

Floodplain mapping using HEC-RAS and GIS in semi-arid regions of Iran

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Abstract

A significant deficiency of most computer models used for stream floodplain analysis is that the locations of structures impacted by floodwaters, such as bridges, roads, and buildings, cannot be effectively compared to the floodplain location. This research presents a straightforward approach for processing output of the HEC-RAS hydraulic model, to enable two- and three dimensional floodplain mapping and analysis in the ArcView. The methodology is applied to a reach of Polasjan River Basin, located in Iran central plateau. A digital terrain model is synthesized from HEC-RAS cross-sectional coordinate data and a digital elevation model of the study area. The resulting surface model provides a good representation of the general landscape and contains additional detail within the stream channel. The results of the research indicate that GIS is an effective tool for floodplain mapping and analysis.

Keywords: ArcView; Computer model; Elevation model; Floodplain mapping; HEC-RAS; Stream channel; Iran

1. Introduction

There are many of drainage control structures along watersheds. These include facilities such as storm drains, culverts, bridges, and water quality and quantity-control structures. An important design component of these facilities involves hydraulic analyses to determine conveyance capacity. Computer models play a pivotal role in these analyses by aiding in determination of water surface profiles associated with different flow conditions. Unfortunately, a consistent deficiency of these programs has been their inability to connect the information describing the water profiles with their physical locations on the land surface. Often the computed water surface elevations are manually plotted on paper maps in order to

delineate floodplains. Automating this manual plotting would result in significant savings of both time and resources. Geographic information systems (GISs) offer the ideal environment for this type of work.

The daily damage caused by flood was increased by 300000 USD especially in arid and semi-arid regions of Iran (Watershed Management, Rangelands & Forests Organization, 2005). The floodplain mapping process generally consisted of three steps (Jones et al, 1998):

1. The stream flow associated with the 100-year flood is estimated based on peak flow data or hydrologic modeling
2. The 100-year flood elevation profiles are computed using hydraulic modeling
3. Areas inundated by floodwaters are delineated on paper maps

Until the last few years, GIS applications to floodplain mapping terrain modeling have been relatively limited. With the rapid advances in GIS in the 1980s, GIS began to be used to

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represent the flow of water on the land surface. Much of the initial work dealt with the analysis of digital elevation models (DEMs), square grids of regularly spaced elevation data, for hydrologic applications. O'Callaghan and Mark (1984) and Jenson and Domingue (1988) developed methods to fill DEM depressions, and create flow direction and flow accumulation grids using a DEM as the sole input. These advances allowed for the automation of watershed and drainage network delineation. Unfortunately, the use of DEM surfaces is generally not suitable for large-scale terrain representation required for the hydraulic analysis of river channels. Because they cannot vary in spatial resolution, DEMs may poorly define the land surface in areas of complex relief (Carter, 1988). For hydraulic modeling of river channels, the triangular irregular network (TIN) model is preferred.

A TIN is a triangulated mesh constructed on the (x,y,z) locations of a set of data points. The TIN model allows for a dense network of points where the land surface is complex and detailed, such as river channels, and for a lower point density in flat or gently sloping areas (Carter, 1988). Djokic and Maidment (1991) used TINs to model storm drainage in an urban setting. The TIN surface was found to be effective for the determination of parameters for design flow calculations. Beavers (1994) performed some of the first work connecting hydraulic modeling of

river channels and GIS. A GIS-based tool, named ARC/HEC2, was developed to assist hydrologists in floodplain analysis. In the years following the release of ARC/HEC2, many hydrologists have switched from using HEC-2 to the Windows based HEC-RAS hydraulic model. HEC-RAS differs from the HEC-2 model in that the capability to import and export GIS data was included in the program. Terrain information stored in a GIS can be translated to conform to the HEC-RAS data exchange file format. In 1997, Thomas Evans of HEC improved on the Beavers work with the release of a set of ArcInfo Macro Language scripts that serve as a pre- and postprocessor for HEC-RAS (Tate et al., 2002). The preprocessing AMLs create a data exchange file consisting of stream geometry descriptions extracted from a triangular irregular network (TIN) model of the land surface. In HEC-RAS, the user is required to provide additional data such as Manning's n, contraction and expansion coefficients, geometric descriptions of any hydraulic structures (e.g., bridges, culverts) in the cross sections, and bank stations and reach lengths (if they are not included in the exchange file). After running the model, HEC-RAS can export the output data into the same digital exchange file format. A TIN of the water surface can then be created from the exchange file using the AML post-processing macros. The process is illustrated in Figure 1.

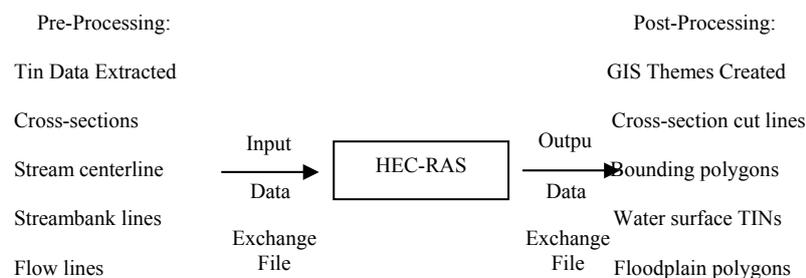


Fig. 1. Evans' pre and post-processing for HEC-RAS (Tate, 2002)

In function, Evans' work is quite similar to the work completed by Beavers and Djokic, with a primary difference being that Evans' programs work with the HEC-RAS model rather than HEC-2. The AML code provides a set of utilities that allows preparation of GIS data for HEC-RAS input and formatting of model output for GIS display. In 1998, the Environmental Systems Research Institute (ESRI) had a limited release of an ArcView extension called AVRAS. Whereas, the previous GIS software operated in the Arc/Info environment, AVRAS was designed to use ArcView as the pre and

post-processing environment for hydraulic modeling in HEC-RAS. AVRAS was initially created by translating Evans' AML code into Avenue (ArcView's scripting language), but several additional utilities were later added to make the program more user friendly. In 1999, AVRAS was released as a commercial product by Dodson & Associates, Inc., under the trade name of GIS Stream Pro.

This study presents a GIS approach for automated floodplain mapping to aid in the flood plain management. The approach establishes a connection between the HEC-RAS

hydraulic model and ArcView GIS, allowing for improved visualization and analysis of floodplain data. It also permits GIS to function as an effective planning tool by making hydraulic data easily transferable to floodplain management, flood insurance rate

determination, economic impact analysis, and flood warning systems. The main research objective is develop a procedure to take computed water surface profiles generated from the HEC-RAS hydraulic model and draws a map of the resulting floodplain in ArcView GIS.

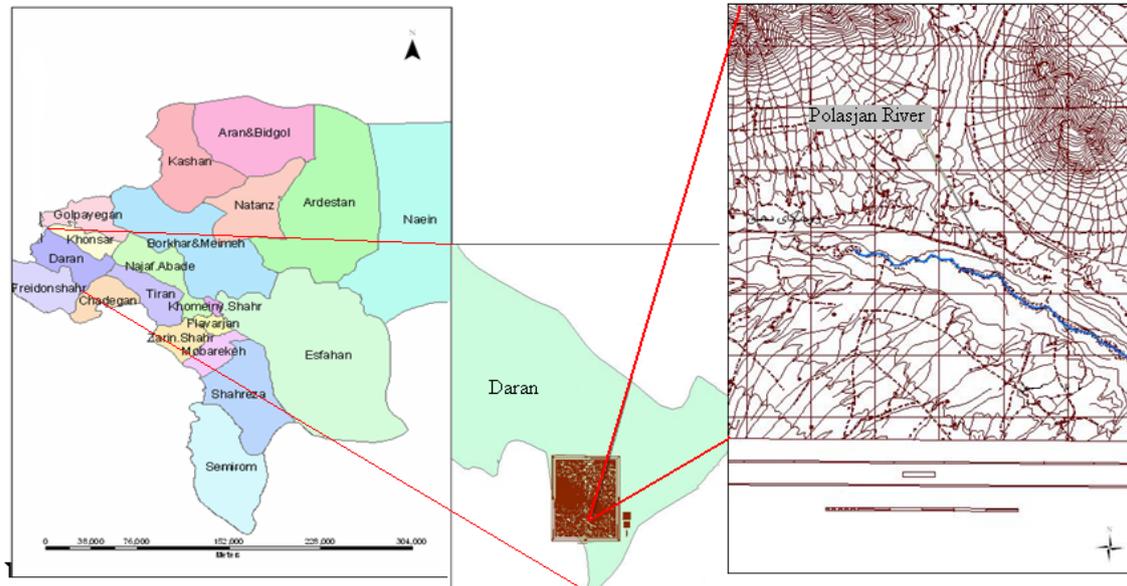


Fig. 2. Location of the study area

2. Materials and methods

Attaining this research objective requires translating hydraulic modeling output from HEC-RAS to ArcView. The difficulty stems from the fact that each program uses entirely different coordinate systems to define its data. HEC-RAS is a one dimensional model, intended for hydraulic analysis of river channels. In HECRAS, the stream morphology is represented by a series of cross-sections called river stations. Proceeding from downstream to upstream, the river station numbering increases. The distance between adjacent cross-sections is termed the reach length. Each cross-section is defined by a series of lateral and elevation coordinates, which are typically obtained from land surveys. The numbering of the lateral coordinates begins at the left bank of the cross-section, (looking downstream) and increases until reaching the right bank. The value of the starting lateral coordinate is arbitrary, only the distance between points is important. The result is that in effect, each cross-section has its own local coordinate system (Figure 3).

In the HEC-RAS coordinate system, the coordinate of any given point is based on its river station along a one-dimensional stream centerline, location along the cross-section line,

and elevation. In contrast, data in ArcView are attributed with real-world map coordinates; the location of a given point in space is based on its easting (x-coordinate), northing (y-coordinate), and elevation (z-coordinate). Where HEC-RAS represents the stream as a straight-line in model coordinates, ArcView represents it as a curved line in map coordinates. In order to map the hydraulic modeling output in GIS, the differences between the HEC-RAS and ArcView coordinate systems must be resolved. This is the fundamental problem that this research solves.

2.1. Study area

Polasjan River Basin located in Iran Central Plateau was selected as the study area for this research. Polasjan River is a stream that flows south through the villages and its farms of Freidan, Freidoonshahr and Chadegaan counties an upstream tributary to Zaiand-e-Rood River Basin (Figure 2). Due to its proximity to numerous homes, farms and school buildings, the Polasjan River Basin's floodplain is of great interest to planners, developers, and property owners (Bakhshaei et al., 2006).

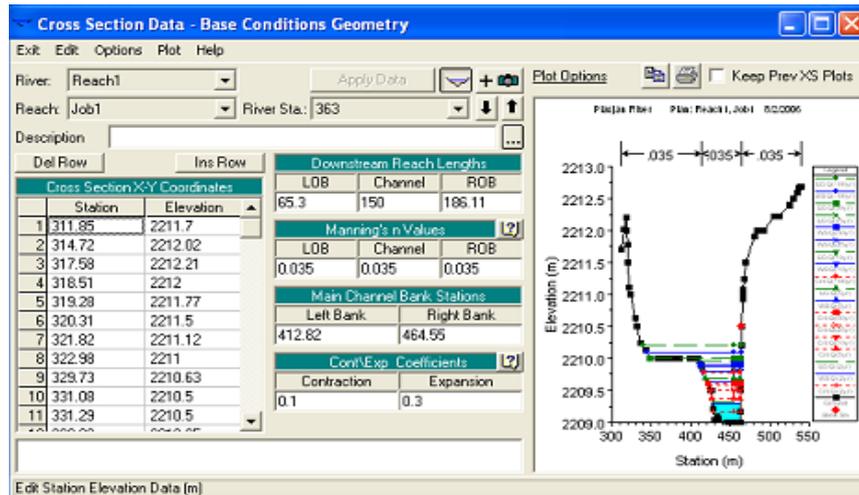


Fig. 3. HEC-RAS cross-section coordinates

2.2. HEC-RAS parameters

HEC-RAS uses a number of input parameters for hydraulic analysis of the stream channel geometry and water flow. These parameters are used to establish a series of

cross-sections along the stream. In each cross-section, the locations of the stream banks are identified and used to divide into segments of left floodway channel, and right floodway channel (Figure 4).

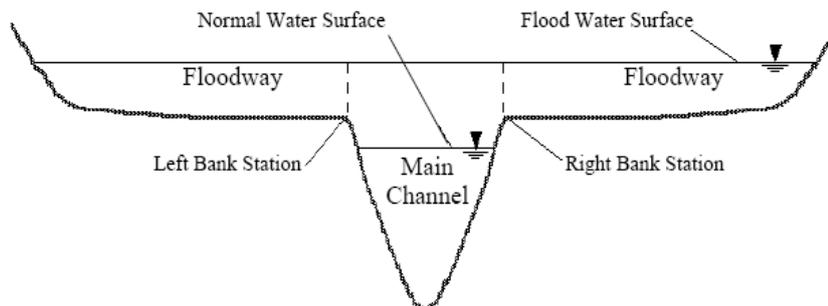


Fig. 4. Stream cross-section schematic (Tate, 1999)

HEC-RAS subdivides the crosssections in this manner, because of differences in hydraulic parameters. Thus, friction forces between the water and channel bed have a greater influence in flow resistance in the floodway, leading to lower values of the Manning coefficient. As a result, the flow velocity and conveyance are substantially higher in the main channel than in the floodway. At each cross-section, HEC-RAS uses several input parameters to describe shape, elevation, and relative location along the stream:

- River station (cross-section) number
- Lateral and elevation coordinates for each (dry, unflooded) terrain point
- Left and right bank station locations
- Reach lengths between the left floodway, stream centerline, and right floodway of adjacent cross-sections (The three reach lengths represent the average flow path through each

segment of the cross-section pair. As such, the three reach lengths between adjacent cross-sections may differ in magnitude due to bends in the stream.)

- Manning's roughness coefficients
- Channel contraction and expansion coefficients
- Geometric description of any hydraulic structures, such as bridges, culverts, and weirs.

HEC-RAS assumes that the energy head is constant across the crosssection and the velocity vector is perpendicular to the cross-section (i.e., quasi one-dimensional flow on a two-dimensional domain). As such, care should be taken that the flow through each selected cross-section meets these criteria. After defining the stream geometry, flow values for each reach within the river system are entered. The channel geometric description and flow rate values are

the primary model inputs for the hydraulic computations.

$$H = Z + Y + \frac{\alpha V^2}{2g} \tag{1}$$

2.3. Water surface profile computation

For open channel flow, the total energy per unit weight (energy head) has three components: elevation head, pressure head, and velocity head (Figure 5):

Where:

- H = energy head (m)
- Z = channel bed elevation above a datum (m)
- Y = pressure head/water depth (m)
- α = velocity weighting coefficient

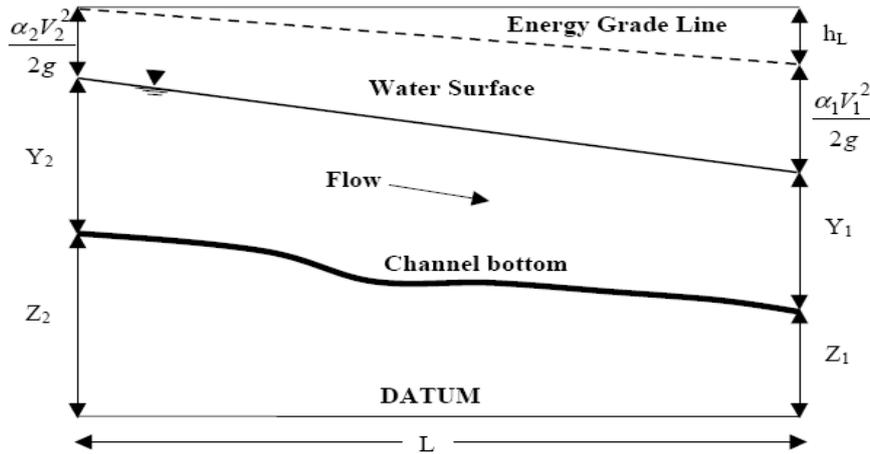


Fig. 5. Energy equation parameters for gradually varied flow (Tate, 1999)

For steady, gradually varied flow, the primary procedure for computing water surface profiles between cross-sections is called the direct step method. The basic computational procedure is based on the iterative solution of the energy equation. Given the flow and water surface elevation at one cross-section, the goal of the standard step method is to compute the water surface elevation at the adjacent cross-section. For subcritical flow, the computations begin at the downstream boundary and proceed upstream; for supercritical flow, the computations begin at the upstream boundary and proceed downstream. At the boundary, the flow and water surface elevation must be known. The procedure is summarized below (assuming subcritical flow).

1. Assume a water surface elevation at cross-section 1.
2. Determine the area, hydraulic radius, and velocity (Eq. 2) of cross-section 1 based on the cross-section profile.

$$Q = V_1 A_1 = V_2 A_2 \tag{2}$$

Where:

- Q = flow rate/discharge (m³/s)
- Vn = average velocity at cross-section n (m/s)
- An = area at cross-section n (m²)

3. Compute the associated conveyance (Eq. 3) and velocity head values.

$$K = (1/n).AR^{2/3} \tag{3}$$

Where:

- R = hydraulic radius (m)
- n = Manning roughness coefficient
- K = conveyance (m⁵/3)

4. Calculate friction slope (Eq. 4), friction loss (Eq. 5), and contraction/expansion loss (Eq. 6).

$$\bar{S}_f = \left(\frac{Q_1 + Q_2}{K_1 + K_2} \right)^2 \tag{4}$$

Where:

\bar{S}_f = average friction slope between adjacent cross-sections

$$h_f = L \bar{S}_f \tag{5}$$

Where:

- hf = friction head loss (m)
- L = distance between adjacent cross-sections (m)

$$h_0 = C \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \tag{6}$$

Where:

ho = contraction or expansion head loss (m)

C = contraction or expansion coefficient

5. Solve the energy equation (Eq. 1) for the water surface elevation at the adjacent cross-section.

6. Compare the computed water surface elevation with the value assumed in step 1.

7. Repeat steps 1 through 6 until the assumed and computed water surface elevations are within a predetermined tolerance. To automate the floodplain mapping process, GIS is required to assign map coordinates to the output data. In the following subsection, some basic GIS concepts are introduced.

2.4. Geographic Information System

The ArcView GIS software package, developed by the Environmental Systems Research Institute, was used as the computer development environment for this research. Specialized ArcView software, called extensions, is required to manipulate and analyze raster and TIN data. The ArcView Spatial Analyst extension is designed for creating, querying, mapping, and analyzing raster data, whereas the 3D Analyst extension is intended for creating, analyzing, and visualizing TINs and three-dimensional vector data (ESRI, 1999).

The approach is based on assigning map coordinates to stream cross-sections and computed water surface profile data stored in HEC-RAS model coordinates. The procedure consists of five primary steps:

1. Data import from HEC-RAS
2. Stream centerline definition
3. Cross-section georeferencing
4. Terrain modeling
5. Floodplain mapping

These steps are discussed in more detail in the following subsections. HEC-RAS and GIS data for the Polasjan River Basin study area are used to illustrate the procedures.

2.5. Data import from HEC-RAS

To move into the GIS environment, the HEC-RAS output data must be extracted. Because the approach presented herein assumes that input terrain model is not the source of the cross-section descriptions, the GIS data export option in HEC-RAS is not employed. Instead an output report using the File/Generate Report menu option from the HEC-RAS main project window is used. In the resulting report generator window, "Plan Data" and "Geometric Data"

should be checked as the general input data, "Reach Lengths" under the summary column, and "Cross Section Table" under the specific tables output option. If model includes more than one flow profile, the specific profile used for the output report can be selected using the "Set Profiles" button.

The parameters processed at each cross-section include the following:

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

For each cross-section, the lateral and elevation coordinates of all points (black squares in Figure 6) are read and stored in an ArcView global variable. Using these points, the coordinates of the point possessing the minimum channel elevation are determined. If there are multiple points possessing the same minimum channel elevation, the lateral coordinate of the channel center is calculated by averaging the lateral coordinates of all points possessing the same minimum elevation. In order to determine the lateral coordinates of the floodplain boundaries, the computed water surface elevation is used. The cross-section coordinates are read from the left end of the cross-section to the right end. When the computed water surface elevation falls between the elevations coordinates of two adjacent points, the coordinates of these bounding points are noted.

$$x3 = [(z3-z1)*(x2-x1)/(z2-z1)] + x1 \quad (7)$$

Where:

x1 = left bounding point lateral coordinate

z1 = left bounding point elevation coordinate

x2 = right bounding point lateral coordinate

z2 = right bounding point elevation coordinate

x3 = lateral coordinate of floodplain boundary

z3 = computed water surface elevation

With the lateral coordinates of the floodplain boundaries known, the lateral distance from the stream center is calculated and stored in an ArcView table. In the same manner, the lateral distance from the bank stations (circles in Figure 6) to the stream center is also calculated and stored in the table along with the elevation coordinates. The remaining cross-section parameters written to the ArcView table are the river station number, any text description of the

crosssection, reach lengths, and the computed water surface elevation. Descriptions of the data stored in each of the columns are provided in Table 1.

The purpose of the data import step is to transform HEC-RAS output from text file format into a tabular format readable by ArcView. However, the crosssection

coordinates are still tied to the HEC-RAS coordinate system. In order to map the floodplain, the cross-sections must be assigned map coordinates. This requires associating the HEC-RAS stream cross-sections with a geographically referenced digital representation of the stream.

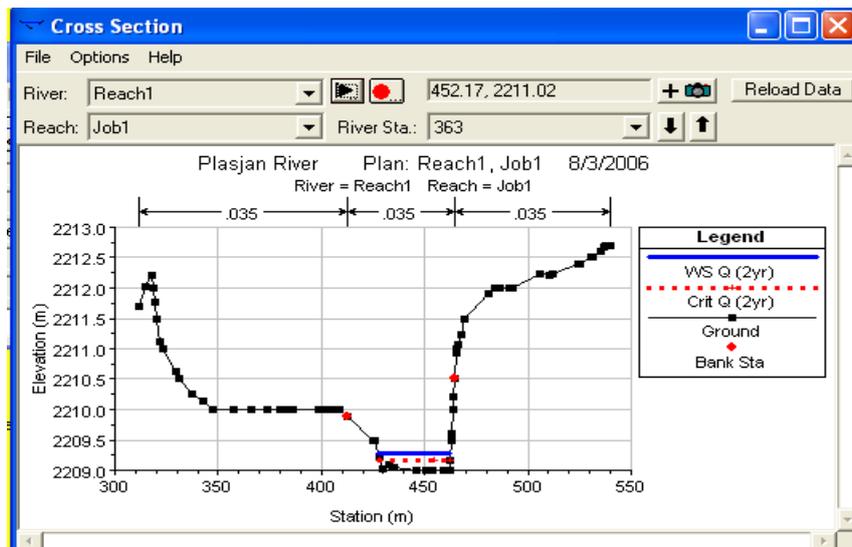


Fig. 6. HEC-RAS cross-section plot The lateral coordinates of the floodplain boundaries are subsequently calculated:

Table 1. Cross-section parameter table data descriptions

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

2.6. Stream centerline definition

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

2.6.1. Reach files

Reach files are a series of national hydrologic databases that uniquely identify and interconnect the stream segments or "reaches" that comprise the nation's surface water drainage system. The databases include such

information as unique reach codes for each stream segment, upstream/downstream relationships, and stream names (where possible).

2.6.2. Dem-based delineation

Using the capabilities of the ArcView Spatial Analyst extension, a vector stream network can be derived using a DEM as the sole input.

2.6.3. Digitize the stream

Using either orthophotography or a digital raster graphic (DRG) as base map, the stream centerline can be digitized using tools in

ArcView. DRGs are digitized and geographically referenced topographic maps.

2.6.4. Land surveys

Data representing the stream centerline may be available from land surveys. If this data is tied to a global coordinate system, it can be used as a vector representation of the stream. From the four methods listed above, the first three were evaluated for this study.

2.7. Cross-section georeferencing

The first step in geographically referencing the cross-sections is to compare the definitions of the RAS stream and their digital counterpart. It is possible for example, that the digital stream centerline is defined to a point previous upstream than the RAS stream, or vice versa. Hence, it is necessary to define the upstream and downstream boundaries of the RAS stream on the digital stream.

2.8. Formation of integrated terrain model

In order to produce a floodplain map, accurate topographic information is required. In GIS, the TIN model is the best data model for large-scale terrain representation. The result of the cross-section georeferencing described in the previous subsection is that every vertex of every cross-section is assigned three-dimensional map coordinates. The easting and northing coordinates come from the mapping process and the elevation coordinate from the global variable created in the data import step. Using these three-dimensional cross-section points, a TIN model of the stream channel and floodplain can be constructed. Unfortunately, a TIN created solely from this vector data would include the stream channel and floodplain, but not the surrounding landscape. To best represent the terrain, the TIN should include areas both inside and outside the floodplain in order to give a sense of context. The grid (DEM) is the standard data model used for small-scale representation of the general land surface. So in order to create a comprehensive TIN, a method to integrate relatively low-resolution digital elevation model (DEM) data with comparatively higher resolution vector floodplain data is required. By combining the vector and raster data to form a TIN, the intended result is a continuous three-dimensional landscape surface that contains additional detail in stream channels. This approach was employed to form the TIN terrain model.

2.9. Floodplain mapping

With the terrain model complete, the final step is to delineate the floodplain. HEC-RAS represents stream floodplains as a computed water surface elevation at each cross-section. During the data import step, these elevations, along with the distance from the stream centerline to the left and right floodplain boundaries, are brought into ArcView and stored in the crosssection parameter table. As inputs, the script requires the cross-section line theme and the crosssection parameter table. The output is a line theme that is identical to the crosssection theme in location and orientation. Using the water surface profile at each cross-section, a TIN representing the entire floodwater surface can be constructed using the Surface/Create TIN from Features menu option in ArcView. The water surface lines are used as breaklines, and the cross-section bounding polygon is used to bound the aerial extent of the water surface.

When viewed in conjunction with the terrain TIN, flooded areas can be seen. The three-dimensional floodplain view is quite useful for floodplain visualization.

3. Results and discussion

3.1. Data generation

For flood analysis, daily maximum flows of Savaran hydrometric station were used to data development and generation in Polasjan station and statistical period length increased to 27 years.

3.2. Flow estimation and *T*-years

Hydrological frequency analysis is one of the essential tasks in hydrological engineering design. It is the work of determining the magnitudes of hydrological variables corresponding to given frequencies or recurrence intervals. In probability distributions within hydrology different methods are used. (Salajegheh et al., 2008).

In order to investigation of suitable probability distribution for peak series, by using of ordinary moment and maximum likelihood methods through hydrometric station of Polasjan which existing in region, suitable probability distributions were determined. According to results for peak series, LP3 distribution and maximum likelihood method, Extreme value type 1 distribution and ordinary moment method, LN2 distribution and

maximum likelihood method and LP3 distribution and ordinary moment method, have

been suitable distinguished for 2, 5, 10, 25, 50 and 100 years, respectively (Table 2).

Table 2. Suitable probability distributions, methods and estimated T-Years for peak series

T-Years	Suitable Probability Distribution	Suitable Method	Estimated T-Years (m ³ /s)
2	LP3	Maximum likelihood	5.65
5	EV1	Ordinary moment	22.77
10	LN2	Maximum likelihood	35.55
25	LP3	Ordinary moment	42.84
50	LP3	Ordinary moment	47.55
100	LP3	Ordinary moment	71.29

3.3. Manning’s coefficients

Manning’s, contraction and expansion coefficient was determined based on Chow’s method and Zaiandab Consulting Company studies in Polasjan River. Regarding to Chow’s method and Zaiandab Consulting Company studies Manning’s coefficient was obtained 0.035.

3.4. TIN model

In order to produce a floodplain map, accurate topographic information is required. In GIS, the TIN model is the best data model for large-scale terrain representation. Using 1/25000 topographic maps a TIN model of the stream channel and floodplain was constructed for Polasjan River Basin.

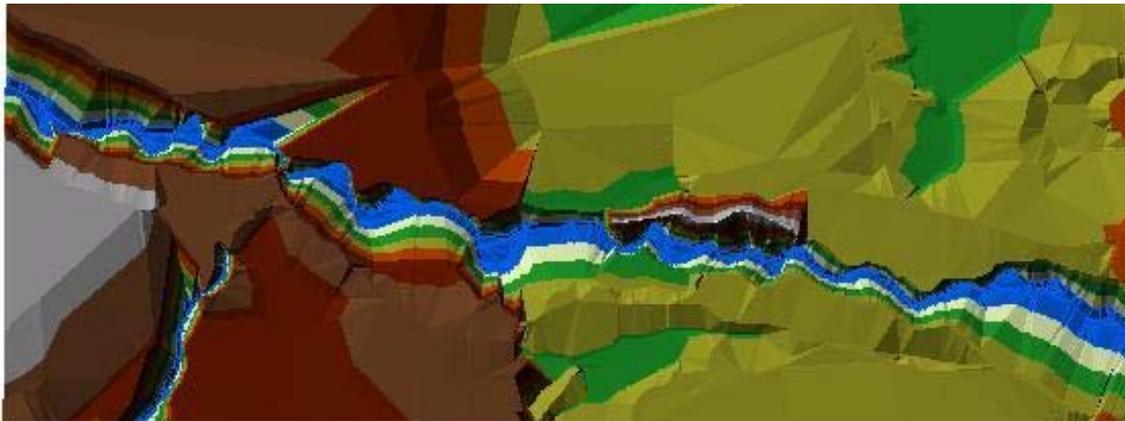


Fig. 7. TIN surface model

3.5. Hydraulic analysis and flood mapping

HEC-RAS using dates such as flow rate with difference return periods, Manning’s coefficient, etc. was presented much outputs such as hydraulic radius, water surface profile, flow velocity, stage-discharge relation, water critical depth, wetted perimeter and area and kind of flow regime for each cross-section (figure 8). After importing, the HEC-RAS output data into ArcView and create link the HEC-RAS stream

representation to the digital representation of the stream in ArcView. Using the procedure detailed in previous, a TIN terrain model and raster floodplain map was developed. Flood mapping studies usually carried out for up to 25-years but in Polasjan River because of farms around the river that flood is damaging for them; flood mapping was carried out for down 25-years too. So flood map simulated for six return periods in Polasjan River Basin (Figure 9).

Table 3. Flood extend for each T-Years

T-Years	2	5	10	25	50	100
Flood extend (ha)	18.8	28.1	32.3	34.2	35.1	39.8

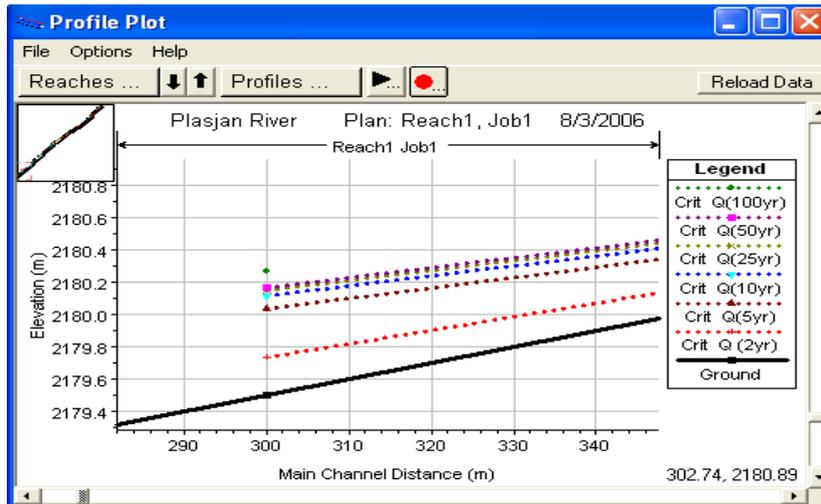


Fig. 8. Critical depth for T-Years

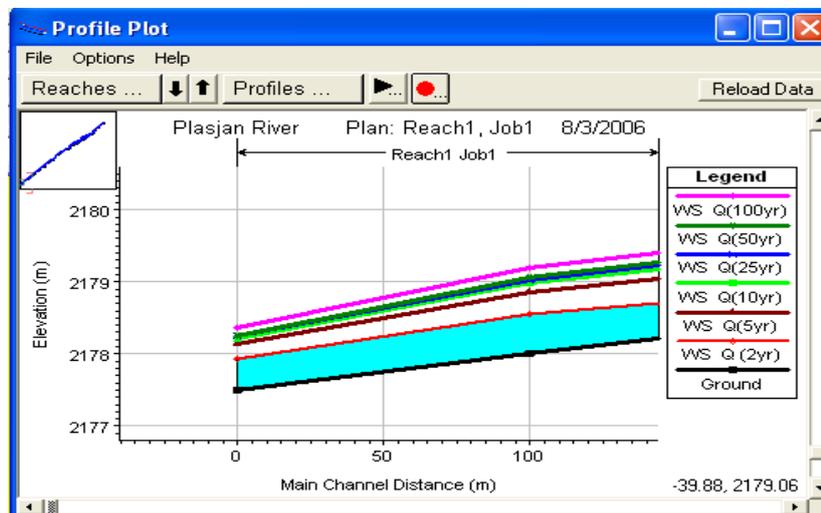


Fig. 9. Water surface profile for T-Years

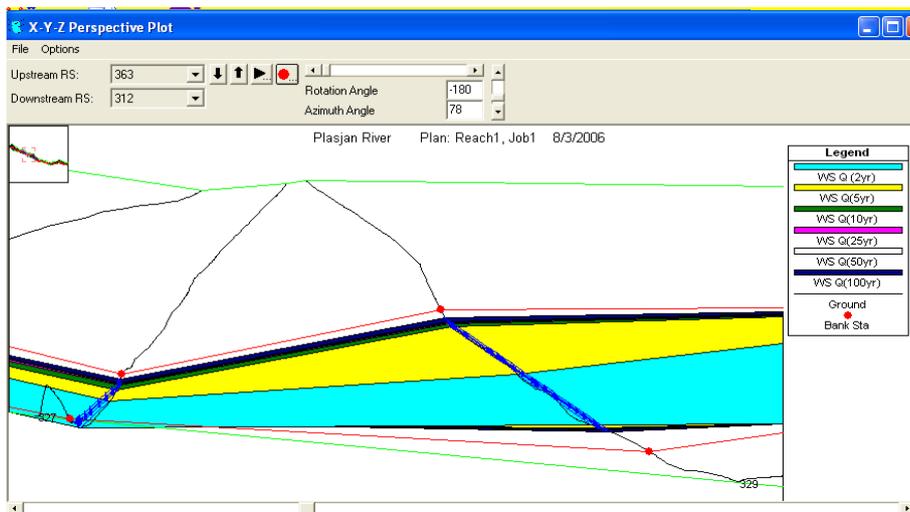


Fig. 10. Three-dimensional floodplain extents for T-Years

4. Conclusions

This study provides a link between hydraulic modeling using HECRAS, and spatial display and analysis of floodplain data in ArcView GIS. As inputs, the approach requires a completed HEC-RAS model simulation and a GIS stream centerline representation. The procedure consists of several steps: data import from HEC-RAS, stream centerline representation, cross-section georeferencing, terrain modeling, and floodplain mapping. The outputs are a digital floodplain map that shows both extent and depth of inundation, and a TIN model of the terrain synthesized from high resolution HEC-RAS cross-section data and lower resolution digital elevation model (DEM) data describing the regional landscape (Figure 10 and Table 3). The advantages of the approach are in the following.

4.1. Advantages

The process developed for automating terrain modeling and floodplain delineation has several noteworthy benefits:

4.1.1. User interface

Through the use of menu items and sample exercises, floodplain mapping is automated and simplified. The user need not be a GIS expert to quickly and easily produce detailed floodplain maps. In addition to showing the aerial extent of flooding, the floodplain delineation includes flood depth information.

4.1.2. Digital output

Rendering the floodplain in digital GIS format allows the floodplain data to be easily compared with other digital data, such as digital orthophotography and GIS coverages of infrastructure, buildings, and land parcels.

4.1.3. Resource savings

Many floodplain maps need to be revised because they are outdated. The automated mapping approach developed for this research saves time and money versus conventional

floodplain delineation on paper maps. Thus, floodplain maps can be updated more frequently, as changes in hydrologic and hydraulic conditions warrant.

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