

An Improved Algorithmic Approach to Iterative Floodway Modeling using HECRAS and GIS

Sivasankkar Selvanathan

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State
University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Civil Engineering

Dr. Randel L. Dymond, Chair
Dr. David F. Kibler
Dr. Lawrence W Carstensen, Jr.
Dr. Kathleen Hancock
Mr. Kendrick Logsdon, Jr.

November 19, 2009
Blacksburg, Virginia

Keywords: Floodway, HECRAS, GIS, tight-coupling, floodway smoothing algorithms

Chapter 2 © 2009 by Journal of Flood Engineering
All other material © 2009 by Sivasankkar Selvanathan

An Improved Algorithmic Approach to Iterative Floodway Modeling using HECRAS and GIS

Sivasankkar Selvanathan

(ABSTRACT)

Hydrologic Engineering Center's River Analysis System (HEC-RAS) software is commonly used to perform hydraulic analysis for floodplain delineation studies. In addition to floodplains, the hydraulic analysis also includes modeling a floodway in detailed floodplain study areas. Floodway modeling is an iterative process in which the 1% annual chance flood discharge is restricted within a floodway without exceeding a designated increase, called the surcharge (usually 1 foot), in water surface elevation. An engineer models flows along a reach to meet Federal Emergency Management Agency's (FEMA) surcharge requirements.

We present a tightly coupled system comprising of a commercial GIS (ArcGIS) and HECRAS that automates HECRAS's floodway encroachments modeling. The coupled system takes an automated approach, in which an initial floodway is developed by running HEC-RAS in an iterative fashion with minimal user intervention. A customized ArcGIS visual environment has been developed to edit, remodel, spatially analyze and map floodway boundaries. Four different encroachments fine-tuning options are provided which eliminates the need for a modeler to switch between HECRAS and GIS in the floodway modeling process. Thus, the tool increases the productivity of a modeler by cutting down on manual modeling time during floodway iterations and transition between HECRAS and ArcGIS. The transfer of HECRAS model output into the ArcGIS environment facilitates quick and efficient spatial analysis.

The final step in the floodway modeling process is to develop a smooth floodway boundary that can be mapped on a DFIRM. We have developed automated mapping algorithms that accomplish this task. Some manual fine-tuning is required to finalize the floodway to be printed on FEMA's Flood Insurance Rate Maps (FIRMs).

Dedication

Amma & Appa: This is for you!

Acknowledgments

First and foremost, I would like to extend my utmost gratitude to my advisor Dr. Randy Dymond for providing me with this opportunity to be part of his GIS research group and guiding me through my PhD process. It was an enjoyable journey working with him, and, at this juncture, I would like to thank him for all his patience in cooperating with my professional pursuits and personal visa related requests. A special mention goes to Mr. Kendrick Logsdon Jr. for serving in my PhD advisory committee and guiding me immensely through the PhD research process. I would also like to thank Dr. Kibler and Dr. Carstensen for sharing their expertise in my field of research through their coursework and professional suggestions. I would also like to thank Dr. Hancock for serving as a contributing member in my PhD advisory panel. I would also like to acknowledge CEE department's graduate secretary Ms. Lindy Cranwell for her adept handling of issues pertaining to an international graduate student like me. Special thanks also to my co-workers at the Center for Geospatial Information Technology – Binaya, Rachel, Thomas, Kevin, Jason, Ana, Dave, Nathaniel, Travis, Matthew and Anahita – for making the lab both fun-filled and a good intellectual sharepoint.

A very special thanks to my dear friends in Blacksburg – Ajit, Anu, Arun, Parthiban, Pradeep, Rajesh and Vidya for being there for me each step of the way supporting me during my stay in Blacksburg.

I would like to thank my eternal support system – my parents. If not for their constant encouragement and support, I wouldn't have seen this day.

Thanks to my wife, Dhivya, for putting up with all my whims towards the end of this long pursuit for a doctorate degree.

Contents

1	Introduction	1
1.1	Background.....	3
1.2	Research goals and objectives	9
1.3	Scope and limitations.....	10
1.4	Overview of the process.....	11
1.5	Outline of the document.....	12
1.6	Theoretical HECRAS modeling background.....	14
1.6.1	Excessive and negative surcharges.....	18
1.7	Floodway encroachment methods in HECRAS.....	19
1.7.1	Method 1: Specify encroachment stations.....	20
1.7.2	Method 2: Specify floodway top width	21
1.7.3	Method 3: Specify percent conveyance reduction.....	22
1.7.4	Method 4: Specify target surcharge with equal conveyance reduction.....	23
1.7.5	Method 5: Optimization with two targets.....	25
1.8	Literature Review.....	26
1.8.1	H&H modeling for floodplain extents.....	26
1.8.2	GIS coupling with H&H models	32
1.8.3	Mapping issues	41
1.9	Research significance.....	42
2	An algorithmic approach to iterative floodway modeling using HECRAS and GIS.....	44
2.1	Introduction.....	44
2.2	Modeling background	46

2.3	Description of the algorithm	51
2.4	User interface options	53
2.5	Study area description and model setup.....	54
2.6	Results and Discussions.....	55
2.7	Limitations of the algorithm	58
2.8	Summary and conclusions	58
2.9	Future work.....	59
2.10	Acknowledgments.....	59
2.11	Paper references	59
3	FloodwayGIS - An ArcGIS visualization environment to remodel a floodway	61
3.1	Introduction.....	61
3.2	Background.....	62
3.3	Coupling GIS with H&H models.....	65
3.4	Current floodway modeling methodology	70
3.5	Software Used.....	71
3.6	FloodwayGIS - System description	71
3.7	Salient features of FloodwayGIS	72
3.8	FloodwayGIS - A walkthrough.....	75
3.9	Summary and Conclusions	82
3.10	Acknowledgments.....	83
3.11	Paper references	84
4	Floodway mapping algorithms: challenges and solutions.....	86
4.1	Introduction.....	86
4.2	Background.....	88

4.3	Mapping algorithms.....	92
4.3.1	Method 1 – Stream morphing.....	92
4.3.2	Method 2 – Normal distances method.....	94
4.3.3	Method 3 – Buffer floodway method.....	96
4.4	Challenges in buffer floodway method.....	99
4.5	Post-processing the floodway polygon output.....	102
4.6	Summary and Conclusions.....	105
4.7	Acknowledgments.....	105
4.8	Paper references.....	106
5	Summary and Conclusions.....	108
5.1	Summary.....	108
5.2	Contributions.....	111
5.3	Future work.....	112
6	References.....	114
	Appendix A: Source code availability and tool distribution.....	119

List of Figures

Figure 1.1.	Floodplain and floodway schematic.....	3
Figure 1.2.	A simplified schematic of a floodway.....	7
Figure 1.3.	Schematic of the developed GIS-model coupling system.....	9
Figure 1.4.	Overview of floodway modeling and development.....	12
Figure 1.5.	HECRAS variables for standard step method.....	16
Figure 1.6.	Method 1 – Specify encroachments.....	21
Figure 1.7.	Method 2 – Specify floodway top width.....	22
Figure 1.8.	Method 3 – Specify percentage conveyance reduction.....	23
Figure 1.9.	Method 4 – Specify target surcharge with equal conveyance.....	24

Figure 1.10. Method 5 – Optimization with two targets	25
Figure 1.11. GIS pre and post processing modeling scenario schematic	35
Figure 1.12. Tight coupling scenario schematic	35
Figure 1.13. A schematic sketch of an interface data model	37
Figure 1.14. ArcCatalog view for HECRAS IDM	39
Figure 1.15. HECGeoRAS capabilities.....	40
Figure 2.1. Computation variables for HEC-RAS standard step method	49
Figure 2.2. Common floodway modeling approach in HEC-RAS: (a) Method 4 cross-section sketch, (b) Method 1 cross-section sketch.....	51
Figure 2.3. Algorithm flowchart schematic.....	52
Figure 2.4. Location map for Plum Creek	55
Figure 2.5. Estimated surcharges along Plum Creek	56
Figure 2.6. Floodway mapping as modeled by HEC-RAS.....	57
Figure 3.1. A simplified schematic of a floodway.....	64
Figure 3.2. A schematic sketch of an interface data model	66
Figure 3.3. GIS pre and post processing modeling scenario schematic	67
Figure 3.4. Tight coupling of GIS and H&H models schematic.....	68
Figure 3.5. Schematic of the developed GIS-model coupling system.....	69
Figure 3.6. Comparison of ArcGIS (left) and HECRAS (right) showing model data.....	72
Figure 3.7. Dynamic encroachment label display (top) and the corresponding topwidth change display (bottom).....	75
Figure 3.8. Downstream end of the reach showing the current encroachments and the floodway boundary.....	76
Figure 3.9. Updated map display after changes to cross-sections 45 and 179	78
Figure 3.10. Floodway encroachments manager	79
Figure 3.11. Straight line floodway and TIN of the river buffer	80
Figure 3.12. Smoothed floodway boundary after TIN intersection	81
Figure 4.1. Schematic of the GIS-HECRAS coupling system.....	89
Figure 4.2. Principle behind transformation techniques	91

Figure 4.3. The stream morph mapping method.....	93
Figure 4.4. Helical patterns in the stream morph method.....	94
Figure 4.5. Schematic of the normal distances method	95
Figure 4.6. Problem with the normal distances approach.....	96
Figure 4.7. Map showing buffer floodway method vs. Stream morphing method	98
Figure 4.8. Improvements in TIN triangulation due to densification.....	100
Figure 4.9. Elevation ‘wall’ along the river centerline.....	101
Figure 4.10. Comparison of the raw floodway and rubbersheeted floodway	103
Figure 4.11. Localized similarity transformation comparison with rubbersheeted floodway.....	104

List of Tables

Table 1.1. FEMA approved list of numerical hydraulic modeling software	6
Table 1.2. Examples of floodplain inundation models	30
Table 2.1. FEMA approved list of numerical hydraulic modeling software	47
Table 2.2. Salient statistics of algorithm runs on various study streams	57
Table 3.1. Initial encroachments and surcharge information at the downstream end.	76
Table 3.2. Encroachments and surcharge information at the downstream end after editing	78

1 Introduction

A floodplain is “an area adjacent to a body of water” that gets inundated by precipitation in that watershed. The Federal Emergency Management Agency (FEMA) defines a floodplain as “any land area susceptible to being inundated by flood waters from any source” (CFR, Vol.1 Sec 59.1). Historically, losses due to flooding have been addressed by structural flood control measures like levees and reservoirs. In the latter half of the 20th century, repeated losses due to flooding caused a shift in focus from flood “control” to flood “management”. The goal of flood management is to prevent life loss, reduce flood damage and formulate effective plans for recovery and rehabilitation efforts. The term “flood management” can be used interchangeably with “floodplain management”. Code of Federal Regulations (CFR) defines floodplain management as “*the operation of an overall program of corrective and preventive measures for reducing flood damage, including, but not limited to, emergency preparedness plans, flood control works and floodplain management regulations*” (CFR, Vol.1 Sec 59.1). Such a transformation from flood control to flood management was due to major efforts in federal policy and program development.

Federal policy changes in floodplain management that started in the 1950s culminated in the formation of the National Flood Insurance Program (NFIP). Three main components of the NFIP are flood insurance, floodplain management and floodplain mapping. Flood insurance was formulated to assist in flood disaster relief thereby reducing property repair costs. Floodplain management constituted regulatory and engineering efforts to minimize flood damages. Floodplain mapping involved identifying and mapping flood hazard areas. The floodplain maps serve as a tool to assess flood insurance for new constructions and land development.

Floodplain mapping studies involve hydrologic and hydraulic modeling of flooding streams to estimate the amount of flooding that may occur in the event of a rainfall. Singh and Woolhiser (2002) list and describe the various hydrologic principles and methods that are used by water resources engineers. US Army Corps of Engineers (USACE) developed hydraulic modeling programs with their Hydrologic Engineering Center (HEC) suite of tools. HEC's River Analysis System (HECRAS), developed in 1995 has served as a comprehensive and popular hydraulic model in the United States. In addition to determining the floodplain or flood inundation boundary, HECRAS also has provisions to model a floodway.

Modeling a floodway is a key step in hydrologic and hydraulic modeling (H&H). It is usually modeled as one of the final steps in determining a floodplain. A floodway is designated as a zone or area around the flooding stream reach where no form of construction or development is allowed. The area near the floodway that get flooded during a heavy rainfall event is termed as the floodway fringe. The floodway and the floodway fringe together make up the floodplain (Figure 1.1). Floodways are modeled following an iterative procedural approach coupled with sound engineering judgment.

Geographical Information Systems (GIS) are now commonly used for spatial and temporal data handling in floodplain analysis. It should be noted that there is a spatial component to the hydrology and hydraulics of water flow along a reach. Maidment and Djokic (2000) have discussed specific interfaces and algorithms integrated in a GIS to account for the spatial influence in hydrologic and hydraulic modeling.

GIS has been extensively used with HECRAS for floodplain modeling and visualization of floodplain extents (Whiteaker et al., 2006). While pioneering steps have been taken towards coupling GIS and HECRAS for flood mapping studies, a void still remains due to lack of a partially or fully automated tool for modeling floodways. The goal of the dissertation is to conceive an algorithmic approach to floodway modeling and to develop an automated floodway modeling tool.

Developing such a tool would increase the productivity of an engineer as it would save an appreciable amount of modeling time.

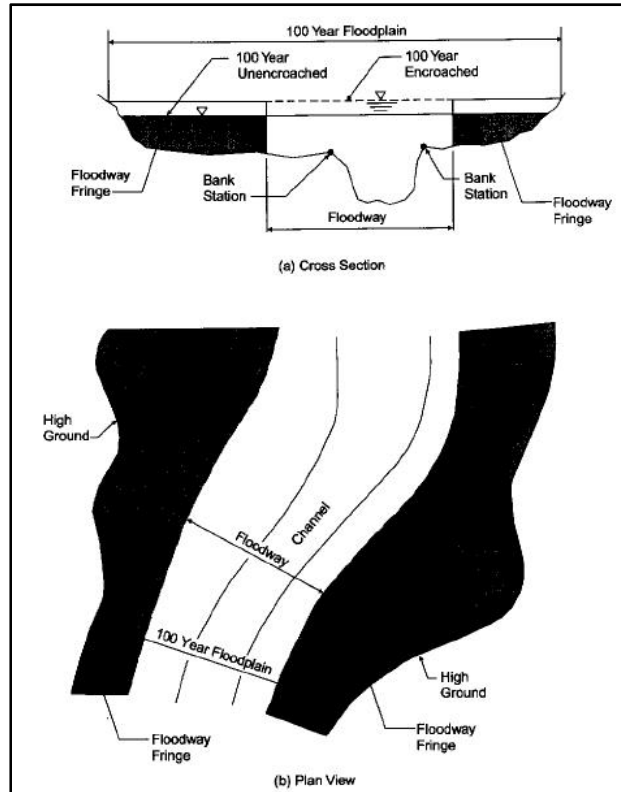


Figure 1.1. Floodplain and floodway schematic (used with permission of Bentley Institute Press and Haestad Press)

1.1 Background

Floodplain delineations are carried out throughout the United States as part of the National Flood Insurance Program (NFIP) administered by the Federal Emergency Management Agency (FEMA). As early as 1950, a Water Resources Policy Commission identified floodplain zoning as an important part of flood management (L.R. Johnston Associates 1992). Since then, there has been a constant evolution in

government policies and the involvement of various governments (federal, state and local) in floodplain management.

The flood control acts legislated in 1917, 1928, 1936, and 1938 continually broadened the scope of federal government involvement in flood control. The continuously increasing urban development and the relationship between land and water uses led to a shift in government policy and a parallel growth in H&H principles and technology. The shift was very clear from the 1950s, when the focus was on controlling floods by structural means (levees and reservoirs), to the 1960s when the focus was more about using non-structural practices largely termed as the floodplain landuse management (Sheaffer J.R 1960, USACE 1968). A floodplain landuse management includes operating guidelines for managing both land and water resources. Day (1973) noted that combining floodplain landuse management with engineering solutions would be a challenging task.

The flood control act of 1960 empowered the Corps of Engineers to formulate a national program for floodplain management services. A Unified National Program for Managing Flood Losses was first submitted for review in Congress in 1966. The unified national program was followed by two key pieces of legislation, the National Flood Insurance Act (1968) and National Environmental Protection Act (1969), which propelled the scientific and environmental development in floodplain management.

The NFIP started in 1968 and has evolved into a collaborative effort by the federal, state and local governments along with the insurance companies to regulate flood insurance. The NFIP involves identifying special flood hazard areas and flood risk, mitigating and managing the flood risk, and spreading awareness about flood risk and mandating flood insurance policies (Burby 2001). The data and models were translated into maps termed as Flood Insurance Rate Maps (FIRMs). Flood insurance rates were determined based on the “zones” (riverine zones like AE, A; coastal zones like V, VE; lesser risk flood zones like B and X).

In the first five years of the NFIP, less than 20% of the local governments identifying flood risk zones and the necessity for establishing floodplain building regulations (Burby and French 1985). As government involvement continued to grow, FEMA took over the chairmanship of the national program in 1982 to help the federal government work with the state and local governments towards floodplain management and mitigation. FIRMs map the floodplains and identify flood hazard areas. In addition to floodplains, FEMA also mandates a floodway concept for flood insurance purposes.

A typical floodplain management workflow to produce floodplain maps consists of performing hydrologic modeling to measure the flows entering a flooding stream, generating hydraulic models to regulate the flow along that stream, mapping the flood inundation extents and disseminating the information to the public. Hydrologic modeling is necessitated by commercial development, which increased surface imperviousness in the area of interest.

Any form of development in a watershed has the potential to increase risk due to flood hazards. Development increases the amount of runoff entering the stream. Hydrologic principles are applied to reduce the runoff to that of pre-development conditions. Many case studies (Burns et al., 2005, Rose and Peters 2001) have been documented explaining the effects of urban runoff on a watershed. Engineers employ Best Management Practices (BMPs) and Low Impact Development (LID) technologies to combat the increase in surface water runoff. From a floodplain management perspective, there is a need to balance the gains of economic development with the increase in flood risk. The concept of floodway and floodplain modeling and delineation is a means to minimize flood hazard risks due to development.

The HECRAS has been used extensively for floodplain and floodway modeling under the NFIP program. FEMA has established a list of numerical hydrologic and

hydraulic models that can be used for NFIP studies. Some of the major hydraulic modeling software packages and their capabilities are listed in Table 1.1.

Table 1.1. FEMA approved list of numerical hydraulic modeling software

Hydraulic Model	Floodway modeling	GIS export	Public Domain
HECRAS	Yes	Yes	Yes
HEC-2	Yes	No	Yes
Water Surface PROfiles (WSPRO)	Yes	No	Yes
Water Surface Pressure Gradient (WSPG)	No	No	No
StormCAD, Pond Pack	No	No	No
XP-SWMM	Yes	Yes	No
Full Equation (FEQ), Full Equation Utilities (FEQUTL)	No	No	Yes
FLDWAV	No	No	Yes
FLO-2D	Under review		No
MIKE FLOOD	No	No	No

HECRAS software was selected for our research based on the following criteria:

1. HECRAS provides five stable steady state methods to model a floodway.
2. It is capable of exporting model output into GIS for further analysis.
3. HECRAS is available for free on public domain and has been widely used in hydraulic studies for many years.

4. It provides a user friendly graphics user interface for modelers.

HECRAS software is capable of estimating floodplain inundation extents for a flooding stream. In detailed hydraulic study areas, as designated by the FEMA as part of their NFIP program, it is also necessary to model floodway extents for the stream. A floodway consists of the main channel of flow and its adjoining areas that are maintained to allow base flood discharges without increasing the water surface elevation beyond a stipulated or designated height. For flood insurance studies, the base flood is the 100 year flood that has a one-percent probability of occurrence or exceedance in any given year. The stipulated height is termed as surcharge, which is the increase in the water surface elevation from the base profile due to constricted flow through a floodway. Figure 1.2 shows a simplified schematic of the floodway concept in which the floodway is shown as a constricted flow area within the floodplain.

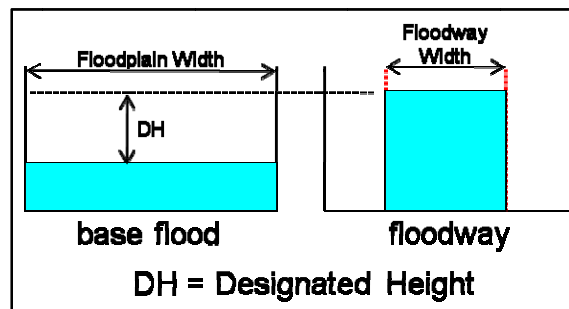


Figure 1.2. A simplified schematic of a floodway

A HECRAS floodway model requires a minimum of two profiles – the base profile and the floodway profile. The base profile contains water surface elevations for the base flood event and the floodway profile contains water surface elevations for the constricted floodway. FEMA flood maps show the floodway in many detailed floodplain study areas. HECRAS uses an encroachment analysis for developing floodways. A detailed explanation of the theory behind HECRAS modeling and

encroachment methods is provided in Section 1.6. The goal is to keep the encroached profile water surface elevations within a pre-determined surcharge value, usually 1 ft. It involves iterative floodway modeling runs to produce a best floodway fit that would satisfy surcharge and other local development requirements.

The modeled HECRAS floodway output can be exported as GIS-compatible files which enable the modeler to examine the results in a GIS environment. If the resultant model output requires changes, the modeler has to remodel the floodway in HECRAS and repeat the process of GIS export in order to take advantage of the spatial analysis capabilities in a GIS. It should be noted that linking HECRAS and GIS facilitates a better approach to floodplain and floodway hydraulic modeling. The process of linking an engineering model (HECRAS) and a GIS is termed as coupling. Sui and Maggio (1999) describe the various coupling concepts that are in used in daily engineering practice.

An effective coupling environment would be one in which both the HECRAS and GIS functionalities are completely available to a modeler. This dissertation introduces a coupled system called FloodwayGIS, in which the GIS and hydraulic model are maintained as separate entities. The GIS contains libraries or functions that facilitate executing the HECRAS model and reading model input-output from within the GIS. A schematic of such a coupling scenario is shown in Figure 1.3.

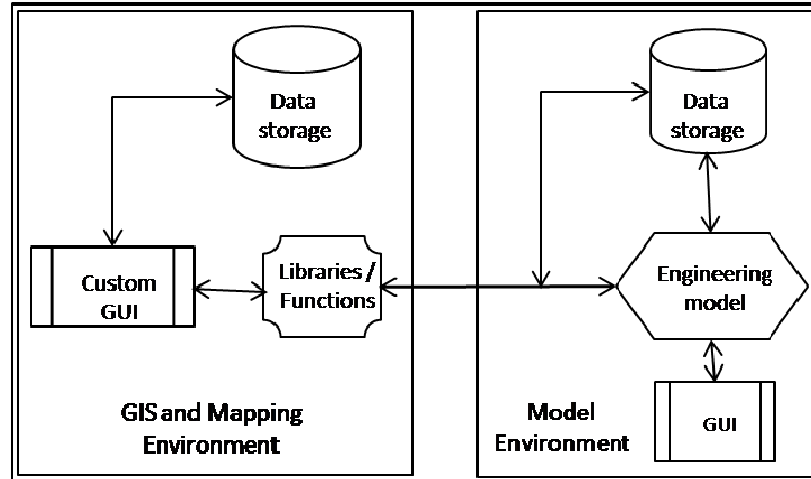


Figure 1.3. Schematic of the developed GIS-model coupling system

GIS coupling with H&H models has been used successfully to delineate floodplains and store the spatial data in a GIS compatible format. Tools like HECGeoRAS and Map-To-Map have demonstrated floodplain mapping capabilities. However, such advanced automation and linking of GIS and H&H models for floodplain mapping scenarios has not been matched by floodway modeling efforts.

1.2 Research goals and objectives

The principal goal of this research is to develop an improved algorithmic approach to perform iterative floodway modeling using HECRAS and GIS. The research work also focuses on providing interactive tools that would aid a modeler in developing a final floodway extent which can be printed on FEMA’s Digital Flood Insurance Rate Maps (DFIRMs). These goals are achieved by completion of the following objectives:

1. Develop and implement an algorithmic, automated approach for iterative floodway modeling using HECRAS's modeling engine and Environmental Systems Research Institute's (ESRI) ArcGIS software.
2. Develop an interactive visual ArcGIS environment for floodway modeling which enables the modeler to alter floodway boundaries within ArcGIS and remodel the floodway using HECRAS engine.
3. Translate the HECRAS floodway output into smooth floodway boundaries (using 3 different methods) that can be modified with minimal user adjustment to be printed on DFIRMs.

1.3 Scope and limitations

The scope of this work is to model floodway boundaries for one flooding reach at a time. A stream network in HECRAS has to be trimmed to contain one reach before it can be imported into the FloodwayGIS environment. The floodway algorithm requires a HECRAS project with exactly two profiles. Multi-profile HECRAS projects are not supported by the algorithm. The floodway modeling process requires engineering judgment, typically, at structures and ineffective flow areas. Hence, the floodway algorithm is restricted in its capability to function as a fully-automated tool for floodway modeling. The research highlights significant savings in modeling time for the floodway. The manual modeling times are based on a modeler's estimate of the time to model the floodway.

The capability of the algorithm and the visual modeling environment is limited by the amount of information that the HECRAS software shares with ArcGIS. For example, the surcharge information for the structures (bridges, culverts etc.) is not readily available from within ArcGIS. Thus, the modeler has to manually check for

the surcharges at the structures and adjust the floodway encroachments upstream or downstream of the structures to satisfy surcharge requirements.

The floodway mapping algorithms described in the dissertation are structured to produce floodway boundaries that can be added to a DFIRM. However, it should be noted that some amount of manual editing is necessary to make the floodway boundary meet FEMA mapping requirements.

1.4 Overview of the process

Floodway modeling is the final step in the hydrologic and hydraulic modeling process performed after delineating the floodplain for the study reach. The HECRAS model for floodway modeling comprises of two profiles. A modeler performs iterative encroachment analysis in HECRAS, followed by a GIS export into ArcGIS to develop a smoothed spatial floodway layer. The overview of the floodway modeling and development process is shown in Figure 1.4. The manual modeling routine can be automated, thereby saving appreciable amount of modeling time.

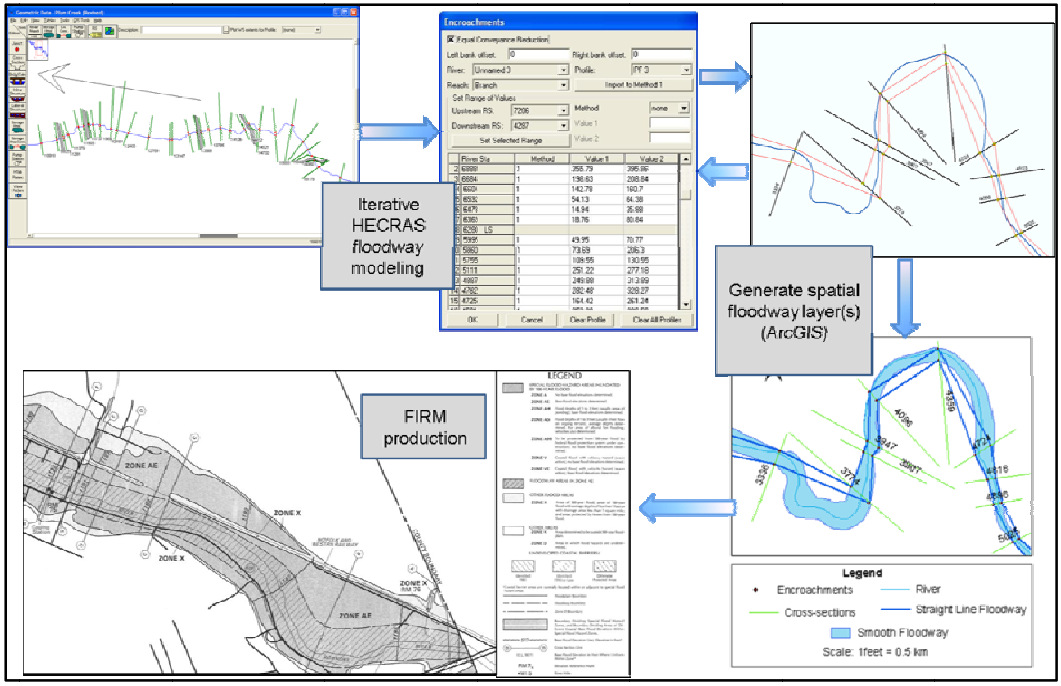


Figure 1.4. Overview of floodway modeling and development

The research automates the process of iterative floodway modeling and generates a smoothed floodway boundary with minimal modeler involvement. The extent of automation is based on the complexity of the hydraulics along the study reach. The automation is achieved by coupling HECRAS with ArcGIS. The customized ArcGIS visual environment allows a modeler to remodel a floodway without switching back to HECRAS. The remodeled floodway is finalized and reviewed before being printed on the FIRM.

1.5 Outline of the document

This dissertation consists of an introductory chapter, three independent chapters and a conclusions chapter to summarize the findings and recommendations from this

work. The three independent chapters (Chapter 2, 3 and 4) are written in manuscript format.

- Chapter 1 – Chapter 1 introduces the goals and objectives of this research and a detailed background of the theory behind hydraulic modeling using HECRAS. The chapter also provides a comprehensive review of literature related to floodplain and floodway modeling and mapping concepts.
- Chapter 2 – *An algorithmic approach to iterative floodway modeling using HECRAS and GIS* – Chapter 2 outlines the proposed algorithm to perform iterative floodway modeling in an automated manner. The algorithm workflow follows manual modeling procedures taking into consideration some of the engineering hydraulic variables that govern the position of the floodway encroachment stations along a cross-section
- Chapter 3 – *FloodwayGIS: An ArcGIS visualization environment to remodel a floodway*. Chapter 3 showcases the capabilities of a visual environment inside ArcGIS to model a floodway. The visual environment is interactive, acting as a visual aid to a modeler trying to edit floodway encroachments. FloodwayGIS is equipped with 4 different encroachment editing tools that enable faster communication between HECRAS and ArcGIS to display the model output on the map.
- Chapter 4 – *Floodway smoothing algorithms: challenges and solutions*. Chapter 4 describes the various algorithms developed to smooth a floodway. The algorithms attempt to produce floodway extents that can be mapped on DFIRMs with minor editing. The algorithms work on the basis of maintaining the floodway topwidth, following the stream sinuosity along the reach. The chapter also highlights the various challenges involved in implementing the algorithms and the workarounds used.

- Chapter 5 – Summary and recommendations: Chapter 5 summarizes the results and also reviews whether or not the research objectives have been met. It also outlines future research directions and enhancements that can be made to the algorithms.

1.6 Theoretical HECRAS modeling background

There are different ways of classifying flows in hydraulics such as: steady-unsteady flow, uniform-varied flow, gradually-rapidly varied flow and subcritical-supercritical flow. HECRAS can model both steady and unsteady flows. A steady flow is one in which the depth and velocity do not change over time. Although, unsteady flow is common in real-world conditions, common hydraulic modeling is performed assuming steady flow. The hypothesis is that depth and velocity change occurs so slowly over time that a steady state solution provides a good estimate of the water surface elevations (Haestad et al 2003). When the velocity and depth change over distance, then the flow is classified as varied flow. A rapidly varied flow (abrupt change over distance) is considered to be a local phenomenon (Chow 1959). Examples of rapidly varied flow are hydraulic jump and hydraulic drop.

Froude number is a dimensionless number used to differentiate subcritical and supercritical flows. It is given as a ratio of inertial forces to gravitational forces. Subcritical flows occur when gravitational flows dominate (Froude number > 1). Subcritical flows are modeled from the most downstream cross-section moving upstream. For NFIP floodplain and floodway modeling, the flow is modeled in a subcritical regime. FEMA does not allow supercritical flows and it is assumed that any flow shift to supercritical regime is a very transient condition during the modeling. HECRAS uses a gradually varied flow regime to model water surface profiles.

HECRAS uses the standard step method (Chow 1959) for computing water surface elevations at cross-sections. The standard step method is suited to compute gradually varied flow under subcritical and supercritical conditions. Bernoulli's energy equation is the basic governing equation in solving steady, gradually varied flow in HECRAS. Figure 1.5 shows the variables at two consecutive cross-section locations (1 and 2) that are used in HECRAS standard step computation method. The governing energy equation for HECRAS can be stated as:

$$WSEL_2 + \frac{\alpha_2 V_2^2}{2g} = WSEL_1 + \frac{\alpha_1 V_1^2}{2g} + h_{L(1-2)} \quad (1)$$

Where,

$WSEL_{1,2}$ = water surface elevation above datum in the channel at the cross-sections (ft)

α_1, α_2 = velocity weighting coefficients

V_1, V_2 = velocities at the cross-sections (ft/s)

g = acceleration due to gravity (ft/s²)

$h_{L(1-2)}$ = total energy head loss between the cross-sections (ft)

EGL = energy grade elevation line between the two cross-sections

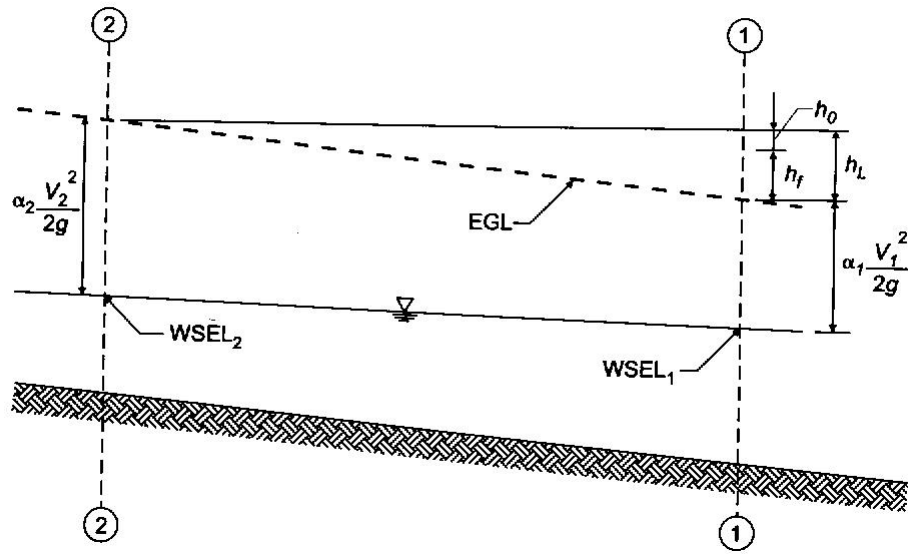


Figure 1.5. HECRAS variables for standard step method (used with permission of Bentley Institute Press and Haestad Press)

The energy head loss is the sum of friction loss (h_f) and expansion-contraction loss (h_0) between the two locations.

$$h_{L(1-2)} = h_f + h_0 \quad (2)$$

Substituting the values for the individual energy losses,

$$h_{L(1-2)} = L \cdot S_f + C_{c,e} \left(\left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \right) \quad (3)$$

Where,

L = length of flow path between the cross-sections (ft)

S_f = average energy slope between the cross-sections (ft/ft)

C_e = Coefficient of expansion

C_c = Coefficient of contraction

The length L is a distance weighted flow path length between the two cross-sections. It is calculated as:

$$L = \frac{L_{lob} * Q_{lob} + L_{ch} * Q_{ch} + L_{rob} * Q_{rob}}{Q_{lob} + Q_{ch} + Q_{rob}} \quad (4)$$

Where,

L_{lob} , L_{ch} , L_{rob} = cross section flow lengths in left overbank, main channel and right overbank respectively

Q_{lob} , Q_{ch} , Q_{rob} = average flow between cross-sections for left overbank, main channel and right overbank respectively

Combining and rearranging equations (1), (2) and (3) , we arrive at an computational equation for water surface elevation at cross-section 2 (upstream cross-section).

$$WSEL_2 = WSEL_1 + \frac{\alpha_1 V_1^2}{2g} - \frac{\alpha_2 V_2^2}{2g} + L.S_f + C_{c,e} \left(\left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \right) \quad (5)$$

FEMA floodway modeling usually assumes subcritical flow. The computation procedure for modeling subcritical flow is outlined below:

1. Usually, the modeling starts from the most downstream cross-section or from the cross-section whose water surface elevation, conveyance and velocity head are known. A water surface elevation is assumed at the next upstream cross-section.
2. The velocity head and the conveyance (flow) are computed based on the assumed water surface elevation.

3. The next step is to calculate the energy slope (S_f) for friction losses and the total energy head loss, $h_{L(1-2)}$.
4. Based on the computed velocity head and energy losses, the water surface elevation ($WSEL_2$) is computed by solving equation (5).
5. If the assumed estimate approximates the computed value, the model moves on to the next upstream cross-section. Otherwise, steps 1-4 are repeated until the water surface elevations between two consecutive iterations are within a user defined tolerance value.

1.6.1 Excessive and negative surcharges

The main goal of floodway modeling is to keep surcharges values above zero up to a maximum allowable limit (typically 1 ft). A modeler traverses each cross-section from downstream to upstream checking for excessive and negative surcharges. The floodway bounds are usually within the floodplain bounds. When flow is constricted at a cross-section, there is an increase in the water surface elevation of the floodway profile. Assume a two cross-sections profile as shown in Figure 1.5. If the flow is constricted at cross-section 2, there is an increase in $WSEL_2$. The velocity head and the friction losses change accordingly to maintain the balance in the energy equation (Equation 5). The final computed $WSEL_2$ might be less than the corresponding water surface elevation of the base profile.

Negative surcharges occur when the water surface elevation in the floodway profile is less than the natural profile. At any cross-section, the energy grade line is given by the sum of the water surface elevation and the velocity head. Negative surcharges can occur during one of the following situations:

1. When the flow is constricted too far into the floodplain (floodway is very narrow), the velocity head increases sharply that the resultant water surface elevation in the floodway profile is less than the base flood profile.
2. The hydraulic structures in the reach are designed differently in the base profile and the floodway profile. It can cause abnormal differences in the energy grade elevation between the two profiles and negative surcharges.
3. The cross-sections are not sufficient to model a study reach. Additional cross-sections may be required if velocity head difference between two consecutive cross-sections is greater than 0.5 ft; the conveyance ratio (ratio of conveyance of current cross-section and the downstream cross-section) is between 0.7 and 1.4; or the distance between two cross-sections is greater than 500 ft.

Excessive surcharges can occur if one of the following hydraulic conditions is observed in the model:

1. If the energy grade elevation difference between the floodway profile and base profile is greater than the maximum allowable surcharge at a cross-section, then the water surface elevation at the next upstream cross-section may increase to balance the energy equation. Hence, it can result in the cross-section upstream to have an excessive surcharge.
2. In the floodway profile, if the velocity head at a cross-section is less, water surface elevation increases to balance the energy grade elevation. If the velocity head is less than that of the base profile, the water surface elevation difference may be higher than the allowable surcharge limit.

1.7 Floodway encroachment methods in HECRAS

HECRAS follows an encroachment analysis procedure to designate a floodway for a flooding stream. The base flood flow is constricted thereby decreasing the

cross-sectional area available for conveying the flow. Reduction in available cross-sectional area increases the water surface elevation for the floodway profile compared to the unencroached profile (base flood). Floodway modeling is an iterative procedure conducted until the surcharges at all cross-sections are within an acceptable limit. Some of the engineering variables that are considered in floodway modeling are conveyance, velocity, top width, energy grade and critical depth (Haestad et al., 2003). HECRAS has 5 methods to model a floodway under steady state. They are as follows:

1. Specify encroachment stations
2. Specify floodway top width
3. Specify percent conveyance reduction
4. Specify target surcharge with equal conveyance reduction
5. Optimization with two targets

1.7.1 Method 1: Specify encroachment stations

Method 1 involves specifying the left and right encroachment stations as shown in Figure 1.6. The modeler specifies the stationing along the cross-section of interest. The difference in elevation between the natural water surface and the encroached water surface indicates the surcharge. Since this method involves manual positioning of the encroachments on either side of the main channel, an equal conveyance condition doesn't exist. It is also the modeler's responsibility to make sure that encroachment stations aren't specified within the channel banks.

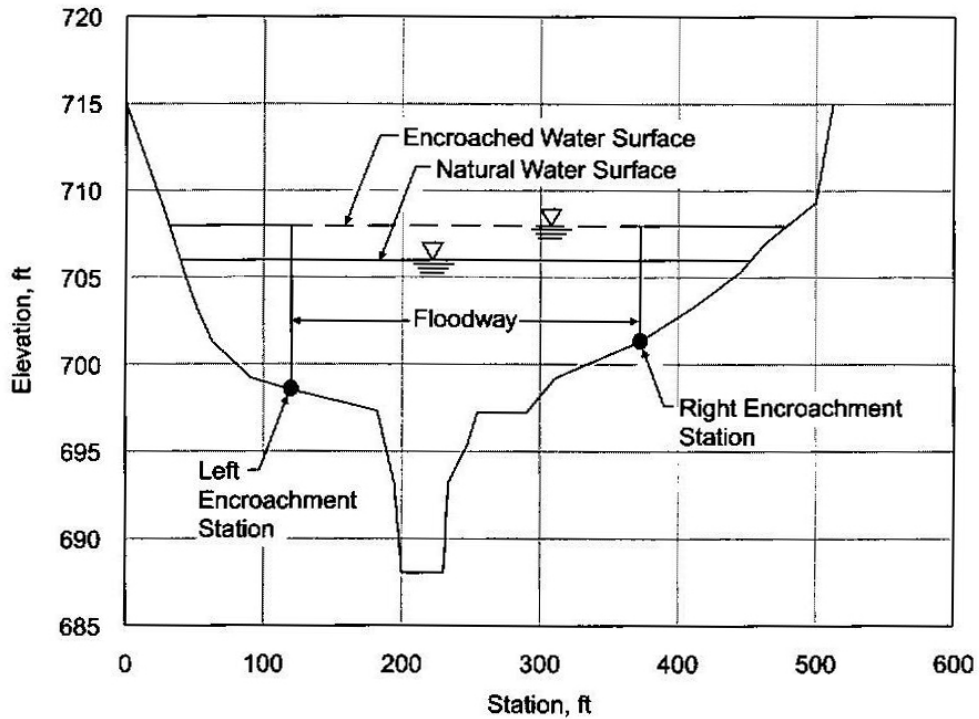


Figure 1.6. Method 1 – Specify encroachments (used with permission of Bentley Institute Press and Haestad Press)

1.7.2 Method 2: Specify floodway top width

In Method 2, a modeler specifies a floodway width for each cross-section. The program designates the floodway encroachment stations on both sides centered from the channel centerline as shown in Figure 1.7. The encroachment stations are positioned in such a way that the floodway width (top width) is split equally on either side. HECRAS doesn't support encroachment into the main channel. So, if the top width is very narrow, then the encroachment stations are fixed at the channel bank stations. The software also allows for an offset on each side which acts like a buffer from the channel bank stations where encroachments are not allowed. Equal conveyance is not maintained on both sides.

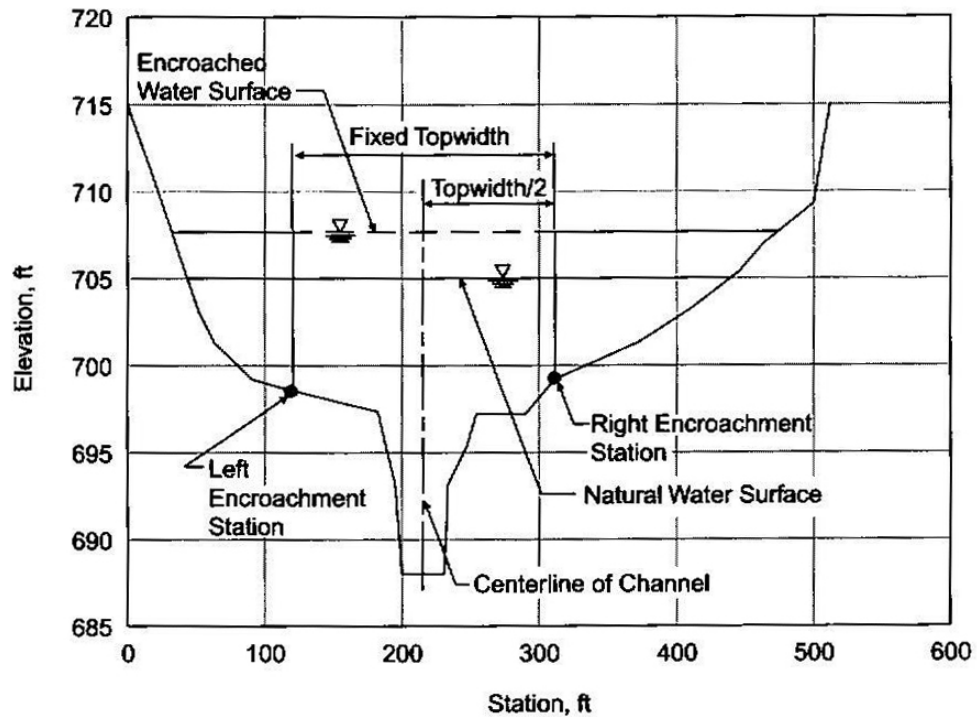


Figure 1.7. Method 2 – Specify floodway top width (used with permission of Bentley Institute Press and Haestad Press)

1.7.3 Method 3: Specify percent conveyance reduction

In Method 3, the modeler inputs a percentage reduction in conveyance half of which will be reduced on each side at the cross-section of interest. The total conveyance is reduced by the specified percent and the reduced conveyance is split equally between two sides of the main channel (Figure 1.8). ‘%K’ represents the percent reduction in conveyance to be modeled. If the conveyance on one side of the channel is less than the amount to be removed, HECRAS will balance the conveyance on the other side. As in method 2, encroachments within the channel banks are not allowed. HECRAS provides options for equal conveyance reduction or a proportional conveyance reduction. In a proportional conveyance reduction scenario, if the conveyance in the left side of the channel is twice as much as the right side,

then, for a 10% conveyance reduction, two-thirds (67%) is removed from the left and one-third (33%) is removed from the right side.

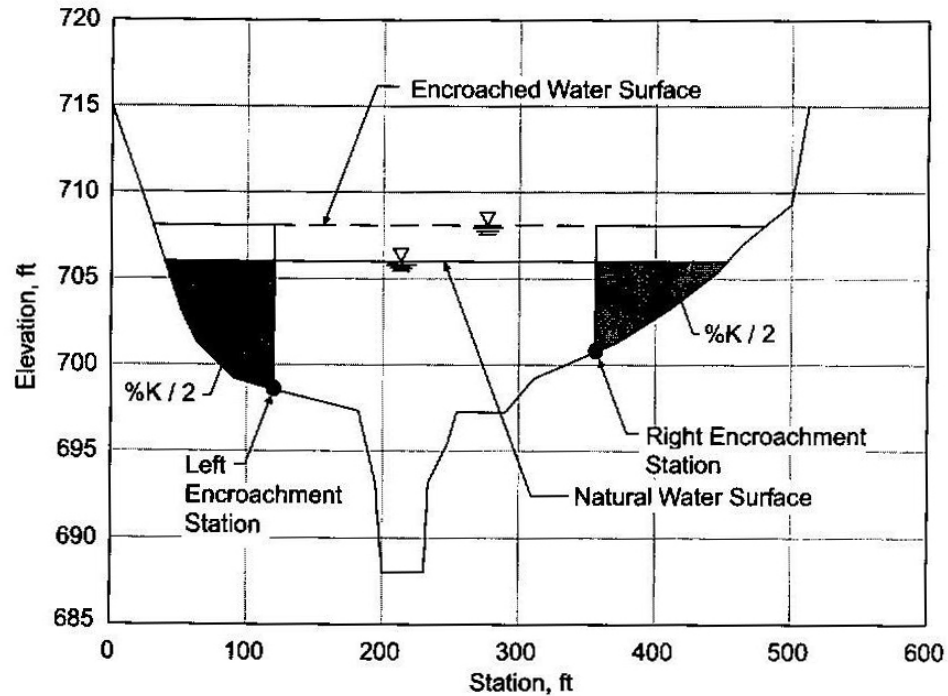


Figure 1.8. Method 3 – Specify percentage conveyance reduction (used with permission of Bentley Institute Press and Haestad Press)

1.7.4 Method 4: Specify target surcharge with equal conveyance reduction

In Method 4, the modeler specifies a target surcharge (difference between the encroached and natural water surface elevations). HECRAS calculates the conveyance difference between the encroached and base flood elevations and an equal conveyance reduction is performed. The conveyance at the encroached cross-section is matched with that of the unencroached. A surcharge of 1ft indicates that the water surface elevation cannot exceed 1 ft more than the base flood elevation of

the 100-year flood profile. The program positions the encroachment stations based on the surcharge value and the equal conveyance reduction. It is not necessary that HECRAS will reduce the conveyance to be contained within the 1 ft surcharge at all cross-sections. In some cross-sections, it is common to have excessive and also negative surcharges (especially near the structures). Figure 1.9 depicts the concept behind method 4. Method 4 also has a default option for equal conveyance as noted in Figure 1.9 (%K/2 on each side). HECRAS also provides a proportional conveyance reduction option as explained in Method 3.

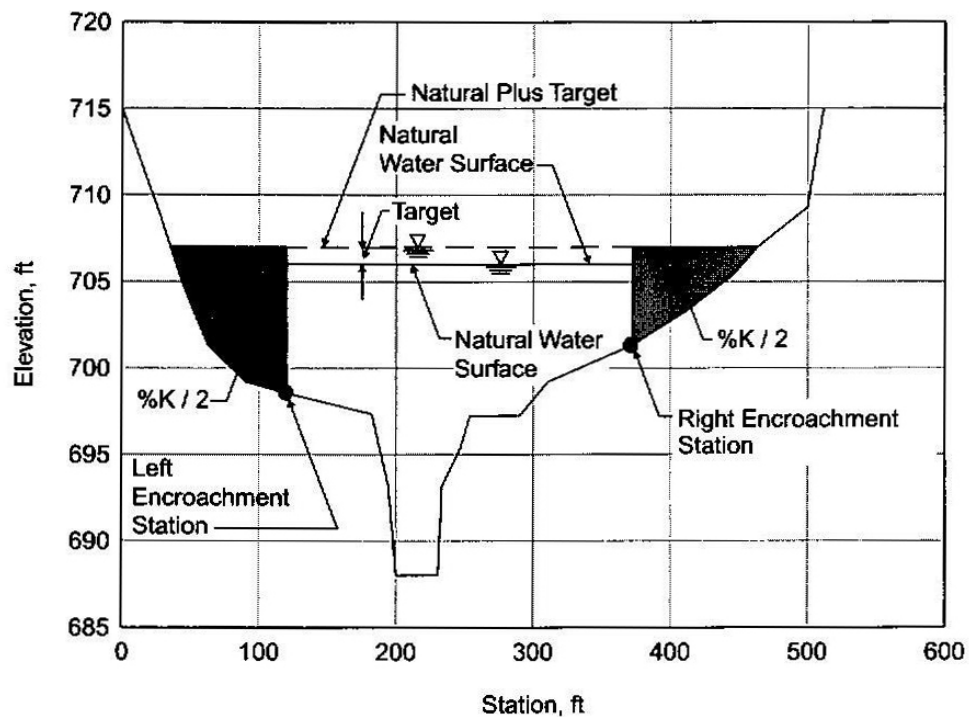


Figure 1.9. Method 4 – Specify target surcharge with equal conveyance (used with permission of Bentley Institute Press and Haestad Press)

1.7.5 Method 5: Optimization with two targets

Two targets are specified, a water surface elevation target and an energy grade elevation target, which would be met by equal conveyance (default). If only one of the target values is provided by the modeler, HECRAS meets only the specified target. HECRAS tries to achieve the water surface elevation target without exceeding the energy grade line target. In situations in which both the targets cannot be achieved, HECRAS meets only the energy grade elevation target. Figure 1.10 shows the two target elevations and the equal conveyance reduction being modeled. HECRAS tries to meet the two targets in 20 iterations. At the end of 20 iterations, if both the targets cannot be met, then the best iteration values are picked from the 20 iterations.

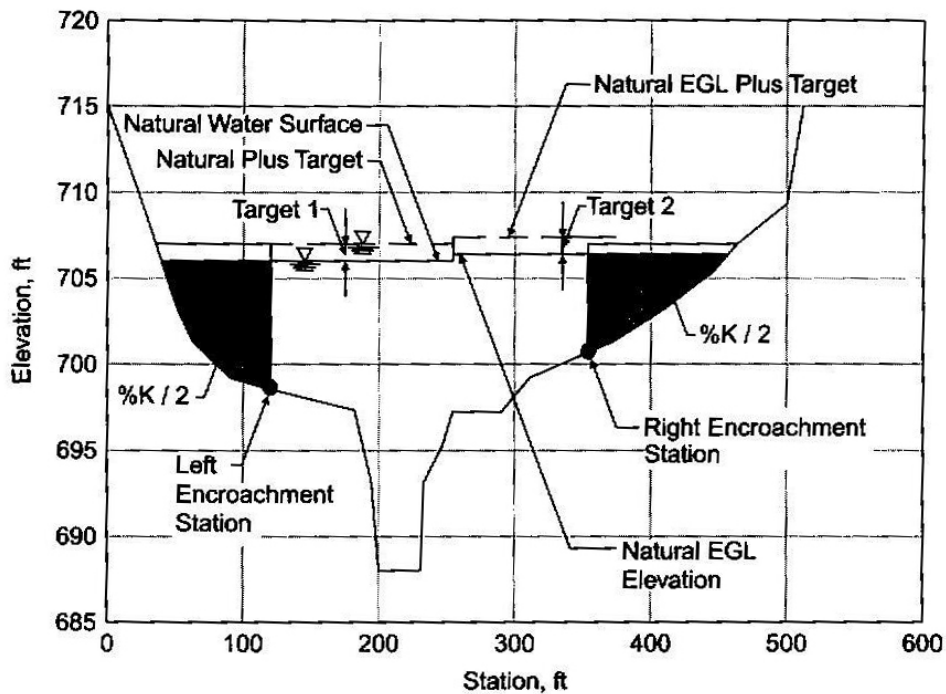


Figure 1.10. Method 5 – Optimization with two targets (used with permission of Bentley Institute Press and Haestad Press)

1.8 Literature Review

Floodway modeling and mapping can be achieved by coupling a H&H model with a commercial GIS. It is important to understand the principles involved in H&H modeling for delineating a floodplain or a floodway boundary. The next step is to take advantage of the H&H modeling capabilities in a GIS environment by coupling techniques. The final step would be to map the H&H output as a smooth boundary. This section provides an extensive review of the current literature pertaining to the use of H&H models and GIS in floodplain management.

1.8.1 H&H modeling for floodplain extents

H&H modeling of flooding streams is an integral part of detailed floodplain management studies. H&H modeling estimates the amount and extent of flooding that may occur in the event of a rainfall. Hydrologic models estimate the flows into a study reach from the contributing watershed which forms the input for hydraulic models to generate floodplain extents. Singh and Woolhiser (2002) list and describe the various hydrologic principles and methods that are used by water resources engineers. These methods include, but are not limited to, Mulvaney's rational method, Green and Ampt's infiltration method, Muskingum flow routing, Modified Puls method for flow routing, United States Geological Survey (USGS) regression equations and the Natural Resources Conservation Service's (NRCS) curve number method.

Watershed models like the Stanford Watershed Model (SWM, now HSPF) (Crawford and Linsley 1966), O'Donnell mathematical model (Dawdy and O'Donnell 1965) and HEC-1 were introduced in the 1960s. It should be noted that these early models of the 1960s were based on a large number of parameters and the calibration

was based on a best-fit scenario. In other words, there were a lot of discrepancy between the models and reality. Such factors inspired the development of physically based hydrologic models like the Storm Water Management Model (SWMM) (Rossman 2009), Systeme Hydrologique Europeen (SHE) (Abbott et al., 1986) and Precipitation-Runoff Modeling System (PRMS) (Leavesley et al., 1983) based on mathematical partial differential equations.

The advent of computers resulted in hydrologic models that estimate flows based on numerical simulations (Pinder and Gray 1977, Abbott et al., 1986, Bates and de Roo 2000, Vieux and Gauer 2008). Todini (1988) identified the importance of satellite and remote sensing technology in hydrology underlining the inherent spatial component in hydrology. Satellite and remote sensing techniques would provide a large amount of data that pertains to the physical conditions on the ground. The processing speed of computers helps in computing differential equations faster. Todini foresaw that computers would be extensively used for hydrologic modeling at very low costs.

Hornberger and Boyer (1995) discuss the need to integrate spatial variability in hydrologic modeling processes. Most of the processes are grid-based systems creating finite element meshes to process hydrologic parameters. Farajalla and Vieux (2006) discuss a case study about identifying an appropriate resolution to capture the spatial variability for infiltration parameters on a watershed scale.

The flows modeled in hydrology are used as input to hydraulic models to delineate floodplains. Hydraulic models like FLOODSIM, HECRAS, MIKE11, MIKE21, WSPRO, FLO-2D and RMA-2 have been applied in channel routing and floodplain studies. The majority of these models were initially developed as standalone applications, usually without any user interface, requiring data to be in American Standard Code for Information Interchange (ASCII) format following certain input rules set up by the developer. Many models lacked a graphical user interface until their later versions.

Simulating flood inundation boundaries for river reaches involves dynamic flood modeling using St. Venant's Equations. A simpler method would be to intersect a water surface elevation plane with digital terrain data to identify areas which are above the natural terrain. The areas above the terrain are categorized as flooded. Many hydraulic models MIKE11, MIKE21, HEC-RAS, ISIS, RMA-2 etc use some form of St. Venant's equation to perform continuous dynamic modeling. The model complexity determines the amount of data that is required. Most of the models deal with channel and floodplain routing separately.

Storage cell models (Cunge et. al., 1976, Estrela and Quintas 1994) treat a floodplain as a series of cells which are hydraulically connected. FLOODSIM and LISFLOOD model floodplains as uniform flow patterns using Manning's equations. More complex models like MIKE11 and HECRAS use 1D equations while RMA-2, and MIKE21 solve for flood inundation boundaries using 2D St Venant equations. The governing equations in each type might be different or the same. The simplest representation would be to assume that the pressure terms are negligible resulting in a kinematic wave approximation. Such an assumption has been found to be sufficient to model flood inundation levels at a small scale (Haestad et al., 2003). Listed below are some of the numerical methods and programs that are available for hydraulic modeling to get floodplain inundation boundaries:

1. Gradually varied steady flow – HEC-2, HEC-RAS, WSP2, WSPRO
2. Gradually varied unsteady flow (1D) – HEC-RAS, FLDWAV, FEQ
3. Gradually varied unsteady flow (2D) – RMA-2, FESWMS-2DH
4. Gradually varied unsteady flow (3D) – RMA-10

Table 1.2 shows some of the models that are currently used in floodplain inundation modeling. The models use some kind of numerical methods like the Newton-Raphson or Range Kutta methods in the finite difference schemes. The finite

element methods also involve using unstructured mesh of usually triangular elements to solve flooding problems (Horritt and Bates 2002).

The RMA-2 (King and Norton 1978) model has been hugely popular in performing numerical finite element scheme solutions to shallow water equations (Gee et al., 1990) for estimating floodplain extents. The finite element mesh schemes were first used on small reaches and their research concluded that the mesh scheme can be scaled up without causing any instability in solving the numerical equations. Baird et al., (1992) discuss a hybrid scheme of using HYMO3 (on reaches with no inundation) and RMA-2 to model flow for reaches that get inundated. The RMA-2 model is structured to solve for the Navier-Stokes equation in a two-dimensional approach. Hardy et al., (1999) identify that the spatial mesh resolution used in hydraulic models affects the numerical simulation results. In addition to modeling and calculating floodplain extents, some hydraulic models such as WSPRO and HECRAS also have the capability to model floodways (Table 1.1).

In the past, floodplain extents have been modeled using flood frequency analysis (Bradley et al., 1996), remote sensing data (Bates et al. 1997, Wang et al. 2002), raster-based one dimensional methods using LISFLOOD-FP and digital elevation models (Bates and De Roo 2000) and two-dimensional finite element methods (Bates and Anderson 1993). The delineation process can be as simple as a planar intersection of water surface elevations with the terrain. On the other hand, 3D solutions of flow equations considering turbulence closures (Thomas and Williams 1995), meandering channels and out-of-bank flow processes (Knight and Shiono (1996) have also been performed. In summary, three different methods are available for tackling a floodplain hydraulics problem:

1. Engineering experience – relying extensively on engineering judgment for making hydraulic decisions due to lack of sufficient data to completely model a hydraulic problem.

2. Physical modeling – mostly started on a research scale in universities and laboratories trying to build a model based on existing ground conditions. These model parameters cannot be universally applied to all the river systems and are expensive to construct and operate.
3. Numerical Modeling – These are based on analytical methods developed using numerical and mathematical principles. Numerical modeling has distinct advantages over the other two types of models. It allows for checking the modeling parameters with sensitivity tests on model performance.

Table 1.2. Examples of floodplain inundation models

Name of the model	Channel Routing	Floodplain Routing	Modeling domain
FLOODSIM	1D model running between floodplain cells	Uniform flow formulae (weir-type equations)	TIN with channels placed on the cell faces.
LISFLOOD-FP	1D kinematic wave approximation solved by explicit finite difference procedure	Uniform flow Manning Equations	Raster-based discretization derived from a DEM
1D models like MIKE11, ISIS, HEC-RAS, ONDA etc	Full solution of 1D St. Venant equations	Full solution of 1D St. Venant equations	Treats domain as a series of cross-sections perpendicular to the flow direction.
2D models like MIKE21, TELEMAC 2D, RMA-2	Full solution of 2D St. Venant equations with turbulence closure	Full solution of 2D St. Venant equations with turbulence closure	Finite difference schemes and Finite element methods using various geometries, but, typically triangles or quadrilaterals.

Bates and de Roo (2000) indicate that a more complex model solving 2D and 3D equations does not guarantee better results than a 1D equation solution. In the United States, HECRAS has been used as a popular hydraulic model under the NFIP. HECRAS models a study reach by partitioning the reach into smaller segments, placing cross-sections at appropriate intervals. The placement of the cross-sections is dictated by the slope of the terrain and the flow along the reach. As mentioned earlier, HECRAS iteratively employs one dimensional gradually varied flow equations to solve for water surface elevations at each cross section (or river station) using the standard step method (Chow 1959, Haestad et al. 2003). It should be noted that there is a strong spatial component to the hydrology and hydraulics of water flow.

Many of the H&H models employ 1D or 2D flow equations with a numerical method scheme to estimate floodplain extents. The floodplain boundary is determined by the water surface elevation above the underlying terrain. The water surface elevations are computed by established hydraulic flow equations. In contrast to a floodplain, a floodway is a best-fit flow boundary that allows the base flood discharge in a constricted flow area. Hence, there is no single solution for a floodway boundary. The best-fit practice allows for automated routines to estimate a potential spatial extent for a floodway.

GIS are now commonly used for spatial and temporal data handling in floodplain analysis (Townsend and Walsh 1996, Dutta et al. 2000, Al-Sabhan et al. 2003). Maidment and Djokic (2000) have discussed specific interfaces and algorithms integrated in a GIS to account for the spatial influence in hydrologic and hydraulic modeling. GIS has successfully been used to develop high resolution terrain models for floodplain mapping (Tate et al. 2002). More recently, GIS data models have been developed to link H&H data with GIS (Whiteaker et al. 2006).

1.8.2 GIS coupling with H&H models

The availability of digital topographic data in raster grid format has aided in computations in hydrology using automated processes inside GIS. The ease of computations using raster-based GIS models is well documented (Maidment 1992, Johnson and Miller 1997, Jain et al., 2004). Hence, GIS, as a standalone application, has the capability to perform hydrologic functions. The automated processes for hydrologic modeling with GIS include the D8 method for flow direction (Fairfield and Laymarie 1991), drainage basin delineation (Marks et al., 1984) and identifying drainage networks and sub-catchments (Martz and Garbrecht 1992). All these concepts have found widespread application in many watershed and vector stream network delineation models.

GIS and H&H modeling have developed as parallel technologies since the 1960s. In the 1980s, researchers identified a need to utilize the spatial capabilities of GIS in H&H modeling. The data structures in GIS cannot handle complex H&H functions as a standalone application. Fotheringham and Rogersen (1994) and Goodchild et al (1992) have documented efforts in the late 1980s to couple GIS with hydrologic models with a focus on harnessing the analytical capabilities of GIS. Demand for higher resolution terrain models (Clark 1998, Singh and Fiorentino 1996) has influenced linking GIS with H&H models.

Interpreting H&H model results can be greatly improved by enabling visualization of model outputs. GIS provides a good visualization platform for model outputs. Most of the earlier efforts (DeVantier and Feldman 1993, Maidment 1993, McDonnell 1996) were focused on linking GIS and hydrologic modeling processes. GIS was extensively used for identifying topographic features in watershed hydrologic models (Garbrecht and Martz 1997, Moore et al. 1988) in a raster grid environment. Storck et al (1998) describe a study in which GIS serves as a pre and post processor in converting GIS data into ASCII format for input into a H&H model.

Interfacing GIS with hydrologic models have been accomplished by simple linking models like HEC-GeoHMS. More complex standalone packages like USEPA BASINS, PRMS and WMS contain a Graphical User Interface (GUI) that interacts between the GIS and the H&H models (Martin et al. 2005). Commercial GIS packages like Environmental Research Systems Institute's (ESRI) ArcGIS have analysis functions for estimating flows on a watershed scale.

There are abundant applications of GIS coupling with hydrologic models. However, the same cannot be said about coupling GIS with hydraulic models. Very few coupling models exist that take advantage of the combined capabilities of GIS and H&H models. One of the earliest linking of GIS with hydraulic modeling was the development of ARC/HEC2 (Beavers 1994). HEC developed ArcInfo Macro Language (AML) scripts in 1997 as a pre and postprocessor for HECRAS software. ESRI developed the AVRAS processor (Griva et al. 2003) which linked HECRAS with ArcView software. The Center for Research in Water Resources (CRWR) at Austin, TX developed the HECGeoRAS geodatabase model and the MapToMap application (Whiteaker et al. 2006) using the HECRAS modeling engine to generate floodplain extent output and export it into GIS-compatible formats.

There are different levels of integrating GIS with hydrologic and hydraulic models. The two fundamental principles of integrating GIS and H&H models are embedding and coupling (Sui and Maggio 1999). Embedding consists of using either the GIS or the H&H software as the host application, with the other software "embedded". The two options are:

1. H&H functionalities in a commercial GIS package – This approach takes advantage of all the spatial analysis capabilities of the GIS. However, the H&H modeling functionalities are limited and very simplistic as it becomes very difficult to bundle the complexity of a H&H system in a GIS.

2. GIS capabilities in a commercial H&H package – This approach results in limiting GIS strictly to act as mapping software. Visualization capabilities of GIS are not completely utilized. However, it provides ample scope for the model developers to produce a sophisticated H&H model and constantly update it without any interference from GIS data structures.

A coupling approach differs from an embedded approach, wherein the GIS and H&H components are kept as separate entities and are linked (or coupled) by input-output manipulation or a common GUI.

1. Loose coupling – Loose coupling is easy to achieve because the model and GIS are independent without a common interface (Figure 1.11). It involves converting model data into a GIS readable format and vice-versa (Karszenberg 2002). Loose coupling has an advantage that it minimizes programming but suffers from the cumbersome conversion process. It also requires extensive knowledge of both the hydrological and spatial models and their input-output formats.
2. Tight coupling – Such systems consist of a shared data model in which the hydrologic model output is stored in a common, shared database which the GIS accesses to perform spatial analysis (Figure 1.12). The GIS and H&H model are kept as separate entities.

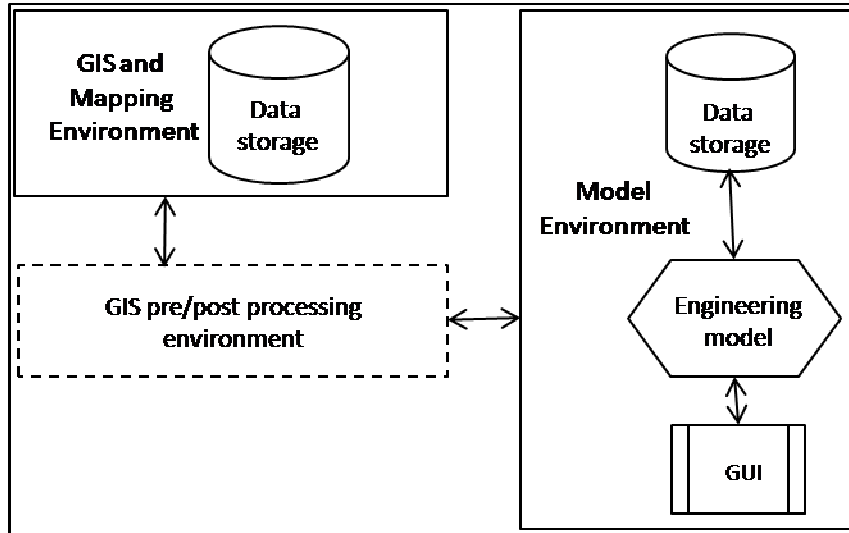


Figure 1.11. GIS pre and post processing modeling scenario schematic

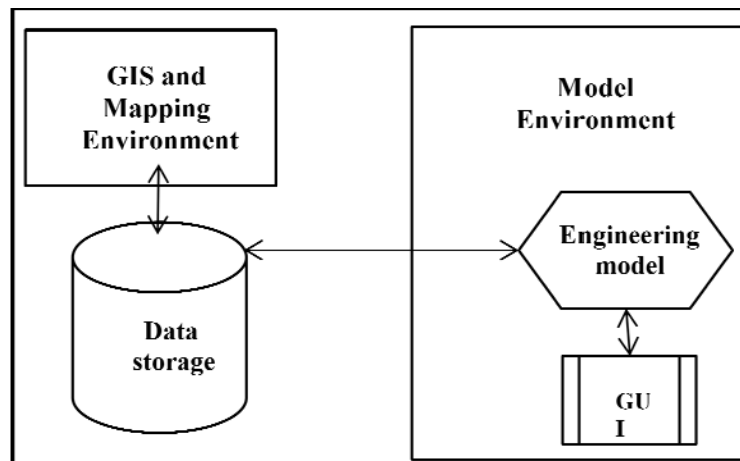


Figure 1.12. Tight coupling scenario schematic

Noman et al., (2001) details the H&H modeling and mapping policy of FEMA that allows automated H&H tools to be placed under one of the three categories listed below:

1. Category 1 tools are those that work with pre and post processor tools that build H&H input files. These tools are independent modules that can modify input files or display output data from H&H models.
2. Category 2 tools comprise models and tools that have modeling capabilities which emulate one or more models in FEMA's accepted model list. These tools are reviewed and approved by FEMA before they can be used for flood hazard modeling.
3. Category 3 tools are those that employ novel H&H methods for floodplain mapping. These methods can be locally-suited to a specific study area or can have a broader scope of application.

Category 2 and 3 tools are accepted if they satisfy the conditions stipulated in Paragraph 65.6 (a)(6) of the NFIP regulations. They are listed below:

1. *The model must be reviewed, tested, and accepted by a government agency responsible for the implementation of programs for flood control and/or regulation of floodplains.*
2. *The model must be well-documented, including source code and user's manuals.*
3. *The model must be available to the Federal Emergency Management Agency (FEMA) and all present and future parties impacted by flood insurance mapping that is developed or amended through the use of the model."*

An Interface Data Model (IDM) is also used for linking GIS with H&H models. An IDM serves the purpose of acting as a bridge between the spatial component and the H&H component (Figure 1.13). Such a data model provides a framework which allows for storing data to be accessed by both the spatial and modeling H&H component. The main difference between an interface data model and a GIS pre/post processor (Figure 1.11) is that the input-output variables of the H&H model are stored in a GIS format.

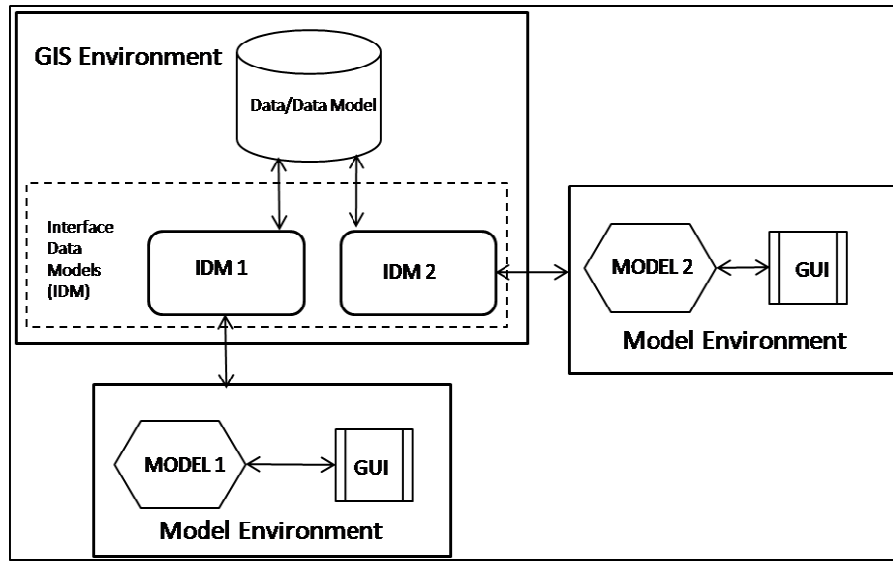


Figure 1.13. A schematic sketch of an interface data model

Interface Data Models facilitate smooth data access between the spatial and multiple modeling components. In other words, GIS-compatible storage of data can be used as inputs for other models also. For example, an interface data model storing time-series HMS data (in GIS format) can be used as an input in any other hydraulic model. There is a separate interface data model for each simulation model linked with GIS. Map-To-Map is a good example that integrates HEC-HMS and HECRAS in an interface data model (Robayo 2005).

The MapToMap application

The MapToMap application involves converting a NEXRAD rainfall map to a floodplain inundation map. The main data models used in the MapToMap are ArcHydro and HECRAS IDM. The HECRAS IDM schema is shown in Figure 1.14.

The process models include the H&H modeling component/programs which are linked with GIS to produce flood inundation output. In MapToMap, the NEXRAD rainfall data is imported into the ArcHydro data model and associated with the watersheds in the area of interest. The watershed-based time series data is modeled in HEC-HMS using HEC Data Storage System (DSS) file format input. HEC-HMS produces runoff hydrographs at stream confluences and watershed outlets. The hydrograph timeseries data are converted to geodatabase timeseries table. The timeseries data is then associated with cross-sections along the reach and a HEC-DSS file is written for HECRAS.

HECRAS is executed from within the GIS and the water surface profiles are written to the geodatabase. It involves converting the HECRAS output to a Spatial Data Format (SDF) and subsequently to XML format. It is important to note that the models (HMS and HECRAS) are executed without user intervention. The water surface elevations are then used to create a water surface elevation TIN which is intersected with the underlying topographic terrain to create the floodplain boundary.

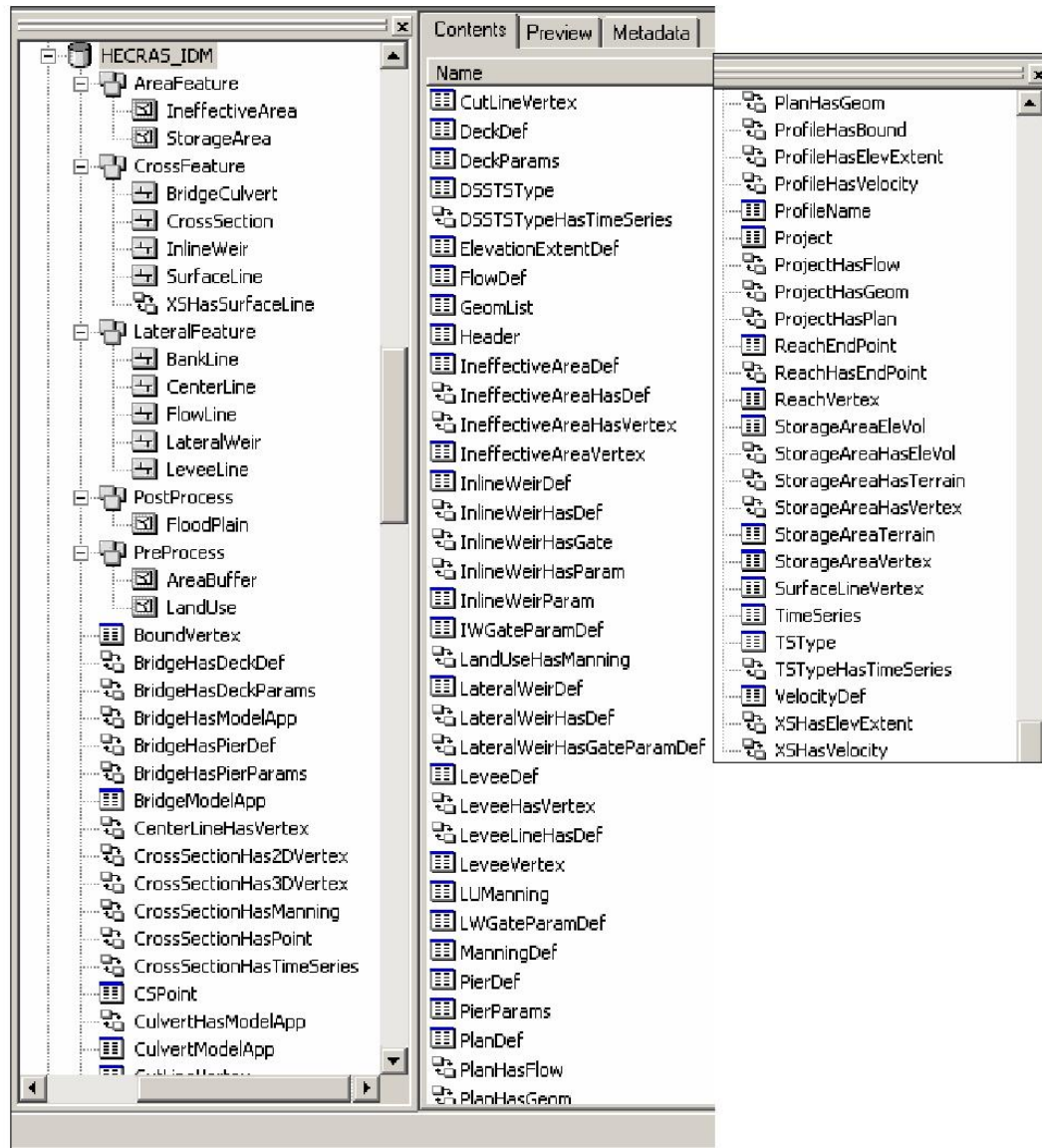


Figure 1.14. ArcCatalog view for HECRAS IDM

HECGeoRAS

HECGeoRAS (Figure 1.15) is another GIS tool suite that employs the HEC object library to execute HECRAS export and import data capabilities. The toolset creates

HECRAS layers and stores them in a geodatabase. This version is called as a pre-RAS database. Once the HECRAS layers are generated, they are imported into

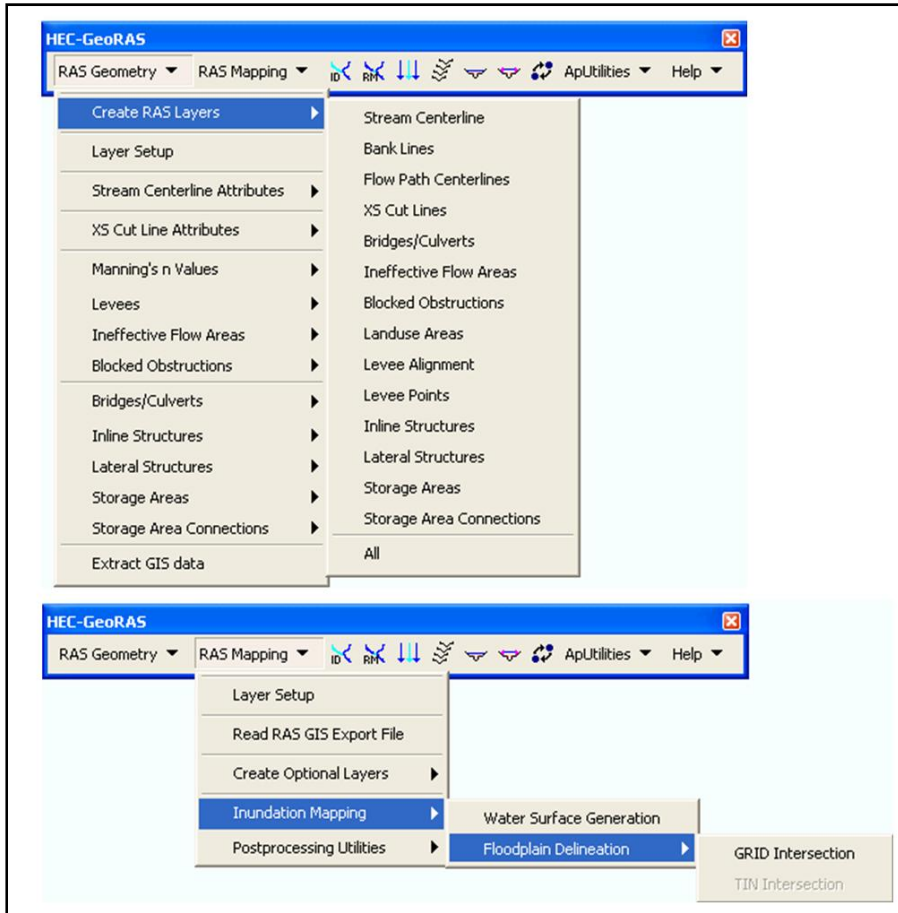


Figure 1.15. HECGeoRAS capabilities

HECRAS. The user executes the HECRAS model and the final water elevation information is stored in a Spatial Data Format (SDF) file. HECGeoRAS allows for HECRAS post-processing and the information is stored in another geodatabase in the working folder. This version is called as a post-RAS database. HECGeoRAS provides tools to read the water surface elevation data and create a surface (TIN) which is intersected with the cross-section TIN to produce the floodplain boundary.

All these data models and programs limit themselves to delineating floodplain boundaries as modeled by the governing equations in HECRAS. Floodway delineation is based on HECRAS encroachments analysis. There is no documentation in academia that automates floodway analysis. H&H modeling is followed by mapping the output on DFIRMs. HECGeoRAS maps the floodplain boundary and the output is stored in a geodatabase that can be added in ArcGIS for display and further editing.

1.8.3 Mapping issues

GIS stores and displays geographic data as discrete objects in digital format. However, in reality, geographic data are complex, continuous data. Hence, displaying spatial data requires generalization, abstraction and approximation (Goodchild et al., 1992). The rules by which the objects are defined and displayed are governed by a data model (Tsichritzis and Lochovsky 1977). Older automated techniques for floodplain mapping were based on DEM models, which are restricted by the raster cell size of the original elevation data. The interpolation methods used in digital terrain models fail to reproduce reality (Schut 1976).

Vector display of objects as points, lines and polygons are closer to retaining real shapes. The evolution of Triangulated Irregular Networks (TINs) and Terrain data models have improved floodplain delineation due to their better representation of the topography in vector format. They are not restricted by grid resolution issues as noticed in DEMs. The floodplain delineation methods using DEMs have since then been superseded by TINs and terrain datasets. A TIN represents topography as irregular triangles. The three vertices of a triangle are termed as the nodes while the line joining any two nodes is termed as an edge. TIN construction is based on the Delaunay Triangulation method (Lee and Schacter 1980, Watson and Philip 1985) which requires that a circle drawn using three nodes do not contain any other node.

ArcGIS software generates TIN data using the Delaunay triangulation method. Typically, correct triangulation satisfying Delaunay's criterion would produce near equiangular triangles (Lawson 1977). However, in floodplain mapping, thin angular triangles are formed when triangulation occurs connecting points that are far apart causing misrepresentation of flood depths (Noman et al., 2001). Hence, care should be taken that mapping is not adversely influenced by spurious triangulation patterns.

The HECRAS model provides data at each cross-section to map a floodplain or floodway boundary. However, the area between the two cross-sections needs to be mapped using smooth lines and interpolated elevations. GIS software creates surfaces from point elevation data. Such interpolation techniques generate smooth surfaces which have been well documented in literature (Franke 1982, Gold 1984, Gold 1988). Generating smooth boundaries also requires sufficient elevation points in order to prevent triangulation across a long distance.

FEMA requires that the floodway boundary match the encroachment stations at each cross-section and a smooth boundary approximately following the shape of the stream centerline between any two cross-sections. It is also recommended that a consistent floodway topwidth be maintained along the reach. ArcGIS provides smoothing and generalizing algorithms that can be employed to map the floodway boundary. ArcGIS also provides multiple spatial adjustment methods like affine transformation, projective transformation (Hartley 1999), similarity transformation, rubbersheeting (White and Griffin 1985) and edge matching that can be used to spatially adjust the floodway boundary to satisfy FEMA requirements.

1.9 Research significance

HECRAS is one of the FEMA approved H&H software to model a floodway under their National Flood Insurance Program. In HECRAS, a modeler has great control in modeling a floodway iteratively by editing encroachments at each cross-section along a

study reach till all the FEMA requirements are met. A modeler makes an editing decision based on the surcharge, floodway topwidth, and other hydraulic variables at a cross-section. Currently, no standard automated method exists to edit encroachments continually to fit a floodway for a reach. Hence, automated floodway modeling holds great promise by the amount of modeling time it can save. An automated floodway routine will provide a modeler with a good starting floodway which can be further fine-tuned to satisfy all stipulated requirements.

HECRAS floodway modeling methods enables a modeler to determine the floodway boundary at each cross-section in a study reach. However, there is a functionality gap in extending the model output to a continuous floodway boundary. The void in floodway mapping is due to the fact that HECRAS visualization and spatial analysis capabilities are very limited. Thus, there is a need to develop an improved and efficient mapping routine that can also perform spatial analysis. ArcGIS is equipped with robust spatial analysis routines to perform overlay and proximity analysis. Coupling ArcGIS with HECRAS enables a modeler to achieve floodway modeling and mapping in a single platform.

The final output of a floodway mapping procedure is a continuous spatial boundary. Currently, there are no automatic floodway mapping routines available in the public domain that translates HECRAS output to a continuous boundary to be printed on a map. This research addresses the void in floodway mapping to produce a smooth floodway boundary. The research significantly contributes to the floodway modeling step in the NFIP's floodplain mapping process.

2 An algorithmic approach to iterative floodway modeling using HECRAS and GIS

Abstract

Hydrologic Engineering Center's River Analysis System (HEC-RAS) software is commonly used to perform hydraulic analysis for floodplain delineation studies. In addition to floodplains, the hydraulic analysis also includes modeling a floodway. Floodway modeling is an iterative process in which the 1% annual chance flood discharge is restricted within a floodway without exceeding a 0.3m increase in water surface elevation. An algorithm has been developed to automate floodway modeling using HEC-RAS. The algorithm was tested on Plum Creek in Montgomery County, Virginia. The algorithm's runtime was 4.4 minutes and all but one of the cross-sections was found to have acceptable surcharges while maintaining sub-critical flow in the model. The floodway was mapped using GIS and HECGeoRAS tools. The algorithm was also tested on 5 other hydraulic study reaches. The algorithm achieved significant savings in modeling time providing a good initial floodway that would require minor fine-tuning before being finalized.

2.1 Introduction

Floodplain management is *“the operation of an overall program of corrective and preventive measures for reducing flood damage, including, but not limited to, emergency preparedness plans, flood control works and floodplain management regulations”* (CFR, Vol.1 Sec 59.1). Floodplain management studies typically involve hydrologic and hydraulic modeling of flooding streams to estimate the amount and extent of flooding that may occur in the event of a rainfall. Hydrologic models estimate the flows into a study reach from the contributing watershed which forms the input for hydraulic models to generate floodplain extents.

A floodplain is any area near the main channel which is susceptible to flooding due to excessive runoff. Floodplain extents are dependent on the terrain and the flows corresponding to the various recurrence intervals for floods. The 100 year and 500 year floods are significant events that are usually considered for modeling and planning purposes. In the past, researchers have mapped floodplains using flood frequency analysis (Bradley et al. 1996), remote sensing data (Bates et al. 1997, Wang et al. 2002), raster-based one dimensional modeling (Bates and De Roo 2000) and two-dimensional finite element modeling (Bates and Anderson 1993).

Floodplain delineations are carried out throughout the United States as part of the National Flood Insurance Program (NFIP) administered by the Federal Emergency Management Agency (FEMA). As early as 1950, a Water Resources Policy Commission identified floodplain zoning as an important part of flood management (L.R. Johnston Associates 1992) A Unified National Program for Managing Flood Losses was first submitted for review in Congress in 1966. The unified national program was followed by two key pieces of legislation, the National Flood Insurance Act (1968) and National Environmental Protection Act (1969), which propelled the scientific and environmental development in floodplain management.

The NFIP started in 1968 and has evolved into a collaborative effort by the federal, state and local governments along with the insurance companies to regulate flood insurance. The NFIP involves identifying special flood hazard areas and flood risk, mitigating and managing the flood risk, and spreading awareness about flood risk and mandating flood insurance policies (Burby 2001). In addition to floodplains, FEMA also mandates a floodway concept for flood insurance purposes.

A floodway consists of the main channel of flow and its adjoining areas that are maintained to allow base flood discharges without increasing the water surface elevation beyond a stipulated height. The base flood is the 100 year flood (1% annual chance flood) that has a one-percent probability of occurrence or exceedance in any given year. The “stipulated height” is termed as surcharge, which is the increase in the water surface elevation from the base flood elevation due to constricted flow through a floodway. The

process of delineating floodplains and floodways emphasizes the strong spatial component of the hydrology and hydraulics of water flow along a reach.

Geographical Information Systems (GIS) increasingly are being used for spatial and temporal data handling in flood analysis (Townsend and Walsh 1996, Dutta et al. 2000, Al-Sabhan et al. 2003). Maidment and Djokic (2000) have discussed specific interfaces and algorithms integrated in a GIS to account for the spatial influence in hydrologic and hydraulic modeling. Previous studies (Tate et al. 2002, Whiteaker et al. 2006) have also established the use of GIS for floodplain mapping.

Advancements in GIS data models to include hydrologic and hydraulic data for floodplain mapping (Whiteaker et al. 2006) has not been matched by floodway modeling efforts. Lack of data models for modeling floodways can be attributed to the iterative nature of a floodway modeling routine. Floodway modeling involves fitting an area around the main channel to carry a given volume of conveyance without exceeding a stipulated flood elevation. The best fit involves repeated modeling trials by a modeler to contain the base flood discharge.

This paper describes an attempt to link floodway modeling and GIS by developing an algorithm that automates floodway modeling. The algorithm aims at producing a floodway which would require some manual fine-tuning to be consistent with the development agenda of the local community. The results from the model would be coupled within a GIS environment. Sui and Maggio (1999) discuss various levels of coupling GIS with hydrologic models and the issues involved with them.

2.2 Modeling background

One of the primary goals of the NFIP is to identify flood hazard areas where special flood insurance policies apply. It involves hydrologic and hydraulic modeling in a watershed or along a stream reach. Some examples of hydrologic principles that are used for estimating flows include the Natural Resources Conservation Service's (NRCS) curve number method, Muskingum flow routing, and the United States Geological Survey

(USGS) regression equations. Singh and Woolhiser (2002) provide a more comprehensive list of the various hydrologic principles and methods that are used by water resources engineers.

FEMA has established a list of numerical hydrologic and hydraulic models that can be used for NFIP studies. Some of the major hydraulic modeling software packages and their capabilities are listed in Table 2.1.

Hydrologic Engineering Center’s River Analysis System (HEC-RAS) software was selected for this research based on the following criteria:

1. HEC-RAS provides five stable steady state methods to model a floodway.
2. It is capable of exporting model output into GIS for further spatial analysis.
3. HEC-RAS is available for free on public domain and has been widely used in hydraulic studies for many years.
4. It provides a user friendly graphics user interface for modelers.

Table 2.1. FEMA approved list of numerical hydraulic modeling software

Hydraulic Model	Floodway Option	GIS Export	Public Domain
HEC-RAS	Yes	Yes	Yes
HEC-2	Yes	No	Yes
Water Surface PROfiles (WSPRO)	Yes	No	Yes
Water Surface Pressure Gradient (WSPG)	No	No	No
StormCAD, Pond Pack	No	No	No
XP-SWMM	Yes	Yes	No
Full Equation (FEQ), Full Equation Utilities (FEQUTL)	No	No	Yes
FLDWAV	No	No	Yes
FLO-2D	Under review		No
MIKE FLOOD	No	No	No

The United States Army Corps of Engineers (USACE) pioneered the development of hydraulic modeling programs with their HEC suite of tools. USACE developed and

released HEC2 in 1968 which served as the most widely used hydraulic program. Deficiencies in the HEC2 program like the outdated bridge and culvert computation routines and fixed format input and output led to the development of HEC-RAS in 1995. Since then, it has served as a comprehensive hydraulic model in the United States.

HEC-RAS uses one dimensional gradually varied flow equations to solve for water surface elevations at each river station along a reach. The program uses the standard step method (Chow 1959, Haestad et al. 2003) in an iterative fashion to compute the water surface elevation. Figure 2.1 shows a typical profile across two cross-sections and the hydraulic variables used for estimating water surface elevations. The water surface elevation computations are used to identify the floodplain boundary limits.

The equation that is used in the standard step method is:

$$WSEL_2 = WSEL_1 + \frac{\alpha_1 V_1^2}{2g} - \frac{\alpha_2 V_2^2}{2g} + LS_f + C_{c,e} \left(\left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \right) \quad (1)$$

Where,

$WSEL_{1,2}$ = water surface elevation above datum in the channel at the cross-sections (m)

α_1, α_2 = velocity weighting coefficients

V_1, V_2 = velocities at the cross-sections (m/s)

g = acceleration due to gravity (m/s^2)

L = length of flow path between the cross-sections (m)

S_f = average energy slope between the cross-sections (m/m)

C_e = Coefficient of expansion

C_c = Coefficient of contraction

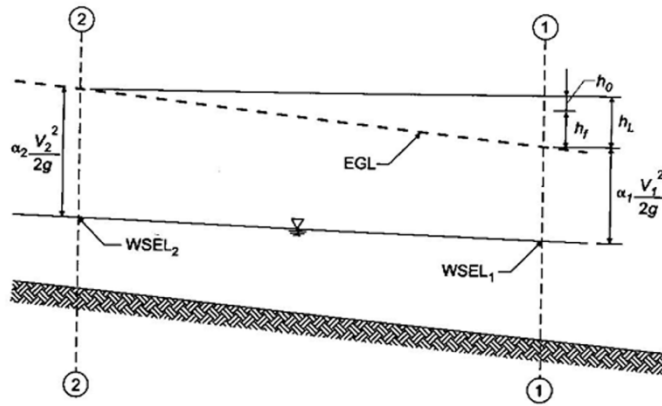


Figure 2.1. Computation variables for HEC-RAS standard step method (used with permission of Bentley Institute Press and Haestad Press)

The software assumes a water surface elevation and computes the velocity head and conveyance based on energy and Manning's equations. Based on these values, the water surface elevation is computed using equation 1. If the assumed estimate is close to the computed value, the software moves to the next cross-section.

For flood insurance purposes, a floodway model in HEC-RAS requires a minimum of two water surface profiles - the base profile and the floodway profile. The base profile contains water surface elevations for the base flood event (1% annual chance flood) and the floodway profile contains water surface elevations for the floodway.

When modeling a floodway, HEC-RAS follows an encroachment methods analysis (Haestad et al. 2003). The software constricts the flow between two encroachments, one on each side of the main channel. The encroachments are placed in such a way that the conveyance is contained within the two encroachments without exceeding the surcharge. In other words, the goal is to keep the encroached (floodway) profile water surface elevations within a pre-determined surcharge value, usually 0.3m. Conveyance is computed using the Manning's equation as

$$K = \frac{1}{n} AR^{2/3} \quad (2)$$

where K denotes the conveyance in m^3/s , n denotes the Manning's roughness, A denotes the cross-sectional area in m^2 and R represents the hydraulic radius of the cross-section in m.

There are five different methods to perform steady-state floodway modeling in HEC-RAS (USACE 2002). They are:

- Method 1: Specify left and right encroachment stations
- Method 2: Specify fixed floodway top width
- Method 3: Specify percent conveyance reduction
- Method 4: Specify target surcharge with equal conveyance reduction
- Method 5: Specify target surcharge and maximum energy increase

The common modeling approach is to perform a Method 4 floodway analysis and then finalize the floodway using a Method 1 analysis.

In Method 4, the modeler specifies a target surcharge value for the encroached profile. HEC-RAS calculates the conveyance difference between the encroached and base flood elevations and an equal conveyance reduction is performed. The program positions the encroachment stations based on the surcharge value and the equal conveyance reduction. Ideally, the resultant increase in water surface elevation should be less than the specified target surcharge at each cross-section. However, it is common to have excessive surcharges or negative surcharges at few cross-sections (especially near the structures). Figure 2.2 (a) depicts the concept behind Method 4. The modeler repeats the process by changing the target surcharge elevation until most of the cross-sections are within the allowable surcharge limit. Another approach is to create multiple floodway profiles and model each profile with different target surcharges.

Method 1 involves specifying the left and right encroachment stations as shown in Figure 2.2 (b). The modeler specifies the stationing along the cross-section of interest. Since Method 1 involves manual positioning of the encroachments on either side of the main channel, an equal conveyance condition does not exist. During the floodway finalization process, there might be a need to further adjust the floodway for hydraulic consistency. A hydraulically consistent floodway may be one where there are no

abnormal jumps in the velocity from one cross-section to another and the top widths are relatively uniform.

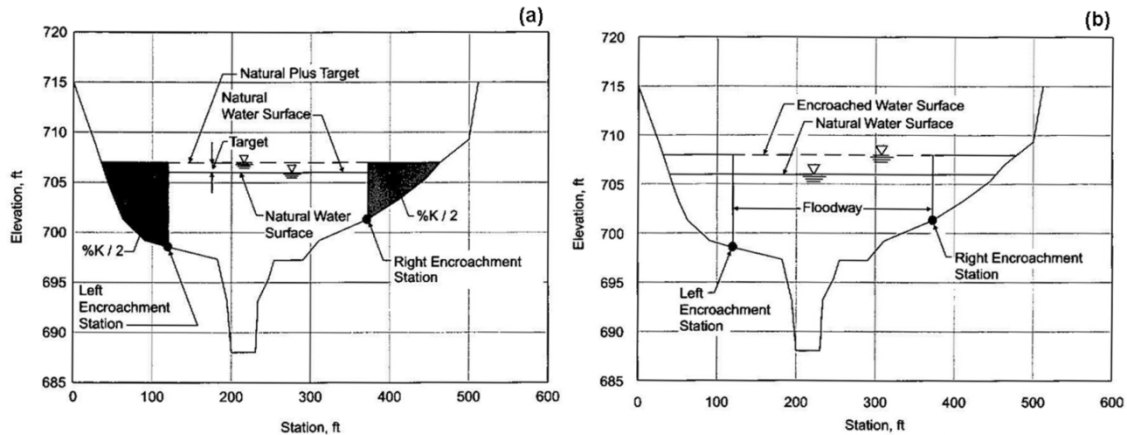


Figure 2.2. Common floodway modeling approach in HEC-RAS: (a) Method 4 cross-section sketch, (b) Method 1 cross-section sketch (used with permission of Bentley Institute Press and Haestad Press)

A typical floodway modeling analysis in HEC-RAS is an iterative process consisting of multiple runs of Method 4 and Method 1 until all the cross-sections along the study reach have an elevation increase less than the allowable surcharge. Thus, there is a need to have an automated procedure in place to perform floodway modeling in HEC-RAS. The automated algorithm described below initiates multiple floodway runs in HEC-RAS without any intervention from the modeler and produces a floodway where most of the cross-sections would satisfy the allowable surcharge requirement. Currently, the algorithm is bundled as a standalone executable file with a user interface, but work is continuing to integrate the software into the ESRI ArcGIS environment.

2.3 Description of the algorithm

The main goal of the algorithm is to provide the modeler with a good floodway model that can be fine-tuned with minimal modeling effort. The algorithm employs the

HEC-RAS modeling engine from within a Visual Basic environment to perform the floodway analysis runs. The algorithm is developed following the common modeling approach outlined previously. The algorithm workflow schematic is shown in Figure 2.3. The algorithm starts with a Method 4 run with an initial target surcharge of 0.15 m (0.5 ft). The user has an option to change the initial surcharge. The floodway at cross-sections with negative surcharges is narrowed by increasing the target surcharge to 0.3 m (1.0 ft) and Method 4 is re-run. The output surcharge information is then imported into a Method 1 input file. In Method 1, the algorithm starts at the most downstream cross-section and moves upstream solving the surcharge to be between -0.003 m and 0.3 m (-0.01 ft and 1.0 ft) at each cross-section. Adjusting encroachment stations at each cross-section is limited by a fixed number of iterations.

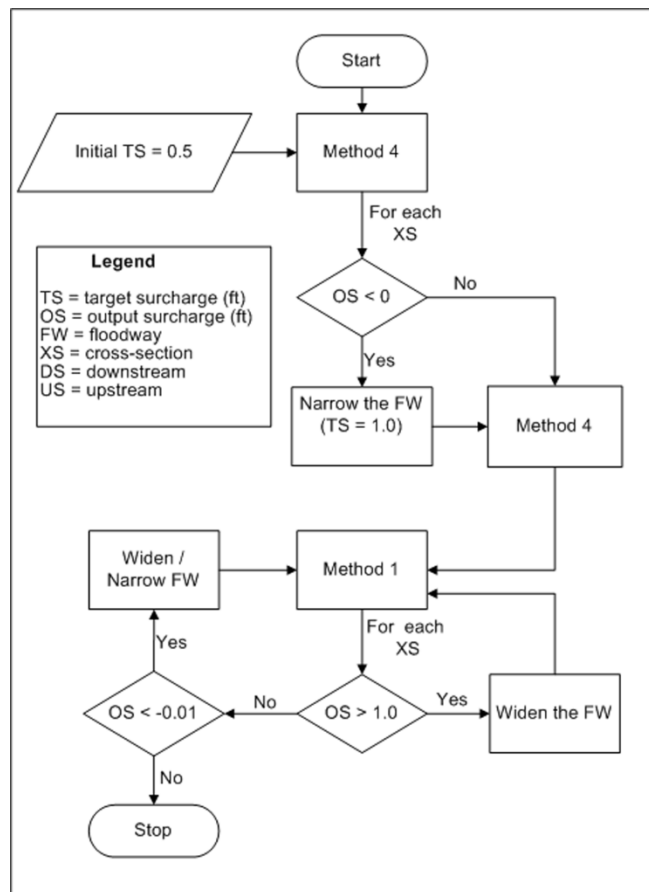


Figure 2.3. Algorithm flowchart schematic

The algorithm takes into consideration various engineering parameters while deciding to narrow or widen the floodway at each cross-section. For example, conveyance of encroached profile may be less than that of the base profile. The algorithm attempts to widen the floodway at that cross-section to allow more conveyance and thereby reducing the surcharge below the acceptable limit. Sometimes, a narrow floodway results in a high velocity head causing negative surcharges. The algorithm widens the floodway at that current cross-section. Thus, the algorithm has been developed to be more intelligent than simply positioning encroachments along a cross-section to model the floodway. It is common modeling practice to adjust encroachments downstream in order to reduce the surcharge upstream. This algorithm is capable of adjusting encroachments at as many cross-sections downstream as necessary to solve for a cross-section. If a cross-section cannot be solved after traversing to the most downstream cross-section, the algorithm moves to the next cross-section upstream of the defaulting cross-section.

2.4 User interface options

The algorithm is supported by an interface which allows the user to set some modeling and computational criteria. The sole input to the program is a HEC-RAS floodway project. The HEC-RAS project should contain exactly two profiles – the first profile is the 100 year flood profile and the second profile is the floodway profile. The HEC-RAS project should also contain the flow data for both the profiles. The program reads the HEC-RAS project and identifies the various river and reach information in the project. The user can identify cross-sections at which the floodway would match the floodplain boundary or the channel boundary.

Some of the key operating parameters that govern the functioning of the algorithm are:

1. Initial target surcharge for the Method 4 run.

2. The maximum number of trials to be performed at each cross-section.
3. Number of cross-sections to traverse downstream for solving a cross-section upstream.
4. Snapping tolerance for encroachments to the floodplain or ineffective area limits

The algorithm was tested on a study creek where hydrologic analysis had previously been completed.

2.5 Study area description and model setup

Plum Creek is a 6.6 km long creek located partially in Montgomery County and partially in Radford City, Virginia. It drains into the New River (Figure 2.4). The land cover in the surrounding areas of Plum Creek is comprised of densely forested trees (28%), thick brush (24%), open field/pasture (18%), medium shrub (7%) and a few paved roads. Thus, the area is primarily rural and the creek is characterized by narrow channels widening out further downstream.

The contributing watershed from Plum Creek and its main tributaries encompass 18.6 square km. Since Plum Creek is not gaged, the hydrologic estimations were based on USGS regression analysis (Bisesse 1995; Mason Jr and Fuste 2001). The terrain model used for this study was developed from LiDAR data for Montgomery County and Radford City. The hydrologic analysis was performed using Watershed Information System (WISE) software developed by Watershed Concepts.

Hydraulic model setup requires information on the structures along the creek. The structure elevations were surveyed and the hydraulic model was developed in HEC-RAS. The flow information was obtained from the hydrologic analysis. In addition to placing cross-sections upstream and downstream of structures, additional cross-sections were placed based on changes in slopes and flow area. Once the HEC-RAS model was set up completely, the algorithm was used to perform floodway modeling.

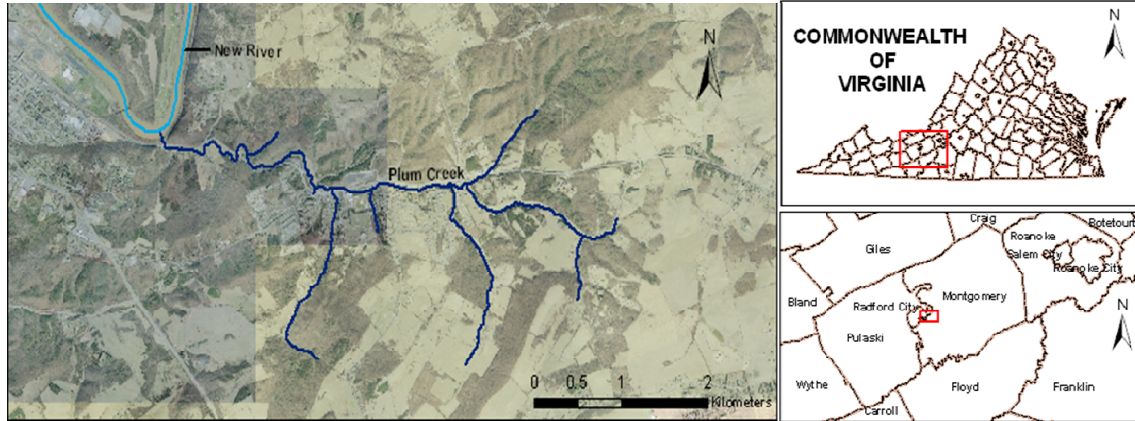


Figure 2.4. Location map for Plum Creek

2.6 Results and Discussions

The primary objective in floodway modeling is to maintain the surcharge below 0.3 m at all cross-sections. The Plum Creek hydraulic model had 114 cross-sections. The algorithm runtime was 4.4 minutes. It performed 22 iterations to solve for all the cross-sections from downstream to upstream. Figure 2.5 shows the surcharges obtained at each cross-section for the entire reach. Each bar represents the magnitude of surcharges obtained at a cross-section. The surcharges at all but one of the cross-section stations are below 0.3 m. The single cross-section that exceeded the 0.3 m surcharge is at a bridge structure. The class library that HEC-RAS provides does not allow access to surcharge information at the structures. So, the algorithm is unable to check for surcharges at the structures. There were three cross-sections with surcharges less than zero. However, the magnitude of surcharges was greater than -0.003 m (-0.01 ft) for those three cross-sections. Thus the surcharge elevation target of 0.3m has been successfully met at more than 95% of the cross-sections for Plum Creek.

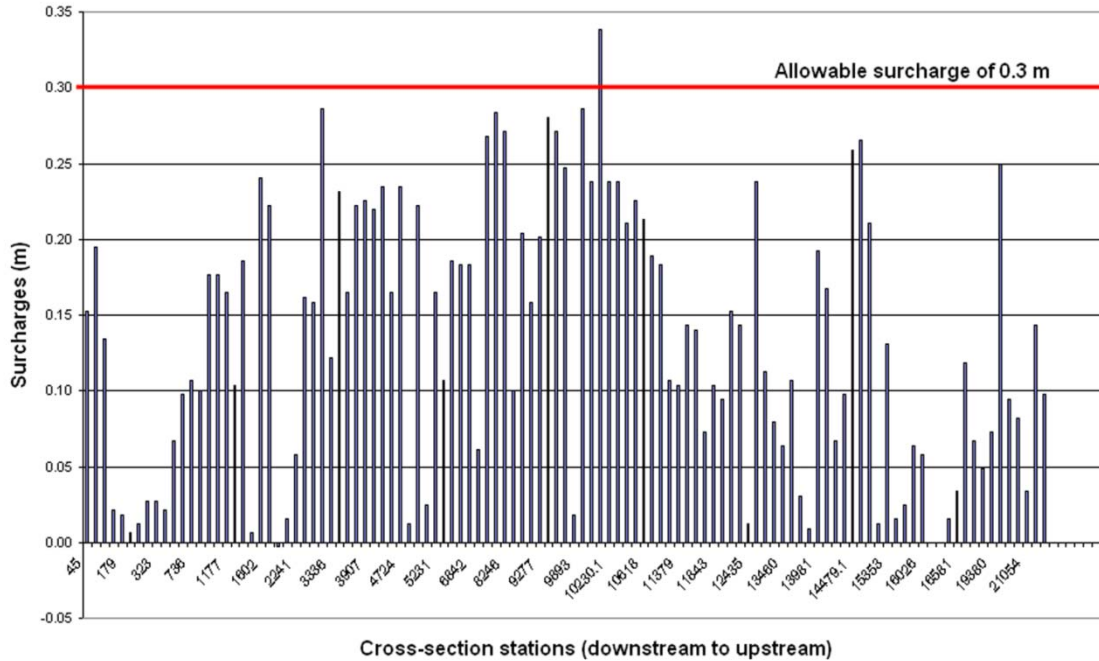


Figure 2.5. Estimated surcharges along Plum Creek

Out of 114 cross-sections, 20 cross-sections were found to be at or close to critical depth. It is critically important to keep the water surface elevations above critical depth in order to prevent supercritical flow conditions. The Froude number was less than or equal to one for all the cross-sections (96% cross-sections had Froude number less than one and 4% were equal to one). Thus, this algorithm is highly successful in maintaining sub-critical flow in the model.

HEC-RAS output can be exported as GIS format and mapped in a GIS environment (Figure 2.6) using HEC-GeoRAS tools. HEC-RAS maps the floodway by joining encroachments along each cross-section by linear line segments. Such a mapping procedure does not consider the sinuosity of the stream centerline. Hence, in order to produce the final floodway polygon, further smoothing is necessary. Another important factor in floodway modeling is the active top width of the floodway. The active top width should be fairly constant or gradually changing along the reach. This algorithm, in its current form, does not check for top width criterion. It will be considered in continuing research to map the floodway within ArcGIS.

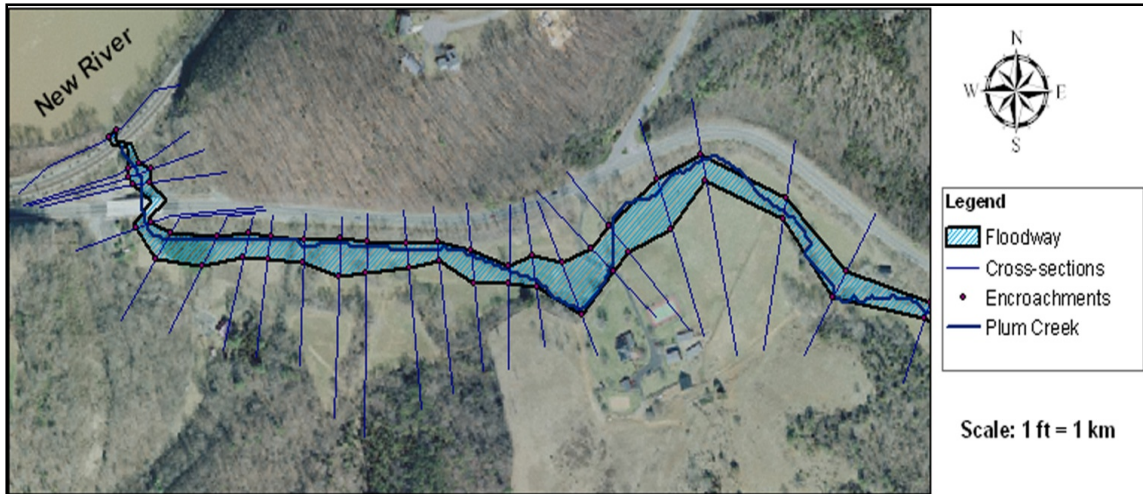


Figure 2.6. Floodway mapping as modeled by HEC-RAS

The algorithm was also tested on five other HEC-RAS floodway models. The efficiency of the algorithm is measured in terms of the number of cross-sections having positive surcharges less than 0.3m. From Table 2.2, it can be observed that the algorithm is efficient in modeling a majority of cross-sections within the stipulated 0.3m surcharge. The algorithm solved at least 96% of the cross-sections in the models used for testing.

Table 2.2. Salient statistics of algorithm runs on various study streams

Model	Length (km)	Manual modeling time (mins)	Algorithm runtime (mins)	Percent time savings (mins)	Number of iterations	Number of cross sections	Percent solved cross sections
Plum Creek	6.6	180	4.4	97.5	22	114	97.4
Pitner Creek	3.67	30	1.8	94	8	51	96
Noonday Creek	17.82	90	8.4	90.6	38	152	96.7
Yellow River	28.94	110	23.2	78.9	41	190	97.4
Waikapu	8.87	75	3.6	95.2	18	84	97.6
Upper Susquehanna	114.26	300	36.5	87.8	63	307	98

The algorithm runtimes indicate greater time efficiency when compared to the time it takes for manual floodway modeling. On average, the algorithm saved about 90% over

manual modeling with HEC-RAS, a significant savings. The longest study reach tested (Upper Susquehanna) reduced modeling time by 88%. However, the length of the reach is not directly correlated to the time savings as the time taken to model a floodway to meet the surcharge requirement depends on the complexity of the hydraulic model, including the structures and the slope of the terrain. The automation of floodway modeling enables modelers to invest time in other areas of building the hydraulic model.

2.7 Limitations of the algorithm

1. The program cannot automatically create new floodway profiles and import boundary conditions in HEC-RAS. So, it is the modeler's responsibility to provide a HEC-RAS project with a base flood profile and a floodway profile.
2. The program cannot rectify structure modeling issues without user involvement. It is also difficult to access surcharge information for the structures.
3. The program does not attempt to adjust the floodway for a consistent topwidth.

2.8 Summary and conclusions

The algorithm is a very good utility tool for automating floodway modeling for floodplain mapping studies. The algorithm provides a good starting floodway which can be fine-tuned with much lesser efforts from the modeler to produce the final floodway. The algorithm also uses key hydraulic engineering parameters in the modeling process, thus making the tool hydraulically reliable. The algorithm saves a lot of modeling time for a modeler performing floodway analysis. Since the algorithm uses HEC-RAS software engine for the hydraulics, it also facilitates easy transfer of output into existing GIS data models like HECGeoRAS.

2.9 Future work

Future work would involve creating an interactive component for visualizing and modifying the floodway within the ArcGIS environment. The interactive model is expected to allow the modeler to adjust encroachments on a map and also perform spatial analysis. A floodway topwidth smoothing routine would also be developed.

2.10 Acknowledgments

The authors would like to thank Mr. Kendrick Logsdon Jr. of Dewberry, LLC for his invaluable technical and design inputs during algorithm development. The authors would like to acknowledge some of the engineers at Dewberry, LLC - Mr. Dinakar Nimmala, Mr. Sam Crampton, Mr. Vikram Shrivastava and Mr. Amit Sachan – for providing us their inputs and also for their hydraulic models that were tested using the algorithm. The authors would also like to acknowledge Mr. Thomas Dickerson, Research Associate, Center for Geospatial Information Technology at Virginia Tech for his hydrologic analysis and hydraulic model set up for Plum Creek.

2.11 Paper references

Al-Sabhan W., Mulligan M., and Blackburn G.A. (2003). “A real-time hydrological model for flood prediction using GIS and the WWW”. *Computers, Environment and Urban Systems*, 27(1), 9-32.

Bates P.D., and Anderson M.G. (1993). “A two-dimensional finite element model for river flow inundation”. *Proceedings: Mathematical and Physical Sciences of the Royal Society of London*, 440 (1909), 481-491.

Bates P.D., and De Roo A.P.J. (2000) “A simple raster-based model for flood inundation simulation”. *Journal of Hydrology*, 236, 54-77

- Bates P.D., Horritt M.S., Smith C.N., and Mason D.C. (1997) "Integrating remote sensing observations of flood hydrology and hydraulic modeling". *Hydrological Processes*, 11, 1777-1795.
- Bisese J.A. (1995). "Methods for estimating the magnitude and frequency of peak discharges of rural, unregulated streams in Virginia". US Department of Interior, Geological Survey, Richmond, VA. Water Investigations Report 94-4148.
- Bradley A.A., Cooper P.J., Potter K.W., and Price T. (1996). "Floodplain mapping using continuous hydrologic and hydraulic simulation models". *Journal of Hydrologic Engineering*, 1(2), 63-68.
- Burby R.J. (2001). "Flood insurance and floodplain management: the US experience". *Environmental Hazards*, 3, 111-122.
- Chow V.T., (1959). "Open Channel Hydraulics". McGraw Hill, New York, New York, USA.
- Code of Federal Regulations (CFR) , Title 44, Volume 1, Part 59, Sec 59.1
- Dutta D., Herath S., and Musiak K. (2000). "Flood inundation simulation in a river basin using a physically based distributed hydrologic model". *Hydrological Processes*, 14, 497-519.
- Haestad Methods, Dyhouse G., Hatchett J., Benn J. (2003). "Floodplain Modeling using HEC-RAS". Haestad Press, First Edition, Waterbury, Connecticut, USA.
- L.R.Johnston Associates, (1992). "Floodplain Management in the United States: An Assessment Report". Vol.2
- Maidment D.R., and Djokic D. (2000). "Hydrologic and Hydraulic Modeling Support with Geographical Information Systems". ESRI Press, California, USA.
- Mason Jr. R.R. and Fuste L.A. (2001). "The National Flood Frequency Program – Methods for estimating flood magnitude and frequency in rural areas of Virginia". US Department of Interior, Geological Survey, Reston, VA. Fact Sheet 023-01.
- Singh V.P., and Woolhiser D.A. (2002). "Mathematical Modeling of Watershed Hydrology". *Journal of Hydrologic Engineering*, 7(4), 270-292.
- Sui D.Z., and Maggio R.C. (1999). "Integrating GIS with Hydrologic Modeling: Practices, Problems and Prospects". *Computers, Environment and Urban Systems*, 23, 33-51.
- Tate E.C., Maidment D.R., Olivera F., and Anderson D.J. (2002). "Creating a terrain model for floodplain mapping". *Journal of Hydrologic Engineering*, 7(2), 100-108.
- Townsend P.A., and Walsh S.J. (1996). "Modeling floodplain inundation using an integrated GIS with radar and optical remote sensing". *Geomorphology*, 21(3-4), 295-312.
- USACE (2002). HEC-RAS User's Manual Ver. 3.1.
- Wang Y., Colby J.D., and Mulcahy K.A. (2002). "An efficient method for mapping flood extent in a coastal floodplain using Landsat TM and DEM data". *International Journal of Remote Sensing*, 23(18), 3681-3696.
- Whiteaker T.L., Robayo O., Maidment D.R., and Obenour D. (2006). "From a NEXRAD Rainfall map to a floodplain map". *Journal of Hydrologic Engineering*, 11(1), 37-45.

3 FloodwayGIS - An ArcGIS visualization environment to remodel a floodway

Abstract

Floodway modeling has been performed extensively using HECRAS in floodplain studies. The model output is typically exported in GIS format and the floodway boundaries are overlaid on other spatial data to further edit or remodel the floodway to meet FEMA and local development requirements. In this paper, a tightly coupled system comprised of a commercial GIS (ArcGIS) and HECRAS is presented. FloodwayGIS provides a comprehensive visual environment to edit, remodel, spatially analyze, and map floodway boundaries. The environment uses the HECRAS executable engine for every remodeling iteration. Four different encroachment editing options are provided within FloodwayGIS, which eliminates the need for a modeler to switch between HECRAS and GIS in the floodway modeling process, and results in savings of modeling time. FloodwayGIS also provides a mapping algorithm based on TIN intersection to produce smooth floodway boundaries that can be mapped in Digital Flood Insurance Rate Maps (DFIRMs) with minor editing.

3.1 Introduction

Floodway modeling involves an iterative process of delineating an area of a stream channel to convey a given volume of water without exceeding a stipulated increase in water surface elevations. The Federal Emergency Management Agency (FEMA) regulates floodway modeling and development by quantifying the allowable increase in the water surface elevations. Floodways are modeled using a hydraulic model that identifies floodway boundaries satisfying FEMA requirements for a floodway.

Floodway modeling using a hydraulic model is preceded by hydrologic modeling that estimates the discharge into a stream. The estimated flow is input into a hydraulic

model to determine the extent of flooding along the stream. The modelers estimate the floodway limits by repeated model runs until all FEMA floodway requirements are met. Selvanathan and Dymond (2009) have documented a method to automate such an iterative process to produce an initial floodway which can be fine-tuned to produce the final floodway for a stream.

Modelers typically use a hydraulic modeling environment to determine floodway limits. There is a constant need to empower hydraulics with spatial analysis capabilities in order to adjust and remodel floodways based on actual field conditions. Hence, many hydraulic models have a simple visual interface that displays a map of the study stream. However, the spatial analysis capabilities are very limited when compared to a commercial Geographical Information System (GIS). A good GIS is important because FEMA does not allow any form of land development inside a floodway and a hydraulic modeling environment does not have the capability to perform overlay functions to identify buildings in a floodway. A better spatial modeling environment would provide more useful information for a modeler to estimate floodway extents.

This paper deals with linking a commercial GIS package with a hydraulic model. It enables the modeler to perform extensive spatial analysis before finalizing a floodway. A visual interface with interactive tools has been developed to help the modeler perform floodway adjustments from within the GIS. While the modeler interacts with the GIS, the floodway extents are modeled by a hydraulic model on the back end. Thus, this interface acts as a bridge for constant communication between the GIS and the hydraulic model in modeling the floodway.

3.2 Background

Hydrologic and hydraulic (H&H) modeling of flooding streams is an integral part of detailed floodplain management studies. H&H modeling estimates the amount and extent of flooding that may occur in the event of a rainfall. Singh and Woolhiser (2002) list and describe the various hydrologic principles and methods that are used by water

resources engineers. These methods include, but are not limited to, Mulvaney's rational method, Green and Ampt's infiltration method, Muskingum flow routing, Modified Puls method for flow routing, United States Geological Survey (USGS) regression equations and the Natural Resources Conservation Service's (NRCS) curve number method. Hydrologic models estimate the flows into a study reach from the contributing watershed, which forms the input for hydraulic models to generate floodplain extents.

Hydraulic models like FLOODSIM, HECRAS, MIKE11, MIKE21, WSPRO, FLO-2D and RMA-2 have been applied in channel routing and floodplain studies. The majority of these models were initially developed as standalone applications, usually without any user interface, requiring data to be in American Standard Code for Information Interchange (ASCII) format following certain input rules set up by the developer. In addition to modeling and calculating floodplain extents, some hydraulic models such as WSPRO and HECRAS also have the capability to model floodways.

Floodplain delineation studies in the United States are managed by the FEMA's National Flood Insurance Program (NFIP). The NFIP, started in 1968, involves identifying special flood hazard areas and flood risk, mitigating and managing the flood risk, spreading awareness about flood risk, and mandating flood insurance policies (Burby 2001). FEMA also mandates a floodway model in certain special flood hazard areas for flood insurance purposes. A floodway consists of the main channel of flow and its adjoining areas that are maintained to allow base flood discharges without increasing the water surface elevation beyond a designated height. For flood insurance studies, the base flood is the 100 year flood that has a one-percent probability of occurrence or exceedance in any given year. The stipulated height is termed as surcharge, which is the increase in the water surface elevation from the base profile due to constricted flow through a floodway. Figure 3.1 shows a simplified schematic of the floodway concept in which the floodway is shown as a constricted flow area within the floodplain. In addition to using qualified hydraulic models, floodway modeling is also subjective to the interpretation of the modeler.

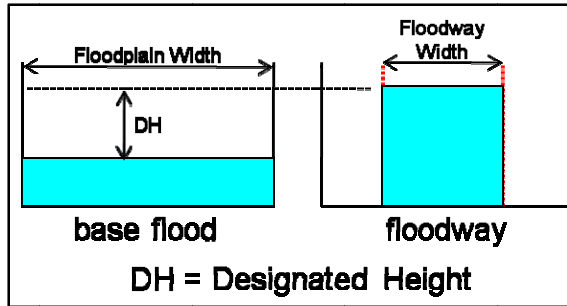


Figure 3.1. A simplified schematic of a floodway

The Hydrologic Engineering Center’s River Analysis System (HECRAS) is one of the FEMA-approved software models under the NFIP. Hence, it has been extensively used for estimating floodplain and floodway extents. HECRAS has served as a comprehensive hydraulic model for floodplain studies in the United States since 1995. HECRAS models a study reach by partitioning the reach into smaller segments, placing cross-sections at appropriate intervals. The placement of the cross-sections is dictated by the slope of the terrain and the flow along the reach. HECRAS iteratively employs one dimensional gradually varied flow equations to solve for water surface elevations at each cross section (or river station) using the standard step method (Chow 1959, Haestad et al. 2003). It should be noted that there is a strong spatial component to the hydrology and hydraulics of water flow.

GIS are increasingly being used to handle spatial data in flood related studies (Townsend and Walsh 1996, Dutta et al. 2000, Al-Sabhan et al. 2003, Maidment and Djokic 2000). In the past, floodplain mapping has been modeled using remote sensing data (Bates et al. 1997, Wang et al. 2002), a raster-based one dimensional method (Bates and De Roo 2000) and a two-dimensional finite element method (Bates and Anderson 1993). GIS has successfully been used to develop high resolution terrain models for floodplain mapping (Tate et al. 2002). More recently, GIS data models have been developed to link H&H data with GIS (Whiteaker et al. 2006).

3.3 Coupling GIS with H&H models

GIS and H&H modeling have developed as parallel technologies since the 1960s. In the 1980s, researchers identified a need to utilize the spatial capabilities of GIS in H&H modeling. Fotheringham and Rogersen (1994) and Goodchild et al (1992) have documented efforts in the late 1980s to integrate GIS with hydrologic models with a focus on improving the analytical capabilities. Demand for higher resolution terrain models (Clark 1998, Singh and Fiorentino 1996, Tate et al. 2002) has influenced linking GIS with H&H models.

Interpreting H&H model results can be greatly improved by enabling visualization of model outputs. GIS provides a good visualization platform for model outputs. Most of the earlier efforts (DeVantier and Feldman 1993, Maidment 1993, McDonnell 1996) were focused on linking GIS and hydrologic modeling processes. GIS was extensively used for identifying topographic features in watershed hydrologic models (Garbrecht and Martz 1997, Moore et al. 1988) in a raster grid environment. Storck et al (1998) describe a study in which GIS serves as a pre and post processor in converting GIS data into ASCII format for input. Interfacing GIS with hydrologic models has been accomplished by simple linking models like HEC-GeoHMS. More complex standalone packages like USEPA BASINS, PRMS and WMS contain a Graphical User Interface (GUI) that interacts between the GIS and the H&H models (Martin et al. 2005). Commercial GIS packages like Environmental Research Systems Institute's (ESRI) ArcGIS have analysis functions for estimating flows on a watershed scale.

One of the earliest linking of GIS with hydraulic modeling was the development of ARC/HEC2 (Beavers 1994). HEC developed ArcInfo Macro Language (AML) scripts in 1997 as a pre and postprocessor for HECRAS software. ESRI developed the AVRAS processor (Griva et al. 2003) which linked HECRAS with ArcView software. The Center for Research in Water Resources (CRWR) at Austin, TX developed the HECGeoRAS geodatabase model, in which the researchers (Whiteaker et al. 2006) have used the

HECRAS modeling engine to generate floodplain extent output and export them into GIS-compatible formats.

An Interface Data Model (IDM) is also used for linking GIS with H&H models. An IDM serves the purpose of acting as a bridge between the spatial component and the H&H component (Figure 3.2). Such a data model provides a framework which allows for stored data to be accessed by both the spatial and modeling H&H component. The main difference between an interface data model and a GIS pre/post processor (Figure 3.3) is that the input-output variables of the H&H model are stored in a GIS format.

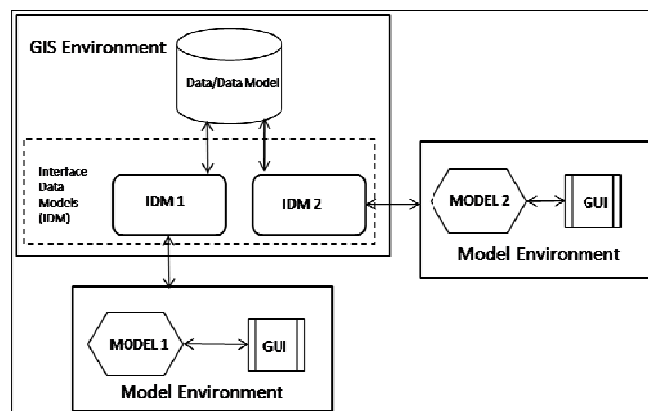


Figure 3.2. A schematic sketch of an interface data model

Interface Data Models facilitate smooth data access between the spatial and multiple modeling components. In other words, GIS-compatible storage of data can be used as inputs for other models also. For example, an interface data model storing time-series HMS data (in GIS format) can be used as an input in any other hydraulic model. There is a separate interface data model for each simulation model linked with GIS. Map-To-Map is a good example that integrates HEC-HMS and HECRAS in an interface data model (Robayo 2005). All these data models and programs limit themselves to delineating floodplain boundaries as modeled by the governing equations in HECRAS.

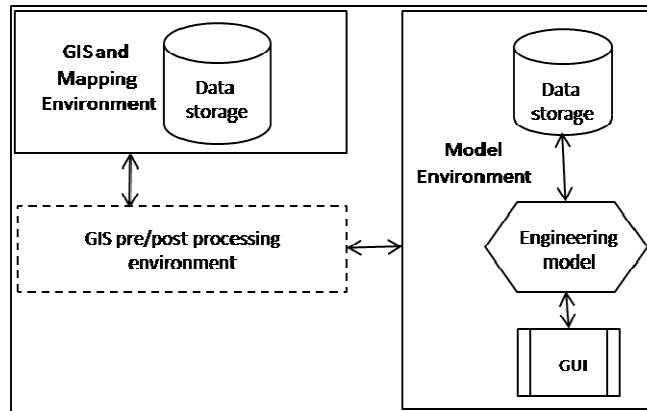


Figure 3.3. GIS pre and post processing modeling scenario schematic

There are different levels of integrating GIS with hydrologic and hydraulic models. The two fundamental principles of integrating GIS and H&H models are embedding and coupling (Sui and Maggio 1999). Embedding consists of using either the GIS or the H&H software as the host application, with the other software “embedded”.

The two options are:

1. H&H functionalities in a commercial GIS package – This approach takes advantage of all the spatial analysis capabilities of the GIS. However, the H&H modeling functionalities are limited and very simplistic as it becomes very difficult to bundle the complexity of a H&H system in a GIS.
2. GIS capabilities in a commercial H&H package – This approach results in limiting GIS strictly to serve as mapping software. Visualization capabilities of GIS are not completely utilized. However, it provides ample scope for the model developers to produce a sophisticated H&H model and constantly update it without any interference from GIS data structures.

A coupling approach differs from an embedded approach, wherein the GIS and H&H components are kept as separate entities and are linked (or coupled) by input-output manipulation or a common GUI.

1. Loose coupling – Loose coupling is easy to achieve because the model and GIS are independent without a common interface. It involves converting

model data into a GIS readable format and vice-versa (Karssenbergh 2002). Loose coupling has an advantage that it minimizes programming but suffers from the cumbersome conversion process. It also requires extensive knowledge of both the hydrological and spatial models and their input-output formats. The loose coupling concept is very similar to the GIS pre- and post processing environment (Figure 3.3)

2. Tight coupling – Such systems consist of a shared data model in which the hydrologic model output is stored in a common, shared database (Figure 3.4) which the GIS accesses to perform spatial analysis. The GIS and H&H model are kept as separate entities.

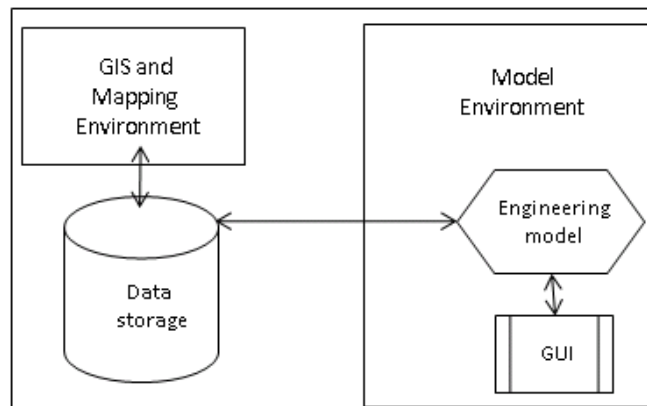


Figure 3.4. Tight coupling of GIS and H&H models schematic

We are introducing a coupled system called FloodwayGIS, in which the GIS and hydraulic model are maintained as separate entities. The GIS contains libraries or functions that facilitate executing the H&H model and reading model input-output from within the GIS. A schematic of such a coupling scenario is shown in Figure 3.5. Sui and Maggio (1999) categorize such an approach as a tightly coupled system, wherein macros or functions are available to access model output while Werner (2004) categorizes it as a loosely coupled system (due to lack of a shared data model). However, it should be noted here that the H&H model shares its input-output data with GIS and there is no data conversion from one format to another.

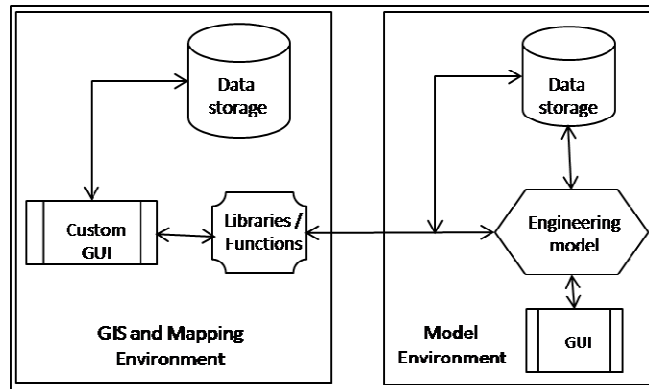


Figure 3.5. Schematic of the developed GIS-model coupling system

GIS coupling with H&H models has been used successfully to delineate floodplains and store the spatial data in a GIS compatible format. Tools like HECGeoRAS and Map-To-Map have demonstrated floodplain mapping capabilities. However, such advanced automation and linking of GIS and H&H models for floodplain mapping scenarios has not been matched by floodway modeling efforts.

Floodway modeling consists of identifying an area around the stream channel (by repeated trials) through which to allow a given discharge of water to flow without increasing the water surface elevation beyond a stipulated height. The “stipulated height” is called the surcharge. Typically, the surcharge should not exceed 0.3m (1.0 ft). Negative surcharges are not allowed at a cross-section. Hence, floodway modeling is an iterative process in which the modeler is expected to satisfy the surcharge requirements at all the cross-sections across a stream reach. An automated method (Selvanathan and Dymond 2009) can be used to perform the iterations to produce an initial floodway which can then be fine-tuned to produce the final floodway. In addition to surcharge requirements, floodway extents are also governed by local criteria such as zoning, landuse patterns and buildings surrounding the reach.

Spatial criteria can be handled effectively in a GIS environment which contains spatial analysis capabilities and a visualization platform. The coupling system described here aims to provide such a platform to remodel a floodway to meet FEMA specifications for flood insurance purposes. A visualization scenario enables the modeler to view a map

in order to alter floodway boundaries and then remodel the floodway to satisfy surcharge and community-specific requirements.

3.4 Current floodway modeling methodology

HECRAS uses one-dimensional steady flow St.Venant equations (Chow 1959) to estimate water surface elevations for a given flow of water. A typical floodway model in HECRAS consists of two water surface profiles – a base flood profile and a floodway profile. For the NFIP, a base flood is the 1% annual chance flood that has a one-percent probability of occurrence or exceedance in any given year. A floodway profile consists of encroachments along each cross-section. HECRAS provides 5 different methods to model a floodway. They are:

1. Specify left and right encroachment stations
2. Specify fixed floodway top width
3. Specify percent conveyance reduction
4. Specify target surcharge with equal conveyance reduction
5. Specify target surcharge and maximum energy increase

A typical floodway modeling approach is to perform a Method 4 analysis, followed by a Method 1 analysis to finalize the floodway. A Method 4 analysis allows the modeler to specify a target surcharge to be attained. A Method 1 provides more flexibility for the modeler to manually adjust the left and the right encroachment stations to meet FEMA's surcharge requirements. USACE (2002) explains all the floodway encroachment methods in detail. Typically, a modeler performs repeated Method 4 runs to produce an initial floodway which is followed by fine-tuning of the floodway using Method 1 runs on HECRAS. In order to perform further spatial analysis, the modeler exports HECRAS output data into GIS format and then uses a database model like HECGeoRAS to view the output within the ArcGIS mapping environment. It should be noted that the export and conversion process becomes tedious when the modeling involves repeated tweaking

of the floodway. This highlights a need for an efficient GIS-Hydraulic coupling system that would provide a visualization environment for mapping model output, thereby minimizing the overall modeling time.

3.5 Software Used

FloodwayGIS links ESRI's ArcGIS v9.3.1 spatial modeling software with HECRAS v4.0 hydraulic modeling software. HECRAS software models a floodway by employing an encroachment method approach (Haestad et al. 2003). The interface and linking has been developed using Visual Basic 9.0 in a Visual Studio 2008 .NET environment. The Visual Studio 2008 Integrated Development Environment (IDE) provides means to build ArcGIS tools and functionalities programmatically using ArcObjects, the ArcGIS library of software components.

3.6 FloodwayGIS - System description

FloodwayGIS is an ArcGIS and HECRAS coupling environment consisting of a custom user interface within ArcGIS, which aids in visualizing the HECRAS model output on a map. It also equips the modelers with interactive tools to re-adjust the floodway. The user interface is integrated into ArcGIS as a new "Floodway" tab in the table of contents in addition to the display, source and selection tabs. The only input that the modeler has to provide is the HECRAS project file (.prj) for the study area of interest. The program reads the HECRAS plan file associated with the project for encroachments from the floodway profile and maps the encroachments, floodplain, and channel banks as point shapefiles on the map.

The current encroachment stations along the cross-sections are marked as point graphic elements on the map. The point graphics are joined together on each side to indicate the current floodway boundary (similar to "Plot profile reach bounds" in

HECRAS). Figure 3.6 shows the visual comparison between HECRAS and FloodwayGIS environment in displaying model data. The current floodway boundary is shown as a graphic line on the map. The “Floodway” tab also displays a datagrid table of the cross-sections with their encroachment and surcharge information. The records in the table are color coded in such a way that cross-sections with surcharges between -0.003 m and 0.3 m (-0.01 ft and 1.0 ft) are shown in green and the cross-sections with excessive or negative surcharges are shown in red.

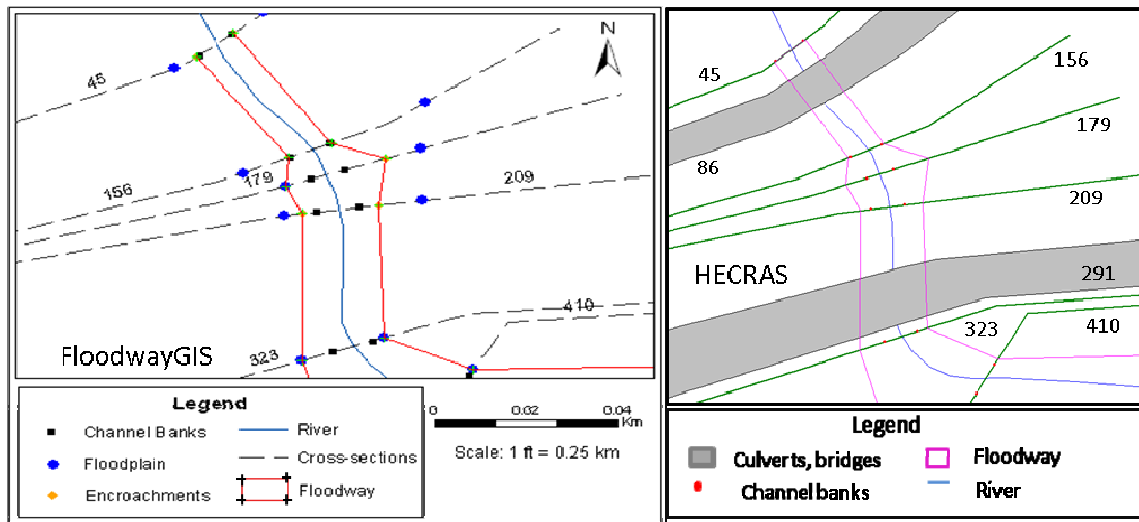


Figure 3.6. Comparison of ArcGIS (left) and HECRAS (right) showing model data

3.7 Salient features of FloodwayGIS

FloodwayGIS consists of tools for editing floodway encroachments and smoothing the raw HECRAS floodway output. A short description about each tool is listed below.

1. Single encroachment editor – Single encroachment editor tool enables a modeler to move an encroachment station (left or right) along the cross-section. The

- modeler is allowed to alter the encroachment to a new position between the floodplain station and the channel bank station at that cross-section.
2. Dual encroachments editor – Dual encroachments editor tool enables the modeler to move both the encroachment stations at a cross-section without changing the floodway topwidth. It facilitates orienting the floodway at a cross-section so that the conveyance can be distributed on both sides of the main channel.
 3. Floodway encroachments manager – FloodwayGIS employs an interactive encroachments management approach in which the modeler is provided information about encroachment stations and surcharges at each of the edited cross-sections. The manager displays encroachments information for five previous trials performed at a cross-section. It provides a means for the modeler to rollback to previous modeling scenarios in the event of a poor model response to the changes made at that cross-section.
 4. Floodway smoothing – FloodwayGIS also incorporates floodway smoothing algorithms to translate the HECRAS encroachments stations output at each cross-section into a smooth boundary along the entire reach. Smoothing involves identifying locations (or points) on the map between two cross-sections by linearly interpolating the top widths between any two cross-sections.

FloodwayGIS also provides other subtle interactive tools which help the modeler with the remodeling process. They are:

- The encroachment information is available on the map (as a graphic) as well as in tabular form. The table provides information about the surcharges at each cross-section. The color coding helps in identifying the cross-sections with excessive or negative surcharges.
- When a record (cross-section) on the datagrid table is selected, the map zooms to the corresponding cross-section extents on the map. It enables faster navigation on the map to cross-sections at which the floodway encroachments need to be altered.

- The environment provides a dynamic label display (Figure 3.7) for encroachment stationing on the map as the modeler moves the mouse along a cross-section using single encroachment editor or dual encroachments editor. It facilitates control of the distance the encroachment station is shifted from the current position. The modeler can move the encroachment by a specific distance by following the dynamic display.
- One of the FEMA guidelines in modeling a floodway is to maintain a consistent floodway top width and minimize drastic changes in top width moving from one cross-section to another. In order to keep an eye on the top width change as the modeler alters the encroachment, a dynamic top width information display for the previous and current modeling trials is provided (Figure 3.7).
- In addition to using the single and the dual encroachments editor, a modeler can also edit the floodway encroachment stations by manual input in the datagrid. It automatically sets up a HECRAS input plan file to model based on the encroachment input.
- Any form of encroachment change immediately is reflected on the datagrid table by changing the row color to white. The color coding makes it easy for the modeler to identify the cross-sections at which the encroachments have been altered during that iterative trial. The map is also updated to reflect the change in encroachment stationing.

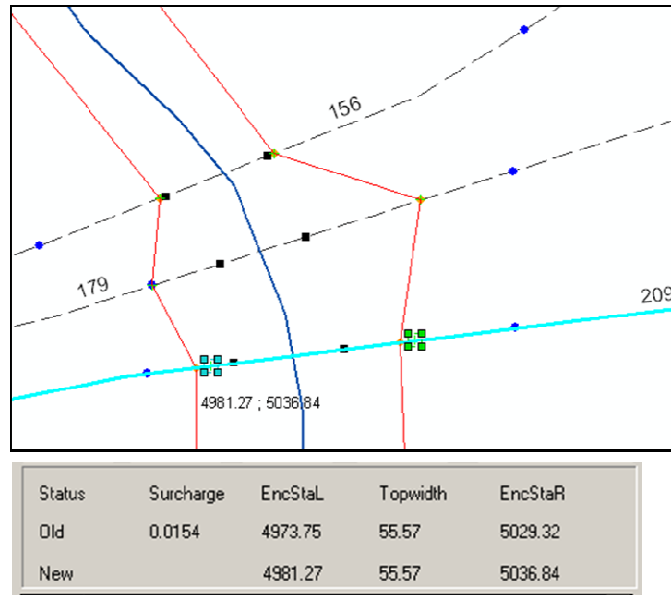


Figure 3.7. Dynamic encroachment label display (top) and the corresponding topwidth change display (bottom)

3.8 FloodwayGIS - A walkthrough

FloodwayGIS requires a HECRAS project with an initial floodway modeled manually or by using an external tool (Selvanathan and Dymond 2009). It also requires a cross-section featureclass output from the HECGeoRAS schema after floodplain delineation. FloodwayGIS reads the selected HECRAS project and creates the encroachments, floodplain limits and channel banks as point shapefiles on the map. It also creates map graphic elements for the current encroachment stations and floodway boundary. Figure 3.8 shows four cross-sections at the downstream end of a study reach. Table 3.1 gives surcharge and encroachment information for the four cross-sections as displayed in the datagrid table.

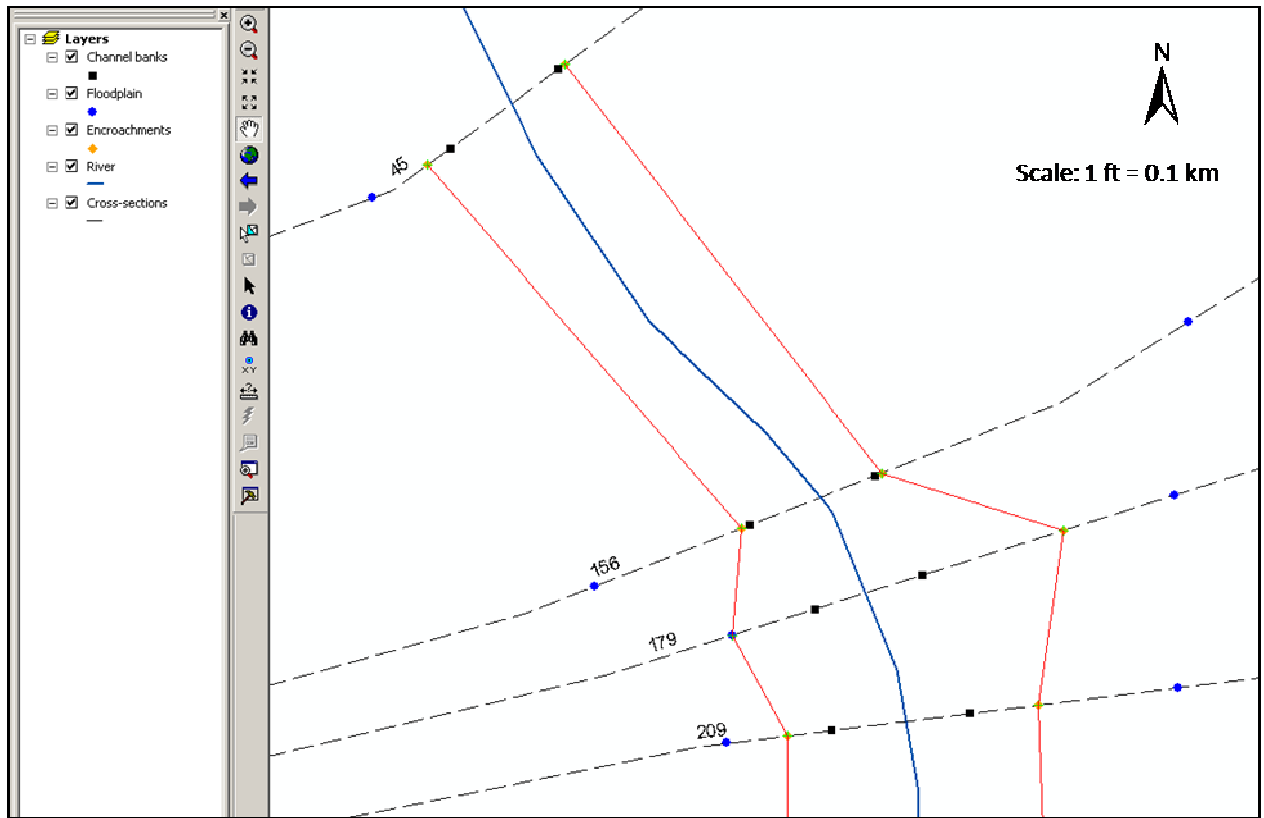


Figure 3.8. Downstream end of the reach showing the current encroachments and the floodway boundary

Table 3.1. Initial encroachments and surcharge information at the downstream end

Cross-section ID	Left encroachment station	Right encroachment station	Surcharge (m)
45	4977.18	5014.66	0.11
156	4981.5	5014.66	-0.008
179	4969.28	5045.4	-0.03
209	4973.75	5029.32	0.021

FloodwayGIS provides four different ways to modify encroachment stations along a cross-section: (1) single encroachment editor, (2) dual encroachments editor, (3) floodway encroachments manager, (4) manual input in the datagrid table. Cross-sections

156 and 179 have negative surcharges (Table 3.1). The floodway can be narrowed at cross-section 45, which would increase the surcharge at that cross-section. The single encroachment editor can be used to perform this operation. Once the single encroachment editor tool is activated, the modeler clicks on the left encroachment graphic at cross-section 45 and moves it towards the channel bank. As the modeler moves the mouse in the desired direction, the encroachment graphic automatically moves along the cross-section line. Once the new encroachment station is finalized, FloodwayGIS provides a command button that would update the encroachment station on the HECRAS plan file and re-run the model to produce a floodway based on the new encroachments. The map display is also updated with the new encroachments. A similar operation is performed at cross-section 179 to narrow the floodway width. Figure 3.9 shows the change in map after remodeling. Table 3.2 shows the encroachment and surcharge information after this change. It can be observed that the adjustments made to encroachments at cross-sections 45 and 179 resulted in acceptable surcharges at all the four cross-sections. The dual encroachments editor also works in a similar fashion, the only difference being that it moves both the encroachments maintaining the floodway topwidth.

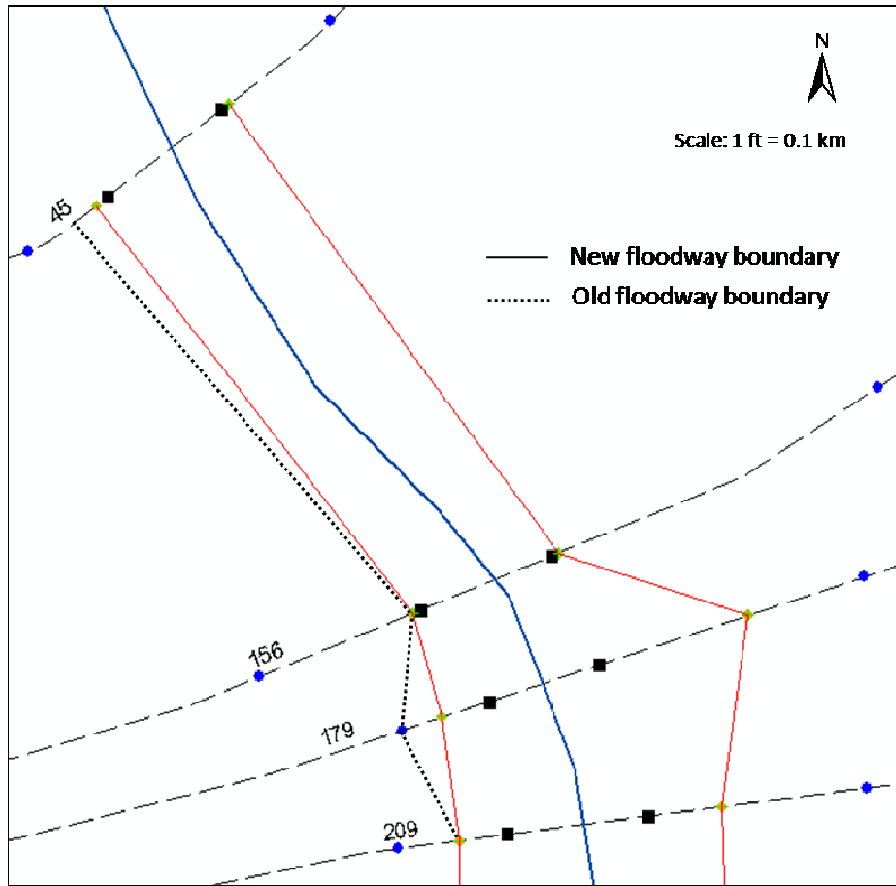


Figure 3.9. Updated map display after changes to cross-sections 45 and 179

Table 3.2. Encroachments and surcharge information at the downstream end after editing

Cross-section ID	Left encroachment station	Right encroachment station	Surcharge (m)
45	4980.36	5014.66	0.14
156	4981.5	5014.66	0.013
179	4977.96	5045.4	0.006
209	4973.75	5029.32	0.023

The floodway encroachments manager stores information about the five previous iterations performed at a cross-section. The manager works on a single cross-section basis at which the modeler has an option to pick from one of the previous trials at that

cross-section. The information is listed (Figure 3.10) when the modeler clicks on a cross-section record in the datagrid table. In this example, four trials at cross-section 179 resulted in successive surcharges of -0.033 m (-0.1097 ft), -0.006 m (-0.0198 ft), -0.0102 m (-0.0337 ft) and 0.0004 m (0.0013 ft). The fifth trial produced a surcharge of -0.007 m (-0.024 ft). The modeler can select the fourth trial that yielded a better surcharge and rollback the changes made by the fifth trial. It should be noted that the changes made to this cross-section does not rollback change made at other cross-sections.

Manual datagrid table input also remodels the floodway based on the encroachments table in the “Floodway” tab. The modeler can directly input an encroachment station value in the datagrid and rerun the HECRAS model. After the cross-sections have met FEMA’s surcharge requirements, the last step is to smooth the floodway boundary to produce a cartographically aesthetic floodway to be printed on FEMA’s Flood Insurance Rate Maps (FIRMs).

ID	RchSta	Surchage	EncStaL	EncStaR	TopWidth
1	45	0.4537	4980.36	5014.66	34.3
2	156	0.0416	4981.5	5014.66	33.16
3	179	0.0013	4976.51	5045.4	68.89
4					57
5					93
6					7.95
7					2.47
8					7.98
9					3.25
10					3.41

Reach Station: 179				
Surchage	EncStaL	EncStaR	Topwidth	
-0.1097	4969.28	5045.4	75.46	
-0.0198	4977.96	5045.4	67.44	
-0.0337	4979.04	5045.4	66.36	
0.0013	4976.51	5045.4	68.89	

Figure 3.10. Floodway encroachments manager

The topwidth of a floodway is one of the important criteria that FEMA checks during the QA/QC process before Digital FIRM (DFIRM) production. The floodway topwidth is published in the floodway data table in a Flood Insurance Study (FIS) document. FloodwayGIS employs a smoothing algorithm that is based on interpolating floodway topwidths between two cross-sections. Figure 3.8 shows the floodway mapped as a straight line between two cross-sections (HECRAS method). We have developed a

TIN intersection technique to map (or interpolate) the floodway topwidths between two cross-sections. The TIN intersection technique has been widely used for floodplain delineations wherein the water surface TIN is intersected with the underlying terrain TIN to produce the floodplain boundary. For floodway smoothing, however, the topwidths at each cross-section is used as elevation inputs in the TIN creation process.

The algorithm creates multiple ring buffers of the river centerline. The buffer widths are governed by the overall minimum and maximum top widths along the reach. This ensures that the coverage area of the buffers include all the encroachment stations on the reach. A TIN is created using the multiple ring buffer layer (Figure 3.11). The buffer TIN extends wider than the encroachment stations at each cross-section. Between cross-sections 3336 and 3774, it can be seen that the straight line floodway crosses the river centerline. The floodway mapped on DFIRMs should satisfy two technical criteria:

1. The floodway boundary should match the encroachments at the cross-sections.
2. The floodway boundary should not intersect with the river centerline.

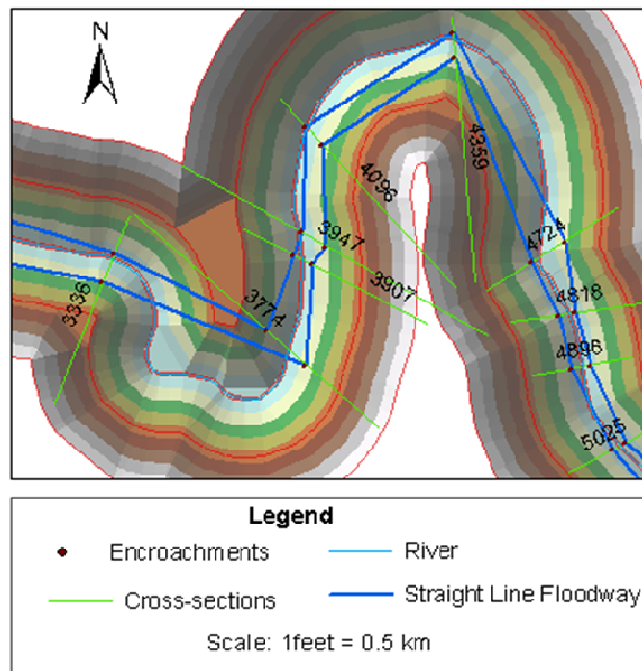


Figure 3.11. Straight line floodway and TIN of the river buffer

It is a recommended practice to map floodways following the sinuosity of the river centerline. The buffering of the river centerline is expected to help in maintaining the river sinuosity to some extent. The second TIN used in the TIN intersection technique is created using the cross-section features, each of which is elevated with the top width at that cross-section. In order to produce a better TIN representation, each cross-section was split into two and elevated accordingly using the left and the right top widths. In addition to that, the cross-sections lines were densified to contain more vertices. The densification process improved the TIN triangulations between each cross-section pair along the reach. The two tins were intersected to produce the smoothed floodway boundary (Figure 3.12).

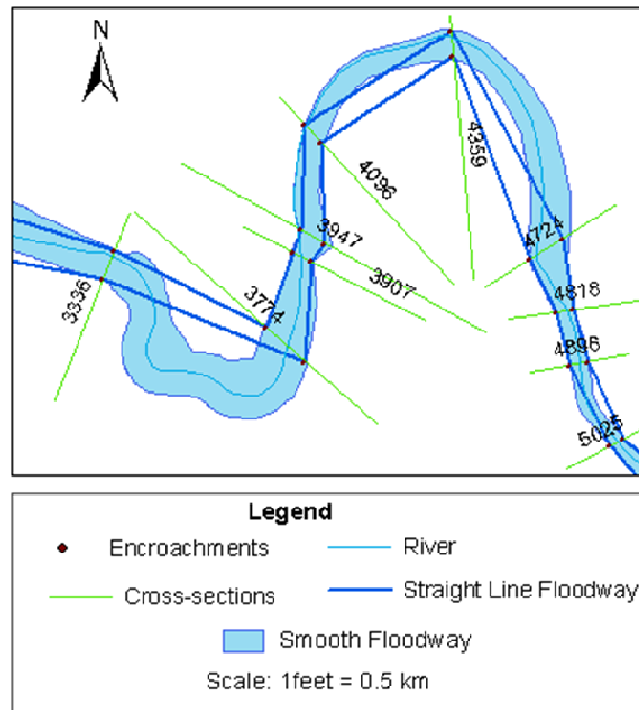


Figure 3.12. Smoothened floodway boundary after TIN intersection

The TIN intersection approach based on the topwidths enables a quick way to map the floodway boundary across the entire length of the stream. It should be noted that

the generated floodway boundary does not match the encroachments stations at all the cross-sections. The advantages of using TIN intersection method are:

1. The river buffer helps to maintain the sinuosity of the river, especially at cross-sections at which the top widths are narrow.
2. TIN intersection approach eliminates the problem of the floodway boundary intersecting with the river centerline.
3. Since the cross-sections are elevated by their top width values (different width on either side of the river centerline), the boundary would match the encroachments in majority of the stations. It also prevents the floodway boundary to be mapped inside the encroachments at any cross-section.

The limitations of the TIN intersection approach are:

1. The first major limitation is that the floodway boundary would not match the encroachment stations at all the cross-sections. Hence, some manual editing is required to finalize the floodway.
2. The buffer rings are generalized moving farther away from the stream centerline. Hence, at cross-sections with very wide topwidths, the boundary would be mapped wider than necessary.
3. Long cross-sections with wings and curved cross-sections might adversely influence the TIN interpolations between them. It might result in underestimating or overestimating the interpolated elevations which would affect the floodway mapped between those two cross-sections.
4. In some cases, the topwidth variations between two consecutive cross-sections might be high, resulting in complex triangulation patterns.

3.9 Summary and Conclusions

FloodwayGIS provides an improved tightly coupled system linking ArcGIS and HECRAS for floodway remodeling and editing. The FloodwayGIS visual environment

combines HECRAS's hydraulic modeling capabilities with ArcGIS's mapping and spatial analysis functionalities to aid the modeler to produce a final floodway boundary that meets FEMA requirements. Within the ArcGIS environment, FloodwayGIS facilitates map overlay with building and landuse layers to help the modeler meet the community's local requirements for floodways. It should be noted that FloodwayGIS works with a HECGeoRAS cross-section output featureclass, which enables the FloodwayGIS outputs (encroachments, floodplain boundary, channel banks and the floodway boundary) to be combined into the existing HECGeoRAS geodatabase schema. The FloodwayGIS outputs act as a bridge providing a visualization interface to the HECRAS model output. FloodwayGIS produces an immediate mapping visual of a floodway during repeated floodway modeling trials, thereby eliminating the need to export HECRAS output to a GIS format. This results in savings in the overall modeling time.

The smoothing algorithm, regardless of its drawbacks, provides a good starting point to fine-tune the floodway boundary to produce final mapping output. There are mapping issues involved in the process, such as the lack of sufficient elevation points for TIN triangulations and scalloped shape of the boundary due to buffering. These can be improved by densifying the data that participate in TIN creation or by defining smaller processing blocks for TIN creations.

3.10 Acknowledgments

The authors would like to thank Mr. Kendrick Logsdon Jr. of Dewberry, LLC for his invaluable technical and design inputs while developing FloodwayGIS. The authors would also like to thank Dr. Janghwoan Choi, engineer/GIS developer, Dewberry, LLC for providing feedback and algorithmic suggestions to improve the features and final output using the visual environment. Mr. Milver Valenzuela, engineer, Dewberry and Mr. Xiaoyi Zhang deserve a special mention for their fundamental algorithmic inputs in the mapping process.

3.11 Paper references

- Al-Sabhan W., Mulligan M., and Blackburn G.A. (2003). "A real-time hydrological model for flood prediction using GIS and the WSW". *Computers, Environment and Urban Systems*, 27(1), 9-32.
- Bates P.D., and Anderson M.G. (1993). "A two-dimensional finite element model for river flow inundation". *Proceedings: Mathematical and Physical Sciences of the Royal Society of London*, 440 (1909), 481-491.
- Bates P.D. and De Roo A.P.J. (2000) "A simple raster-based model for flood inundation simulation". *Journal of Hydrology*, 236, 54-77
- Bates P.D., Horritt M.S., Smith C.N., and Mason D.C. (1997) "Integrating remote sensing observations of flood hydrology and hydraulic modeling". *Hydrological Processes*, 11, 1777-1795.
- Beavers, M. A. (1994). "Floodplain determination using HEC-2 and geographic information systems" Masters Thesis, Department of Civil Engineering, University of Texas at Austin, Austin, TX.
- Burby R.J. (2001). "Flood insurance and floodplain management: the US experience". *Environmental Hazards*, 3, 111-122.
- Chow V.T., (1959). "Open Channel Hydraulics". McGraw Hill, New York, New York, USA.
- Clark, M. J. (1998). "Putting water in its place: A perspective on GIS in hydrology and water management". *Hydrological Processes*, 12(6), 823-834.
- DeVantier, B. A., & Feldman, A. D. (1993). "Review of GIS applications in hydrologic modeling". *Journal of Water Resources Planning and Management*, 119, 246-261.
- Dutta D., Herath S., and Musiak K. (2000). "Flood inundation simulation in a river basin using a physically based distributed hydrologic model". *Hydrological Processes*, 14(3), 497-519.
- Fotheringham, A. S., & Rogerson, P. A. (Eds.). (1994). "Spatial analysis and GIS". Taylor & Francis, London.
- Garbrecht, J. and L.W. Martz. (1999). "Digital Elevation Model Issues in Water Resources Modeling". *Proceedings of the 19th ESRI International User Conference*, San Diego, California.
- Goodchild, M. F., Haining, R., & Wise, S. (1992). "Integrating GIS and spatial data analysis: Problems and possibilities". *International Journal of Geographical Information Systems*, 6, 407-423.
- Griva A., Baltas E.A., Varanou A., and Mimikou M.A. (2003). "GIS-based Floodplain Mapping in Greece". *International conference - Towards natural flood reduction strategies*, Warsaw.
- Haestad Methods, Dyhouse G., Hatchett J., Benn J. (2003). "Floodplain Modeling using HEC-RAS". Haestad Press, First Edition, Waterbury, Connecticut, USA.
- Karssenberg D., (2002). "The Value of Environmental Modeling Languages for Building Distributed Hydrological Models". *Hydrological Processes*, 16(14), 2751-2766.

- Maidment, D. R. (1993). "GIS and hydrological modeling". In M. F. Goodchild, B. Parks, & L. Steyaert, (Eds.), *Environmental modeling with GIS*, Oxford University Press, New York, 147-167.
- Maidment D.R., and Djokic D. (2000). "Hydrologic and Hydraulic Modeling Support with Geographical Information Systems". ESRI Press, California, USA.
- Martin P.H., Lebouef E.J., Dobbins J.P., Daniels E.B., and Abkowitz M.D. (2005) "Interfacing GIS with water resource models: A state of the art review". *Journal of American Water Resources Association*, Paper No. 03208.
- McDonnell, R. A. (1996). "Including the spatial dimension: Using geographical information systems in Hydrology". *Progress in Physical Geography*, 20, 159-177.
- Moore, I.D., Grayson R.B., and Brunsch G.J. (1988). A Contour-Based Topographic Model for Hydrological and Ecological Applications. *Earth Surface Processes and Landforms*, 13, 305-320.
- Robayo O., (2005) "Map to Map: Converting a NEXRAD rainfall map into a floodplain map". PhD dissertation, University of Texas at Austin
- Selvanathan S., Dymond, R.L. (2009) "An algorithmic approach to iterative floodway modeling using HEC-RAS and GIS". Accepted to be printed in the *Journal of Flood Engineering* 1 (1).
- Singh, V. P., & Fiorentino, M. (1996). "Geographical information systems in hydrology". Dordrecht, Netherlands: Kluwer Academic Publishers.
- Singh V.P., and Woolhiser D.A. (2002). "Mathematical Modeling of Watershed Hydrology". *Journal of Hydrologic Engineering*, 7(4), 270-292.
- Storck P., Bowling L., Wetherbee P., and Lettenmaier D. (1998) "Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak streamflow in the Pacific Northwest". *Hydrological Processes*, 12(6), 889-904
- Sui D.Z., and Maggio R.C. (1999). "Integrating GIS with Hydrologic Modeling: Practices, Problems and Prospects". *Computers, Environment and Urban Systems* 23, 33-51.
- Tate E.C., Maidment D.R., Olivera F., and Anderson D.J. (2002). "Creating a terrain model for floodplain mapping". *Journal of Hydrologic Engineering*, 7(2), 100-108.
- Townsend P.A., and Walsh S.J. (1996). "Modeling floodplain inundation using an integrated GIS with radar and optical remote sensing". *Geomorphology*, 21(3-4), 295-312.
- USACE (2002). *HEC-RAS User's Manual Ver. 3.1*.
- Wang Y., Colby J.D., and Mulcahy K.A. (2002). "An efficient method for mapping flood extent in a coastal floodplain using Landsat TM and DEM data". *International Journal of Remote Sensing*, 23(18), 3681-3696.
- Werner M., (2004) "Spatial Flood Extent Modeling: A Performance-Based Comparison". PhD dissertation, de technische Universiteit Delft
- Whiteaker T.L., Robayo O., Maidment D.R., and Obenour D. (2006). "From a NEXRAD Rainfall map to a floodplain map". *Journal of Hydrologic Engineering*, 11(1), 37-45.

4 Floodway mapping algorithms: challenges and solutions

Abstract

Floodway modeling using HECRAS is based on encroachment analysis methods. The floodway output from HECRAS consists of encroachment stations (or encroachment points) identified at each cross-section. For mapping purposes, the point floodway output has to be transferred onto a map that would display the floodway as a smooth boundary. In this paper, we have discussed three different algorithms that were considered for floodway mapping. We also present the deficiencies and capabilities of each method. We have developed a floodway mapping algorithm that is based on TIN intersection for floodway delineation. The TIN intersection algorithm was found to produce a smooth floodway boundary that reduces manual smoothing and editing by a modeler to a large extent. This paper details the challenges during implementation and the solutions that were used to produce the smoothed floodway. Rubbersheeting transformation was employed to fit the floodway output to pass through the encroachments at each cross-section. It was found that a localized similarity transformation method also produced desirable floodway boundary output.

4.1 Introduction

The Federal Emergency Management Agency (FEMA) administers the National Flood Insurance Program (NFIP) regulating flood insurance for property owners to protect themselves from flood hazards and risk. In exchange, the property owners and the communities are required to accept the federal floodplain management policies. The NFIP, started in 1968, involves identifying special flood hazard areas and flood risk, mitigating and managing the flood risk, spreading awareness about flood risk, and mandating flood insurance policies (Burby 2001). In addition to these goals, the NFIP

also identifies and maps floodplains across the United States. However, it should be noted that flood insurance estimates and mapping extents cannot be achieved without a risk assessment standard.

NFIP established the 1-percent annual chance flood (100 year flood) as the base standard for flood risk assessment and mapping. The 1-percent annual chance flood is the base flood that has a one-percent probability of occurrence or exceedance in any given year. It was chosen on the basis that the 1% chance flood provides a good balance between providing flood protection and economic costs incurred by the property owners ((L.R.Johnston Associates 1992). In addition to mapping floodplains, FEMA also mandates a floodway at special flood hazard areas that are prone to higher flood risk.

HECRAS is one of the hydraulic models approved by the NFIP to perform floodway modeling. Floodway modeling follows floodplain modeling in the sequence of steps undertaken to produce Flood Insurance Rate Maps (FIRMs). Thus, there is a need to transfer HECRAS modeling output to a mapping environment that can additionally perform spatial analysis before creating the final floodplain or floodway boundary.

The floodway boundary has to be aesthetically appealing and it should also follow FEMA guidelines as stipulated in the Code for Federal Regulations. Transferring the HECRAS encroachment output points at each cross-section to a smooth boundary along a study reach involves good understanding of the mathematical capabilities of GIS with regards to mapping. We have described various algorithms that were considered for floodway mapping listing their advantages and disadvantages. The mapping algorithms are part of a visual environment which is capable of accessing the HECRAS executable engine and repeatedly run the software for floodway modeling. Selvanathan and Dymond (2009) have documented a method to automate the iterative process to produce an initial starting floodway. The final smoothed boundary has to be checked by the modeler and some fine-tuning will be required.

4.2 Background

GIS and H&H modeling have developed as parallel technologies since the 1960s. In the 1980s, researchers identified a need to utilize the spatial capabilities of GIS in H&H modeling. Fotheringham and Rogersen (1994) and Goodchild et al (1992) have documented efforts in the late 1980s to integrate GIS with hydrologic models with a focus on improving the analytical capabilities. Demand for higher resolution terrain models (Clark 1998, Singh and Fiorentino 1996, Tate et al. 2002) has influenced linking GIS with H&H models. There is extensive literature available linking GIS with hydrologic models for modeling water quality and quantity (Di Luzio et al. 2004, Baker et al. 2001, De Roo et al. 2000, Stork et al., 1998). The Center for Research in Water Resources (CRWR) at Austin, TX developed ArcHydro as a full geodatabase model for linking hydrologic modeling (Maidment 2002).

One of the earliest linking of GIS with hydraulic modeling was the development of ARC/HEC2 (Beavers 1994). HEC developed ArcInfo Macro Language (AML) scripts in 1997 as a pre and postprocessor for HECRAS software. ESRI developed AVRAS processor (Griva et al. 2003) which linked HECRAS with ArcView software. In addition to ArcHydro, the CRWR also developed the HECGeoRAS geodatabase model, in which the researchers (Whiteaker et al. 2006) have used the HECRAS modeling engine to generate floodplain extent output and export it into GIS-compatible formats.

The two fundamental paradigms of integrating GIS and H&H models are embedding and coupling. Sui and Maggio (1999) describe these paradigms in greater detail discussing the major issues involved. We have developed a tight-coupling system with ArcGIS and HECRAS (Figure 4.1). In this system, ArcGIS and HECRAS interact with each other through libraries and functions that facilitate executing HECRAS model from within ArcGIS.

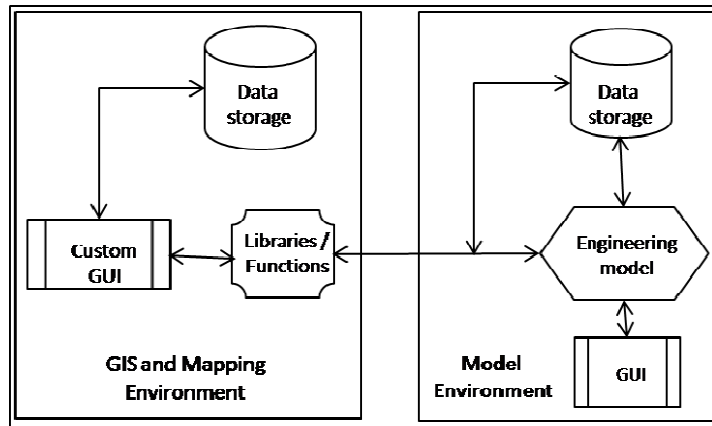


Figure 4.1. Schematic of the GIS-HECRAS coupling system

ArcGIS stores and displays geographic data as discrete objects in digital format. However, in reality, geographic data are complex, continuous data. Hence, displaying spatial data requires generalization, abstraction and approximation (Goodchild et al., 1992). The rules by which the objects are defined and displayed are governed by a data model (Tsichritzis and Lochovsky 1977). Older automated techniques for floodplain mapping were based on DEM models, which are restricted by the raster cell size of the original elevation data. The interpolation methods used in digital terrain models fail to reproduce things 100% as found in reality (Schut 1976).

Vector display of objects as points, lines and polygons are closer to retaining real shapes. The evolution of Triangulated Irregular Networks (TINs) and Terrain data models have improved floodplain delineation. The floodplain delineation methods using DEMs have since then been superseded by TINs and terrain datasets. TIN construction is based on the Delaunay Triangulation method (Lee and Schacter 1980, Watson and Philip 1985) which requires that a circle drawn using three nodes do not contain any other node. Correct triangulation satisfying Delaunay's criterion would produce near equiangular triangles (Lawson 1977). However, in floodplain mapping, thin angular triangles are formed when triangulation occurs connecting points that are far apart causing misrepresentation of flood depths (Noman et al., 2001).

The HECRAS model provides data at each cross-section to map a floodplain or floodway boundary. However, the area between the two cross-sections needs to be mapped using smooth lines and interpolated elevations. GIS software creates surfaces from point elevation data. Such interpolation techniques generate smooth surfaces which have been well documented in literature (Franke 1982, Gold 1984, Gold 1988). Generating smooth boundaries also requires sufficient elevation points in order to prevent triangulation across a long distance.

FEMA requires that the floodway boundary match the encroachment stations at each cross-section and a smooth boundary approximately following the shape of the stream centerline between any two cross-sections. It is also recommended that a consistent floodway topwidth be maintained along the reach. ArcGIS provides smoothing and generalizing algorithms that can be employed to map the floodway boundary. In addition to smoothing and generalizing, ArcGIS also provides transformation techniques to modify lines and polygons.

Spatial adjustment in ArcGIS is performed by five different methods – affine transformation, projective transformation, similarity transformation, rubbersheeting and edge matching (ESRI 2009). In ArcGIS, the transformation methods (affine, projective and similarity) are used to move or convert data into a coordinate system. The general principle behind transformation is shown in Figure 4.2. Based on the method used, the shape may be preserved or skewed followed by rotation and translation. The source and the destination control points are provided as displacement links (shown as lines joining the four corners of the square in Figure 4.2).

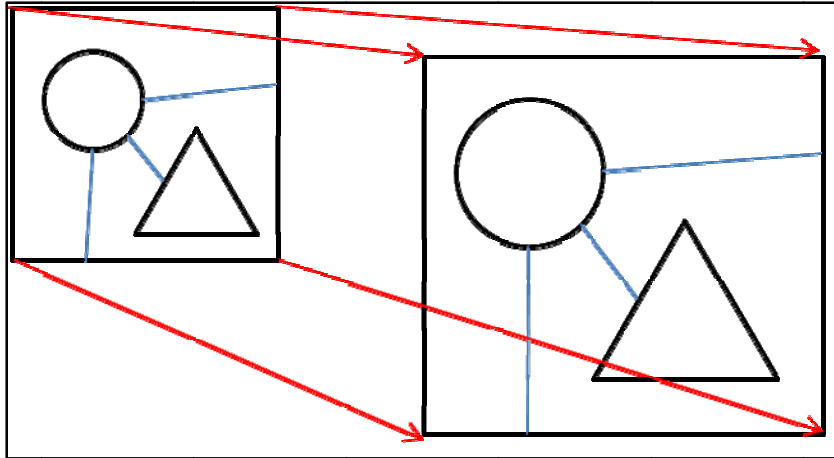


Figure 4.2. Principle behind transformation techniques (adapted from ArcGIS help documentation)

The affine transformation method maintains the collinearity and ratio of distances between points along a line through a series of linear transformations. The projective transformation does not preserve the size and shapes during transformation. The similarity transformation does not introduce skew in the input data and it also maintains the aspect ratio of the input features. The root mean square error statistically quantifies the accuracy of these transformation methods.

The rubbersheeting technique interpolates the new location of a point by using two TINs in memory. There are two types of links that are used – displacement links and identity links. The identity links are those points that are preserved in both the input and output surfaces (or shapes). The displacement links indicate the respective point on the transformation plane. Both the links serve as nodes in the TIN. The destination points are interpolated on the TIN and the surface is transformed. Rubbersheeting follows piecewise transformation to move and stretch the features on the input plane onto the new transformation plane. This method preserves straight lines.

4.3 Mapping algorithms

Floodway mapping involves creating a smooth boundary around the river centerline that maintains the floodway topwidth at each cross-section as modeled by HECRAS. Three different algorithms were considered to map the floodway boundary for a flooding reach. All three methods considered floodway topwidth while trying to interpolate the width between two cross-sections. Two of the three methods were based on linear interpolation of floodway topwidth between two consecutive cross-sections.

4.3.1 Method 1 – Stream morphing

The stream morphing method is a simple rubbersheeting technique based on the shape of the river centerline. In stream morphing method, the source control points were defined along with the river centerline where it intersects with the cross-sections. The destination points were the points of floodway encroachments at the cross-section. In other words, the displacement links were drawn from the point of intersection of river with the cross-section to the encroachment station on each cross-section. The input curve is the river centerline that gets transformed to match the destination points as defined by the displacement links. Figure 4.3 shows the output from the stream morph method. In ArcGIS, rubbersheeting stretches the surface stretched using a piecewise transformation method preserving the linear portions. Thus, this method ‘morphs’ the river centerline between two cross-sections in such a way that the transformed curve pass through the encroachment stations at each cross-section.

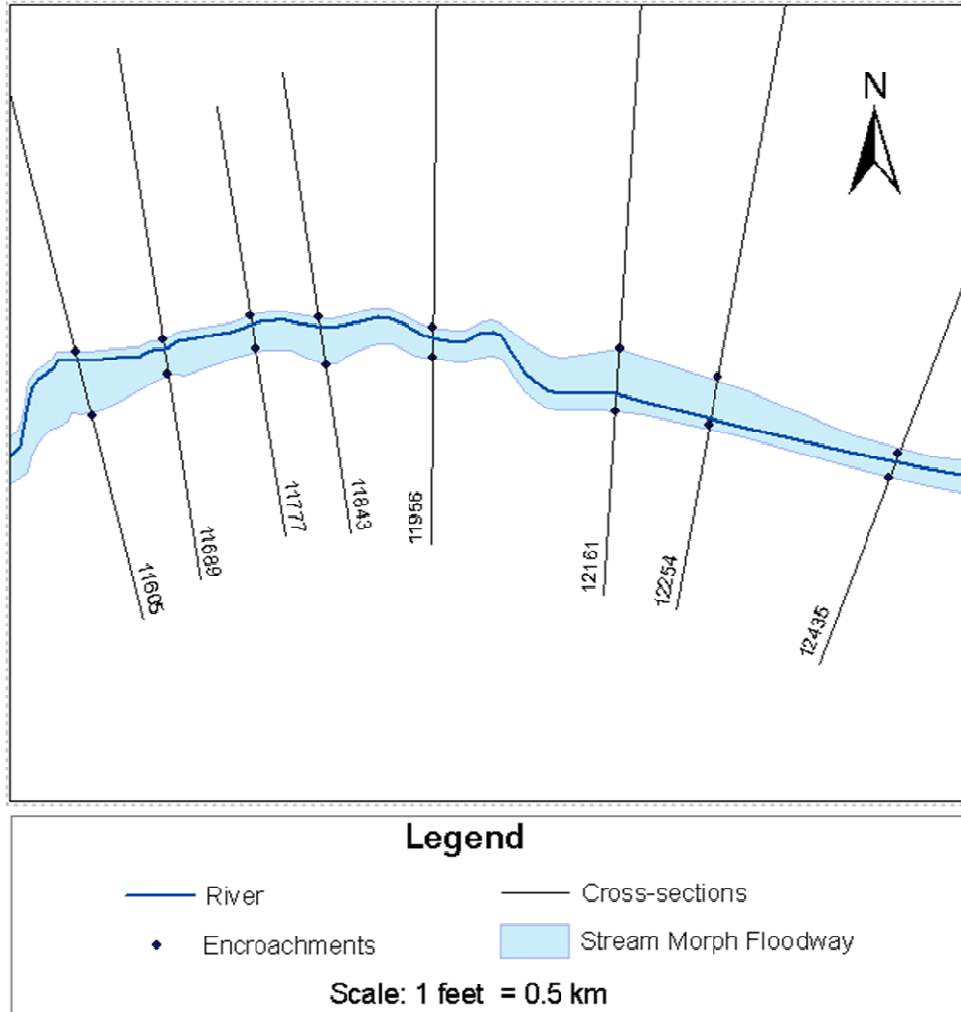


Figure 4.3. The stream morph mapping method

The main advantage of stream morphing method is that it requires no pre-processing of the data. The river centerline is transformed separately on the left and the right (of the river centerline) as polylines. The polylines were converted to a closed polygon to produce the boundary. However, stream morphing method was found to produce helix patterns especially in areas where the river was sinuous with no cross-sections in between (Figure 4.4). Since there are no displacement links between two cross-sections, the transformed curves on the left and right side of the river intersect the river centerline causing helical patterns. The floodway boundary

output lacks definition due to the fact that there are no displacement links between cross-sections.

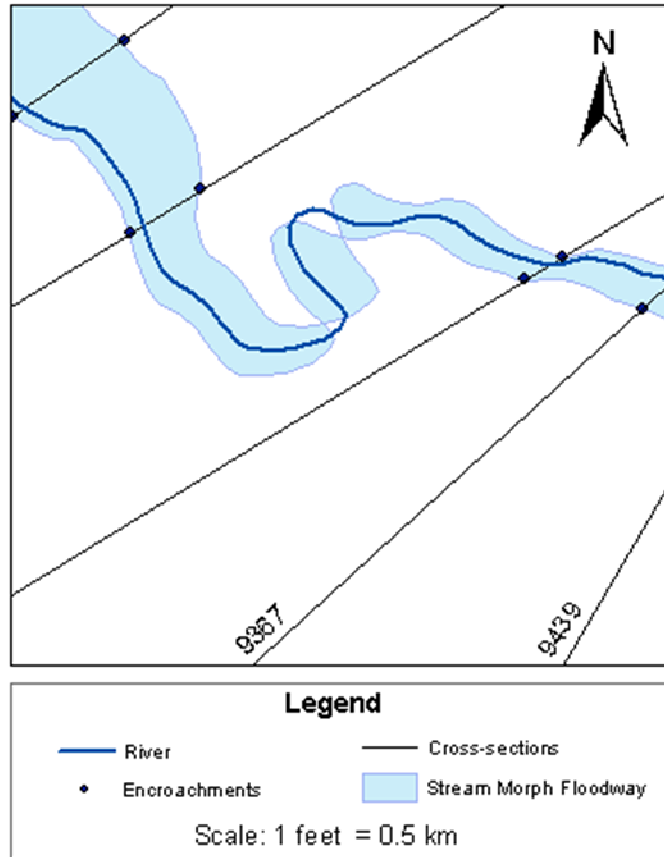


Figure 4.4. Helical patterns in the stream morph method

4.3.2 Method 2 – Normal distances method

Normal distances method consists of identifying locations on either side of the stream centerline that would match the interpolated topwidth between two cross-sections at each vertex on the river centerline. The points were identified by drawing normal lines at the point of tangency for each vertex. The length of the normal lines was determined by the

interpolated topwidth and the distance of the vertex along the river centerline. A schematic of the normal distances approach is shown in Figure 4.5.

The normal distances method calculates interpolated top widths between two consecutive cross-sections. The difference between the two topwidths (TW1 and TW2) indicates if the section is an increasing section or a decreasing section. In this example (Figure 4.5), the floodway topwidth increases from TW1 to TW2 forming an increasing section. It should be noted that the normal distances method considers the vertices between the cross-sections, hence providing a better definition of the floodway boundary. The method requires pre-processing of the river centerline. The river centerline should be densified to add vertices along the line. This would result in better identification of intermediate points (or vertices) along the floodway boundary.

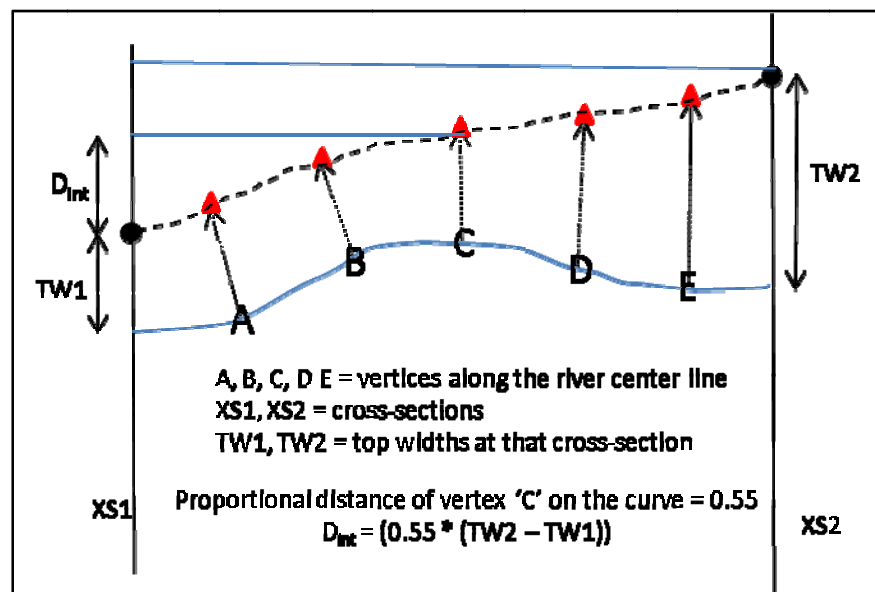


Figure 4.5. Schematic of the normal distances method

The normal distances method would be ideal for stream reaches that don't meander much and have almost uniform floodway topwidths. The method would fail if

the river meanders and the topwidth at that section is very narrow (Figure 4.6). The normal lines would meet on the other side of the river centerline. Hence, care should be taken that each of the interpolated vertices fall on the same side of the floodway being mapped. Additionally, the densification process has to be supervised to capture farthest points on the bends. Improper densification would result in the floodway boundary being clipped. The mapping method can be improved if we consider a buffer of the river centerline and identify the interpolated vertices along that buffer. The buffering technique would ensure that a majority of the vertices can be identified on the desired side of the river centerline. This inherent advantage in buffering the river has been adeptly employed in the third mapping method.

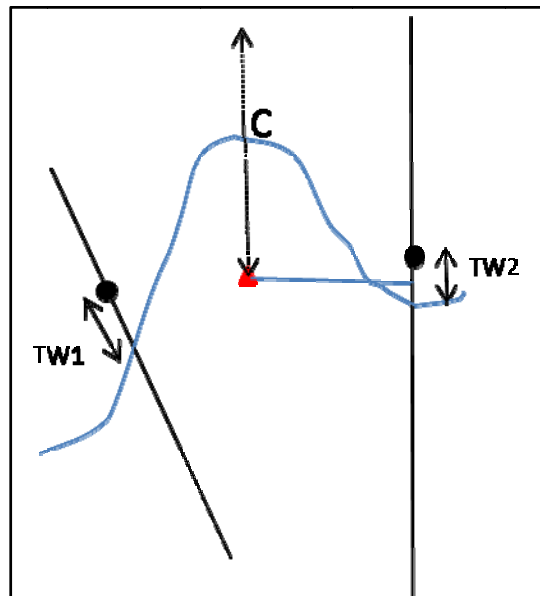


Figure 4.6. Problem with the normal distances approach

4.3.3 Method 3 – Buffer floodway method

The buffer floodway method combines the strengths of proximity and TIN interpolation tools available in ArcGIS. In the buffer floodway method, multiple buffer rings of the river centerline are generated and a TIN of these rings (buffertin) is created.

The topwidths at each cross-section are used as elevation values to create another TIN (XSTin). The two TINs are intersected and the difference between them would yield the floodway boundary. The TIN intersection approach is widely used for floodplain delineation purposes. For floodway mapping, the TIN elevations are based on the floodway topwidths at each cross-section. Figure 4.7 shows the difference in floodway delineation as mapped by the buffer floodway technique and the stream morph method. In this paper, more focus has been provided on the challenges in implementing the buffer floodway algorithm. We also detail the potential workarounds that have been employed to improve the algorithm to produce an aesthetically pleasing floodway boundary.

The buffer floodway method based on the topwidths enables a quick way to map the floodway boundary across the entire length of the stream. It should be noted that the generated floodway boundary does not match the encroachments stations at all the cross-sections. The advantages of using the buffer floodway method are:

1. The river buffer helps to maintain the sinuosity of the river, especially at cross-sections at which the top widths are narrow.
2. The buffer floodway approach eliminates the problem of the floodway boundary intersecting with the river centerline.
3. Since the cross-sections are elevated by their top width values (different width on either side of the river centerline), the boundary would match the encroachments in the majority of the stations. It also prevents the floodway boundary being mapped inside the encroachments at any cross-section.

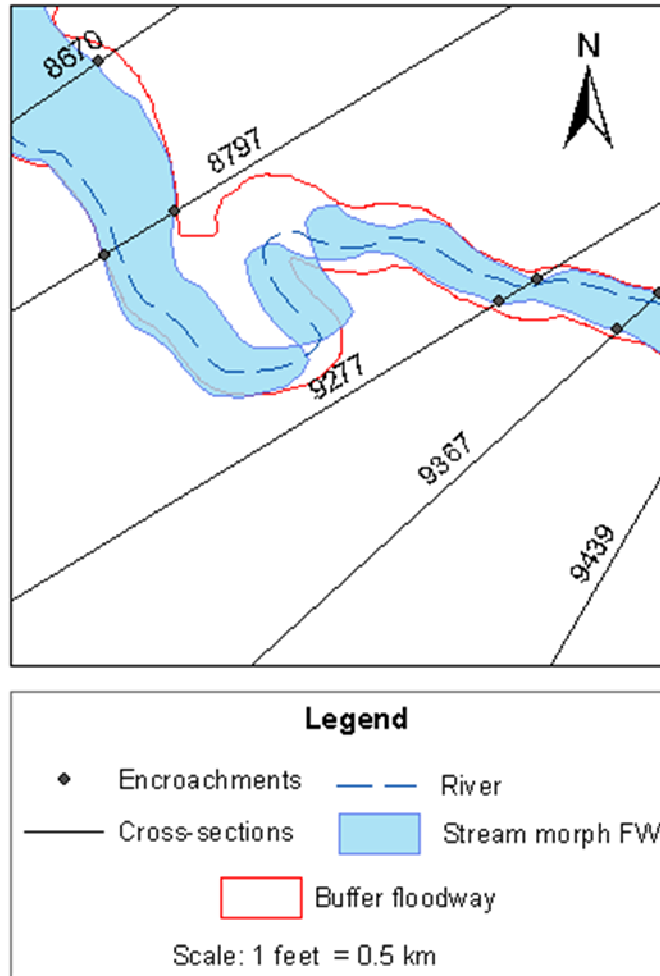


Figure 4.7. Map showing buffer floodway method vs. Stream morphing method

The limitations of the TIN intersection approach are:

1. The first major limitation is that the floodway boundary would not match the encroachment stations at all the cross-sections. Hence, some manual editing is required to finalize the floodway.
2. The buffer rings get generalized as we move far away from the stream centerline. Hence, at cross-sections with very wide topwidths, the boundary would be mapped wider than necessary.

3. Long cross-sections with wings and curved cross-sections might adversely influence the TIN interpolations between them. It might result in underestimating or overestimating the interpolated elevations which would affect the floodway mapped between those two cross-sections.
4. In some cases, the topwidth variations between two consecutive cross-sections might be high, resulting in complex triangulation patterns.

4.4 Challenges in buffer floodway method

The buffer floodway method necessitated both data pre-processing and post-processing of the resultant floodway. The river buffer widths were determined based on the minimum and maximum floodway width on either side of the river centerline. It ensured that the buffer rings would encompass all the encroachment stations along the reach. The minimum and maximum topwidths also determined the buffer ring intervals. The XSTin was created with cross-sections with an elevation value equal to the floodway topwidth at that cross-section. Numerous pre-processing procedures were applied before building the XSTin. They are listed below:

1. The left and right topwidths at each cross-section are different. Each cross-section was split at the point where it intersected with the river centerline. The left and right cross-section features were then assigned elevations pertaining to the topwidth. This preprocessing of the cross-section was necessary to generate accurate TINs on either side of the river centerline.
2. The cross-section input features contain no intermediate vertices. Lack of sufficient vertices affected the TIN triangulation patterns as shown in Figure 4.8 (left). It can be seen that the TIN interpolation bands between two consecutive cross-sections is not smooth. Such triangulations are not desirable while interpolating between two cross-sections. Typically, the TIN interpolation process is expected to produce long near-linear striations.

Hence, the cross-sections were densified in order to eradicate abnormal triangulation patterns. It could be seen that the TIN interpolation bands between cross-sections 7617 and 8797 improved vastly after densification (Figure 4.8, right). There is a smooth linear transition in elevation from one cross-section to the next.

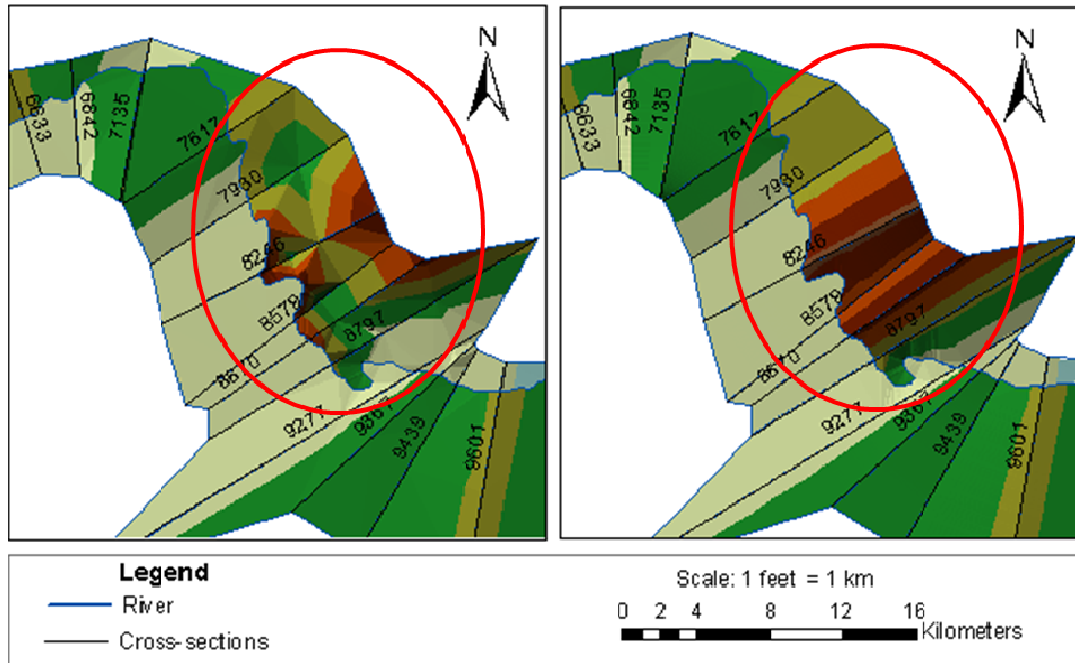


Figure 4.8. Improvements in TIN triangulation due to densification

3. As the TIN elevations on the cross-sections are different on each side of the river, the TIN triangulations on one side influenced the triangulation on the other side. It is due to high differences in topwidths at a given cross-section. In order to overcome this issue, an elevated ‘wall’ was created near the river centerline which improved the quality of TIN triangulation. Figure 4.9 shows a perspective view of the elevated ‘wall’ near the river centerline. It can be seen that the elevated wall acted like a hard breakline in TIN creation. The

elevation wall prevented triangulation to cross across to the other side of the river centerline.

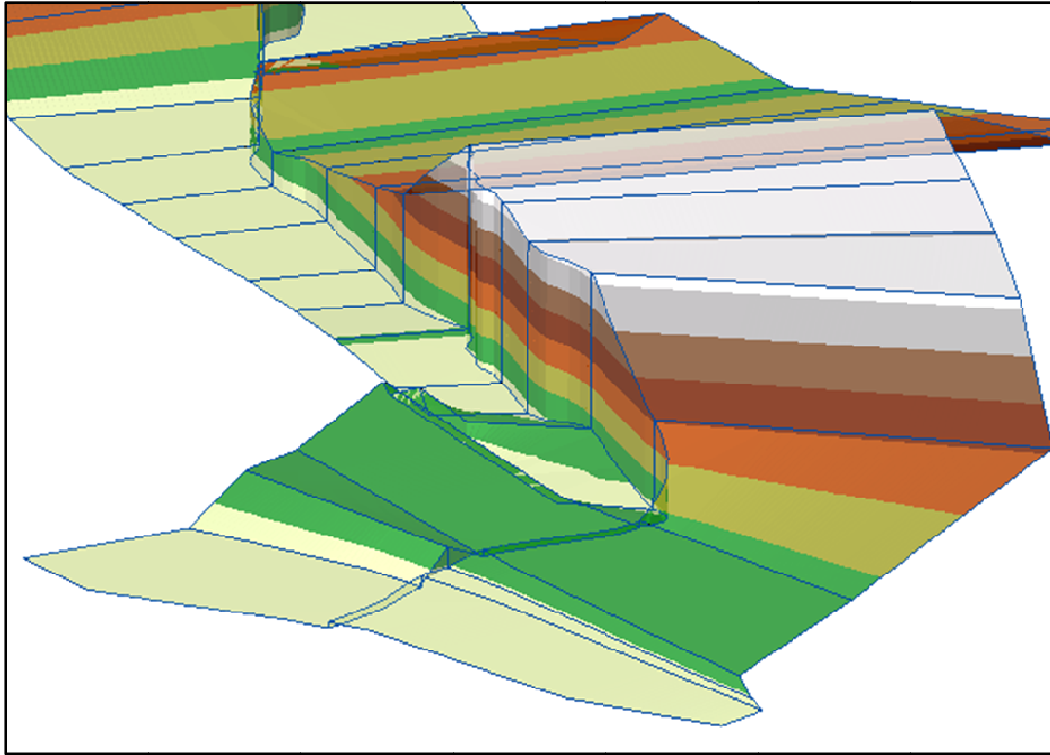


Figure 4.9. Elevation 'wall' along the river centerline

4. Any area outside of the cross-section limits should not be used in the TIN intersection method. Hence, a bounding polygon was generated surrounding the ends of the cross-sections. The bounding polygon was elevated based on interpolated elevations between the cross-sections and used as a hard clip in the XS tin creation process.

4.5 Post-processing the floodway polygon output

The TIN intersection output is a polygon that shows areas where one TIN was higher in elevation than another. Two major post-processing operations on the TIN intersection polygon were geometry cleanup and transformation. The geometry cleanup involved exploding the multipart features and simplifying the floodway boundary polygon. These cleanups resulted in the deletion of small internal and external islands. Such artifacts are attributed to the tightly constructed multiple buffer rings and large differences in topwidth from one cross-section to the next.

The last post-processing operation was to transform the curve to pass through the encroachment stations at each cross-section. ArcGIS software provides five spatial adjustment routines – affine, projective, similarity, rubbersheeting and edge matching. Manual tests were conducted to see which method fit the curve to intersect with the encroachment stations along each cross-section. Since the transformations were aimed at generating a visually pleasing floodway boundary, the statistical validity like the Root Mean Square (RMS) error of the fitted curve was not considered.

We concluded that the rubbersheeting technique gave the best fit for the application at hand. The rubbersheeting process managed to transform the curve to pass through a majority of the cross-sections. The rubbersheeting process provided the most acceptable floodway boundary that made the boundary pass through most of the cross-sections. Figure 4.10 shows the difference between the rubbersheeted boundary and the raw floodway from TIN intersection. It can be seen that the transformed rubbersheeted boundary (hatched symbology) has a good fit.

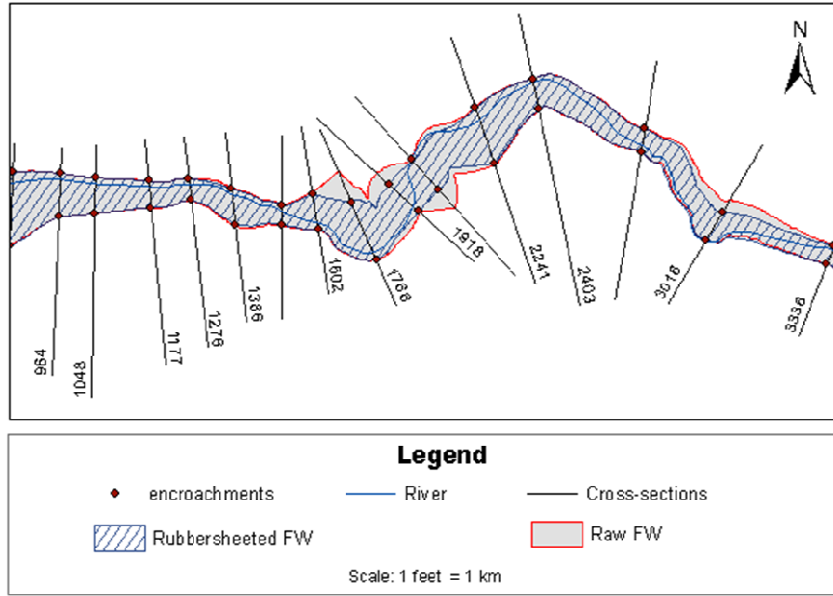


Figure 4.10. Comparison of the raw floodway and rubbersheeted floodway

In theory, similarity transformation should give the best fit for the floodway curves as it maintains the aspect ratio of the features to be transformed. Further tests were conducted wherein subcurves between a cross-section pair were extracted to perform localized similarity transformations. There were two control points for each pair and it was observed that localized similarity transformations also gave very desirable results (Figure 4.11). It can be seen that the similarity transformation method produced a better curve shape between cross-sections 1766 and 1918 on the left side. The similarity transformation technique also produced a better output between cross-sections 2036 and 2241 on the right side.

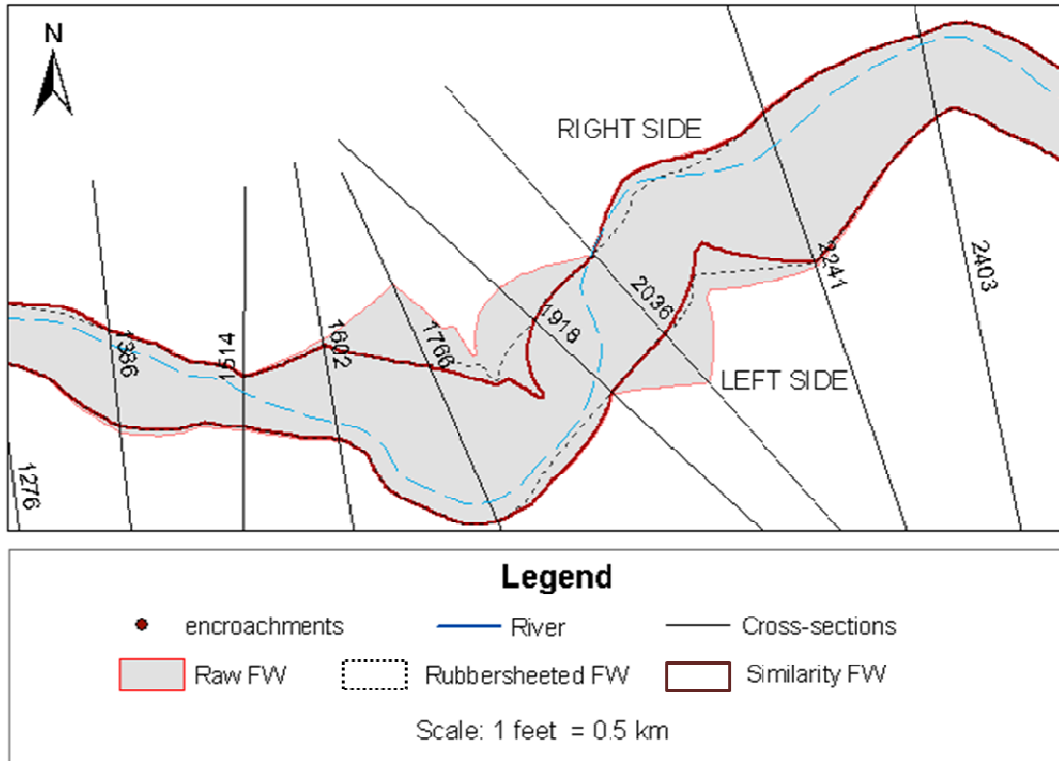


Figure 4.11. Localized similarity transformation comparison with rubbersheeted floodway

It should be added that the buffer floodway method output is not the final floodway boundary that can be directly exported to DFIRMs in the map production environment. The modeler has to do some fine-tuning at some areas to factor the local community's development interests and also the aesthetics of the boundary. For example, in Figure 4.11, the fitted rubbersheeted boundary cuts the river centerline between cross-sections 1918 and 2241. It is possible to notice such effects using a similarity transformation too. It is the modeler's responsibility to check the mapping output to finalize the floodway boundary to be mapped on a DFIRM. It is suggested that the modeler take into consideration the mapping scale at which the floodway boundary would be drawn.

4.6 Summary and Conclusions

The floodway mapping process involves identifying a best-fit curve that satisfies FEMA requirements and passes their QA/QC process. Any automated mapping process should take into consideration the topwidth of the floodway and minimize jagged lines that traverse in and out from one cross-section to another. This paper presented three algorithms that would perform floodway smoothing. We have also highlighted some of the issues that can affect or unduly influence the floodway boundary. Preprocessing the data (densification and elevated wall) is vital to the success of the recommended buffer floodway algorithm.

The buffer floodway algorithm is not without its drawbacks. However, it should be noted that the final output (after post-processing) from the algorithm provides a very good floodway boundary for the modelers to fine-tune manually. The DFIRM production mapping scales should also be considered. There is still room for improvement in this algorithm. For example, we found that localized rubbersheeting provided better results in some locations. Alternatively, we can also provide the outputs from various transformation methods and let the modeler pick the best fit for the study reach. The buffer floodway algorithm makes good use of the spatial and cartographic capabilities of ArcGIS to develop smoothed floodway boundaries between modeled cross-sections.

4.7 Acknowledgments

The authors would like to thank Mr. Kendrick Logsdon Jr. of Dewberry, LLC for his invaluable technical and design inputs while developing the algorithms for floodway mapping. The authors would also like to thank Dr. Janghwoan Choi, engineer/GIS developer, Dewberry, LLC for providing feedback and algorithmic suggestions to

improve the features and final floodway mapping output. Mr. Milver Valenzuela, engineer, Dewberry and Mr. Xiaoyi Zhang deserve a special mention for their fundamental algorithmic inputs in the mapping process.

4.8 Paper references

Baker M.E., Wiley M.J. and Seelbach P.W. (2001). "GIS based hydrologic modeling of riparian areas: implications for stream water quality". JAWRA 37 (6), 1615-1628.

Beavers, M. A. (1994). "Floodplain determination using HEC-2 and geographic information systems" Masters Thesis, Department of Civil Engineering, University of Texas at Austin, Austin, TX.

Burby R.J. (2001). "Flood insurance and floodplain management: the US experience". Environmental Hazards, 3, 111-122.

Clark, M. J. (1998). "Putting water in its place: A perspective on GIS in hydrology and water management". Hydrological Processes, 12(6), 823-834.

De Roo A.P.J., Wesseling C.G., and Van Duersen W.P.A. (2000). "Physically-based river basin modeling within a GIS: the LISFLOOD model". Hydrological Processes, 14 (11-12), 1981-1992.

Fotheringham, A. S., & Rogerson, P. A. (Eds.). (1994). "Spatial analysis and GIS". Taylor & Francis, London.

Franke R. (1982). "Scattered data interpolation: Test of some methods", Math. Of Computation, 38 (157), 181-200.

ESRI (2009). ArcGIS 9.3 software help documentation

Gold C.M. (1984). "Common-sense automated contouring – some generalization", Cartographica, 21, 121-129.

Gold C.M., (1988). "Point and area interpolation and the digital terrain model", Proc. Second Int. Seminar on trends and concerns of spatial sciences, 133-147.

Goodchild, M. F., Haining, R., & Wise, S. (1992). "Integrating GIS and spatial data analysis: Problems and possibilities". International Journal of Geographical Information Systems, 6, 407-423.

Griva A., Baltas E.A., Varanou A., and Mimikou M.A. (2003). "GIS-based Floodplain Mapping in Greece". International conference - Towards natural flood reduction strategies, Warsaw.

- Haestad Methods, Dyhouse G., Hatchett J., Benn J. (2003). "Floodplain Modeling using HEC-RAS". Haestad Press, First Edition, Waterbury, Connecticut, USA.
- Lawson C.L. (1977). "Software for C1 surface interpolation", Mathematical software III, J.R.Rice ed., Academic Press, New York, New York, USA, 161-194.
- Lee D.T., and Schacter B.J (1980). "Two algorithms for constructing a Delaunay triangulation", International Journal of Computer and Information Science, 9 (3) 219-242.
- L.R.Johnston Associates, (1992). "Floodplain Management in the United States: An Assessment Report". Vol.2
- Luzio M.D., Srinivasan R., and Arnold J.G. (2004). "A GIS coupled hydrologic model system for the watershed assessment of agricultural nonpoint and point sources of pollution". Transactions In GIS, 8(1), 113-136.
- Maidment D.R., (2002). "ArcHydro: GIS for water resources". ESRI Press, California, USA.
- Noman N.S., Nelson J.E., and Zundel A.K. (2001). "Review of automated floodplain delineations from digital terrain models". Journal of Water Resources Planning and Management., 127 (6), 394-402.
- Selvanathan S., Dymond, R.L. (2009) "An algorithmic approach to iterative floodway modeling using HEC-RAS and GIS". Accepted to be printed in the Journal of Flood Engineering 1 (1).
- Singh, V. P., & Fiorentino, M. (1996). "Geographical information systems in hydrology". Dordrecht, Netherlands: Kluwer Academic Publishers.
- Storck P., Bowling L., Wetherbee P., and Lettenmaier D. (1998) "Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak streamflow in the Pacific Northwest". Hydrological Processes, 12(6), 889-904
- Sui D.Z., and Maggio R.C. (1999). "Integrating GIS with Hydrologic Modeling: Practices, Problems and Prospects". Computers, Environment and Urban Systems 23, 33-51.
- Tate E.C., Maidment D.R., Olivera F., and Anderson D.J. (2002). "Creating a terrain model for floodplain mapping". Journal of Hydrologic Engineering,, 7(2), 100-108.
- Tsichritzis C., and Lochovsky F.H., (1977). "Database Management Systems", Academic Press, New York, New York, USA.
- Schut G., (1976). "Review of the interpolation methods in digital terrain models". Canadian Surveyor, 30, 389-412
- Watson D.F., and Philip G.M., (1985). "A refinement of inverse distance weighted interpolation", Geoprocessing, 2, 315-327.
- Whiteaker T.L., Robayo O., Maidment D.R., and Obenour D. (2006). "From a NEXRAD Rainfall map to a floodplain map". Journal of Hydrologic Engineering,, 11(1), 37-45.

5 Summary and Conclusions

Manual floodway modeling is a time-consuming process depending on the complexity of the study reach. The floodway outputs are then exported to a GIS and analyzed in order to factor in the local community's development constraints and other spatial variables. The next step is to generate a smooth floodway boundary that is fine-tuned to produce the final floodway extents. This final output is then mapped on DFIRMs and made available in the public domain.

5.1 Summary

FEMA administers the National Flood Insurance Program (NFIP) in the United States for regulating flood insurance for property owners. One of the main goals of the NFIP is to identify the nation's floodplains and map them for flood insurance purposes. FEMA designates the areas covered by the base flood as Special Flood Hazard Areas (SFHAs). In some of the SFHAs, termed as detailed study areas, it is mandatory to perform both floodplain and floodway modeling.

Floodway modeling is an iterative process of identifying a best-fit boundary around the main river channel that allows the base flood discharge without increasing the water surface elevation above a stipulated surcharge. A typical manual modeling process takes repeated HECRAS model runs and exporting the results to a GIS whenever necessary to perform a spatial check on the model results. It should be noted that the iterative process coupled with repeated export of HECRAS model output to a GIS results in wastage of modeling time. In a professional working environment, it becomes necessary to minimize time losses and improve efficiency.

The principal goal of the research is to develop an algorithmic approach to automate the HECRAS floodway modeling process aimed at saving modeling time. The HECRAS software lacks a good mapping and spatial analysis environment that

can display and analyze the model output. The ArcGIS environment has been used to act as a visual platform setting up HECRAS input files and communicating the floodway output to the modeler. The ArcGIS software also facilitates the modeler to perform extensive spatial analysis and topology checks before sending the floodway for FEMA's QA/QC process prior to final mapping. The research goal was achieved by completing the following objectives:

1. Develop and implement an algorithmic, automated approach for iterative floodway modeling using HECRAS's modeling engine and Environmental Systems Research Institute's (ESRI) ArcGIS software.
2. Develop an interactive visual ArcGIS environment for floodway modeling which enables the modeler to alter floodway boundaries within ArcGIS and remodel the floodway using HECRAS engine.
3. Translate the HECRAS floodway output into smooth floodway boundaries (using 3 different methods) that can be modified with minimal user adjustment to be printed on DFIRMs.

The first objective was achieved by developing an algorithm which executed the HECRAS software engine repeatedly until all the cross-sections along the reach are within acceptable floodway surcharges. Chapter 2 provided detail information about the algorithm that was used to automate floodway modeling. A typical manual approach to HECRAS floodway modeling would be to perform Method 4 encroachment analyses, followed by repeated Method 1 runs before finalizing the floodway model output based on the surcharges. The algorithm does the same wherein it checks for excessive and negative surcharge cross-sections along the study reach (Figure 2.3). Such cross-sections are iteratively modeled by editing the HECRAS input file based on engineering decisions.

The key engineering variables that govern the algorithmic routines are output surcharges, critical depth, encroachment stations, ineffective areas, channel banks, floodplain boundary, and change in energy grade elevations. The algorithm achieved significant time savings (Table 2.2). It should be noted that the algorithm may not

produce a floodway output that has all cross-sections with acceptable surcharge. A modeler has to manually perform some fine-tuning to the encroachments and ensure that the model is ready to be mapped.

The second objective has been met by developing a tight-coupling system (Figure 3.5) called FloodwayGIS, which enables the modeler to edit, remodel and analyze floodway output from HECRAS. Chapter 3 in the dissertation explains the components of FloodwayGIS. FloodwayGIS environment translates HECRAS model output into a visual map output. The visual environment is equipped with four different tools to edit floodway encroachments. The modeler can use these tools to remodel floodway extents while visually inspecting the new position of the encroachments on the map. In addition to being more efficient in displaying HECRAS model output, FloodwayGIS also saves time during the process. The sequential procedure with manual modeling includes going back and forth between HECRAS and ArcGIS by using 'Export GIS Data' in HECRAS. FloodwayGIS eradicates the need for repeated transfers and the model output after each edit trial is immediately updated on the map display.

The next step in floodway modeling is to translate the floodway output (encroachment stations) at each cross-section into a smooth and continuous floodway boundary. FloodwayGIS provides various automatic mapping routines and algorithms that achieve this task. The modeler is provided with different mapping outputs from which the best fit boundary can be chosen. It should be reiterated that some manual fine-tuning will be necessary before finalizing the mapping output.

Smooth floodway boundary generation is a complicated task in which care should be taken not to delineate boundaries inside the main channel and also snapping the boundaries at the encroachment stations at the cross-sections. Objective 3 was aimed at generating such boundaries which would require minimal user adjustments. Chapter 4 details the various algorithms that have been developed to smooth a raw floodway output from HECRAS. Smoothing has been achieved by a combination of TIN interpolation and mathematical curve transformation techniques (Figures 4.10, 4.11). In addition to achieving Objective 3, Chapter 4 also discusses the various

advantages and disadvantages of using a particular method for mapping. It also highlights the spatial interpolation capabilities of ArcGIS. Some pre- and post-processing procedures were performed which vastly improved the floodway boundary output.

The research presented here outlines FEMA's technical requirements for a floodway modeling and mapping process for the NFIP. The research also highlights the significance of automating the floodway modeling process and the time savings thus achieved. A sophisticated and efficient mapping environment in ArcGIS has been developed to map a floodway. Employing a fully commercial GIS like ESRI's ArcGIS as a mapping environment empowers a modeler to perform detailed spatial analysis on the floodway output. The research also evaluates multiple GIS algorithms for floodway mapping and combines spatial and mathematical techniques to establish a continuous floodway boundary.

5.2 Contributions

Numerous GIS-H&H coupling systems exist that tap into the analytical capabilities of ArcGIS while still using the full capabilities of a full-fledged H&H model. ArcGIS has been coupled with HECRAS to map and manage floodplain mapping studies. However, there has been a big void in coupling ArcGIS and HECRAS for floodway modeling purposes. This research has made a successful attempt to fulfill that functionality gap coupling ArcGIS and HECRAS for floodway modeling. Some of the principal contributions are as follows:

1. The automation procedure provides an improved algorithmic approach to HECRAS floodway modeling. Computers have the capability to perform engineering computations more rapidly without human error. Although operator errors are inevitable, this study has contributed a smartly implemented algorithm for iterative floodway modeling.

2. The time savings are significant which translates into better productivity in a professional environment.
3. The FloodwayGIS visual platform provides the ability to perform a full-fledged HECRAS floodway modeling. Visualizing the changes being made almost immediately provides the modeler with useful spatial information with regards to placement of encroachments. This information can be efficiently used to improve the quality of floodway modeling.
4. FloodwayGIS also lets a modeler map older floodway boundaries done in a previous study by just re-running the HECRAS model. Again, the time savings can be significant especially if aerial photos and existing floodway boundaries are readily available to be used as guides in editing encroachments.
5. The smoothing algorithms and their investigation have brought forth pointers about best utilizing the capabilities of ArcGIS in mapping applications. Such techniques may be extended to other engineering applications.

5.3 Future work

1. There is high potential to use this research as a starting point in developing flood risk maps. Future projection estimates of urbanization, population growth, increase in the number of structures and river channel modifications (based on development) are some of the information that can be very useful in generating risk maps. Such risk maps can be a good predictive tool in urban planning applications.
2. The present research was based on 1-percent chance flood for FEMA's NFIP program. However, local communities can use the tool to generate similar extents for shorter and higher frequency storm events. Such investigations can reveal susceptibility to a more immediate flood risk. From an insurance standpoint, flood risk involves estimating damage to a property in an area. Based on the

design life expectation and the location of the property, the flood risk can be calculated. Such data can be used for emergency disaster management procedures and flood damage assessments.

3. Availability of spatial data like the landuse, buildings, population density, and watershed buildout can be used to develop a decision support system for finalizing the floodway during modeling.
4. More investigation can be done on the performance of the floodway modeling algorithm based on the length, sinuosity and flow volumes along a reach.
5. Another interesting study would be to assess the performance of the algorithm when there are a lot of structural obstructions regulating the flow. The floodway morphology can be investigated near the structures and identify any structural design parameters that adversely affect the floodway morphology.

6 References

- Abbott M.B., Bathurst C.J., Cunge J.A., O'Connell P.E., and Rasmussen J. (1986). "An introduction to European Hydrologic System – Systeme Hydrologique Europeen, SHE: History and philosophy of a physically based distributed modeling system. *Journal of Hydrology*, 87, 45-59.
- Al-Sabhan W., Mulligan M. and Blackburn G.A. (2003). "A real-time hydrological model for flood prediction using GIS and the WSW". *Computers, Environment and Urban Systems*, 27(1), 9-32.
- Baird L., Gee, D.M., and Anderson M.G. (1992). "Ungauged catchment modeling II. Utilization of hydraulic models for validation". *Catena*, 19, 33-42.
- Bates P.D., and Anderson M.G. (1993). "A two-dimensional finite element model for river flow inundation". *Proceedings: Mathematical and Physical Sciences of the Royal Society of London*, 440 (1909), 481-491.
- Bates P.D., and De Roo A.P.J. (2000) "A simple raster-based model for flood inundation simulation". *Journal of Hydrology*, 236, 54-77
- Bates P.D., Horritt M.S., Smith C.N., and Mason D.C. (1997) "Integrating remote sensing observations of flood hydrology and hydraulic modeling". *Hydrological Processes*, 11, 1777-1795.
- Beavers, M. A. (1994). "Floodplain determination using HEC-2 and geographic information systems". Masters thesis, Department of Civil Engineering, University of Texas at Austin, Austin, TX.
- Bisese J.A. (1995). "Methods for estimating the magnitude and frequency of peak discharges of rural, unregulated streams in Virginia". US Department of Interior, Geological Survey, Richmond, VA. Water Investigations Report 94-4148.
- Bradley A.A., Cooper P.J., Potter K.W., and Price T. (1996). "Floodplain mapping using continuous hydrologic and hydraulic simulation models". *Journal of Hydrologic Engineering*, 1(2), 63-68.
- Burby R.J. (2001). "Flood insurance and floodplain management: the US experience". *Environmental Hazards*, 3, 111-122.
- Burby R.J., French S.P., (1985). "Floodplain landuse management: A National Assessment". Westview Press, Boulder, Colorado, USA.
- Burns D., Vitvar T., McDonnell J., Hassett J., Duncan J., and Kendall C. (2005) "Effects of suburban development on runoff generation in the Croton River Basin, New York, USA". *Journal of Hydrology*, 311 (1-4), 266-281.
- Chow V.T., (1959). "Open Channel Hydraulics". McGraw Hill, New York, New York, USA.
- Clark, M. J. (1998). "Putting water in its place: A perspective on GIS in hydrology and water management". *Hydrological Processes*, 12(6), 823-834.
- Code of Federal Regulations (CFR), Title 44, Volume 1, Part 59, Sec 59.1
- Crawford N.H., and Linsley R.K., (1966). "Digital Simulation in hydrology", Stanford Watershed Model, Tech Report No.39, Stanford University.

- Cunge J.A., Holly Jr. F.M., Verwey A., (1976). *Practical Aspects of Computational River Hydraulics*, Pitman London.
- Dawdy D.R. and O'Donnel T., (1965). "Mathematical models of catchment behavior". *Journal of Hydraulic Division, Proceedings of ASCE HY4*.
- Day J.C. (1973). "A linear programming approach to floodplain landuse planning in urban areas". *Journal of Agricultural Economics*, 55 (2), 165-174.
- DeVantier, B. A., & Feldman, A. D. (1993). "Review of GIS applications in hydrologic modeling". *Journal of Water Resources Planning and Management*, 119, 246-261.
- Dutta D., Herath S., and Musiak K. (2000). "Flood inundation simulation in a river basin using a physically based distributed hydrologic model". *Hydrological Processes*, 14, 497-519.
- Estrela T., and Quintas L., (1994). "Use of a GIS in the Modeling of Flows on Floodplains". White W.R., Watts J., (Eds). *Proceedings of the 2nd International Conference on River Flood Hydraulics*, Wiley, 177-189
- Fairfield J., and Leymarie P., (1991). "Drainage Networks from Grid Digital Elevation Models". *Water Resources Research*, 27 (5), 709-717.
- Farajalla N.S., and Vieux B.E. (2006) "Capturing the essential spatial variability in distributed hydrologic modeling: Infiltration parameters". *Hydrological Processes*, 9(1), 55-68.
- Fotheringham, A. S., & Rogerson, P. A. (Eds.). (1994). "Spatial analysis and GIS". Taylor & Francis, London.
- Franke R. (1982). "Scattered data interpolation: Test of some methods", *Mathematics Of Computation*, 38 (157), 181-200.
- Garbrecht, J. and L.W. Martz. (1999). "Digital Elevation Model Issues in Water Resources Modeling". *Proceedings of the 19th ESRI International User Conference*, San Diego, California.
- Gee D.M., Anderson M.G., and Baird L. (1990). "Large scale floodplain modeling" *Earth Surface Processes And Landform*, 15, 513-523
- Gold C.M. (1984). "Common-sense automated contouring – some generalization", *Cartographica*, 21, 121-129.
- Gold C.M., (1988). "Point and area interpolation and the digital terrain model", *Proc. Second international seminar on trends and concerns of spatial sciences*, 133-147.
- Goodchild, M. F., Haining, R., & Wise, S. (1992). "Integrating GIS and spatial data analysis: Problems and possibilities". *International Journal of Geographical Information Systems*, 6, 407-423.
- Griva A., Baltas E.A., Varanou A., and Mimikou M.A. (2003). "GIS-based Floodplain Mapping in Greece". *International conference - Towards natural flood reduction strategies*, Warsaw.
- Haestad Methods, Dyhouse G., Hatchett J., Benn J. (2003). "Floodplain Modeling using HEC-RAS". Haestad Press, First Edition, Waterbury, Connecticut, USA.

- Hardy R.J., Bates P.D., Anderson M.G. (1997). "The importance of spatial resolution in hydraulic models for floodplain environments". *Journal of Hydrology*, 216, 124-136.
- Hartley R.I. (1999). "Theory and practice of projective rectification". *International Journal of Computer Vision*, 35 (2), 115-127.
- Hornberger G.M., and Boyer E.W. (1995). "Recent advances in watershed modeling" *Reviews of Geophysics*, 33, 949-957.
- Horritt M.S., and Bates P.D., (2002). "Evaluation of 1D and 2D Numerical Models for Predicting River Flood Inundation". *Journal of Hydrology*, 268 (1-4), pp.87-99.
- Jain M.K., Kothiyari U.C., and Ranga Raju K.G. (2004). "A GIS based distributed rainfall-runoff model". *Journal of Hydrology*, 299 (1-2), 107-135.
- Johnson D.L., and Miller A.C., (1997). "A spatially distributed hydrologic model utilizing raster data structures". *Computers and Geosciences*, 23 (3), 267-272.
- Karssenberg D., (2002). "The Value of Environmental Modeling Languages for Building Distributed Hydrological Models". *Hydrological Processes*, 16(14), 2751-2766.
- King L.P., and Norton W.R. (1978). "Recent applications of RMA's finite elements model for two dimensional hydrodynamics and water quality". *Proceedings 2nd Int. Conf. on finite elements for water resources*, Pentech Press, London, 81-99.
- Knight D.W., and Shiono K., (1996). *River Channel and Floodplain Hydraulics*. In: *Floodplain Processes*, Anderson M.G., Walling D.E., Bates P.D (Eds.), John Wiley and Sons
- Leavesley G.H., Lichty R.W., Troutman B.M., and Saindon L.G. (1983). "Precipitation runoff modeling system, user manual". *USGS Water Resources Investigation Report 83-4238*
- Lawson C.L. (1977). "Software for C1 surface interpolation", *Mathematical software III*, J.R.Rice ed., Academic Press, New York, New York, USA, 161-194.
- Lee D.T., and Schacter B.J (1980). "Two algorithms for constructing a Delaunay triangulation", *International Journal of Computer and Information Science*, 9 (3) 219-242.
- L.R.Johnston Associates, (1992). "Floodplain Management in the United States: An Assessment Report". Vol.2
- Maidment D.R., (1992). "Grid-based computation of runoff: A Preliminary Assessment". *Hydrologic Engineering Center, USACE, Davis California*.
- Maidment, D. R. (1993). "GIS and hydrological modeling". In M. F. Goodchild, B. Parks, & L. Steyaert, (Eds.), *Environmental modeling with GIS*, Oxford University Press, New York, 147-167.
- Maidment D.R., and Djokic D. (2000). "Hydrologic and Hydraulic Modeling Support with Geographical Information Systems". *ESRI Press, California, USA*.
- Marks D., Dozier J., and Frew J., (1984). "Automated Basin Delineation from Digital Elevation Data". *Geo-Processing*, 2, 299-311.

- Martin P.H., Lebouef E.J., Dobbins J.P., Daniels E.B., and Abkowitz M.D. (2005) "Interfacing GIS with water resource models: A state of the art review". *Journal of American Water Resources Association*, Paper No. 03208.
- Martz L.W, and Garbrecht J., (1992) "Numerical Definition of Drainage Network and Subcatchment Areas from Digital Elevation Models". *Computers and Geosciences*, 18 (6), 747-761.
- Mason Jr. R.R. and Fuste L.A. (2001). "The National Flood Frequency Program – Methods for estimating flood magnitude and frequency in rural areas of Virginia". US Department of Interior, Geological Survey, Reston, VA. Fact Sheet 023-01.
- McDonnell, R. A. (1996). "Including the spatial dimension: Using geographical information systems in Hydrology". *Progress in Physical Geography*, 20, 159-177.
- Moore, I.D., Grayson R.B., and Brunsch G.J. (1988). A Contour-Based Topographic Model for Hydrological and Ecological Applications. *Earth Surface Processes and Landforms*, 13, 305-320
- Noman N.S., Nelson J.E., and Zundel A.K. (2001). "Review of automated floodplain delineations from digital terrain models". *Journal of Water Resources Planning and Management*, 127 (6), 394-402.
- Pinder G.F., and Gray W.G. (1977). "Finite element simulation in surface and subsurface hydrology". Academic Press, New York, New York, USA.
- Robayo O., (2005) "Map to Map: Converting a NEXRAD rainfall map into a floodplain map". PhD dissertation, University of Texas at Austin
- Rose S., and Peters N.E. (2001). "Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach". *Hydrological Processes*, 15(8), 1441-1457
- Rossman L.A., (2009). "Storm Water Management Model, user manual v.5". National Risk Development Research Laboratory, EPA Document EPA/600/R-05/040.
- Schut G., (1976). "Review of the interpolation methods in digital terrain models". *Canadian Surveyor*, 30, 389-412
- Sheaffer J.R. (1960). "Flood proofing: An element in a flood damage reduction program". In *Papers on flood problems*, editor: Gilbert F.White, Res. Paper 65.
- Singh V.P., and Woolhiser D.A. (2002). "Mathematical Modeling of Watershed Hydrology". *Journal of Hydrologic Engineering*, 7(4), 270-292.
- Storck P., Bowling L., Wetherbee P., and Lettenmaier D. (1998) "Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak streamflow in the Pacific Northwest". *Hydrological Processes*, 12(6), 889-904
- Sui D.Z., and Maggio R.C. (1999). "Integrating GIS with Hydrologic Modeling: Practices, Problems and Prospects". *Computers, Environment and Urban Systems* 23, 33-51.
- Tate E.C., Maidment D.R., Olivera F., and Anderson D.J. (2002). "Creating a terrain model for floodplain mapping". *Journal of Hydrologic Engineering*, 7(2), 100-108.
- Thomas T.G., and Williams J.J.R., (1995) Large Eddy Simulation of Turbulent Flow in an Asymmetric Compound Open Channel". *Journal of Hydraulic Research*, 33, 27-41.

- Todini E. (1988). "Rainfall runoff modeling: past, present and future". *Journal of Hydrology*. 100, 341-352.
- Townsend P.A., and Walsh S.J. (1996). "Modeling floodplain inundation using an integrated GIS with radar and optical remote sensing". *Geomorphology*, 21(3-4), 295-312.
- Tsichritzis C., and Lochovsky F.H., (1977). "Database Management Systems", Academic Press, New York, New York, USA.
- USACE (1968). Survey Investigations and Reports. Circular 1120-2-40, Washington D.C.
- USACE (2002). HEC-RAS User's Manual Ver. 3.1.
- Vieux B.E., and Gauer N. (2008). Finite element modeling of storm water runoff using GRASS GIS". *Computer aided Civil and Infrastructure Engineering* 9(4), 263-270.
- Wang Y., Colby J.D., and Mulcahy K.A. (2002). "An efficient method for mapping flood extent in a coastal floodplain using Landsat TM and DEM data". *International Journal of Remote Sensing*, 23(18), 3681-3696.
- Watson D.F., and Philip G.M., (1985). "A refinement of inverse distance weighted interpolation", *Geoprocessing*, 2, 315-327.
- White M.S. and Griffin. P., (1985). "Piecewise linear rubber-sheet map transformation", *Cartographic and Geographic Information Science*, 12 (2), 123-131.
- Whiteaker T.L., Robayo O., Maidment D.R., and Obenour D. (2006). "From a NEXRAD Rainfall map to a floodplain map". *Journal of Hydrologic Engineering*, 11(1), 37-45.

Appendix A

Source code availability and tool distribution

Primary contacts: Sivasankkar Selvanathan (sivasankkar@gmail.com) or Dr. Randy Dymond (dymond@vt.edu).

Source code availability: public. It can be requested by emailing one of the contacts.

Client side requirements: Visual Studio 2008 professional edition, .NET Framework 2.0 (or higher) to view and make modifications to the source code.

Code dependencies: ArcGIS 9.3 libraries and HECRAS 4.0 libraries.

Tool distribution: Dynamic Link Libraries (dlls)

Main distribution library: CustomsContentsView.dll

Interoperability libraries: Interop.ADOODB.dll, Interop.ADOR.dll, Interop.ADOX.dll, Interop.ADOODB.dll, Interop.MsComDlg.dll and Microsoft.VisualBasic.PowerPacks.dll

Registration utility: regasm

Regasm location: “C:\WINDOWS\Microsoft.NET\Framework\v2.0.50727”

Regasm usage syntax: regasm “<path to dll>” /codebase

Appearance: Custom tab in ArcGIS’s ArcMap