Description	Type	FloodElev	LFloodX'	LBankX'	LBankZ'
Cross Section From Schul Esta		18.0	1.7	0.7	17.6
Section AL		17.9	5.0	0.7	17.6
Cross Section 47.0 From Schu		17.8	13.3	2.6	17.5
Section 46.0 from Schul Estate		17.7	11.8	0.6	17.5
Section 45.0 from Schul Estate		17.7	15.2	0.6	17.3
Section Al		17.7	12.5	0.6	17.4
Section 43.4 and 44.0 from Mil		17.7	6.6	2.1	17.4
This is a REPEATED section.		17.7	12.6	1.1	17.5
Bridge #9	Bridge			1.1	17.5
Tylersville Road		17.6	12.5	1.1	17.5
Survey section 3.1		17.6	5.8	0.7	17.4
Section AC		17.5	17.4	0.2	17.4

Table 9-1. HEC-RAS Imported Cross-section Table.

For each cross-section in the HEC-RAS output file, the following data has been retrieved and stored.

- Station - cross-section number

- Description - description of the cross-section, if provided in HEC-RAS

- Type - type of hydraulic structure

- FloodElev - water elevation stored in a global variable, not in the table - the lateral and elevation coordinates of all cross-section points

- LFloodX, RfloodX - the width of the left and right floodplain as measured from the stream centerline

- LBankX, RbankX - the distance to the bank stations as measured from the stream centerline

- LBankZ, ChannelZ, RbankZ - the elevation of the left bank station, stream center, and right bank station

- ChannelY - the additive reach lengths between cross-sections starting from the upstream end

9.4   Stream Centerline Representation

The overall goal of mapping HEC-RAS output is to take cross-sectional and water surface profile data from a one-dimensional model and transform it into two-dimensional map coordinates. The previous step brought the model data into ArcView, and a reference system is now needed to assign map coordinates to these data in geographic space. This reference system is a GIS representation of the stream centerline. There are four primary sources from which to obtain a digital representation of the HEC-RAS stream including:

1. Survey Data - Data representing the stream centerline may be available from field surveys. If so, this is perhaps the quickest way to generate a vector GIS representation of the stream.

2. Reach Files - Reach files are a series of national hydrologic databases, which uniquely identify and interconnect the stream

segments (reaches) that comprise the nation's surface water drainage system. The databases include such information as unique reach codes for each stream segment, upstream/downstream relationships, and stream names (where possible). The latest release, reach file 3 (RF3), consists of attributed 1:100,000 scale digital line graph hydrography. The data can be downloaded from the U.S. Environmental Protection Agency (EPA) BASINS website.

3. DEM-Based - A program such as CRWR-PrePro can be used to derive a vector stream representation using a DEM as the sole input.

4. Digitize the Stream - Using either a digital orthophotograph or digital raster graphic (DRG) as base map, the stream can be digitized using tools in ArcView. DRGs are digitized and geographically referenced topographic maps.

The RF3 file was used for Mill Creek to create the stream centerline. The original RF3 file was added to View 1. Using the Select Feature, the main channel was selected; selecting **Theme/Convert to Shapefile** created a single line representation as shown below.
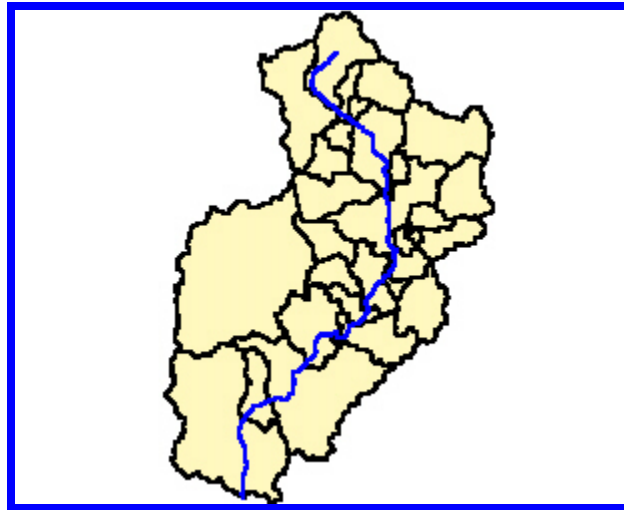
Figure 9-3. Center Line Representation.

Regardless of the source of the stream centerline, the attribute table of the shapefile will need to be modified to enable its use in subsequent steps of the floodplain mapping. To modify the attribute table, the digitized line theme must be active. Select **Floodmap/Format Digital Stream** and enter Centerrf3. It is important to know the direction of the stream line theme. Although common sense says that it should point upstream to downstream, HEC-RAS defines streams in the opposite direction. To be consistent with the HEC-RAS data, the digital stream should point from downstream to upstream.

To check the direction of the line, double click on the theme in the legend bar to bring up the legend editor. Click on the pen palette and choose an arrow representation. In actuality, Mill Creek flows from north to south. In this case, the digital stream is oriented correctly, from downstream to upstream. If this wasn't the case, the direction could be reversed by making the theme active selecting **Flood-Utility/Flip Polyline**.
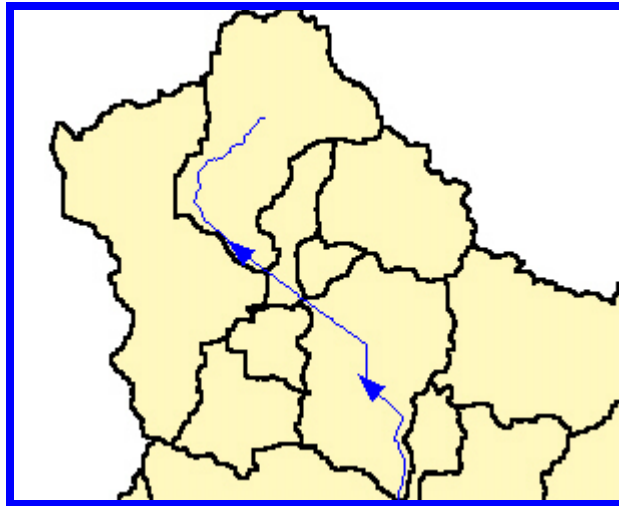
Figure 9-4. Stream Direction.

9.5   Cross-Section Mapping

The first step in assigning map coordinates to the cross-sections is to compare the reach lengths according to HEC-RAS and their counterparts on the digital stream centerline. It is possible, for example, that the digital stream is defined to a point farther upstream than the RAS stream or vice versa. Hence, it is necessary to delineate the upstream and downstream boundaries of the RAS stream on the digital stream. Intermediate stream definition points corresponding to important RAS cross-sections such as bridges or culverts can also be defined.

To help define the upstream, downstream, and intermediate points, we'll use a theme of roads in the point delineation process. Add the roads.shp to the view, and activate the view and select **Theme/Auto-label**. In the label field, select **Street_nam**. The roads theme will now be labeled with the individual street names. Next, activate Mcwshd.shp in the legend bar, and click on the **Label Points** tool. The project is now prepared to start defining points on the digital stream. The points we will define are as follows.

Type	Station	Location
Upstream boundary	231761	Tylersville Road
Intermediate point	212180	Bridge #5
Intermediate point	201935	Bridge #29
Intermediate point	195540	Bridge #25
Intermediate point	194228	Bridge #23
Intermediate point	188635	Bridge #21
Intermediate point	183540	SHARON CREEK
Intermediate point	182205	Bridge #15
Intermediate point	171035	Bridge #10
Intermediate point	164879	Bridge #5
Intermediate point	162615	Bridge #4
Intermediate point	161750	WEST FORK OF MILL CREEK
Intermediate point	156740	Bridge #3
Intermediate point	155808	Bridge #1
Intermediate point	153675	VINE STREET BRIDGE: REDONE BY
Intermediate point	148103	Bridge #10
Intermediate point	146810	Bridge #9
Intermediate point	131835	Bridge #12
Intermediate point	129860	Bridge #11
Intermediate point	122720	LUDLOW VIADUCT
Intermediate point	119235	Bridge #6
Intermediate point	114975	Bridge #5
Intermediate point	109951	Bridge #3 WESTERN HILLS VIADUC
Intermediate point	103608	Bridge #2
Downstream boundar	102618	Bridge #1

Table 9-2. Cross Section Georeferencing.

To begin the process, the intersection of Tylersville Road and Mill Creek was found and selected. When queried for the type of boundary, **Upstream boundary** was chosen. The click of the mouse causes the script attached to the **Label Points** tool to determine the nearest point along the stream centerline and snap the point onto the digital stream. Next the intersection of Bridge #5 (Station 212180) and Mill Creek was selected and defined as an intermediate point. The process was continued using the remainder of the points as shown above from upstream to downstream. The view window should look as follows.
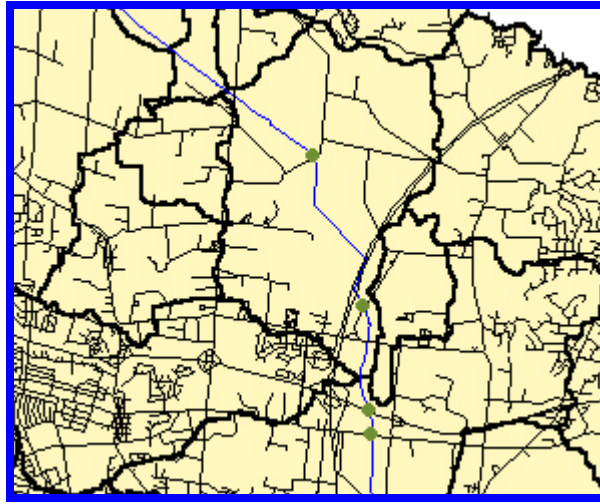
Figure 9-5. Stream Definition Points.

The stream definition points will form the backbone of the cross-section georeferencing process. Using the data table resulting from the data import step, the HEC-RAS data corresponding to the definition point locations will be associated with these map coordinates.

To select the relevant HEC-RAS data, return to Table1. Using the **Station** and **Description** columns as a guide, select the records for the designated stream definition points using the shift key. All of the selected records should be the ones shown in the table above.

When finished, the **Promote** tool is used to promote the highlighted records to the top. The highlighted records should be cross-referenced to ensure that all of the records are included. Next, select **Floodmap/Map HEC-RAS Cross-Sections** in the view window. *(Note: It is important that this step is performed in the same sitting as the data import step. Otherwise, you'll receive the error message "A(n) nil object does not recognize the request get." This is due to that fact that many of the cross-section data is stored in global variables, which are not saved when exiting ArcView.)* When queried,

Bounds.shp is chosen as the stream definition point theme, Centerrf3.shp as the stream centerline theme, and Table1 as the HEC-RAS geometry table. A prompt will query the user to choose a distance for calculation of cross-section orientation. This input window is for a parameter that will determine the orientation of the cross-section relative to the stream centerline. A value of 0 will cause each cross-section to be mapped perpendicular to the stream, at the precise cross-section location. Using a zero value could cause some cross-sections to intersect near bends in the stream. As the orientation parameter increases, perpendicularity is determined based on a longer segment of the stream. For this project the default value of 5 was used.
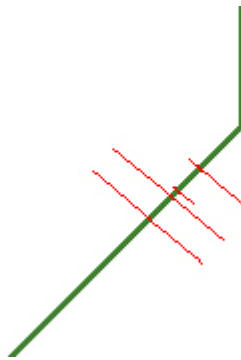
Figure 9-6. Cross Section Orientation.

The resulting line theme of the HEC-RAS cross-sections should appear like the graphic shown above.

9.6 Terrain Modeling

Most available digital elevation models, regardless of the resolution, do not achieve a high level of accuracy or resolution within stream banks. This is due to the interference of trees and water in point selection during the photogrammetric process. HEC-RAS is a good source of elevation data describing the channel, but typically these data do not possess map

coordinates. Combining the DEM and HEC-RAS data to form an integrated terrain model enables the data to be used for 3D terrain and floodplain visualization. The triangular irregular network (TIN) data model is used to form the integrated terrain model.

Creating a TIN terrain model from two different data sources presents its challenges: the DEM and HEC-RAS data have different collection times, methods, and resolutions. The point where the HEC-RAS data ends and the DEM data begins, called the transition zone, results in elevation differences. A method to smooth the transition zone is applied. For each cross-section, between the stream banks and the ends, the elevations are resampled using elevation values from the DEM. To initiate this process, the 30-meter DEM is added to the view. Some work on the DEM is necessary because the DEM is constructed with latitude and longitude measured in meters and elevation measured in feet. To begin, both the Analysis Extent and Analysis Cell Size must be set to **Same as Mcgridpro** using **Analysis/Properties**. Next the Map Calculator must be set up selecting **Analysis/Map Calculator** as follows.
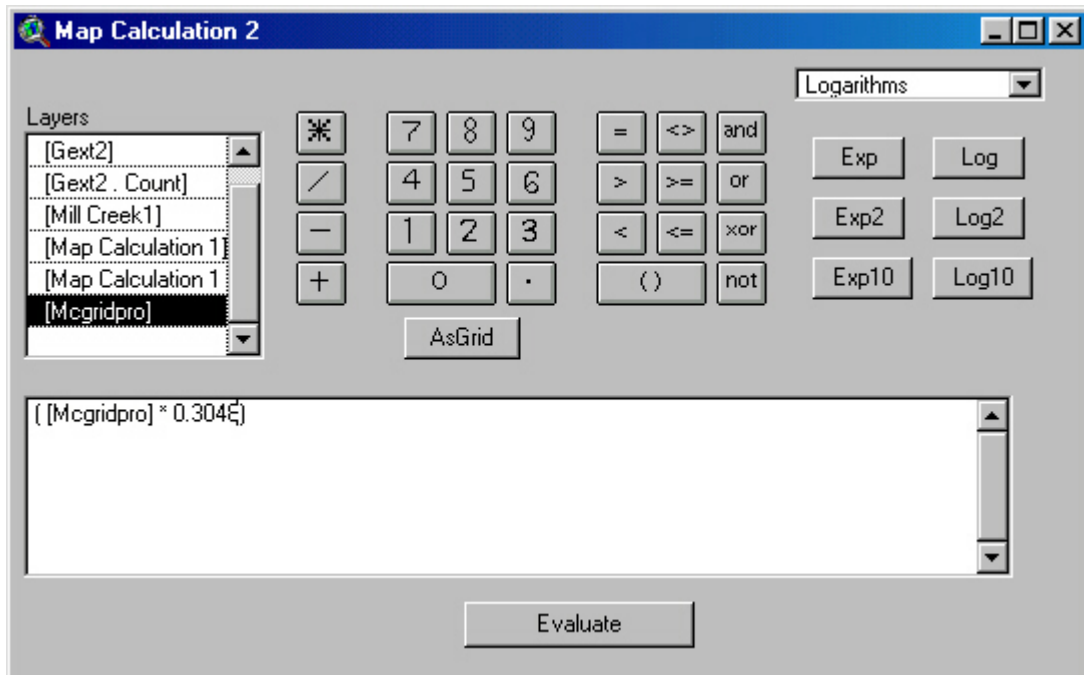
Figure 9-7. Map Calculation to Convert Grid Elevation to Meters.

Selecting **Evaluate** creates a new grid with the elevations in meters. To begin terrain modeling, **Floodmap/Re-Sample Cross-Section Elevations** is selected. When queried, select Terrain3d.shp and Mcgridpro1 as the inputs. The execution takes a few minutes as the elevation of every cross-section point outside of the main channel is being recalculated. To help visualize the result of the cross-section resampling, a tool with which to create three profiles of any given cross-section has been developed, based on the original cross-section, the DEM, and the resampled cross-section. Selecting **Flood-Utility/Compare Cross-Section Profiles** and the appropriate themes to profile the cross-section (231761) for comparison. The coordinate data is written to an ASCII text file that can be plotted using Microsoft Excel. After saving the text file, open it in Excel with the import wizard. The data can then be graphed on an x-y scatter plot as found below.

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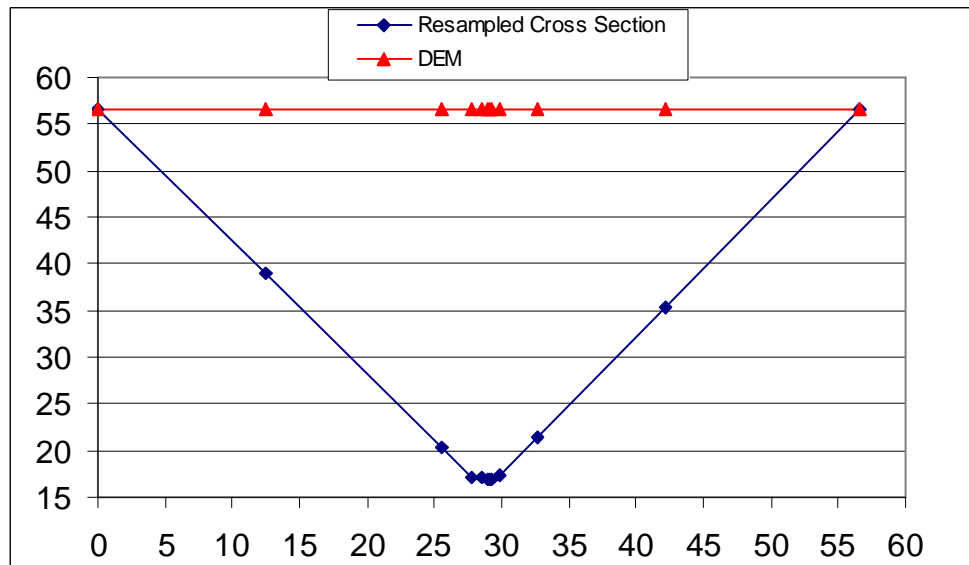
Figure 9-8. Cross-Section Profile.

The figure above shows two things:

1. The resampled cross-section (in blue) is identical to the original cross-section between the stream banks. But in the floodway, it begins to approximate the DEM (Red) as it moves to the end of the cross-section. This ensures a smooth transition from the hydraulic data to the DEM data.

2. By looking at the figure, it is easy to see why 30-meter DEM data is not good enough to use as the basis for hydraulic modeling: the representation of the stream channel provides little to no detail when using 30 cells. This is why the DEM (Red) appears so flat. In the area that the DEM represents, there may be two cells that represent the channel.

Next, data must be developed that will serve as TIN breaklines. TIN breaklines are the three-dimensional stream centerline and banklines. Breaklines indicate significant terrain features that represent a change in slope and the TIN triangles do not cross these breaklines. Next **Floodmap/Stream Centerline and Banklines** must be selected with 3dxsects.shp as the cross-section line theme.

To create a TIN with ArcView 3D Analyst, the input data must be either raster or vector, but not both. As a result, a raster to vector conversion must be conducted on the DEM. To do this, select **Floodmap/Convert Grid to Points**.

The terrain TIN will basically be made up of two areas, the area within the floodplain and the area outside the floodplain. As input for the TIN, the cross-sections will represent areas within the floodplain, which provides greater resolution due to channel properties. The DEM points will provide elevations for the landscape outside the floodplain. A polygon, which bounds the cross-sections, will be used to delineate the transition zone between the two data sources. To build the polygon, **Floodmap/Cross-Sections Bounding Polygon** is used with 3dxsects.shp as the queried line theme.

The final step before creating the TIN is to eliminate any DEM points falling within the cross-sections bounding polygon. To identify these points, the DEM point theme must be intersected with the bounding polygon theme. To do this, the bounding polygon theme (Boundary.shp) is made active and highlighted with the **Select Feature** tool. Next the DEM point theme (Gridpt.shp) is made active and **Theme/Select by Theme** is used. The drop-down lists should look like the following figure and the **New Set** button selected.
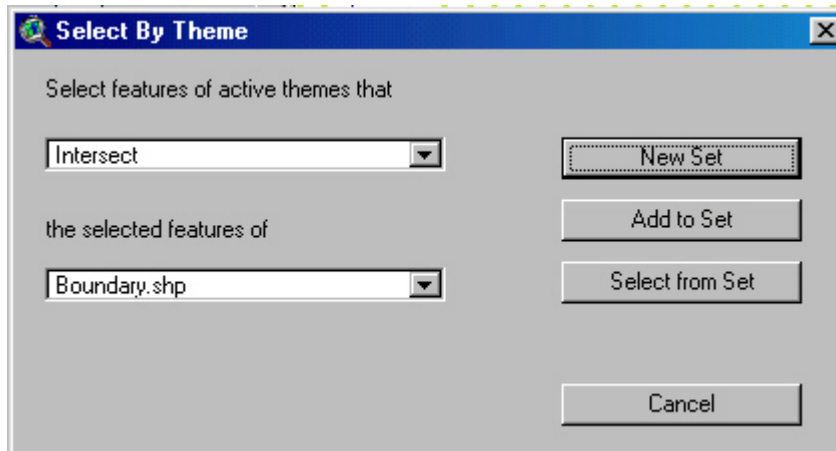
Figure 9-9. Select By Theme Window.

Clicking on the **Open Theme Table** button displays the attribute table of the DEM point theme. In the table window, select the **Promote** button needs to promote the selected DEM points within the floodplain. These points need to be edited out of the shapefile. Select **Table/Start Editing** and then the **Edit/Delete Records** to eliminate the points. To save the edits, select **Table/Stop Editing**. In the view window, the DEM should look like the following with the points within the floodplain eliminated.
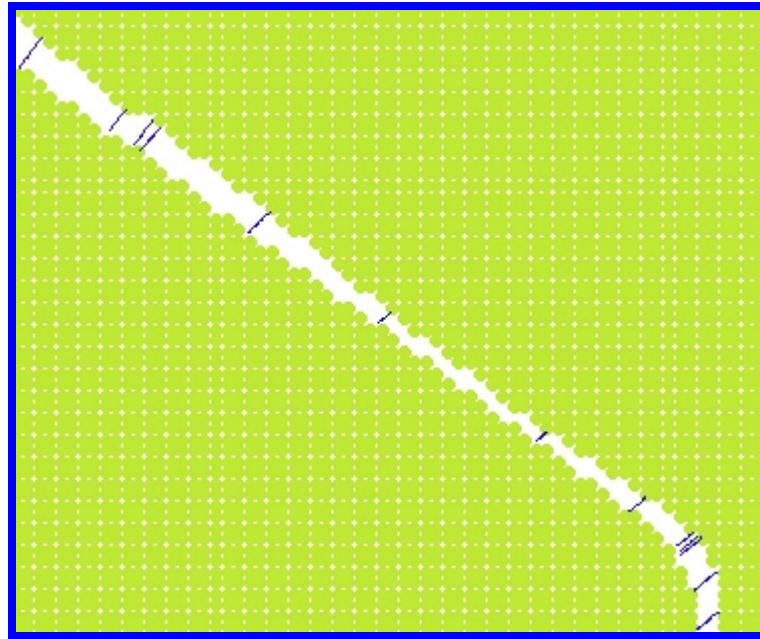
Figure 9-10. Point Representation of DEM with Floodplain Points Eliminated.

All of the necessary steps are complete to create the terrain TIN. The following themes must be made active in the legend bar: Stream3D.shp, 3dxsects.shp, and Mcgridpt.shp. Then, selecting **Surface/Create TIN from Features** to make the following window appear:
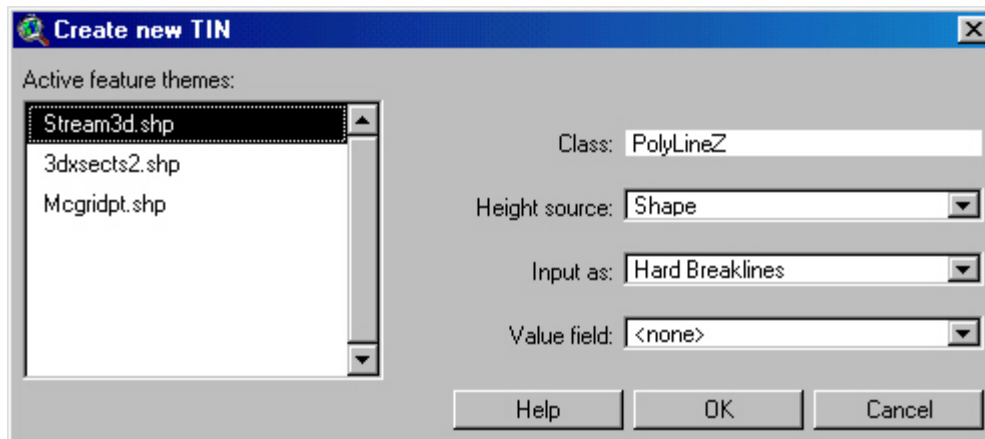
Figure 9-11. Create New TIN Window.

The theme Stream3d.shp is a three-dimensional line shapefile of the stream
centerline and banklines. These data will be enforced in the TIN as
breaklines. Fill in the window as shown in the graphic. Next, select the
cross-section line theme 3dxsects.shp on the left side of the window. In the
Input as: drop down list, select Mass Points. Finally, select the DEM point
theme Gridpt.shp. Select Mass Points from the Input as: window and
Grid_code as the Height Source. Click on the OK button to create the TIN.
When ArcView has finished processing the data, the TIN theme will appear in
the legend bar. The figure below shows a zoomed in portion of the TIN. The
green portion is the channel of Mill Creek.

Figure 9-12. TIN of Mill Creek

Notice that there is a smooth transition where the hydraulic data (cross-sections) meets the DEM data. The **Add Theme** button, build.shp and streets.shp can be added to the view to get a perspective of the 2-D visualization. The figure below shows the same area as above with the building and roads added.
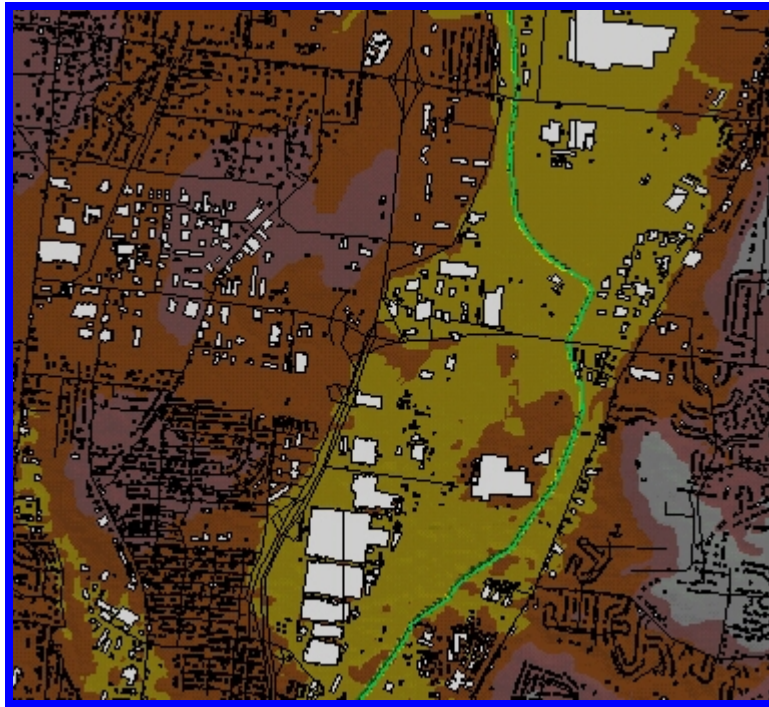
Figure 9-13. TIN with Buildings and Streets.

To view the TIN in 3D, **View/3D Scene** is selected. Prior to doing this, the
buildings and streets shape file must be converted to a 3D format. This is
done by selecting the theme and selecting **Theme/Convert to 3D Shapefile**.
The files will be renamed Streets3d.shp, and Buld3d.shp. Once this is
complete, **View/3d Scene** can be selected. The When queried to **Add the
View To 3D Scene As**: **Themes** is chosen. When ArcView opens the 3D
theme, it may take a while to present the view. To maneuver in the 3D scene,
click and hold the left mouse button while moving the mouse. The time
required to render the image will depend on the computer's processor speed,
RAM, and video card. The right mouse button can be used to zoom in and
out. The pan tool is enabled when clicking and holding both mouse buttons.
Below are a series of 3D views with the buildings and roads. Initially, the
structures will not have a 3D view. To obtain some perspective, each of the

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themes 3D properties must be adjusted. To do this, select **Theme/3D Properties** as shown below.
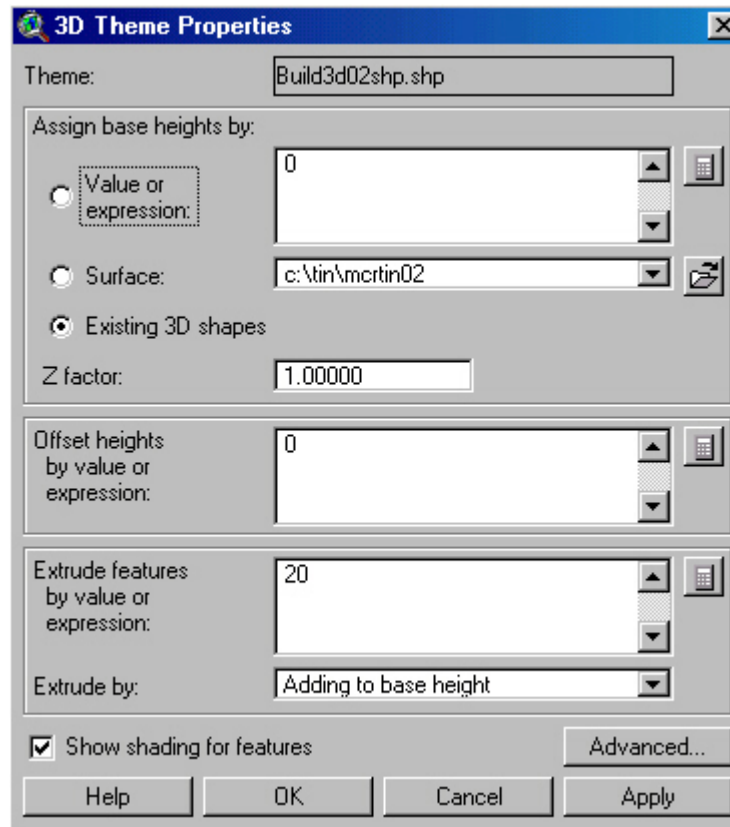
Figure 9-14. 3D Theme Properties.

Here the building 3D shapefile is assigned a building height of 20 meters. The reference height of the building's base is assigned in the **Extrude by:** box. Here the buildings are added to the base height of the TIN, more commonly known as the ground surface. The same procedure is done for the Streets3d.shp file. The only exception is setting the height to 2 meters instead of 20-meters as was the case with the buildings. Once the OK button is clicked, the following can be viewed after maneuvering around the 3D View.
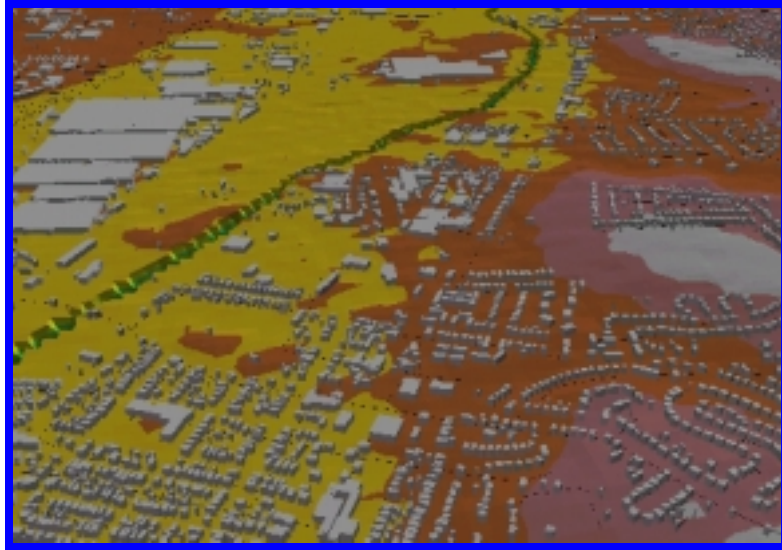
Figure 9-15. 3D View of Mill Creek.

In the view above several structures can be seen. General Electric is the set of buildings in the upper left of the view, in the center to the west of Mill Creek is Formica Corporation. Residential areas are also shown in the view.
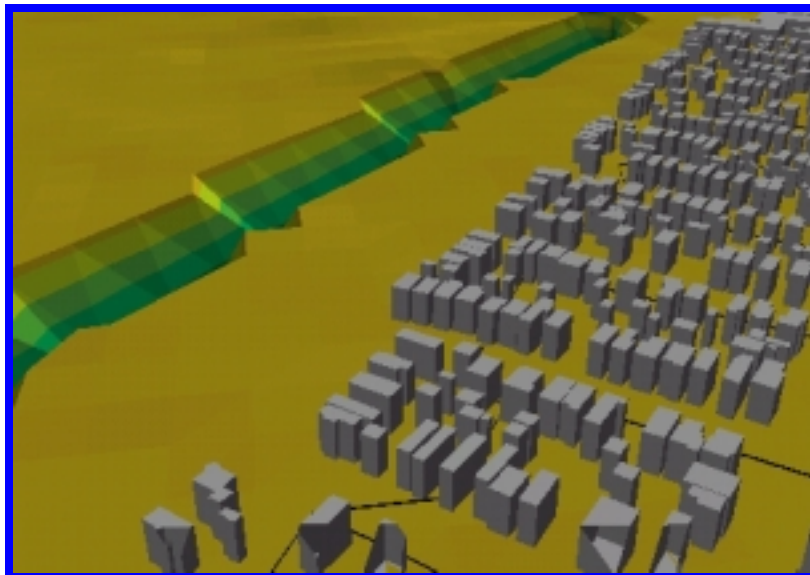
Figure 9-16. Representation of Mill Creek with Buildings set to 20 meter Height.

The two views below show how other shapefiles can be added to improve the 3D visualization effect. Shown in red are the levees that many of the private industries have constructed to protect themselves from flooding. The levees were added in a similar manner as the buildings and roads but were given a height of 6 meters for effect.
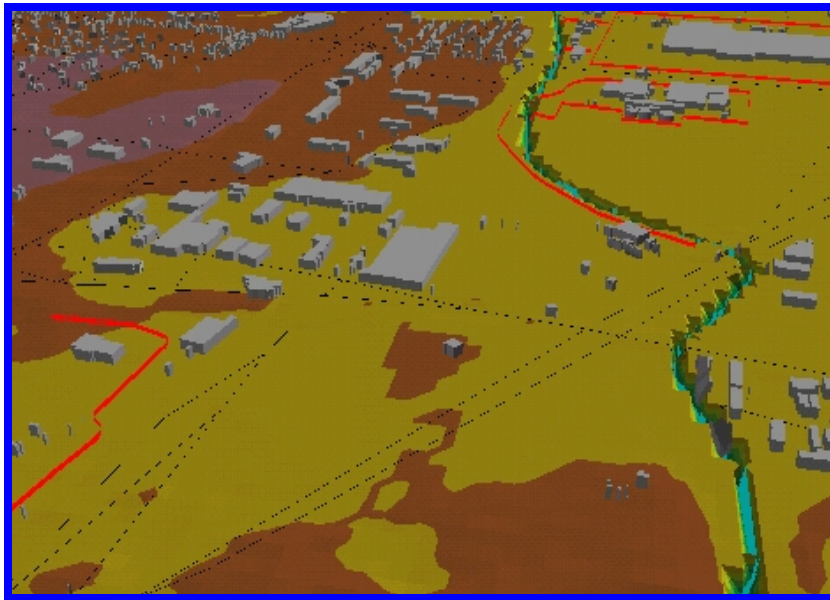
Figure 9-17. 3D View with Levees Added.

In the view above, Ford Motor Company is in the top right with Astro Containers just south. As Mill Creek winds, another levee can be seen protecting Ashland Chemical which sits right next to the creek and Sysco which makes up the series of building to the west of Ashland Chemical. Another levee is visible in the bottom left just below Sysco. The view below shows a view from west to east of Ford Motor Company with its protecting levees.
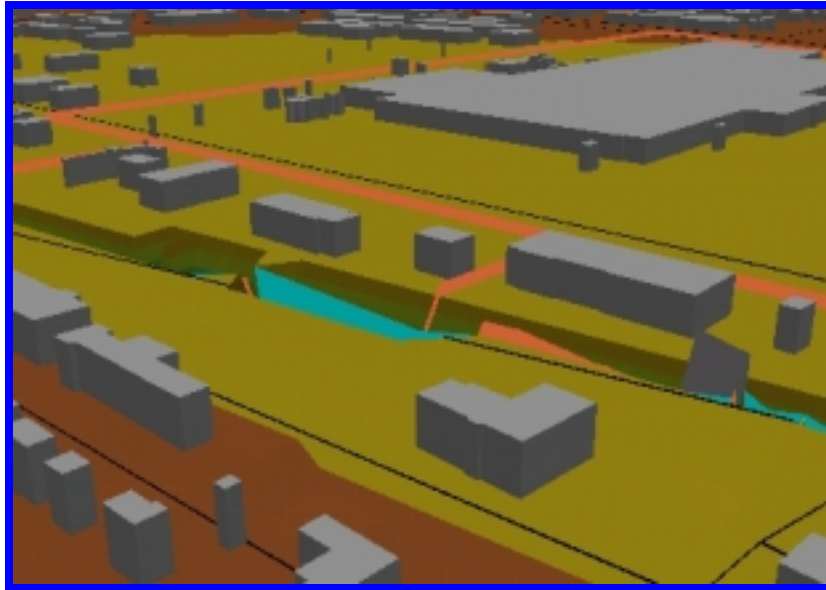
Figure 9-18. 3D View of Ford Motor Company and its Levees for Protection.

Now a TIN is built that depicts the general landscape and has additional detail in the stream channel and floodplain. The density of points within the channel is sufficient for hydraulic modeling.

9.7 Floodplain Delineation

Areas inundated by flooding occur wherever the elevation of the floodwater exceeds that of the land. To delineate these areas, we'll create surface models of the floodwater and land surface, and then compare the elevations. Let's start with the floodwater model. HEC-RAS represents the floodplain as a computed water surface elevation at each cross-section. During the data import step, these elevations were brought into ArcView, along with the distance from the stream centerline to the left and right floodplain boundaries. Hence, two things are known about the floodplain at each cross-section: water surface elevation and width on each side of the centerline.

Select **Floodmap/Map Water Surface Profiles** to map the water surface info. The data inputs are the original cross-section line theme ("Terrain3d.shp") and the HEC-RAS geometry table ("Table1").

The water surface line theme can be used to create a TIN model of the floodwater surface. Providing that the HEC-RAS model was set up correctly, the water surface extent will not exceed the cross-section extent. As such, the cross-section bounding polygon will serve as the outer boundary of the water surface TIN. Activate the water surface theme ("Water3d.shp") and the bounding polygon theme ("Boundary.shp") in the legend bar and select **Surface/Create TIN from Features**. In the TIN creation window, input the water surface theme into the TIN as hard breaklines and the bounding polygon theme as a hard clip polygon; then click OK. The default color scheme really doesn't look much like floodwater, so if you like, you can load the legend named "water1.avl." When viewed in a 3D scene in conjunction with the terrain TIN, flooded areas can be seen as below.

Figure 9-19. 2-D TIN With Water Surface TIN.

For detailed analysis, the floodplain can be viewed from a planimetric perspective. In order to be accurate, inundated areas should not be delineated using the terrain TIN. The HEC-RAS water surface profiles used to create the water surface TIN were determined using the original cross-sections and not the resampled cross-sections. Hence, a new TIN of the surface terrain needs to be constructed.

Activating the themes "Terrain3d.shp", "Stream3d.shp", and "Gridpt.shp" in the legend bar, select **Surface/Create TIN from Features**. The parameters are specified just as in the Terrain Modeling section. When this is complete, click OK. At this point, delete the resampled cross-section line theme ("3dxsects.shp") and its associated terrain TIN from the view.

Now a TIN model exists for both the land surface and the floodwater. However, the floodplain delineation is more readily performed using the raster data model instead of TINs. Convert both TINs to grids and make the land TIN active. Then select **Theme/Convert to Grid**. Select landgrid when prompted for a grid name. In the conversion extent window, set the Output Grid Extent to be the same as the land TIN, Output Grid Cell Size to "As Specified Below," and input the cell size as 1 meter as shown below.
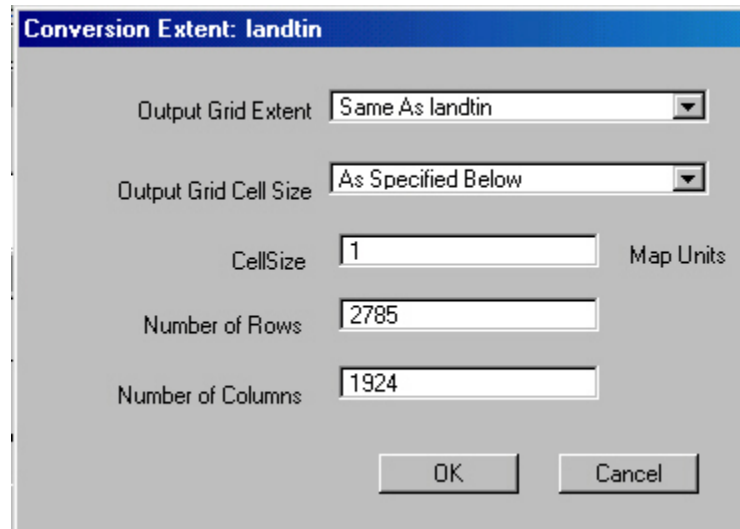
Figure 9-20. TIN to Grid Conversion Extent.

Selecting OK will convert the TIN to a 1-meter resolution grid. The same must be done for the water surface TIN by naming the grid watergrid and setting the Output Grid Extent to be the same as the water surface TIN. Both surfaces are now represented as grids. Before comparing the two grids, define the analysis extent. Select **Analysis/Properties** and set the Analysis Extent to Same as Watergrid, the Analysis Cell Size "As Specified Below" and input it as 1 meter. Select **Floodmap/Delineate Floodplain** and the script will compare the two grids and create an output grid consisting only of areas where the floodwater elevation exceeds the land surface elevation. For the floodplain grid, the color scheme "water2.avl" can be loaded from the legend editor. Once the color scheme is loaded, the color ramp values may need to be adjusted in order to get the effect.

Figure 9-21. 2-D TIN with Floodplain Grid.

The result is a floodplain map, in which the extent of flooding can easily be compared to structures of interest such as businesses, schools, and homes. The query tool can be used to query the depth of flooding at any point in the floodplain.

This floodplain can be used in a 3-D setting as well. Using the map calculator, convert the floodplain grid to integer format. Then convert the floodplain to a 3-D shapefile called floodplain3D.shp. Close the view and open the 3-D Scene Viewer and add floodplain3D.shp to the view. After setting the 3-D properties of floodplain3D.shp, the following views are possible.
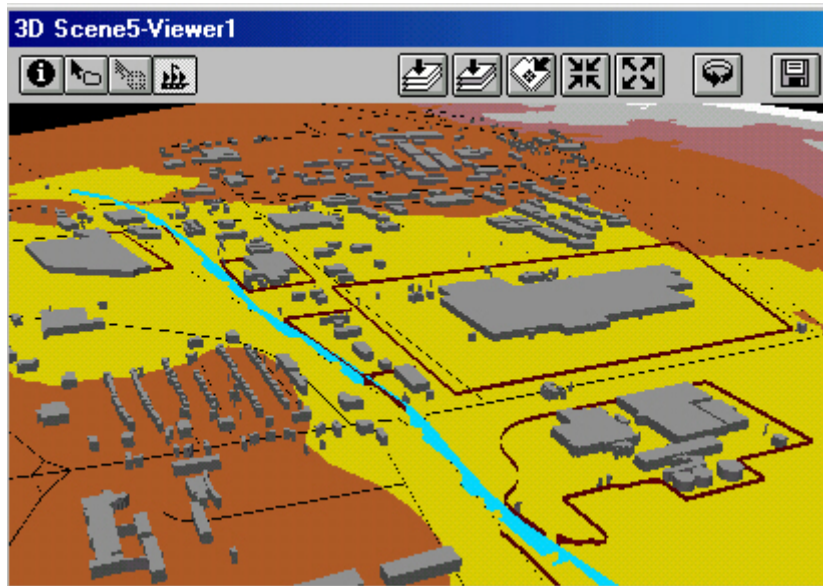
Figure 9-22. Aerial 3-D View with Flooding Effects.
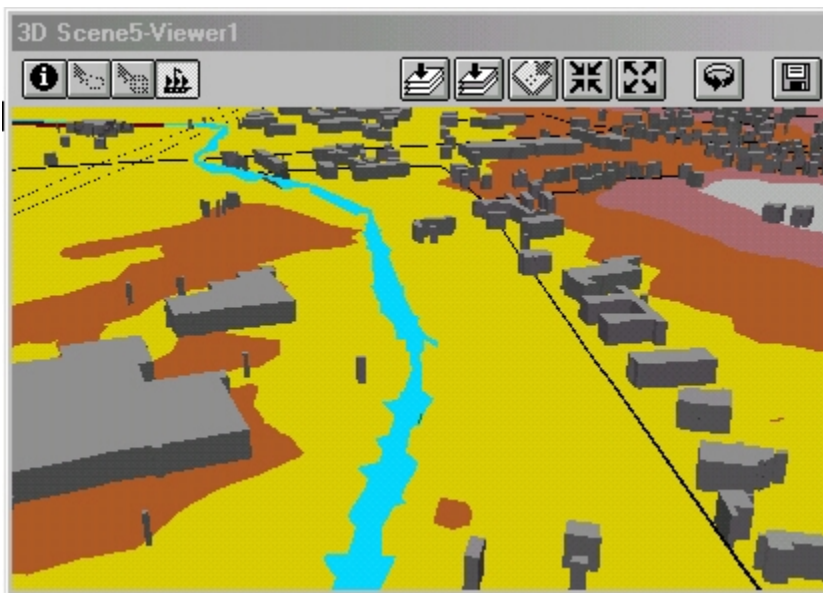
Figure 9-23. Close-up 3-D View of Flooding Effects.
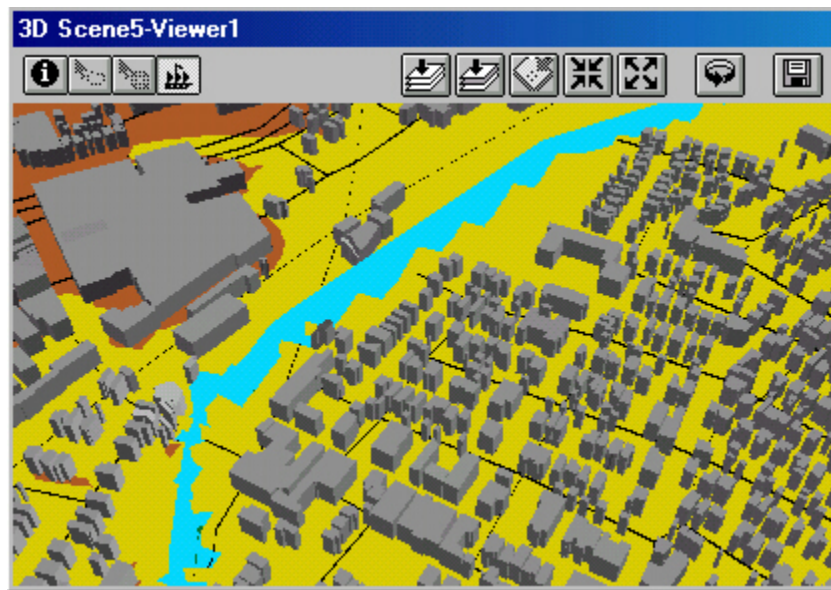
Figure 9-24. 3-D View of 10-year Rain Event.

10 Conclusions and Recommendations

The modeling procedures began with ArcView delineating a watershed and the calculating its hydrologic attributes for use in HEC-HMS. The uncalibrated flows from HEC-HMS were imported into HEC-RAS for hydraulic modeling. Finally the HEC-RAS geometry data was imported into ArcView to create a visual floodplain model. This procedure is intended for the Louisville Corps of Engineer District's use as a future endeavor in flood studies. This chapter discusses the approaches results, advantages and limitations, potential applications, and suggestions for future research
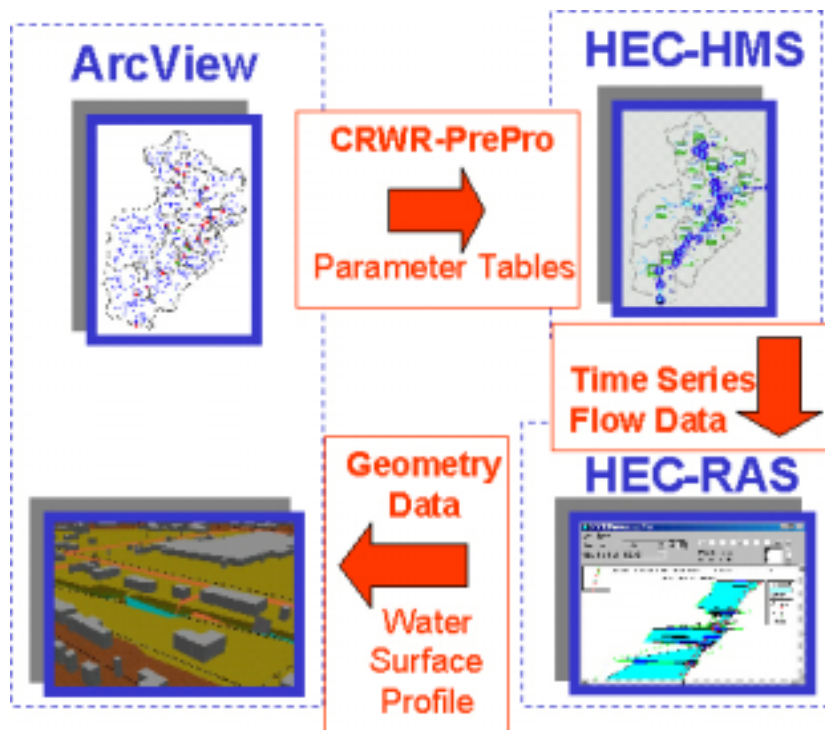
Figure 10-1. Modeling Procedure.

10.1 Watershed Characterization with CRWR-Prepro

The Mill Creek Watershed was delineated using the scripts available in CRWR-PrePro. The ArcView delineated watershed was very similar to the Louisville District's hand delineated version in that it was less than 3 square miles off in total drainage area. PrePro generated basin curve numbers using Land Cover and Land Use data for use in its generation of a HEC-HMS basin file with hydraulic attributes. The hydraulic attributes used assumed values for stream velocities that must be refined in HEC-HMS in order to calibrate the model correctly. CRWR-PrePro is a quick and efficient tool for characterizing a watershed.

10.2 Modeling with HEC-HMS

HEC-HMS interfaced well in the basin file created with CRWR-PrePro. This is attributed to the work done to refine PrePro. The three required components for HMS were created without incident. The Precipitation Model required some work to acquire the User Specified Gage Weights. Using precipitation data from recording gages, ArcView generated a Thiessen Polygon and the results were entered manually.

Calibration of the model was a lengthy process and was never completed. Due to the difficulty of calibration, Chapter 7 was dedicated to its discussion. Numerous attempts were made to calibrate the model against a USGS gage. The complexity and size of the heavily urbanized basin forced all parameters to be considered. First, the velocities were refined to replicate the varying channel properties. The basin lag times were adjusted and curve numbers were considered. When the hydrograph cold not be calibrated, the effects of the basins 100 plus combined sewer outfalls were then analyzed. Assumptions were developed regarding the amount of runoff captured by the

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combined sewer. The assumptions were supported by actual flow data recorded during the event at the Mill Creek Wastewater Treatment Plant. The model's best attempt at calibration was with a combination of assumptions about basin lag time and the combined sewer effects.

10.3 Modeling with RAS

Time spent modeling with RAS was minimal compared to the other programs. Creating the RAS model was not a difficult task. The difficulty of the task was alleviated with the geometry data provided by the Louisville District. The report generator was used numerous times to extract data needed for ArcView and HMS. When calibration was abandoned, the best HMS "Run" flow data was used in RAS. Once relationships were established with HMS junctions and corresponding RAS cross-sections, transferring the flow data to from HMS to RAS was simple. The RAS results could not be analyzed correctly using the uncalibrated HMS flow data.

10.4 Floodmapping with Floodmap

Floodmapping with the Floodmap.apr project generated some revealing 2-D and 3-D images. The process of generating the views was rather simple but it did require some extensive data processing. Creating a TIN using the DEM and RAS cross-sections resulted in a quality model. The TIN accuracy was not validated through a spot elevations comparison. Sufficient data was not available for this comparison. The floodplain delineation was not validated against digital Q3 flood data that is available through FEMA. Once again, the calibration problems in HMS do not predict accurate flows for RAS. The floodplain delineation computation in Floodmap uses this RAS data in its computations.

10.5 Advantages

The methodology used can save time and resources when conducting flood studies. GIS data is available at numerous websites for downloading. Providing that the user has some knowledge of GIS operation, the process can be followed with little difficulty. The generation of this data can allow a practicing engineer to focus on the results achieved and not the burden of manual calculations. The procedure allows a quick generation of floodplain maps that are typically drawn by hand. This task could easily become tedious if the goal is to evaluate different flow scenarios.

Automated floodplain mapping processes also bring more efficient and standardized results. Some manual tasks are subjective and the results can vary. An example of this is the making of a floodplain map that is done by hand. This task can be accomplished using this process in less time and with greater accuracy. Its digital format provides for easier updating and data sharing.

Working in the digital environment allows the user to access any information in a quicker and more accurate manner. This digital output can usually be used in other software applications making it versatile as well.

Communicating with individuals and organizations about flood studies can be difficult. Often proposed projects are cost shared and require additional support and funding. A method other than a hand generated floodplain map is needed to communicate the effects of flooding. With the ability to produce a digital floodplain map, this communication barrier can be alleviated. The use of 2-D and 3-D representations can be revealing and convincing of certain effects. Animations are possible as well for visualization purposes.

Through animations, time series-data effects can be replicated. Azagra (1999) demonstrates the capabilities of animations.

10.6 Limitations

The main limitation during the course of this research was the calibration of the hydrologic model (HEC-HMS). Complicated urban basins require detailed research in and of themselves. The specifics are discussed in great detail in Chapter 7.

The digital media is accurate, but the best results are achieved using a TIN generated from aerial photography in the floodplain. Accuracy is critical to reliable results. This accuracy is crucial to obtain reliable results; differences of one foot in the stage height can cause the floodplain to widen. This is especially true in areas with little relief.

The proposed methodology is still dependent on field data. In order to define the channel, cross section data must be collected through field surveying. In the case of this research, this was not an issue as the Louisville district already had the data collected and in and existing model.

10.7 Applications

There are many applications for this work. Flood control studies rely heavily on the hydrologic and hydraulic results to make decisions. Often the results are presented in table form such as those found in RAS. RAS can even provide an X-Y-Z Perspective Plot that reveals the extent of the floodplain with given flow conditions. The plot does not show terrain aspects or other structures that are in the floodplain. Visual floodplains such as those provided in this document can alleviate some of the mystery and provide focus for further study.

Floodplain modeling results can identify locations in need of remediation. The view can give a perspective on certain problem areas not seen with other models. The identified problem areas may help determine the location and suitability of building certain flood control structures. The best example of this is trying to identify an area upstream suitable for a detention basin. The floodplain model with structures will easily assist in this process. Regardless of the results that the user is seeking, the floodplain model provides focus on areas that need further research.

The National Flood Insurance Program relies heavily on accurate floodplain maps. The location of ones home in a floodplain determines the price paid for flood insurance, especially for those structures located within Special Flood Hazard Areas. FEMA currently has these maps available on line to assist in this process.

As technology continues to develop, real-time flood management will be a reality. This may be accomplished using recording precipitation and flow gages that beam signals to a controlling station. This data will then be processed through similar models that reveal upcoming events or effects. This technology will save lives and allow for the implementation of control measures.

10.8 Recommendations for Future Work

The purpose of this work was to serve two fold. First, it was to give the Louisville Corps of Engineer District a perspective on the capabilities of the applications in this document. This task was accomplished using Mill Creek, which is currently under study by the Louisville District. This work resulted in sound results through a systematic and simple process. More importantly, the work demonstrates the visual capabilities of the applications. As this

technology continues to evolve, the ability to apply certain applications will become easier and more efficient with more accurate results. The second purpose of this work was to provide the Louisville District with a document allowing them to capture and utilize the applications. The format of Chapter 4 will help to accomplish this task. It is recommended that the Louisville District should carry out the procedure described in Chapter 4 and learn from the results. This will familiarize personnel with the capabilities of the applications and allow them to use the results to formulate plans or make decisions.

The combined sewer problem identified in Chapter 4 should be reviewed with the Cincinnati Municipal Sewer District. The combined sewer effects contribute a great deal to the flooding problems in the basin. A probable solution is to use ArcView with coverages of the sewer system. This will help to redefine the hydrologic model in HMS. The natural system has been altered as a result of the sewer system. ArcView will help redefine the watersheds that reflect actual conditions. The redefined watersheds and treatment plant flow data will assist in the calibration of the HMS model. With accurate flow data, the visual floodplain model will then be effective for making decisions in flood studies.

Appendix A. USGS Gage Data

Carthage Gage

Date	Flow (cfs)
04/15/1998 12:00	111
04/15/1998 12:30	111
04/15/1998 13:00	111
04/15/1998 13:30	111
04/15/1998 14:00	113
04/15/1998 14:30	116
04/15/1998 15:00	126
04/15/1998 15:30	146
04/15/1998 16:00	183
04/15/1998 16:30	198
04/15/1998 17:00	221
04/15/1998 17:30	261
04/15/1998 18:00	312
04/15/1998 18:30	312
04/15/1998 19:00	305
04/15/1998 19:30	315

04/15/1998 20:00	341
04/15/1998 20:30	371
04/15/1998 21:00	368
04/15/1998 21:30	354
04/15/1998 22:00	336
04/15/1998 22:30	325
04/15/1998 23:00	312
04/15/1998 23:30	300
04/16/1998 0:00	295
04/16/1998 0:30	325
04/16/1998 1:00	515
04/16/1998 1:30	1150
04/16/1998 2:00	2230
04/16/1998 2:30	3780
04/16/1998 3:00	4750
04/16/1998 3:30	5240
04/16/1998 4:00	5520
04/16/1998 4:30	5980
04/16/1998 5:00	7570

04/16/1998 5:30	8100
04/16/1998 6:00	8420
04/16/1998 6:30	8620
04/16/1998 7:00	8390
04/16/1998 7:30	7970
04/16/1998 8:00	7360
04/16/1998 8:30	6920
04/16/1998 9:00	6610
04/16/1998 9:30	6410
04/16/1998 10:00	6240
04/16/1998 10:30	6000
04/16/1998 11:00	5840
04/16/1998 11:30	5590
04/16/1998 12:00	5470
04/16/1998 12:30	5340
04/16/1998 13:00	5190
04/16/1998 13:30	5110

Carthage Flow Gage

174
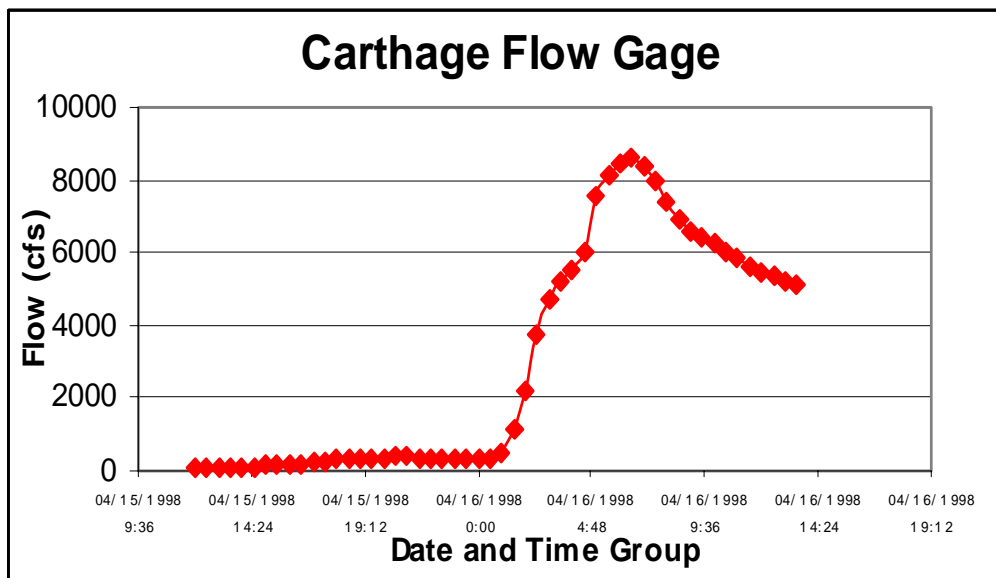
Appendix B. Recording Precipitation Gages.

Gage Location	Date	Time	Depth (in)
Spring Grove - CWW	15-Apr-98	1345	0.04
		1400	0.04
		1415	0
		1430	0
		1445	0.04
		1500	0.08
		1515	0.04
		1530	0
		1545	0
		1600	0
		1615	0
		1630	0.04
		1645	0.04
		1700	0
		1715	0
		1730	0

		1745	0
		1800	0
		1815	0
		1830	0
		1845	0
		1900	0
		1915	0
		1930	0
		1945	0
		2000	0
		2015	0
		2030	0
		2045	0
		2100	0
		2115	0
		2130	0
		2145	0
		2200	0
		2215	0
		2230	0

		2245	0
		2300	0
		2315	0
		2330	0
		2345	0.08
		0	0
	16-Apr-98	15	0.04
		30	0.12
		45	0.12
		100	0.2
		115	0.28
		130	0.08
		145	0.04
		200	0.12
		215	0
		230	0.16
		245	0.16
		300	0.12
		315	0.08

		330	0.04
		345	0.04
		400	0.08
		415	0.12
		430	0.43
		445	0.16
		500	0.04
		515	0.08
		530	0.04
		545	0
		600	0.04
		615	0
		630	0.04
		645	0
		700	0.04
		715	0.04
		730	0.08
		745	0.04
		800	0
		815	0

		830	0
		845	0
		900	0
		915	0
		930	0
		945	0
		1000	0
		1015	0
		1030	0
		1045	0
		1100	0
		1115	0
		1130	0
		1145	0
		1200	0
		1215	0
		1230	0
		1245	0
		1300	0
		1315	0

		1330	0
		1345	0
		1400	0
		1415	0
		1430	0
		1445	0
		1500	0
		1515	0
		1530	0
		1545	0
		1600	0
		1615	0
		1630	0
		1645	0
		1700	0
		1715	0.04
		1730	0.04
		1745	0
		1800	0
		1815	0

		1830	0
		1845	0.04
		1900	0
		1915	0
		1930	0
		1945	0
		2000	0
		2015	0
		2030	0
		2045	0
		2100	0
		2115	0
		2130	0
		2145	0
		2200	0
		2215	0
		2230	0
		2245	0
		2300	0
		2315	0

		2330	0
		2345	0
Total Rainfall (inches)			2.95

Gage Location	Date	Time	Depth (in)
Mt. Healthy	15-Apr-98	1445	0.04
		1500	0.08
		1515	0.08
		1530	0
		1545	0
		1600	0
		1615	0
		1630	0
		1645	0.04
		1700	0.04
		1715	0
		1730	0
		1745	0
		1800	0
		1815	0
		1830	0
		1845	0
		1900	0

		1915	0
		1930	0
		1945	0
		2000	0
		2015	0
		2030	0
		2045	0
		2100	0
		2115	0
		2130	0
		2145	0
		2200	0
		2215	0
		2230	0
		2245	0
		2300	0
		2315	0.04
		2330	0
		2345	0.12
		2400	0.04

		0	0
Mt. Healthy	16-Apr-98	15	0.04
		30	0.28
		45	0.16
		100	0.08
		115	0.12
		130	0.04
		145	0.04
		200	0.2
		215	0.08
		230	0.28
		245	0.16
		300	0.16
		315	0.12
		330	0.12
		345	0.24
		400	0.08
		415	0.04
		430	0.24

		445	0.08
		500	0.04
		515	0.08
		530	0.04
		545	0.04
		600	0
		615	0
		630	0.04
		715	0.04
		730	0.04
		745	0.04
		800	0.04
		815	0
		830	0
		845	0
		900	0
		915	0
		930	0
		945	0
		1000	0

		1015	0
		1030	0
		1045	0
		1100	0
		1115	0
		1130	0
		1145	0
		1200	0
		1215	0
		1230	0
		1245	0
		1300	0
		1315	0
		1330	0
		1345	0
		1400	0
		1415	0
		1430	0
		1445	0
		1500	0

		1515	0
		1530	0
		1545	0
		1600	0
		1615	0
		1630	0
		1645	0
		1700	0
		1715	0.04
		1730	0
		1745	0
		1800	0
		1815	0
		1830	0.04
		1845	0.04
Total Rainfall (in)			**3.56**

Gage Location	Date	Time	Depth (in)
Mount Airy Water Tower	15-Apr-98	1445	0.04
		1500	0.16
		1515	0.04
		1645	0.08
		2330	0.04
		2345	0.08
Mount Airy Water Tower	16-Apr-98	30	0.28
		45	0.12
		100	0.16
		115	0.12
		130	0.16
		145	0.04
		200	0.24
		215	0.12
		230	0.2
		245	0.12
		300	0.16

		315	0.08
		330	0.08
		345	0.04
		400	0.12
		415	0.16
		430	0.16
		445	0.12
		500	0.04
		515	0.04
		530	0.08
		615	0.04
		645	0.04
		715	0.04
		730	0.04
		745	0.04
		800	0.04
		1715	0.08
		2030	0.08
Total (in)			**3.48**

Gage Location	Date	Time	Depth (in)
Brecon Water Tower	15-Apr-98	1445	0.04
		1500	0.04
		1515	0.08
		1530	0.04
		1700	0.04
		1715	0.08
		2345	0.04
		2400	0.16
Brecon Water Tower	16-Apr-98	15	0.08
		30	0.12
		45	0.35
		100	0.08
		115	0.16
		130	0.2
		145	0.08
		215	0.08
		230	0.08

		245	0.2
		300	0.12
		315	0.16
		330	0.04
		345	0.04
		400	0.08
		415	0.2
		430	0.16
		445	0.24
		500	0.24
		515	0.08
		530	0.04
		545	0.04
		600	0.04
		630	0.04
		715	0.04
		730	0.04
		745	0.04
		815	0.04
		1730	0.04

		2045	0.24
		2100	0.08
		2115	0.04
Total (in)			**4.03**

Gage Location	Date	Time	Depth (in)
Mill Creek TP	15-Apr-98	2400	0.04
Mill Creek TP	16-Apr-98	30	0.24
		100	0.31
		115	0.63
		200	0.04
		230	0.12
		245	0.04
		330	0.04
		400	0.28
		415	0.12
		430	0.39
		445	0.12
		515	0.28
		530	0.08
		600	0.04
		615	0.04
		645	0.04

			700	0.04
			715	0.04
			745	0.04
			800	0.04
			1730	0.04
			1815	0.04
			2045	0.04
Total				**3.13**

Gage Location	Date	Time	Depth (in)
Wastewater Collections	15-Apr-98	1445	0.04
		1500	0.08
		1515	0.08
		1700	0.04
		2330	0.04
		2345	0.04
		2400	0.04
Wastewater Collections	16-Apr-98	15	0.04
		30	0.08
		45	0.12
		100	0.16
		115	0.16
		130	0.08
		145	0.04
		200	0.12
		215	0.04
		230	0.08

		245	0.16
		300	0.04
		315	0.12
		330	0.04
		345	0.04
		400	0.04
		415	0.12
		430	0.2
		445	0.12
		500	0.04
		515	0.04
		530	0.04
		600	0.04
		700	0.04
		715	0.04
		745	0.04
		800	0.04
		1715	0.04
		1730	0.04
		1845	0.04

		2045	0.04
		2100	0.04
Total			**2.68**

Gage Location	Date	Time	Depth (in)
Sharonville	15-Apr-98	1445	0.04
		1500	0.04
		1515	0.16
		1700	0.28
		1715	0.04
		1900	0.04
		2345	0.24
		2400	0.12
Sharonville	16-Apr-98	15	0.08
		30	0.16
		45	0.16
		100	0.08
		115	0.16
		130	0.12
		145	0.04
		200	0.08
		215	0.12

		230	0.04
		245	0.24
		300	0.12
		315	0.24
		330	0.08
		345	0.08
		400	0.12
		415	0.35
		430	0.2
		445	0.35
		500	0.12
		515	0.08
		530	0.04
		545	0.04
		615	0.04
		700	0.04
		715	0.04
		730	0.04
		800	0.04
		815	0.04

		1745	0.04
		2045	0.2
		2100	0.04
Total (in)			**4.58**

Gage Location	Date	Time	Depth (in)
Deer Park	15-Apr-98	1445	0.04
		1500	0.04
		1515	0.04
		1700	0.04
		2330	0.04
		2400	0.04
Deer Park	16-Apr-98	30	0.04
		100	0.16
		115	0.08
		130	0.16
		145	0.08
		200	0.04
		230	0.04
		315	0.12
		415	0.08
		430	0.08

		445	0.16
		500	0.08
		530	0.04
		545	0.04
		630	0.04
		715	0.04
		730	0.04
		800	0.04
		1830	0.04
Total (in)			**1.64**

Appendix C. Stream Parameters

River Reach Routing Version 2

ARCID	LENGTH	Vel(ft/s)	Vel(m/s)	L/V	L/V (adj)	MUSK X	ROUTE	MUSKK (hrs)	Subreaches	LAGTIME (min)	TIMESTEP
4	5926.57	1.85	0.56	98.78	175.17	0.20	Muskingum	2.92	2.00	0.00	15.00
6	104.76	2.92	0.89	1.75	1.96	0.20	Lag		1.00	1.96	15.00
9	1186.40	2.92	0.89	19.77	22.22	0.20	Muskingum	0.37	1.00	0.00	15.00
10	104.76	3.55	1.08	1.75	1.61	0.20	Lag		1.00	1.61	15.00
12	38.70	3.55	1.08	0.64	0.60	0.20	Lag		1.00	0.60	15.00
16	6440.26	3.55	1.08	107.34	99.20	0.20	Muskingum	1.65	2.00	0.00	15.00
18	93.43	6.34	1.93	1.56	0.81	0.20	Lag		1.00	0.81	15.00
21	373.71	6.34	1.93	6.23	3.22	0.20	Lag		1.00	3.22	15.00
25	663.39	6.34	1.93	11.06	5.72	0.20	Lag		1.00	5.72	15.00
28	1089.89	6.34	1.93	18.16	9.40	0.20	Lag		1.00	9.40	15.00
38	2053.48	6.34	1.93	34.22	17.71	0.20	Muskingum	0.30	1.00	0.00	15.00
41	104.76	7.18	2.19	1.75	0.80	0.20	Lag		1.00	0.80	15.00
46	797.46	7.18	2.19	13.29	6.07	0.20	Lag		1.00	6.07	15.00
51	1738.39	7.18	2.19	28.97	13.24	0.20	Lag		1.00	13.24	15.00

52	154.80	5.15	1.57	2.58	1.64	0.20	Lag		**1.00**	**1.64**	**15.00**
55	325.63	5.15	1.57	5.43	3.46	0.20	Lag		**1.00**	**3.46**	**15.00**
63	2214.11	5.15	1.57	36.90	23.51	0.20	Musking um	**0.39**	**1.00**	**0.00**	**15.00**
67	1628.93	6.81	2.08	27.15	13.08	0.20	Lag		**1.00**	**13.08**	**15.00**
69	66.06	6.81	2.08	1.10	0.53	0.20	Lag		**1.00**	**0.53**	**15.00**
68	27.37	10.10	3.08	0.46	0.15	0.20	Lag		**1.00**	**0.15**	**15.00**
76	1795.06	10.10	3.08	29.92	9.72	0.20	Lag		**1.00**	**9.72**	**15.00**
75	1831.82	7.16	2.18	30.53	13.99	0.20	Lag		**1.00**	**13.99**	**15.00**
78	1767.70	7.16	2.18	29.46	13.50	0.20	Lag		**1.00**	**13.50**	**15.00**
79	772.04	7.16	2.18	12.87	5.90	0.20	Lag		**1.00**	**5.90**	**15.00**
81	116.10	19.43	5.92	1.93	0.33	0.20	Lag		**1.00**	**0.33**	**15.00**
82	77.40	19.43	5.92	1.29	0.22	0.20	Lag		**1.00**	**0.22**	**15.00**
85	1036.30	19.43	5.92	17.27	2.92	0.20	Lag		**1.00**	**2.92**	**15.00**
86	834.22	19.43	5.92	13.90	2.35	0.20	Lag		**1.00**	**2.35**	**15.00**
89	1355.28	19.43	5.92	22.59	3.81	0.20	Lag		**1.00**	**3.81**	**15.00**
92	3720.30	14.72	4.49	62.01	13.82	0.20	Lag		**1.00**	**13.82**	**15.00**
94	143.46	15.76	4.80	2.39	0.50	0.20	Lag		**1.00**	**0.50**	**15.00**
96	2837.66	15.76	4.80	47.29	9.85	0.20	Lag		**1.00**	**9.85**	**15.00**
98	2933.44	15.76	4.80	48.89	10.18	0.20	Lag		**1.00**	**10.18**	**15.00**

44353.64

27.72

Miles

West Fork											
ARCID	LENGTH	Vel(ft/s)	Vel(m/s)	L/V	L/V (adj)	MUSK X	ROUTE	MUSKK	Subreaches	LAGTIME	TIMESTEP
45	2990.85	5.00	1.52	49.85	32.71	0.20	Muskingum	0.55	1.00	0.00	15.00
66	7259.25	5.00	1.52	120.99	79.39	0.20	Muskingum	1.32	1.00	0.00	15.00
South of Sharon Lake											
53	144.18	5.00	1.52	2.40	1.58	0.20	Lag	0.03	1.00	1.58	15.00
56	1646.90	5.00	1.52	27.45	18.01	0.20	Muskingum	0.30	1.00	0.00	15.00

Sharon Lake											
30	2665.20	5.00	1.52	44.42	29.15	0.20	Muskingum	0.49	1.00	0.00	15.00
33	915.50	5.00	1.52	15.26	10.01	0.20	Lag	0.00	1.00	10.01	15.00
34	1084.00	5.00	1.52	18.07	11.85	0.20	Lag	0.00	1.00	11.85	15.00
35	93.42	5.00	1.52	1.56	1.02	0.20	Lag	0.00	1.00	1.02	15.00
39	1004.20	5.00	1.52	16.74	10.98	0.20	Lag	0.00	1.00	10.98	15.00
42	104.70	5.00	1.52	1.75	1.15	0.20	Lag	0.00	1.00	1.15	15.00

North of Sharon Lake		

| 20 | 3718.35 | 5.00 | 1.52 | 61.97 | 40.66 | 0.20 | Musking um | 0.68 | 1.00 | 0.00 | 15.00 |
| 22 | 104.76 | 5.00 | 1.52 | 1.75 | 1.15 | 0.20 | Lag | 0.02 | 1.00 | 1.15 | 15.00 |

North Most											
8	1602.37	5.00	1.52	26.71	17.52	0.20	Musk	0.29	1.00	0.00	15.00
11	82.09	5.00	1.52	1.37	0.90	0.20	Lag	0.00	1.00	0.90	15.00

Appendix D. Watershed Parameters.

Watershed Parameters 12 Mar 1300hrs															CN Lag	V=1 m/s	V=1.5 m/s	V=1.5m/s
GRID CODE	AREA(A)	A(KM2)	LNG FLW PTH	LFP Ft	V(m/s)	V(m/s)	SLOPE	slope %	CN	New CN	LAGTIME	New Lag	(15 m ts)	Lag (l/v)	LAG=L/V 15*3.5		
74.00	17845118.15	17.85	10322.00	33856.15	1.00	1.50	0.01	0.62	87.89	90.00	309.32	284.46	309.21	103.01	103.01	68.68	68.68
73.00	10320979.54	10.32	4858.28	15935.16	1.00	1.50	0.02	1.78	86.68	91.00	105.00	88.12	104.49	48.49	53.00	32.32	53.00
76.00	1615203.72	1.62	2447.92	8029.18	1.00	1.50	0.01	1.44	89.39	90.00	105.00	59.03	60.51	24.43	53.00	16.29	53.00
77.00	3968743.49	3.97	5211.27	17092.97	1.00	1.50	0.01	1.33	89.60	90.00	114.32	112.42	114.28	52.01	53.00	34.67	53.00
79.00	20615750.40	20.62	10360.36	33981.99	1.00	1.50	0.01	1.08	87.68	90.00	236.90	216.17	236.82	103.40	103.40	68.93	68.93
75.00	23137025.75	23.14	10194.24	33437.10	1.00	1.50	0.01	0.83	88.87	91.00	254.84	233.48	254.75	101.74	101.74	67.83	67.83
78.00	9474813.48	9.48	5861.72	19226.43	1.00	1.50	0.01	1.22	88.05	90.00	139.33	128.96	139.28	58.50	58.50	39.00	53.00
80.00	16261364.85	16.26	8136.09	26686.37	1.00	1.50	0.01	0.75	89.58	92.00	217.52	196.37	217.44	81.20	81.20	54.13	54.13
82.00	2851504.76	2.85	3921.28	12861.80	1.00	1.50	0.00	0.21	92.13	93.00	205.86	197.82	205.79	39.13	53.00	26.09	53.00
81.00	13379907.31	13.38	8620.07	28273.83	1.00	1.50	0.01	0.96	90.00	91.00	197.98	189.83	197.91	86.03	86.03	57.35	57.35
83.00	12183293.71	12.18	5488.83	18003.36	1.00	1.50	0.01	1.41	83.60	91.00	144.29	109.16	144.24	54.78	54.78	36.52	53.00
85.00	4360376.11	4.36	4474.41	14676.07	1.00	1.50	0.02	1.89	83.47	91.00	106.30	80.07	106.26	44.65	53.00	29.77	53.00
86.00	746573.07	0.75	2282.95	7488.08	1.00	1.50	0.03	2.68	90.26	91.00	105.00	39.25	40.49	22.78	53.00	15.19	53.00
88.00	23099584.77	23.10	9763.63	32024.70	1.00	1.50	0.01	1.07	88.12	94.00	223.18	173.43	223.10	97.44	97.44	64.96	64.96
89.00	1929707.92	1.93	2321.65	7615.01	1.00	1.50	0.00	0.22	93.56	94.00	123.81	121.21	123.77	23.17	53.00	15.45	53.00
84.00	7812434.13	7.81	6479.81	21253.78	1.00	1.50	0.01	1.25	85.06	94.00	166.44	115.59	166.38	64.67	64.67	43.11	53.00
90.00	7928501.15	7.93	6488.40	21281.96	1.00	1.50	0.01	1.01	88.55	90.00	162.94	153.73	162.88	64.75	64.75	43.17	53.00
91.00	5148883.07	5.15	4850.89	15910.91	1.00	1.50	0.02	1.65	87.00	94.00	107.16	79.81	107.12	48.41	53.00	32.27	53.00

92.00	1406283.07	1.41	2526.48	8286.86	1.00	1.50	0.02	2.24	84.73	92.00	105.00	44.58	59.19	25.21	53.00	16.81	53.00
94.00	9687478.22	9.69	7607.63	24953.01	1.00	1.50	0.01	0.56	90.39	91.00	230.79	224.91	230.70	75.92	75.92	50.62	53.00
95.00	11039097.47	11.04	9731.90	31920.63	1.00	1.50	0.01	0.84	87.31	90.00	259.07	233.15	258.98	97.12	97.12	64.75	64.75
93.00	12893923.44	12.89	6238.24	20461.43	1.00	1.50	0.01	1.21	84.48	94.00	167.44	113.97	167.39	62.26	62.26	41.51	53.00
87.00	76821395.29	76.82	17527.32	57489.60	1.00	1.50	0.00	0.44	85.58	90.00	610.59	515.77	610.37	174.92	174.92	116.62	116.62
96.00	12280640.24	12.28	9753.75	31992.30	1.00	1.50	0.01	1.01	85.44	91.00	253.35	204.30	253.26	97.34	97.34	64.90	64.90
97.00	16901605.55	16.90	8077.79	26495.16	1.00	1.50	0.02	1.52	86.49	91.00	171.05	143.22	170.99	80.62	80.62	53.74	53.74
99.00	10751550.77	10.75	7324.51	24024.40	1.00	1.50	0.02	1.66	86.54	90.00	151.05	132.12	150.99	73.10	73.10	48.73	53.00
98.00	42500749.90	42.50	12634.24	41440.31	1.00	1.50	0.01	0.84	87.22	94.00	320.29	240.56	320.18	126.09	126.09	84.06	84.06
100.00	56999393.58	57.00	14603.36	47899.03	1.00	1.50	0.01	0.91	85.27	90.00	370.90	309.92	370.77	145.74	145.74	97.16	97.16

Appendix E. Cross Sections and Velocity Refinement.

River Sta	Mann Wtd Total	Hydr Radius	Invert Slope	Arc View	Vel Chnl	10.9 Vel	Vel	Vel of Avgs Vel	Vel of Avgs Vel	Avgs of Vel Vel	Average of Velocities Ve
		(ft)		Slope	(ft/s)	(ft/s)	Arc View	(ft/s)	Arc View	(ft/s)	ArcView
236431	0.06	2.06	0.01	0.01	11.75	3.23	3.33				
235781	0.06	0.82	0.00	0.01	6.34	1.32	1.62				
234741	0.06	1.59	0.00	0.01	3.67	1.91	2.70				
233681	0.06	1.14	0.00	0.01	3.88	0.89	2.33				
233161	0.06	0.80	0.00	0.01	3.01	1.33	1.80				
232711	0.06	0.96	0.00	0.01	1.76	0.67	2.00				
232011	0.05	1.83	0.00	0.01	2.97	2.26	3.50				
231811	0.07	2.72	0.00	0.01	2.69	2.18	3.36				
231786	Bridge			0.01							
231761	0.07	2.71	0.00	0.01	2.92	2.51	3.16				

231661	0.07	0.74	0.00	0.01	5.06	1.09	1.37			
230861	0.08	0.58	0.00	0.01	5.18	0.88	1.01			
230061	0.08	1.08	0.00	0.01	2.49	0.62	1.54			
229421	0.08	0.84	0.00	0.01	4.46	0.65	1.37			
229351	0.07	1.03	0.00	0.01	3.72	0.86	1.81			
229350	0.07	1.01	0.00	0.01	3.75	0.85	1.80			
229344	Bridge			0.01						
229337	0.07	0.99	0.00	0.01	3.84	0.84	1.76			
229237	0.07	1.00	0.00	0.01	1.16	0.84	1.78			
228927	0.19	1.24	0.00	0.01	2.52	0.47	0.71			
228227	0.42	1.11	0.00	0.01	7.87	0.20	0.30			
228147	0.07	1.01	0.00	0.01	3.12	1.05	1.59			
228131	Bridge			0.01						
228115	0.07	0.55	0.00	0.01	5.20	0.66	1.11			
227865	0.12	0.69	0.00	0.01	6.95	0.19	0.74			
226965	0.08	1.57	0.00	0.01	1.10	0.77	2.03			
224365	0.11	2.01	0.00	0.01	1.02	1.01	1.78			
223245	0.11	1.94	0.00	0.01	0.88	0.90	1.63			
	0.09	**1.28**	**0.00**	**0.01**				**0.92**	**1.48**	**1.13**	**1.85**
222670	0.10	1.53	0.00	0.01	0.98	0.99	2.33			
222130	0.09	1.52	0.00	0.01	1.05	0.22	2.55			

221010	0.09	2.14	0.00	0.01	0.85	0.29	3.32				
219460	0.09	2.27	0.00	0.01	1.01	0.61	3.50				
	0.09	**1.87**	**0.00**	**0.01**				**0.69**	**2.90**	**0.53**	**2.92**
218948	0.09	2.44	0.00	0.01	1.26	1.77	2.62				
218048	0.08	2.10	0.00	0.01	0.90	1.78	2.65				
217818	0.11	2.30	0.00	0.01	2.42	1.41	2.10				
217778	Bridge			0.01							
217738	0.11	2.26	0.00	0.01	2.21	0.97	1.98				
216623	0.11	3.20	0.00	0.01	0.77	0.71	2.50				
215323	0.14	3.59	0.00	0.01	1.25	0.64	2.25				
213690	0.06	3.79	0.00	0.01	0.35	2.30	4.98				
212728	0.06	3.04	0.00	0.01	0.50	1.75	4.37				
212243	0.09	3.03	0.00	0.01	0.64	1.24	3.10				
212193	0.12	4.26	0.00	0.01	0.32	1.15	2.88				
212180	Bridge			0.01							
212167	0.10	4.23	0.00	0.01	0.62	1.24	3.24				
211847	0.07	4.50	0.00	0.01	0.31	1.78	4.87				
211527	0.07	4.60	0.00	0.01	0.31	2.81	4.96				
210827	0.10	4.15	0.00	0.01	0.44	1.37	3.43				
210167	0.14	4.04	0.00	0.01	0.69	0.77	2.35				
209427	0.32	3.63	0.00	0.01	2.24	0.25	0.96				

209027	0.17	3.92	0.00	0.01	1.24	0.55	1.95			
208537	0.15	4.92	0.00	0.01	0.86	0.72	2.55			
207267	0.08	5.36	0.00	0.01	0.59	0.97	4.87			
206919	0.06	5.16	0.00	0.01	0.45	1.35	6.75			
206903	Bridge			0.01						
206887	0.06	5.15	0.00	0.01	0.31	1.84	6.52			
205840	0.09	4.89	0.00	0.01	0.67	1.24	4.37			
204970	0.14	4.18	0.00	0.01	1.02	0.67	2.37			
203450	0.06	4.05	0.00	0.01	3.69	1.57	5.56			
203220	0.12	5.49	0.00	0.01	0.70	0.98	3.46			
203015	Bridge			0.01						
202810	0.12	5.42	0.00	0.01	0.70	1.98	3.44			
202530	0.09	5.06	0.00	0.01	3.61	3.02	4.14			
202140	0.10	5.59	0.00	0.01	2.06	1.71	4.11			
201950	0.10	5.42	0.00	0.01	1.83	1.64	3.95			
201935	Bridge			0.01						
201920	0.10	5.41	0.01	0.01	1.84	3.28	3.94			
201780	0.12	4.95	0.01	0.01	1.79	2.71	3.25			
201680	0.12	5.08	0.00	0.01	1.49	2.41	3.08			
201030	0.13	5.23	0.00	0.01	1.23	2.30	2.94			
200100	0.08	4.97	0.01	0.01	5.60	6.28	4.75			
200070	0.12	5.16	0.01	0.01	1.08	4.11	3.11			

200055	Bridge			0.01							
200040	0.12	5.16	0.00	0.01	1.09	1.08	3.11				
199940	0.08	4.74	0.00	0.01	5.90	1.62	4.67				
198820	0.14	5.79	0.00	0.01	1.27	1.06	3.06				
	0.11	**4.38**	**0.00**	**0.01**				**1.77**	**3.18**	**1.71**	**3.56**
197690	0.13	5.99	0.00	0.01	1.68	1.77	4.00				
196730	0.11	6.20	0.00	0.01	2.19	2.02	4.57				
196000	0.09	6.21	0.00	0.01	2.83	2.72	6.13				
195920	0.06	5.13	0.00	0.01	2.64	3.34	7.53				
195910	Bridge			0.01							
195900	0.06	5.02	0.00	0.01	2.70	4.99	7.53				
195830	0.10	5.41	0.00	0.01	2.87	3.31	5.00				
195770	0.10	5.57	0.00	0.01	2.51	3.11	4.70				
195710	0.06	4.34	0.00	0.01	2.56	4.85	7.32				
195678	Bridge			0.01							
195645	0.06	4.33	0.02	0.01	2.56	9.73	7.32				
195620	0.06	4.46	0.02	0.01	2.47	9.91	7.46				
195610	0.06	4.46	0.02	0.01	2.48	9.91	7.46				
195580	0.06	4.46	0.02	0.01	2.48	9.91	7.46				
195540	Bridge			0.01							
195500	0.06	4.46	0.01	0.01	2.48	7.32	7.46				

195400	0.06	5.94	0.01	0.01	2.70	8.00	8.15			
195325	0.06	5.57	0.01	0.01	2.73	7.66	7.81			
195305	Bridge			0.01						
195285	0.06	5.42	0.01	0.01	2.80	5.70	7.81			
195230	0.06	5.79	0.01	0.01	2.79	5.47	8.00			
194865	0.08	5.35	0.00	0.01	1.95	0.79	5.75			
194315	0.08	5.39	0.00	0.01	2.22	0.78	5.70			
194255	0.06	5.12	0.00	0.01	2.78	0.99	7.27			
194228	Bridge			0.01						
194200	0.06	5.06	0.01	0.01	2.81	6.54	7.22			
194040	0.08	5.69	0.01	0.01	1.95	5.79	6.39			
193420	0.08	5.88	0.00	0.01	1.85	2.15	6.70			
191920	0.07	5.45	0.00	0.01	1.56	2.18	7.13			
191100	0.07	5.81	0.00	0.01	3.50	2.73	7.54			
191030	0.08	5.60	0.00	0.01	3.11	2.34	6.47			
191023	Bridge			0.01						
191015	0.08	5.57	0.00	0.01	3.13	2.33	6.45			
190900	0.08	5.14	0.00	0.01	2.13	1.21	5.60			
189615	0.07	5.85	0.00	0.01	2.35	1.15	6.86			
188750	0.08	5.39	0.00	0.01	3.79	0.94	5.63			
188670	0.09	5.43	0.00	0.01	1.64	0.85	5.07			
188635	Bridge			0.01						

188600	0.09	5.41	0.00	0.01	1.65	2.72	5.05				
188410	0.08	5.46	0.00	0.01	3.16	1.92	6.29				
188000	0.11	6.02	0.00	0.01	2.44	1.87	4.55				
187500	0.10	6.01	0.00	0.01	3.64	2.01	4.91				
187340	0.06	6.14	0.00	0.01	2.44	3.72	9.06				
187330	Bridge			0.01							
187320	0.06	6.05	0.00	0.01	2.49	3.01	8.98				
187150	0.10	5.81	0.00	0.01	3.78	2.02	4.79				
185860	0.13	6.53	0.00	0.01	1.54	2.76	4.20				
185270	0.10	6.28	0.00	0.01	3.22	3.58	5.46				
185170	0.12	6.74	0.00	0.01	0.85	3.14	4.78				
185155	Bridge			0.01							
185140	0.12	6.74	0.00	0.01	0.85	1.46	4.78				
185040	0.10	6.22	0.00	0.01	3.26	1.66	5.43				
184540	0.09	6.28	0.00	0.01	2.02	1.87	5.59				
183930	0.09	5.85	0.00	0.01	3.13	2.95	5.57				
183800	0.07	5.78	0.00	0.01	2.78	3.70	6.99				
183765	Bridge			0.01							
183730	0.07	5.67	0.00	0.01	2.84	3.66	6.90				
183710	0.08	5.74	0.00	0.01	4.09	3.15	5.94				
	0.08	**5.59**	**0.00**	**0.01**				**3.88**	**6.04**	**3.66**	**6.35**

183695	0.08	5.73	0.01	0.02	4.09	5.69	7.38				
183680	0.06	4.10	0.01	0.02	2.93	6.62	8.60				
183655	Bridge			0.02							
183630	0.06	4.06	0.01	0.02	3.41	6.69	8.68				
183600	0.06	4.07	0.03	0.02	3.40	11.04	8.72				
183580	0.06	4.07	0.03	0.02	3.38	10.92	8.72				
183555	0.08	4.54	0.03	0.02	3.01	8.76	6.99				
183548	Bridge			0.02							
183540	0.07	4.40	0.00	0.02	3.10	2.23	6.96				
183260	0.10	5.17	0.00	0.02	3.71	1.89	5.90				
182335	0.08	4.76	0.00	0.02	3.72	2.16	6.94				
182230	0.06	4.39	0.00	0.02	2.93	2.75	8.84				
182205	Bridge			0.02							
182180	0.06	4.18	0.00	0.02	3.06	3.05	8.55				
181950	0.08	5.19	0.00	0.02	3.44	1.99	7.09				
180950	0.07	5.22	0.00	0.02	4.11	1.84	8.35				
180320	0.12	4.57	0.00	0.02	2.04	1.58	4.54				
179140	0.10	5.77	0.00	0.02	2.01	1.18	6.16				
178800	0.10	5.77	0.00	0.02	2.14	1.21	6.35				
178715	0.06	3.86	0.00	0.02	3.16	1.55	8.12				
178700	Bridge			0.02							
178685	0.06	3.29	0.01	0.02	4.31	4.44	7.42				

178585	0.09	4.40	0.00	0.02	2.81	1.42	5.52				
177845	0.08	3.27	0.00	0.02	2.57	1.46	5.40				
176850	0.09	4.24	0.00	0.02	1.27	1.72	5.70				
	0.08	**4.53**	**0.01**	**0.02**				**4.27**	**6.92**	**3.82**	**7.19**
175515	0.08	4.93	0.00	0.01	1.51	2.33	3.99				
175050	0.07	5.59	0.00	0.01	1.91	1.20	5.17				
174740	0.05	6.31	0.00	0.01	3.56	1.69	7.31				
174735	Bridge			0.01							
174730	0.05	5.43	0.00	0.01	3.60	5.21	6.50				
174640	0.06	5.14	0.00	0.01	2.59	4.27	5.83				
173740	0.06	4.92	0.00	0.01	2.39	3.36	5.03				
173620	0.06	4.93	0.00	0.01	2.34	3.48	5.22				
173613	Bridge			0.01							
173605	0.06	4.92	0.01	0.01	2.35	5.64	5.20				
173500	0.08	4.55	0.02	0.01	1.88	6.17	3.77				
173465	0.07	4.98	0.02	0.01	2.15	8.20	5.01				
173458	Bridge			0.01							
173450	0.07	4.97	0.00	0.01	2.16	3.34	4.99				
173410	0.09	4.47	0.00	0.01	1.98	1.46	3.28				
172200	0.08	5.39	0.00	0.01	1.67	1.99	4.29				
171150	0.08	5.60	0.00	0.01	1.53	2.06	4.45				

171050	0.05	5.30	0.00	0.01	2.70	2.91	6.28				
171035	Bridge			0.01							
171020	0.05	5.28	0.00	0.01	2.71	4.10	6.26				
170940	0.08	6.01	0.00	0.01	1.22	1.99	4.49				
169780	0.09	6.10	0.00	0.01	1.60	2.09	4.33				
168560	0.09	5.83	0.00	0.01	1.87	1.73	4.11				
168460	0.05	8.63	0.00	0.01	2.84	4.05	9.58				
168410	Bridge			0.01							
168360	0.05	8.62	0.01	0.01	2.84	9.39	9.56				
168250	0.08	5.92	0.01	0.01	1.17	4.26	4.34				
168200	0.14	5.80	0.01	0.01	2.09	3.12	2.50				
168140	0.06	4.59	0.01	0.01	3.50	6.85	5.50				
168115	Bridge			0.01							
168090	0.05	2.88	0.01	0.01	5.41	5.50	4.42				
168010	0.10	3.83	0.01	0.01	4.10	3.44	2.76				
167840	0.13	4.58	0.00	0.01	3.59	1.23	2.46				
167650	0.05	4.84	0.00	0.01	4.01	3.25	6.51				
167575	Bridge			0.01							
167500	0.05	4.84	0.00	0.01	4.01	3.25	6.51				
	0.07	**5.35**	**0.00**	**0.01**				**3.97**	**4.73**	**3.71**	**5.16**
167130	0.08	4.23	0.00	0.01	2.53	1.14	4.69				

166770	0.15	4.11	0.00	0.01	3.60	0.93	2.28				
166700	0.06	4.26	0.00	0.01	4.06	2.67	6.53				
166675	Bridge			0.01							
166650	0.06	4.11	0.01	0.01	4.33	6.49	6.38				
166560	0.06	4.83	0.00	0.01	4.26	3.95	6.30				
165760	0.06	4.86	0.00	0.01	4.31	3.49	6.53				
164920	0.06	4.51	0.00	0.01	4.62	4.25	6.78				
164890	0.06	4.32	0.00	0.01	4.45	4.05	6.46				
164879	Bridge			0.01							
164867	0.06	3.95	0.02	0.01	5.30	8.99	6.21				
164800	0.05	4.80	0.00	0.01	5.54	2.88	7.32				
163925	0.06	4.60	0.00	0.01	5.62	2.61	6.39				
162800	0.05	5.65	0.00	0.01	6.07	2.72	8.32				
162660	0.05	5.78	0.00	0.01	4.24	2.94	8.97				
162615	Bridge			0.01							
162570	0.05	5.71	0.01	0.01	4.26	9.35	8.89				
162420	0.05	5.67	0.00	0.01	4.52	4.00	8.19				
161970	0.05	5.35	0.00	0.01	5.51	3.78	7.74				
161870	0.06	5.37	0.00	0.01	4.03	4.17	7.36				
161750	0.06	5.34	0.00	0.01	4.01	1.59	7.31				
	0.06	**4.86**	**0.00**	**0.01**				**4.08**	**6.34**	**3.89**	**6.81**

161600	0.02	5.87	0.00	0.01	4.12	10.53	21.16				
161400	0.04	4.36	0.00	0.01	3.98	4.34	9.52				
161150	0.02	6.24	0.00	0.01	3.91	9.64	21.15				
161141	0.02	6.24	0.00	0.01	3.91	9.64	21.15				
161140	0.03	3.52	0.00	0.01	4.19	7.05	13.90				
161091	0.03	3.52	0.00	0.01	4.20	7.02	13.84				
161090	0.05	5.42	0.00	0.01	3.23	4.43	8.73				
161055	0.05	5.36	0.00	0.01	3.27	4.39	8.65				
160905	0.07	5.15	0.00	0.01	3.40	2.92	6.56				
160405	0.08	5.11	0.00	0.01	3.45	2.64	5.93				
159905	0.08	5.06	0.00	0.01	3.53	2.62	5.89				
159405	0.08	5.30	0.00	0.01	3.38	2.63	5.91				
159225	0.04	6.74	0.00	0.01	3.44	6.80	15.27				
159217	0.04	6.75	0.00	0.01	3.44	7.75	15.27				
159216	0.03	5.21	0.00	0.01	3.45	6.70	13.21				
159166	0.03	5.20	0.00	0.01	3.45	6.70	13.21				
159165	0.07	5.00	0.00	0.01	3.35	3.08	6.07				
159140	0.07	5.01	0.00	0.01	3.34	2.27	6.09				
158800	0.07	5.12	0.00	0.01	3.29	2.19	6.09				
158500	0.07	5.21	0.01	0.01	3.24	4.58	6.09				
158180	0.07	5.64	0.01	0.01	4.02	5.02	6.69				
157080	0.10	6.12	0.01	0.01	3.81	3.78	4.95				

156845	0.06	6.66	0.01	0.01	3.41	6.53	8.55				
156795	0.05	5.77	0.01	0.01	2.65	7.68	10.05				
156740	Bridge			0.01							
156685	0.05	5.74	0.01	0.01	2.85	9.40	10.01				
156635	0.05	5.76	0.01	0.01	3.52	10.03	10.68				
156410	0.06	4.30	0.01	0.01	8.14	5.03	6.70				
155990	0.04	6.38	0.04	0.01	5.57	23.27	11.98				
155940	0.07	4.35	0.04	0.01	5.19	11.95	6.15				
155923	Bridge			0.01							
155905	0.06	3.49	0.04	0.01	5.36	10.97	5.65				
155870	0.06	6.78	0.04	0.01	5.06	18.93	9.75				
155835	0.03	6.49	0.04	0.01	3.65	34.90	17.97				
155808	Bridge			0.01							
155780	0.03	6.02	0.07	0.01	3.84	45.28	17.09				
155730	0.06	4.25	0.07	0.01	8.23	17.04	6.43				
154930	0.12	3.60	0.07	0.01	5.44	7.64	2.88				
154880	0.08	3.85	0.07	0.01	2.26	12.35	4.66				
	0.05	**5.29**	**0.02**	**0.01**				**10.35**	**8.28**	**9.38**	**10.11**
154820	0.14	3.99	0.00	0.02	2.15	1.04	3.31				
154380	0.08	3.82	0.00	0.02	2.35	1.57	5.60				
154240	0.08	3.84	0.00	0.02	2.35	1.02	5.63				

153990	0.08	3.83	0.00	0.02	2.35	2.19	5.63			
153890	0.08	3.81	0.00	0.02	2.38	2.18	5.60			
153825	0.05	4.70	0.00	0.02	2.39	4.03	9.74			
153775	0.05	7.15	0.00	0.02	2.38	6.13	14.82			
153738	Bridge			0.02						
153700	0.05	7.00	0.00	0.02	2.38	5.69	14.62			
153675	0.05	5.92	0.00	0.02	2.30	5.19	13.35			
153635	0.04	3.31	0.00	0.02	5.24	5.09	10.46			
152670	0.07	3.29	0.04	0.02	3.74	9.24	5.56			
152620	0.04	7.11	0.04	0.02	2.68	28.25	16.99			
152605	Bridge			0.02						
152590	0.04	6.77	0.00	0.02	2.74	7.18	16.44			
152540	0.07	2.54	0.00	0.02	4.10	2.26	5.18			
151015	0.20	4.12	0.00	0.02	3.46	0.86	2.38			
150525	0.13	3.49	0.00	0.02	3.07	0.96	3.15			
150035	0.10	5.20	0.00	0.02	2.03	2.74	5.40			
148580	0.10	5.57	0.00	0.02	3.22	2.95	5.83			
148180	0.11	4.77	0.00	0.02	2.15	2.32	4.58			
148130	0.08	4.77	0.00	0.02	1.71	3.26	6.44			
148103	Bridge			0.02						
148075	0.08	4.75	0.00	0.02	1.73	2.50	6.42			
148025	0.14	4.35	0.00	0.02	3.24	1.36	3.49			

146875	0.12	3.44	0.00	0.02	2.90	1.39	3.58				
146825	0.09	2.79	0.00	0.02	2.42	1.63	4.18				
146810	Bridge			0.02							
146795	0.09	2.77	0.03	0.02	2.42	5.86	4.16				
146745	0.11	2.96	0.03	0.02	2.84	4.85	3.44				
145800	0.09	4.32	0.03	0.02	3.02	8.07	5.73				
145750	0.08	2.58	0.03	0.02	2.84	5.87	4.16				
145743	Bridge			0.02							
145735	0.08	2.54	0.00	0.02	2.89	1.51	4.17				
145685	0.10	1.86	0.00	0.02	3.95	1.01	2.77				
144880	0.14	2.53	0.00	0.02	3.80	0.89	2.44				
143470	0.15	2.78	0.01	0.02	5.32	1.39	2.39				
142280	0.06	2.38	0.01	0.02	6.38	3.01	5.19				
142230	0.04	4.12	0.01	0.02	6.52	6.36	10.98				
142210	Bridge			0.02							
142190	0.02	3.63	0.03	0.02	8.13	38.19	27.10				
	0.09	**4.08**	**0.01**	**0.02**				**4.10**	**5.36**	**5.09**	**7.17**
142140	0.02	3.38	0.00	0.01	5.64	4.11	15.36				
141980	0.02	3.62	0.00	0.01	4.85	6.34	16.11				
141680	0.03	3.92	0.00	0.01	4.68	4.13	10.92				
141430	0.03	5.39	0.00	0.01	4.65	6.11	15.53				

141210	0.03	5.11	0.00	0.01	4.72	6.56	15.02			
141150	0.03	5.14	0.00	0.01	4.70	8.70	15.07			
141115	0.03	1.62	0.00	0.01	4.86	4.03	6.98			
141100	0.03	4.92	0.00	0.01	4.70	7.13	14.62			
141050	0.03	1.56	0.00	0.01	4.96	3.31	6.78			
141035	0.03	4.79	0.00	0.01	4.77	7.84	14.36			
140995	0.03	1.53	0.00	0.01	4.98	3.67	6.73			
140980	0.03	4.74	0.00	0.01	4.78	7.78	14.26			
140940	0.03	1.43	0.00	0.01	4.91	3.50	6.42			
140925	0.04	2.49	0.00	0.01	4.81	2.93	7.18			
140830	0.03	4.82	0.00	0.01	4.77	5.67	14.41			
140530	0.03	5.31	0.00	0.01	4.79	6.71	15.38			
139234	0.03	6.55	0.00	0.01	4.66	7.73	17.70			
139231	0.03	6.55	0.00	0.01	4.66	7.73	17.70			
139230	0.03	4.85	0.00	0.01	4.65	6.53	14.52			
139211	Bridge			0.01						
139191	0.03	4.82	0.00	0.01	4.66	6.48	14.41			
139190	0.04	2.84	0.00	0.01	4.61	3.32	7.38			
139180	0.04	2.84	0.00	0.01	4.61	2.13	7.38			
139030	0.03	2.86	0.00	0.01	4.64	3.94	8.07			
138930	0.03	2.63	0.00	0.01	5.09	4.90	10.03			
138780	0.02	2.35	0.00	0.01	7.11	4.93	12.09			

138640	0.02	2.64	0.01	0.01	6.90	11.28	11.86			
138630	0.02	2.20	0.01	0.01	6.96	11.55	12.15			
138590	0.02	2.20	0.01	0.01	6.97	11.55	12.15			
138580	0.02	2.13	0.00	0.01	7.13	5.04	11.93			
138380	0.02	2.52	0.00	0.01	7.02	4.94	10.98			
138265	0.02	2.80	0.00	0.01	6.93	7.19	15.99			
138263	Bridge			0.01						
138260	0.02	2.80	0.00	0.01	7.26	5.78	15.99			
138060	0.01	5.80	0.00	0.01	7.27	11.40	31.51			
138045	Bridge			0.01						
138030	0.01	5.29	0.00	0.01	7.61	10.73	29.65			
137970	0.01	4.23	0.00	0.01	7.85	13.94	25.56			
137930	0.01	3.47	0.00	0.01	8.76	12.19	22.34			
137928	Bridge			0.01						
137925	0.01	4.19	0.00	0.01	8.26	12.98	25.36			
137895	0.02	2.25	0.00	0.01	7.78	7.25	15.66			
137860	0.02	2.02	0.00	0.01	7.90	6.32	13.66			
137850	0.02	2.02	0.00	0.01	7.90	6.32	13.66			
137845	0.02	2.01	0.00	0.01	7.94	7.57	14.48			
137760	0.02	1.91	0.00	0.01	7.86	7.34	14.02			
137750	0.02	2.04	0.00	0.01	7.81	7.50	13.74			
137710	0.02	2.24	0.00	0.01	7.66	5.66	12.97			

136810	0.02	2.09	0.01	0.01	7.05	12.29	13.09				
136770	0.02	1.63	0.01	0.01	6.47	11.88	12.65				
136740	Bridge			0.01							
136710	0.02	1.63	0.00	0.01	6.84	5.31	12.56				
136510	0.02	1.63	0.00	0.01	6.75	4.33	12.56				
136410	0.02	1.70	0.00	0.01	6.76	3.96	9.70				
135610	0.02	2.00	0.00	0.01	6.42	4.82	9.87				
135410	0.03	2.43	0.00	0.01	5.51	4.64	9.51				
135360	0.01	4.51	0.00	0.01	5.71	12.99	26.63				
135310	0.01	4.51	0.00	0.01	5.72	14.82	26.63				
135260	0.02	4.35	0.00	0.01	6.58	10.61	24.31				
134710	0.02	4.49	0.00	0.01	6.18	10.81	24.76				
134610	0.02	4.69	0.00	0.01	5.58	14.72	25.49				
134360	0.02	4.95	0.00	0.01	5.22	15.24	26.40				
134310	0.01	7.58	0.00	0.01	5.23	21.74	37.65				
134300	Bridge			0.01							
134290	0.02	4.83	0.00	0.01	5.38	15.03	26.04				
134210	0.02	4.83	0.01	0.01	5.40	25.73	26.04				
134110	0.01	4.66	0.00	0.01	6.11	9.39	27.21				
133910	0.01	4.53	0.00	0.01	6.35	9.22	26.73				
133710	0.02	4.57	0.00	0.01	6.22	8.64	25.04				
133510	0.02	4.61	0.00	0.01	6.12	12.31	25.22				

133310	0.02	4.60	0.00	0.01	6.18	6.15	25.22			
133110	0.02	4.64	0.00	0.01	6.16	5.52	25.31			
132885	0.02	4.32	0.00	0.01	6.08	5.26	24.13			
132660	0.02	4.31	0.00	0.01	6.13	9.49	24.13			
132435	0.02	4.44	0.00	0.01	6.02	5.36	24.58			
132260	0.02	4.18	0.00	0.01	5.84	5.15	23.58			
132010	0.02	6.06	0.00	0.01	5.75	12.77	30.23			
131945	0.01	6.44	0.00	0.01	5.39	14.26	33.75			
131935	Bridge			0.01						
131925	0.01	6.14	0.04	0.01	5.48	70.59	32.68			
131920	0.01	6.04	0.04	0.01	5.68	69.75	32.29			
131915	0.01	6.04	0.04	0.01	5.68	69.75	32.29			
131913	Bridge			0.01						
131910	0.01	5.80	0.04	0.01	5.82	68.06	31.51			
131890	0.01	5.87	0.04	0.01	5.73	68.69	31.80			
131850	0.01	5.87	0.04	0.01	5.74	68.48	31.70			
131835	Bridge			0.01						
131820	0.01	5.50	0.01	0.01	5.89	30.79	30.43			
131760	0.02	4.11	0.01	0.01	5.45	22.19	21.94			
131560	0.02	4.21	0.01	0.01	4.78	24.04	23.76			
131385	0.02	3.87	0.00	0.01	5.34	10.97	22.49			
131185	0.02	3.86	0.00	0.01	5.22	10.93	22.40			

130985	0.02	4.00	0.00	0.01	5.38	15.57	21.51				
130785	0.02	3.68	0.00	0.01	5.14	13.84	19.12				
130585	0.02	4.07	0.00	0.01	5.17	11.63	21.76				
130410	0.02	3.81	0.00	0.01	5.19	4.85	22.21				
129960	0.01	3.21	0.00	0.01	5.14	15.39	21.26				
129885	0.01	6.10	0.00	0.01	4.99	23.58	32.58				
129860	Bridge			0.01							
129835	0.01	5.73	0.00	0.01	5.06	22.07	31.21				
129785	0.02	1.64	0.00	0.01	4.98	8.95	12.65				
129635	0.02	2.30	0.00	0.01	4.80	9.33	13.20				
129485	0.02	3.62	0.01	0.01	4.27	24.47	21.49				
129395	0.01	5.83	0.01	0.01	4.75	36.00	31.60				
129365	Bridge			0.01							
129335	0.01	5.52	0.00	0.01	4.95	16.93	30.43				
129285	0.02	1.74	0.00	0.01	5.00	7.34	13.20				
129015	0.02	2.15	0.00	0.01	4.00	6.18	12.67				
	0.02	**3.88**	**0.00**	**0.01**				**13.60**	**17.63**	**13.67**	**19.44**
128915	0.02	2.43	0.00	0.02	3.22	3.55	20.44				
128715	0.04	2.89	0.00	0.02	3.04	5.26	11.13				
128415	0.04	2.95	0.00	0.02	2.94	2.02	9.84				
128015	0.04	2.85	0.00	0.02	2.80	1.50	9.65				

127185	0.04	2.77	0.00	0.02	2.86	2.13	9.70			
126565	0.03	2.63	0.00	0.02	2.85	2.75	11.83			
126460	0.03	2.60	0.00	0.02	2.86	2.73	11.70			
126450	0.04	2.52	0.00	0.02	2.86	1.88	8.07			
126425	0.04	2.49	0.00	0.02	2.98	1.65	8.03			
126375	0.04	2.45	0.00	0.02	3.05	3.10	9.98			
126355	0.03	2.42	0.00	0.02	3.10	5.31	11.92			
126335	0.03	2.06	0.00	0.02	3.97	1.61	11.96			
126225	0.03	2.07	0.00	0.02	3.96	2.67	10.37			
126075	0.03	2.05	0.00	0.02	3.99	2.53	10.30			
125975	0.03	2.05	0.00	0.02	4.00	4.59	10.30			
125875	0.03	4.02	0.00	0.02	4.17	5.00	19.43			
124450	0.03	4.02	0.00	0.02	3.61	6.66	15.67			
123450	0.04	4.21	0.00	0.02	2.66	5.92	13.92			
123310	0.04	4.69	0.00	0.02	2.67	6.53	15.36			
123260	0.03	4.69	0.00	0.02	2.68	7.62	17.92			
123255	Bridge			0.02						
123250	0.03	4.63	0.00	0.02	2.68	5.69	17.79			
123200	0.03	4.63	0.00	0.02	2.68	5.51	17.22			
122940	0.03	3.58	0.00	0.02	4.10	4.36	13.61			
122770	0.03	5.77	0.00	0.02	3.81	6.92	24.73			
122720	0.03	7.12	0.00	0.02	3.81	7.64	26.31			

122685	Bridge			0.02							
122650	0.03	6.37	0.00	0.02	3.82	9.30	24.46				
122620	0.03	3.32	0.00	0.02	4.20	5.79	15.22				
122370	0.04	4.16	0.00	0.02	3.41	2.55	12.43				
121720	0.04	4.60	0.00	0.02	3.09	4.50	12.37				
121220	0.04	7.07	0.01	0.02	2.73	12.53	20.18				
121170	0.04	6.87	0.01	0.02	3.30	12.29	19.80				
121150	Bridge			0.02							
121130	0.04	6.76	0.01	0.02	3.18	17.11	19.64				
	0.03	**3.87**	**0.00**	**0.02**				**5.30**	**14.20**	**5.29**	**14.73**
121030	0.04	3.42	0.00	0.01	2.95	1.76	7.50				
119800	0.04	4.94	0.00	0.01	2.32	2.16	10.30				
119320	0.04	7.06	0.00	0.01	2.18	3.13	14.94				
119250	0.04	7.18	0.00	0.01	2.08	3.17	15.11				
119235	Bridge			0.01							
119220	0.04	7.08	0.04	0.01	2.09	31.92	14.99				
119160	0.04	4.62	0.00	0.01	2.31	1.58	10.64				
116720	0.04	6.06	0.00	0.01	2.23	1.41	13.48				
115420	0.04	6.51	0.00	0.01	2.30	8.40	14.17				
115070	0.04	6.52	0.00	0.01	2.41	8.40	14.17				
115000	0.04	6.96	0.00	0.01	2.41	8.77	14.78				

114975	Bridge			0.01						
114950	0.04	6.95	0.00	0.01	2.42	5.14	14.78			
114775	0.03	7.38	0.00	0.01	2.18	6.94	19.95			
114600	0.02	7.23	0.00	0.01	2.35	8.39	25.31			
114500	0.01	7.25	0.00	0.01	2.34	10.56	38.07			
114410	0.01	7.31	0.00	0.01	2.58	10.62	38.28			
114360	0.01	7.32	0.00	0.01	2.58	10.62	38.28			
114310	0.01	6.09	0.00	0.01	3.58	12.78	33.81			
114260	0.01	6.16	0.00	0.01	3.57	8.00	34.11			
113985	0.01	6.32	0.00	0.01	3.56	10.30	34.72			
113860	0.01	6.35	0.00	0.01	3.55	10.33	34.82			
113760	0.01	5.94	0.00	0.01	3.89	9.87	33.30			
113485	0.01	5.98	0.00	0.01	3.85	10.50	33.40			
113410	0.01	6.02	0.00	0.01	4.30	10.57	33.61			
113310	0.01	6.21	0.00	0.01	3.66	3.60	34.32			
113010	0.01	6.31	0.00	0.01	3.57	3.63	34.62			
112430	0.01	6.03	0.00	0.01	3.63	3.52	33.61			
112230	0.01	5.59	0.00	0.01	3.81	3.35	31.98			
111510	0.01	5.45	0.00	0.01	3.78	3.30	31.47			
111410	0.01	5.18	0.00	0.01	3.88	3.18	30.36			
111310	0.01	5.85	0.00	0.01	3.69	5.99	33.00			
111210	0.01	6.04	0.00	0.01	3.44	3.53	33.71			

110760	0.01	6.04	0.00	0.01	3.44	3.53	33.71				
110600	0.01	6.19	0.00	0.01	3.40	3.59	34.21				
110595	Bridge			0.01							
110590	0.01	6.10	0.00	0.01	3.40	3.55	33.91				
110510	0.01	6.12	0.00	0.01	3.40	3.57	34.01				
110060	0.01	5.85	0.00	0.01	3.36	3.46	33.00				
110020	0.01	6.04	0.00	0.01	3.36	3.53	33.71				
109981	0.01	5.82	0.00	0.01	3.36	3.45	32.89				
109980	0.01	4.93	0.00	0.01	3.83	3.09	29.44				
109951	Bridge			0.01							
109921	0.01	4.93	0.01	0.01	3.83	37.04	29.44				
109920	0.02	6.51	0.01	0.01	3.34	41.60	33.07				
109880	0.02	6.51	0.01	0.01	3.34	41.60	33.07				
109780	0.02	6.32	0.00	0.01	4.56	10.59	27.01				
108850	0.05	6.17	0.01	0.01	4.54	10.58	10.19				
108740	0.05	6.48	0.01	0.01	4.87	10.06	9.70				
108395	0.05	6.42	0.01	0.01	4.96	10.01	9.64				
106440	0.05	6.48	0.00	0.01	2.97	4.39	9.13				
106210	0.07	5.97	0.00	0.01	2.88	3.30	6.88				
106010	0.06	5.36	0.00	0.01	4.25	3.67	7.63				
105960	0.06	5.36	0.00	0.01	4.27	3.73	7.77				
105600	0.06	6.29	0.00	0.01	3.36	3.76	7.82				

105200	0.06	6.23	0.00	0.01	3.46	3.72	7.75				
104874	0.05	6.56	0.00	0.01	3.62	4.51	9.39				
104740	0.06	6.81	0.01	0.01	3.63	6.26	8.37				
103850	0.05	5.88	0.00	0.01	4.82	3.43	8.74				
103780	0.05	4.43	0.00	0.01	4.71	3.01	7.68				
103680	0.04	4.55	0.00	0.01	4.76	4.38	11.17				
103630	0.04	6.10	0.00	0.01	4.78	5.32	13.56				
103608	Bridge			0.01							
103585	0.04	5.75	0.01	0.01	4.79	10.13	13.04				
103525	0.04	5.04	0.01	0.01	5.24	8.33	10.71				
102845	0.04	5.86	0.00	0.01	4.31	4.84	11.55				
102705	0.04	6.19	0.00	0.01	4.08	5.29	12.61				
102655	0.04	9.29	0.00	0.01	4.20	6.59	15.71				
102618	Bridge			0.01							
102580	0.04	8.90	0.03	0.01	4.37	28.29	15.28				
102540	0.04	5.55	0.03	0.01	4.38	19.16	10.35				
102480	0.04	5.54	0.03	0.01	4.39	19.16	10.35				
102400	0.04	6.19	0.03	0.01	4.19	24.64	13.31				
	0.03	**6.15**	**0.00**	**0.01**				**11.17**	**15.77**	**8.81**	**21.51**

Appendix F. Mill Creek Wastewater Treatment Plant Flow Data, April 15th and 16th 1998.

Date	Discharge (MGD)
15-Apr-98	124.2
15-Apr-98	123.5
15-Apr-98	120.9
15-Apr-98	118.0
15-Apr-98	113.6
15-Apr-98	108.3
15-Apr-98	94.0
15-Apr-98	94.9
15-Apr-98	97.7
15-Apr-98	100.5
15-Apr-98	118.0
15-Apr-98	119.3
15-Apr-98	136.6
15-Apr-98	134.9
15-Apr-98	138.6
15-Apr-98	205.6

15-Apr-98	181.6
15-Apr-98	180.3
15-Apr-98	180.6
15-Apr-98	184.7
15-Apr-98	178.0
15-Apr-98	175.2
15-Apr-98	155.0
15-Apr-98	157.4
15-Apr-98	169.8
16-Apr-98	195.2
16-Apr-98	398.7
16-Apr-98	372.4
16-Apr-98	372.1
16-Apr-98	387.9
16-Apr-98	401.0
16-Apr-98	393.6
16-Apr-98	381.5
16-Apr-98	385.1
16-Apr-98	376.4

16-Apr-98	214.7
16-Apr-98	368.9
16-Apr-98	374.6
16-Apr-98	328.8
16-Apr-98	313.5
16-Apr-98	305.6
16-Apr-98	290.9
16-Apr-98	296.9
16-Apr-98	289.9
16-Apr-98	293.4
16-Apr-98	295.2
16-Apr-98	292.3
16-Apr-98	273.4
16-Apr-98	271.5
16-Apr-98	266.2
16-Apr-98	274.8

Mill Creek WWTP Flow 15 & 16 April 1998
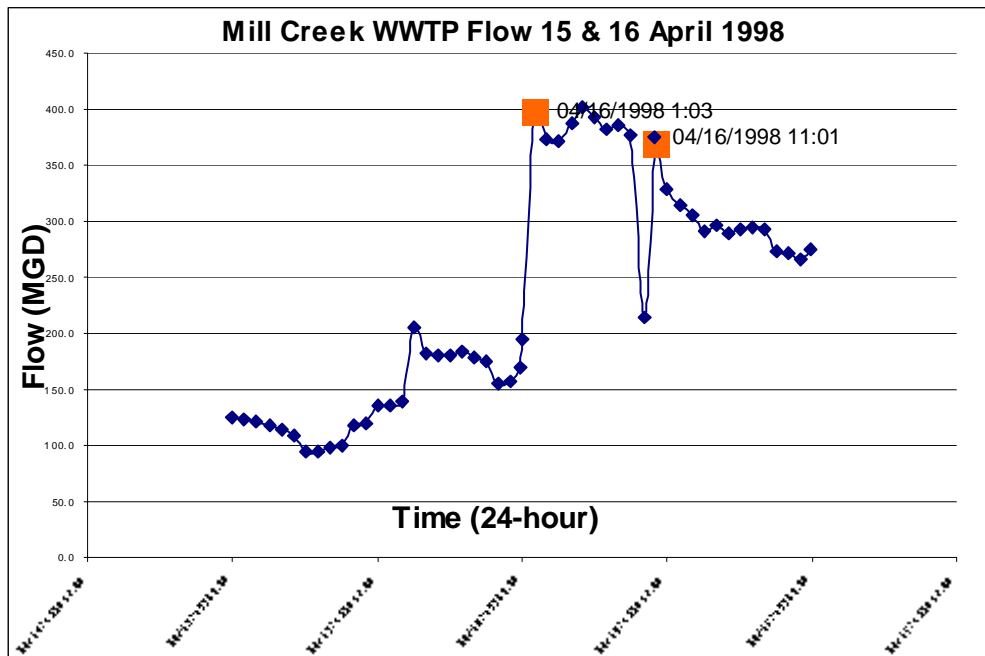
Appendix G: Data Dictionary

Data	Description	Class	Attribute	Units
05080002_rf3	River Reach File for HUC 05080002	Polyline		
05090202_rf3	River Reach File for HUC 05090202	Polyline		
05090203_dem	DEM For HUC 05090203 from Basins 2	Grid	Value	Feet
05090203_rf3	River Reach File for HUC 05090203	Polyline		
10.precip	HEC-HMS precipitation file for a 10-year design storm	Text file		
3dxsects	Cross section line theme	Polyline		
addAsOutlets	Shapefile with the outlets/junctions manually added for the analysis of Mill Creek	Point	Id	

Data	Description	Class	Attribute	Units
Boundary	Shapefile with the bounding polygons generated for the floodplain analysis	Polygon	Profile_id	
bounds	Stream definition point theme of cross section locations	Point		
Build	Shapefile of Mill Creek buildings	Polygon	Elevation	Feet
Burned_dem	DEM raised 1000m except in streams	Grid	Value	Meters
Calibration#.run	HEC-HMS files with the Simulate/Run configurations	Text file		
Calibration.control	HMS file with the control specifications used for the analysis of parameters			
Centerline	Shapefile of the stream centerlines used	PolyLine	Is_outlet Length Reach_id	

Data	Description	Class	Attribute	Units
	used		Stream_id	
Cleanrf	River Reach file edited to exclude lakes or banks	Polyline		
Comp.dbf	DBase attribute table of Statsgo	DBF file		
Curvenumber	Curve Number Grid of Mill Creek	Grid	Value	Curvenu mber
Demgrid	1 degree by 1 degree seamless DEM provided by Louisville Corps of Engineer District	Grid	Value	meters
Demgridp	1 degree by 1 degree seamless DEM provided by Louisville Corps of Engineer District Clipped to HUC 05090203 projected into Ohio State Plan	Grid	Value	meters
Fdr.avl	Theme color			

Data	Description	Class	Attribute	Units
	scheme			
Flood	Shapefile representing the flooded areas corrected from the fa?? files	Polygon		
Floodmap.apr	ArcView project for the Mill Creek containing scripts and menus needed for floodplain mapping	Text file		
gagespro	Shapefile of the Mill Creek gages defined in CRWR-PrePro projected in Ohio State Plane	Point		Feet
Gridpt	Shape file of DEM	Point	Elevation	Meters
hecdiv.dbf	Table for attribute transfer from ArcView shape files to HMS basin files	DBF file		

Data	Description	Class	Attribute	Units
hecjunct.dbf	Table for attribute transfer from ArcView shape files to HMS basin files	DBF file		
hecreach.dbf	Table for attribute transfer from ArcView shape files to HMS basin files	DBF file		
hecres.dbf	Table for attribute transfer from ArcView shape files to HMS basin files	DBF file		
hecsink.dbf	Table for attribute transfer from ArcView shape files to HMS basin files	DBF file		
hecsourc.dbf	Table for attribute transfer from ArcView shape files to HMS basin	DBF file		

Data	Description	Class	Attribute	Units
	files			
hecsub.dbf	Table for attribute transfer from ArcView shape files to HMS basin files	DBF file		
Huc	Shapefile of HUC 05090203	Polygon		Feet
Hydrol#	Shape files generated by HEC-PrePro with hydrologic information necessary for HMS	Polyline		
Hydrop#	Shape files generated by HEC-PrePro with hydrologic information necessary for HMS	Point		
land.avl	Theme color scheme			
Levee	Shapefile of Mill	Polygon		Feet

Data	Description	Class	Attribute	Units
	Creek levees			
lfp	Longest flow path calculated for each sub-basin	Grid	Value	
lulc	Shapefile of the Mill Creek area land use according to the USGS	Polygon	Lucode	Anderson's land use code
MCbasinSCSv1	Basin file generated by CRWR-PrePro for the analysis of Mill Creek	Text file		
MCfag	Flow accumulation	Grid	Value	Drainage area measured in cells
Mcgridp	DEM clipped for the Mill Creek area projected in Ohio State Plane,	Grid	Value	Feet
MClnk	Stream network links of the Mill Creek watershed	Grid	Value	

Data	Description	Class	Attribute	Units
MCmodout	Outlets manually added to create watersheds as described by the Louisville District	Grid	Value	
MCmodstr	Modified Stream network for Mill Creek based on a 1000-cell threshold	Grid	Value	
Mcout	Outlets calculated for the Mill Creek basin considering the junction added manually	Grid	Value	
MCrvr	Shapefile with the river network determined from centerl_m	PolyLine	Length WshCode StreamVel MuskX Route MuskK LagTime TimeStep	
MCstr	Stream network for Mill Creek based on	Grid	Value	

Data	Description	Class	Attribute	Units
	a 1000-cell threshold			
MCwshd	Subwatersheds delineated for each outlet in MCmodout	Grid	Value	
MCwshdply	Shapefile with the subbasins determined from MCwshd	Ploygon	Area, Baseflow, Transform, Lossrate, CurveNum, LagTime, LagMethod	
Merge5	Merged RF3 files for HUCs 05090203, 05090202, and 05080002	Polyline		
Mill Creek Basin.hms	HEC-HMS project file for Mill Creek	Text file		
Mill.prj	HEC-RAS project file for Mill Creek	Text file		
MCBasinSCSv1. map	HEC-HMS map file for the Mill Creek	Text file		

Data	Description	Class	Attribute	Units
	watershed			
MillCreek.f01	HEC-RAS flow profiles for the different junctions at different times for the 10-year event	Text file		Cubic feet per second
Millcrk2.g01	HEC-RAS geometry import file	Text file		Feet
Millfdr	Flow direction	Grid	Value	Arc/Info flow direction code
Millfill	Filled DEM based on burned_m	Grid	Value	Meters
Milltin	TIN terrain representation for the Mill Creek area	TIN	Elevation	Feet
prepro04.apr	ArcView project for the Mill Creek PrePro analysis	Text file		
Railroad	Shapefile of Mill Creek rail network	Polygon		Feet

Data	Description	Class	Attribute	Units
Rcn.txt	Lookup Table for Curvenumber	Text file		
Roads	Shapefile of Mill Creek road network	Polygon		Feet
Soils	Shapefile of the Mill Creek area soils according to the USGS	Polygon		
Soilstorage	Soil Storage Grid of Mill Creek	Grid	Value	Inches
Stream3d	3D line shapefile of stream centerline and banklines	PolylineZ		
streamp.txt	Table with the stream parameters	Text file	Muskingum X Stream veloc.	m/s
Syml#	Shape files generated by HEC-PrePro with hydrologic information			

Data	Description	Class	Attribute	Units
	necessary for HMS			
Symp#	Shape files generated by HEC-PrePro with hydrologic information necessary for HMS			
Thiessen8	Shape file generated using Thiessen Polygons, with the precipitation are corresponding to each of the 8 gages in the basin	Polygon	Area	
Water_m	Subwatersheds delineated for each outlet in moutlet_m	Grid	Value	
water1.avl	Theme color scheme			
Water2.avl	Theme color scheme			
watertin*	TIN representing	TIN		

Data	Description	Class	Attribute	Units
	the water surface			
watpol_m	Shapefile with the subbasins determined from water_m	Polygon	Area, Baseflow, Transform, LossRate, CuerveNum, LagTime, LagMethod	
WshPar.txt	Table of watershed hydrologic parameters	Text File		

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