
Advances in Floodplain Modeling and Mapping

Uzair (Sam) M. Shamsi

Accurate floodplain maps are the key to better floodplain management. The days of expensive and unwieldy floodplain mapping by hand using paper maps are long gone. However, much of the analysis in floodplain management studies is still performed using separate modeling and mapping programs, which is less efficient than an integrated modeling and mapping approach. Today, new technologies, such as geographical information systems (GIS), global positioning systems (GPS) and remote sensing are helping floodplain managers to create accurate and current floodplain maps, with improved efficiency and speed, and at a reasonable cost. Today, it is possible to create floodplain maps that are dynamically linked to hydrologic and hydraulic models. This linkage allows more efficient map updates if the hydrologic or hydraulic parameters are changed. This chapter describes the latest technology and applications for developing floodplain models and maps. Examples and case studies, including the Federal Emergency Management Agency (FEMA)'s map modernization (Map Mod) and new risk mapping, assessment and planning (Risk MAP) programs, are discussed to illustrate the advances in floodplain modeling and mapping applications.

20.1 Introduction

When, because of rainfall, snow melt or a dam break, water reaches a usually dry place where it is generally not expected, it is called a flood. Flooding is the most destructive and costly natural disaster in many countries, including the United States (Grigg, 2003). The work of floodplain managers is

fundamental to effectively managing floodplain resources and mitigating floods. Floodplain management entails corrective and preventive measures for reducing flood damage, such as emergency response plans, flood control structures (e.g. levees and dams) and floodplain management regulations. Accurate and current floodplain maps can be the most valuable tools to help floodplain managers avoid severe social and economic losses from floods. Accurately updated floodplain maps also improve public safety. The early identification of flood prone properties during emergencies allows public safety organizations to establish warning and evacuation priorities. Armed with definitive information, government agencies can initiate corrective and remedial efforts before disaster strikes (Chapman and Canaan, 2001).

There are two types of floods: river and coastal (lakes and oceans). This chapter focuses on river flooding. The severity of a river flood is affected by three characteristics: the depth, the velocity, and the duration of the flood. These characteristics can be studied by creating and running hydrologic and hydraulic (H&H) models. These three characteristics are themselves affected by three main factors: topography, soil, and vegetation (land cover) (Lathrop, 2001). These factors can in turn be studied by GIS, which can also help to develop H&H models and floodplain maps.

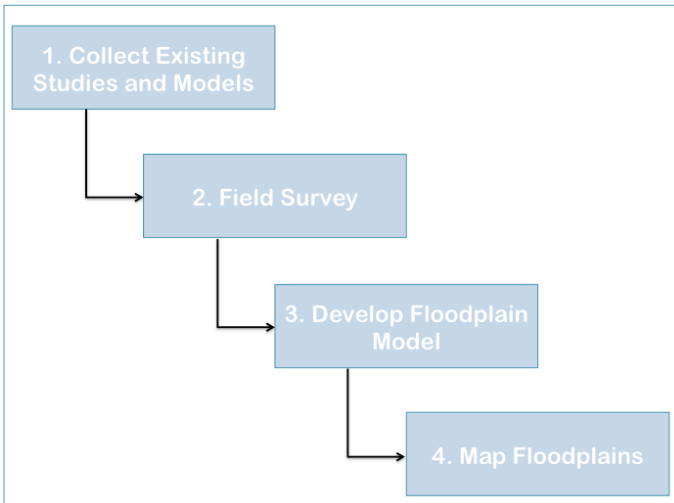


Figure 20.1 Typical floodplan analysis steps.

As shown in Figure 20.1, floodplain analysis involves four typical steps (Dodson and Li, 1999):

1. Information collection and preparation, including:
 - Existing studies and models;

- Hydrologic Data: discharge rates for the storm(s) of interest;
 - Hydraulic Data: loss coefficients and hydraulic boundary conditions;
2. Field survey:
 - Topographic Data: stream channel cross-sections and reach lengths;
 - Obstructions Data: bridge and culvert cross-sections;
 3. H&H model creation and execution; and
 4. Floodplain mapping.

20.2 FEMA's Floodplain Management Programs

In the United States, FEMA is the nation's primary source for flood maps. Established in 1803, FEMA coordinates the federal government's role in preparing for, preventing, mitigating the effects of, responding to and recovering from all domestic disasters, whether natural or caused by humans—including acts of terror. The Mitigation Directorate, a component of FEMA, manages the National Flood Insurance Program (NFIP). The three components of NFIP are flood insurance, floodplain management and flood hazard mapping. Nearly 20 000 communities across the United States and its territories participate in NFIP by adopting and enforcing floodplain management ordinances to reduce future flood damage. In exchange, NFIP makes federally backed flood insurance available to homeowners, renters and business owners in these communities. Community participation in the NFIP is voluntary.

FEMA has been providing flood hazard maps since the 1970s to help manage and reduce risk. The NFIP mapping work includes a study that yields a flood hazard boundary map, which is usually upgraded to a flood insurance rate map (FIRM). Flood prone communities rely on FIRMs for the following uses (Chapman and Canaan, 2001):

- obtaining definitive floodplain information;
- educating the public on flood risk;
- enacting regulatory requirements for new development; and
- establishing flood insurance rates.

Historically, FEMA has provided flood hazard information through paper flood insurance rate maps (FIRMs). FIRMs show zones with high flood risk, the height of the flood water, and other important information (FEMA, 2010a). The flood risk information shown on FIRMs is based on historic, meteorological, hydrologic and hydraulic data and models, as well as open space conditions, flood control structures and development. Figure 20.2

shows a sample FIRM flood map for a quadrangle (panel) in Pittsburgh, Pennsylvania. FIRMs show 100 y (base) and 500 y flood plain boundaries and elevations for most rivers and major streams of a flood prone community.

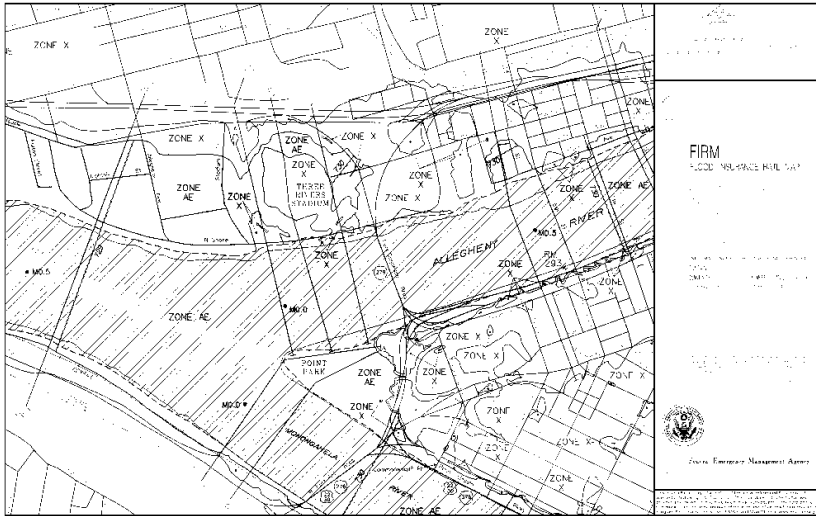


Figure 20.2 FEMA's FIRM flood map for Pittsburgh.

A flood insurance study (FIS) report usually accompanies a FIRM. These engineering studies are conducted by FEMA contractors who use H&H models to compute 100 y and 500 y peak flows and flood elevations. Most of the initial hydrologic and hydraulic modeling to compute flood plain elevations was done using the U.S. Army Corps of Engineers' Hydrologic Engineering Center's (HEC) legacy computer programs HEC-1 and HEC-2. These DOS programs are now obsolete and have been replaced by the Windows programs HEC-HMS and HEC-RAS (HEC, 2010).

20.2.1 FEMA's Map Modernization Program

FEMA's map modernization program, Map Mod, established a foundation for the easier depiction and distribution of mapped flood hazards. To complete the process, it is imperative to maintain the integrity and credibility of the engineering data for reliable risk identification, and to ensure that the information can be leveraged to improve mitigation activities beyond the minimum federal requirements for participation in NFIP (FEMA, 2010a).

Map Mod transformed the majority of the flood hazard mapping inventory to twenty-first century digital technology, and restored confidence in the reliability of floodplain boundaries, while making updates to the underlying engineering data. The dynamic nature of floodplains requires updated analysis of flood hazards periodically to maintain a reliable inventory.

FEMA’s digital products are:

- FIRM scan, which is a set of images which are digital pictures of entire flood maps;
- FIRMettes, which show a section of a FIRM scan image which can be saved and printed;
- MapViewer Web, which allows online users to select the flood hazard information to be displayed and to create custom maps and reports; and
- Digital Flood Insurance Rate Map (DFIRM) data, which is designed for use with specialized GIS software, and provides data for mapping and analysis that is more powerful than traditional map products.

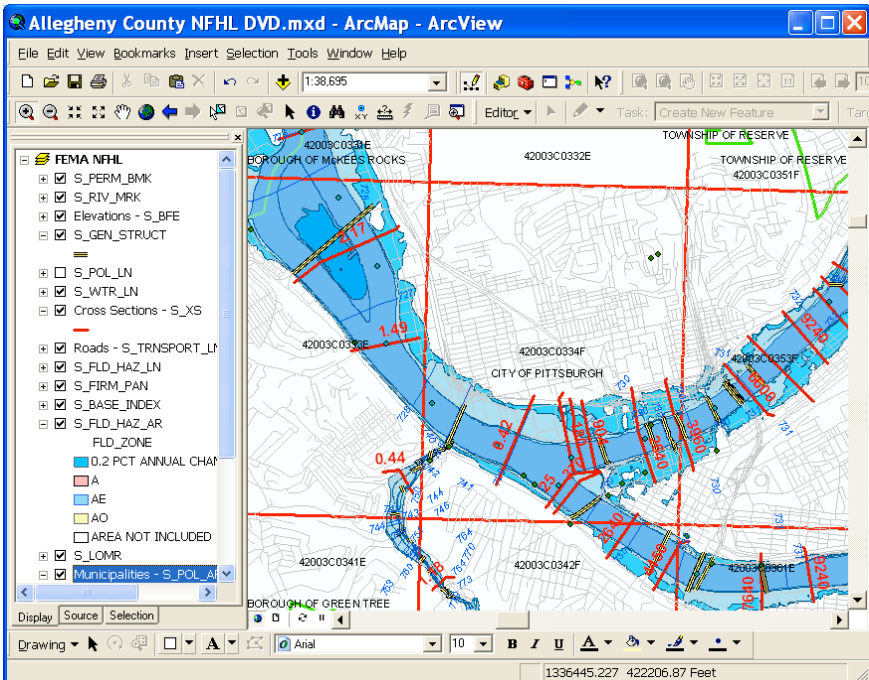


Figure 20.3 NFHL data in ArcGIS software for Pittsburgh.

DFIRM data is available for many of the highest flood risk areas. The data is available as community or county based DFIRM databases that can be downloaded or delivered on CD. The data also is available as state-based national flood hazard layer (NFHL) datasets that are delivered on DVD. FEMA also offers a MapViewer Desktop tool for viewing DFIRM databases and NFHL datasets that have been loaded on user computers. Figure 20.3 shows a sample flood map for Pittsburgh, Pennsylvania, created in ArcGIS using NFHL data. To fully appreciate FEMA’s digital revolution, compare this map and an enormous amount of attribute data (not visible but used to make this map) to the black and white paper map shown in Figure 20.2.

20.2.2 FEMA’s Risk Mapping, Assessment and Planning Program

Risk mapping, assessment, and planning (Risk MAP) is a new FEMA program that builds on the strengths of Map Mod to help communities nationwide in risk assessment and mitigation planning. The program combines quality engineering with updated flood hazard data to help communities plan for and prevent risk using the best possible information. Proper planning translates into saving more lives and money. FEMA headquarters and regional offices are leading a team of contractors and stakeholders to deliver its Risk MAP program. FEMA’s vision (Figure 20.4) for Risk MAP is to deliver quality data that increases public awareness and leads to action that reduces risk to life and property (FEMA, 2010b).



Figure 20.4 Vision for FEMA’s Risk MAP program.

The five goals of Risk MAP are:

- Data Gaps: Address gaps in flood hazard data;
- Awareness and Understanding: Measurably increase the public's awareness and understanding;
- Mitigation Planning: Lead effective engagement in mitigation planning;
- Digital Platform: Provide an enhanced digital platform; and
- Synergize Programs: Align risk analysis programs and develop synergies.

Data Gaps is a key goal of the program which will address gaps in flood hazard data to form a solid foundation for flood risk assessments, floodplain management and the soundness of the NFIP. Elevation data acquisition is an important part of Risk MAP because its objective is to use the best available elevation data. The program will leverage available data and acquire limited new data. New data will be acquired on a watershed basis taking into account economies of scale.

Risk MAP couples mapping and assessment in a watershed jurisdiction to enable risk assessment using a watershed approach. The watershed approach allows for a better depiction of flood hazards, known to follow streams within watersheds.

On March 16, 2009 the U.S. Congress approved Risk MAP multi-year plan spanning the years 2010–2014. As part of its activities related to NFIP, FEMA began the transition from Map Mod to Risk MAP in fiscal year 2009, by initiating flood map update projects to address gaps in required engineering and mapping for high flood risk areas impacted by coastal flooding, levees, and other flood hazards (e.g. lakes, rivers and ponds).

20.3 Geographic Information System Applications

Digital ground surface elevation data structures include contours, digital elevation model (DEM), digital terrain model (DTM), triangular irregular network (TIN), and light detection and ranging (LiDAR) (Shamsi, 2001; 2005). TIN data structure has the ability to precisely represent linear features (e.g. banks, channel bottom and ridges) and point features (e.g. hills and sinks), which is critical to accurately defining the channel and floodplain geometry. These data can also be used for computing floodplain elevations and mapping floodplain boundaries, using new automated floodplain mapping software.

GIS is ideally suited to create the data layers to study flooding and its impacts. Although floodplain analysis can benefit DEM, DTM, TIN, and other GIS data sets (e.g. satellite imagery and LiDAR), the complexity and

unfamiliarity of GIS programs deters hydraulic engineers from using them (Cameron et al., 1999). The recent growth of GIS literacy and user friendliness (Shamsi, 2002; 2005) provides unforeseen floodplain analysis capabilities. This allows the creation of simple and logical user environments to view a real world representation of the floodplain, and help the engineer to develop error free H&H models and to make informed decisions.

GIS is also ideal in various NFIP mapping activities such as base mapping, topographic mapping, and the post-disaster verification of mapped floodplain extents and depths. For example, GIS was used to develop a river management plan for the Santa Clara River in Southern California. A GIS overlay process was used to further plan efforts and identify conflicting uses along the river and areas for enhancing stakeholder objectives. A 1:4 800 scale base map was created to show topography, planimetric features, and parcels. Attribute data were entered into a separate database and later linked to the work: 100 y floodplain, 100 y floodway, 25 y interim line, existing facilities, proposed facilities, and flood deposition. This mapping project indicated that GIS is useful in capturing and communicating a vast amount of information about the study area and the river. While the use of GIS and the process of gathering and recording data were not without problems, the overall value of GIS was found to outweigh them (Sheydayi, 1999).

20.4 Field Survey

Field survey is an important component of floodplain analysis. It involves inspecting and surveying floodplain cross sections and floodplain obstructions such as culverts and bridges, and collecting data on stream encroachment, erosion, sedimentation, banks and bed material (e.g. silt, sand, gravel, cobble, weeds and plants).

Using GIS in the field for collecting data directly fed into a GIS database is referred to as mobile or field GIS. The ultimate goal of a mobile GIS is to link the field crews with the most recent GIS data to make their job easier and more efficient. Mobile GIS technology can be used to efficiently inspect floodplains and obstructions such as culverts and bridges. Mobile GIS integrates field inspections, digital photos and videos and GPS data in one manageable system (Shamsi, 2008; 2009).

GeoLink is an example of mobile GIS software that has been successfully used for flood plain field survey work (Michael Baker Jr. Inc., 2010). GeoLink is patented mobile GIS software and the first commercially available GPS mapping software. It integrates GIS, GPS and other external devices (e.g. digital cameras, laser rangefinders, radiation detectors) for paperless field inspections.

Figure 20.5 shows a GeoLink screenshot displaying a color orthophoto base map, stream, inspection points and an existing plot of the cross section being inspected. Field data are stored in a shapefile which allows the immediate mapping and querying of field inspection data. Figure 20.6 below shows an ArcGIS screenshot displaying floodplain cross section data and digital photo captured from GeoLink captured field data.

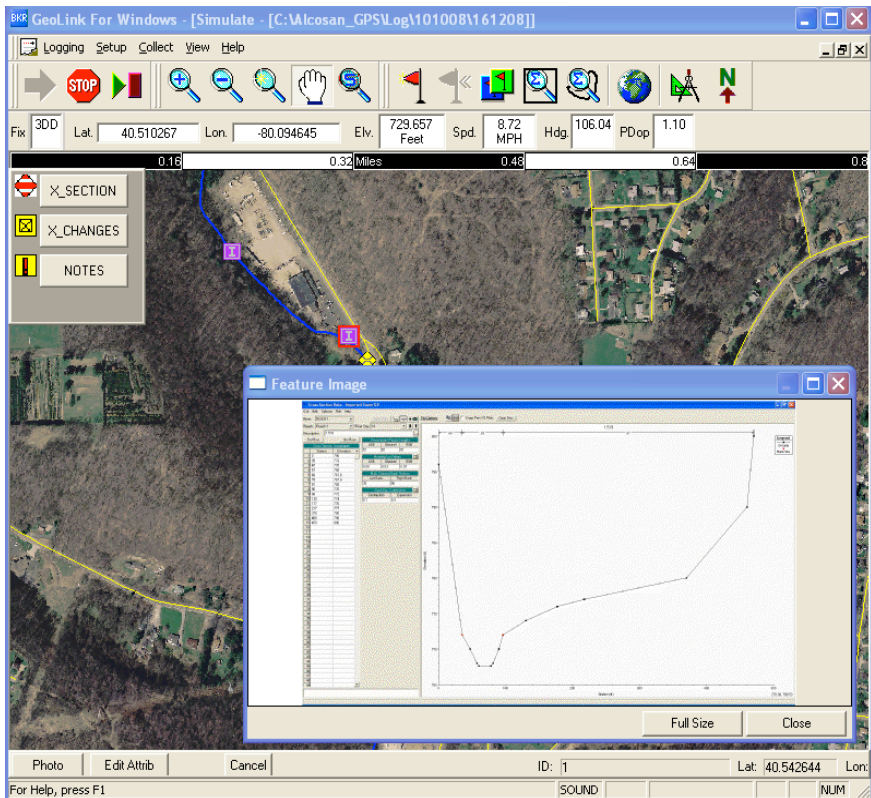


Figure 20.5 GeoLink screenshot showing a color orthophoto base map, stream, inspection points, and a cross-section plot.

In another project, GIS was used to develop an interactive watershed inventory database for Northern California’s 10 430 acre (4 224 ha) Alhambra Creek watershed for use in decision making. The inventory process focused on seven resource areas: soils, rangeland characteristics, water quality, hydrology, biology, geology, and cultural resources. The GIS and CAD technologies were used to create maps of location, land use, soils, soil erosion potential, range site description, hydrology, sub-watersheds, endangered

sis that determines flood discharges, and hydraulic analysis that determines peak water surface elevations. A rainfall-runoff or hydrologic model, such as HEC-HMS or SWMM can be used to model stormwater runoff. This calculation is based on the physical characteristics of a drainage area that can be estimated from a GIS database as described above. In essence, GIS provides a comprehensive means of automating the creation of H&H models. The runoff information from the hydrologic model can then be combined with stream cross-section information in a hydraulic model, such as HEC-RAS or SWMM to determine the depth of flooding. These H&H models can identify existing flooding problems and reveal locations that might be problematic in the future. The models can also simulate the effect of development in upstream watersheds and potential future development on the existing flood elevations. The modeling results are also used to revise the existing FIRMS of the communities.

Floodplain models can also be used for managing riparian floodplain ecosystems including fisheries, wildlife, water quality and land use issues. This has been accomplished by using a floodplain model in conjunction with other layers, such as salmon spawning, wildlife observations, land use, ownership, temperature and soils (Miyamoto et al., 1997).

In increasing order of their sophistication, various types of H&H models that can be used for floodplain modeling are:

- 1-D steady;
- 1-D unsteady (hydrodynamic);
- quasi 2-D flood cell (reservoir units);
- 2-D raster routing;
- 2-D hydrodynamic;
- linked 1-D–2-D hydrodynamic;
- 3-D hydrodynamic; and
- linked 1-D–3-D hydrodynamic.

In steady flow models, a hydrologic model has a runoff component for an individual subbasin and a channel routing routine. A hydraulic model receives peak discharges from the hydrologic model. In unsteady flow models, a hydrologic model has a runoff component. Channel routing is done by the hydraulic model; the hydraulic model receives hydrographs at upstream boundaries and as lateral inflows.

Representative examples of public domain floodplain modeling software are HEC-HMS: Hydrology (1-D steady and unsteady); HEC-RAS: Hydraulics (1-D steady and unsteady); and GIS: HEC-GeoHMS and HEC-GeoRAS from US Army Corps of Engineers and U.S. EPA's SWMM5 program.

The Hydrologic Engineering Center (HEC) is an office of the U.S. Army Corps of Engineers which was established to support the nation's hydrologic

engineering and water resources planning and management needs. To accomplish this goal, HEC develops state-of-the-art comprehensive computer programs which are available to the public. HEC-1 and HEC-2 are legacy DOS programs for hydrologic and hydraulic modeling, respectively. Recently HEC-1 and HEC-2 have been replaced with new object-oriented Windows programs called Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS), respectively. HEC-HMS is designed to simulate the precipitation-runoff processes of dendritic watershed systems. HEC-RAS is intended for calculating water surface profiles in a full network of channels, a dendritic system, or a single river reach. The information required for the new programs is similar to that required for the old HEC-1 and HEC-2 programs with one exception. The HEC-2 system provided only a steady state modeling capability; the 2001 HEC-RAS release (Version 3.0) provided both steady and unsteady gradually varied flow routing capability.

HEC-GeoHMS and HEC-GeoRAS have been developed as geospatial hydrology toolkits for HEC-HMS and HEC-RAS users with GIS experience. They allow users to expediently create hydrologic input data for HEC-HMS and HEC-RAS models using ArcGIS. Free downloads of these programs are available from the HEC software website www.hec.usace.army.mil/software. HEC-GeoHMS uses ArcGIS Spatial Analyst Extension to develop a number of hydrologic modeling inputs. Analyzing digital terrain information (e.g. a DEM), HEC-GeoHMS transforms the drainage paths and watershed boundaries into a hydrologic data structure that represents the watershed response to precipitation. HEC-GeoHMS also includes the development of grid-based data for linear quasi-distributed runoff transformation using the ModClark method. GIS has excellent capabilities for storing and manipulating a 3-D surface as a DTM or TIN. GIS can create line features from a TIN of the channel and adjacent floodplain area. These line coverages can be used to create the input data for HEC-RAS.

The USEPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. SWMM was first developed in 1971, and has since undergone several major upgrades since then. It continues to be widely used throughout the world for planning, analysis and design related to stormwater runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas, with many applications in non-urban areas as well. SWMM has been approved by FEMA for floodplain modeling. The first Windows version (Version 5) of the program is referred to as SWMM 5. Figure 20.7 shows a SWMM5 screenshot displaying a floodplain cross section referred to as a transect created from LiDAR DEM data.

Representative examples of in-house and commercial floodplain modeling software are:

- RiverSystems (Integrated hydrology, hydraulics and GIS) in-house software from Michael Baker Jr. Inc.;
- MIKE11 (1-D), MIKE 21 (2-D), and MIKE FLOOD (1-D/2-D) commercial software from Danish Hydraulic Institute;
- InfoWorks-RS (1-D/2-D) commercial software from Wallingford Software/MWH Soft;
- TUFLOW (1-D/2-D) commercial software from BMT WBM (Australia); and
- ISIS (2-D) commercial software from Halcrow (UK).

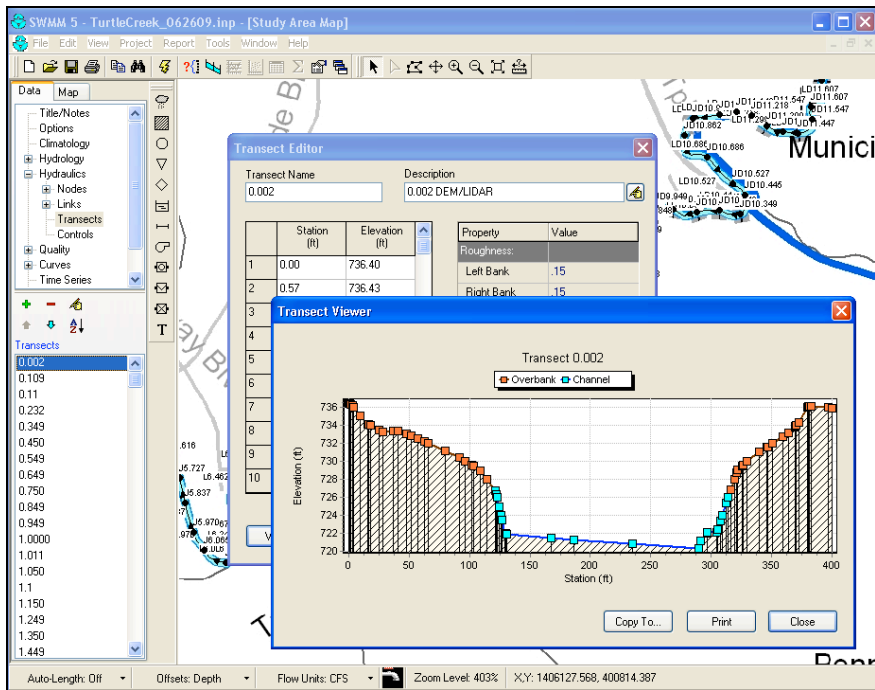


Figure 20.7 SWMM5 screenshot showing a floodplain transect created from LiDAR DEM data.

In order to be used in NFIP projects, the hydraulic models must obtain FEMA approval. The NFIP regulations require the models to have the following features:

- the model must have been reviewed and accepted by a government agency responsible for the implementation of

programs for flood control and the regulation of floodplain lands;

- the model must be available to FEMA and all present and future parties impacted by flood insurance mapping developed or emended through the use of programs; and
- the model must be well-documented, including source codes and user manual.

FEMA approval requires a comprehensive review process including testing, examination of the quality of the documentation of the package, and the model's track record in flooding studies. COE's HEC-2 and HEC-RAS and USEPA's SWMM models are examples of FEMA approved programs. In addition to floodplain modeling programs developed by government agencies, FEMA also approves commercially available models for NFIP projects. For example, in 2000 FEMA included Danish Hydraulic Institute (DHI)'s MIKE 11 program in their list of hydraulic models accepted for use in the NFIP program. In 2001, FEMA approved DHI's MIKE 21 program for use in coastal flood insurance studies. MIKE 11 includes a floodplain encroachment model to assess the hydrodynamic impacts of floodplain encroachments on the water and energy levels.

Today, many flood studies require detailed spatial resolution which can be achieved through the application of 2-D techniques. DHI's floodplain modeling package, MIKE FLOOD combines the best features of 1-D and 2-D flood modeling technology. MIKE FLOOD is assembled from the components taken from MIKE 11 and MIKE 21. This combination allows users to model some areas in 2-D detail, while other areas can be modeled in 1-D. Like MIKE 11 and MIKE 21, MIKE FLOOD also has GIS linkage capabilities which can be used, for example, to produce inundation maps as a result of levee or embankment failures. These maps can be used to develop flood related emergency response procedures.

20.6 Floodplain Mapping

A study conducted in the 3.42 mi² (8.86 km²) portion of the Mill Creek watershed located in Lufkin, Texas, indicated that the 100 y floodplain boundaries created using the GIS (Stream Pro) method were different from the effective FIRM boundaries (Kraus, 1999). Some reaches had wider floodplains, while other areas showed distinct reductions in floodplain widths. This study also noted a reduction in the time required to manually code the cross-section points into the HEC-RAS model and the elimination of human errors due to typographical mistakes. The GIS approach was also found to improve the plotting of floodplains. Before GIS, floodplain plots

between cross sections were subject to the interpolation of contours. With GIS, the floodplain is plotted continuously according to the terrain TIN, and no interpolation between cross sections is required.

The modeled water surface profiles (elevations) can be imported in a GIS and overlaid upon the terrain surface to create flood maps and determine which areas will flood. Applications have been developed to connect HEC-HMS and HEC-RAS models in a single ArcGIS environment that allow moving easily from a DEM to a floodplain map within a single software. For example, the RiverSystems program allows both hydrologic and hydraulic modeling inside ArcGIS, automatic creation of floodplain cross sections from contours or DTMs, and draping of floodplain maps on user specified base maps. RiverSystems is an ArcGIS extension and toolbar, which gives access to the toolbox and to various quick launch tools that are part of the toolbox. This is currently an in-house program that is customized for clients. Figure 20.8 shows a screen shot of RiverSystems displaying floodplain cross sections created from DTM data. Figure 20.9 below shows a screen shot of RiverSystems displaying computed 100-year floodplain draped over a color orthophoto (Michael Baker Jr. Inc., 2010).

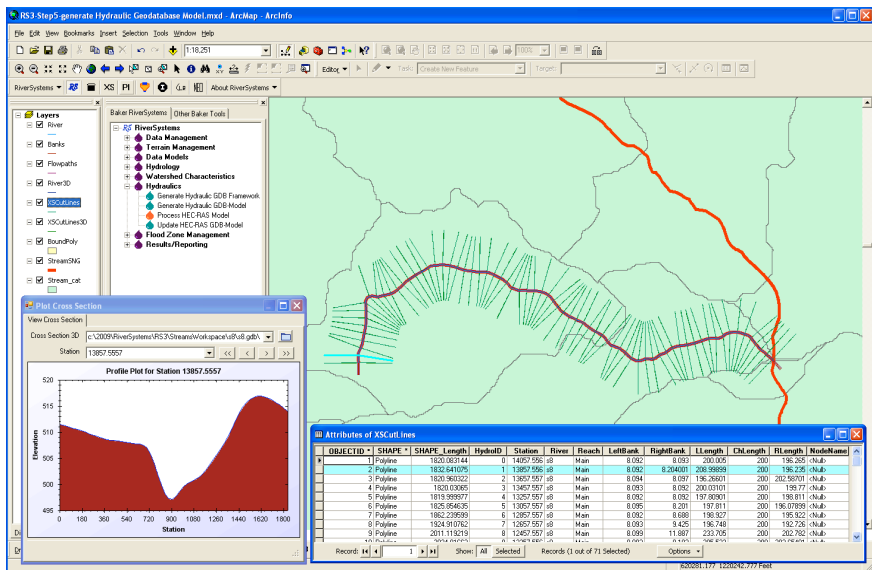


Figure 20.8 Screenshot of RiverSystems software showing DTM-based floodplain cross sections (Michael Baker Jr. Inc.).

20.7 Summary

The GIS based floodplain mapping and modeling provides significant improvements in efficiency for many of the tasks involved in floodplain analysis. The mobile GIS approach that combines GIS, GPS, and external data capture devices (digital cameras, camcorders, laser range finders, etc.) improves the data collection, documentation, and reporting efficiency. Unsteady (hydrodynamic) 2-D models are now available that can provide additional information to understand complex urban and tidal flooding events. Modeling results can be presented as 2-D, 3-D, and 4-D animations to improve the communication efficiency with stakeholders.

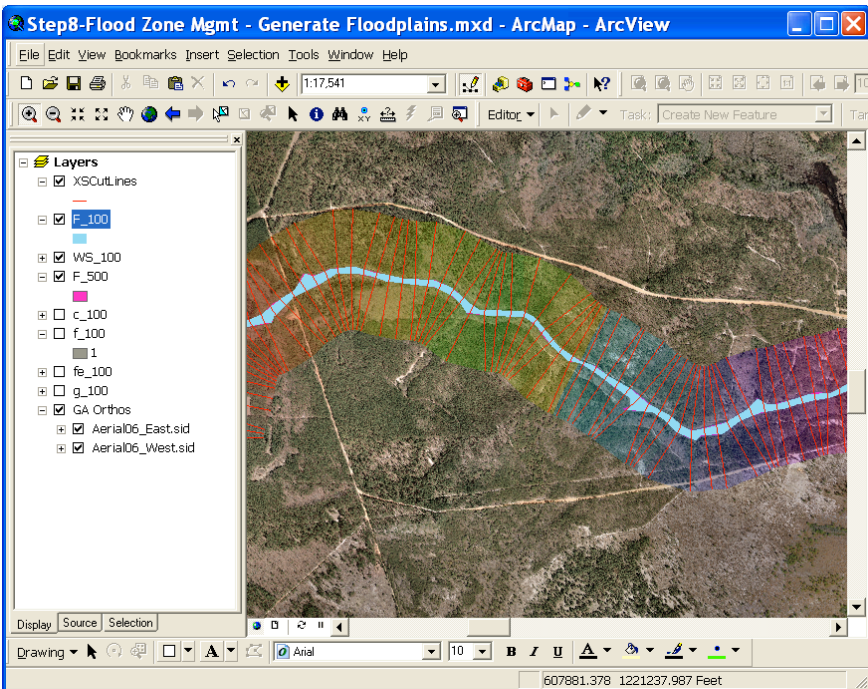


Figure 20.9 Screenshot of RiverSystems software showing 100 y floodplain draped over an aerial photograph (Michael Baker Jr. Inc.).

References

- Cameron, T.A., T.A. Avans, G.W. Brunner. 1999. "HEC-GeoRAS: Linking GIS to Hydraulic Analysis Using ARC/INFO and HEC-RAS." Proceedings of the 1999 User Conference, San Diego, ESRI.

- Chapman, J. B. and W.D. Canaan. 2001. "Flood Maps are Key to Better Flood Damage Control." *CE News*, March 2001, 58-60.
- Dodson, R.D. and X. Li. 1999. "The Accuracy and Efficiency of GIS-Based Floodplain Determinations." Proceedings of the 1999 User Conference, San Diego, ESRI.
- FEMA. 2010a. Map Modernization Web Site, United States Federal Emergency Management Agency, www.fema.gov/plan/prevent/fhm/mm_main.shtm.
- FEMA. 2010b. Risk MAP Web Site, United States Federal Emergency Management Agency, www.fema.gov/plan/prevent/fhm/rm_main.shtm
- Grigg, N. 2003. "Surviving Disasters: Learning From Experience." *Journal of the American Water Works Association*, Vol. 95, No. 9, September 2003, 64-75.
- HEC. 2010. Hydrologic Engineering Center Web Site, U.S. Army Corps of Engineers, www.hec.usace.army.mil/
- Kraus, R.A. 1999. "Flood Plain Determination Using ArcView and HEC-RAS." Proceedings of the 1999 User Conference, San Diego, ESRI.
- Lathrop, W. (2001). "In the Flow: A Primer." *Professional Surveyor*, April 2001, 40-41.
- Michael Baker Jr. Inc. 2010. Technology Exchange Forum Presentation. Pittsburgh, Pennsylvania, www.mbakercorp.com.
- Miyamoto, J. R. Ghezlbash, and M. Jackson. 1997. "Using GIS for Managing Floodplain Ecosystems." Proceedings of the 1997 User Conference, San Diego, ESRI.
- Myers, R.L., N. Stein and J. Fishleder. 1999. "Coordinated Resource Management Planning in the Alhama Creek Watershed." *Geo Info Systems*, February 1999, 30-35.
- Sheydayi, A. 1999. "GIS Facilitates River Management Plan Development." *Watershed & Wet Weather Technical Bulletin*, WEF, January, 10-12.
- Shamsi, U.M. 2001. "DEM Applications in Hydrologic Modeling." *Journal of Water Management Modeling* R207-12. doi: 10.14796/JWMM.R207-12.
- Shamsi, U.M. 2002. *GIS Tools for Water, Wastewater, and Stormwater Systems*, 375 pages, ASCE Press.
- Shamsi, U.M. 2005. *GIS Applications for Water, Wastewater, and Stormwater Systems*, 413 pages, CRC Press.
- Shamsi, U.M. 2008. "GIS-Based Sewer System Inspection and Maintenance," Collection Systems 2008 Conference, Regional Planning for Compliance, Water Environment Federation, May 18-21, 2008, Pittsburgh, Pennsylvania.
- Shamsi, U.M. 2009. "GIS Applications for Regulatory Compliance." *Journal of Water Management Modeling* R235-04. doi: 10.14796/JWMM.R235-04.

