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GIS MAPPING ALGORITHMS FOR FLOODWAY MODELING

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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. The Stream Morphing, Normal Distance, and Buffer Floodway algorithms were evaluated for their capabilities and deficiencies with regards to floodway mapping. The Buffer Floodway method, based on TIN intersection, was found to produce a smooth floodway boundary that reduces manual smoothing and editing by a modeler to a large extent. The challenges in implementing and producing a smoothed floodway are discussed. Postprocessing with a rubbersheeting transformation was found to produce the best floodway output that passes through the encroachments at each cross-section. A localized similarity transformation method was also found to produce a desirable floodway boundary output.

Keywords: Floodway modeling, GIS mapping, TIN intersection, spatial interpolation, mathematical transformations

1. INTRODUCTION

Floodway Modeling

The Federal Emergency Management Agency (FEMA) administers the National Flood Insurance Program (NFIP) in the United States, 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). The water surface elevation for the 1% chance flood in a stream is termed the Base Flood Elevation (BFE). In addition to mapping floodplains, FEMA also mandates a floodway at special flood hazard areas that are prone to higher flood risk.

A floodway is the area identified in the main channel of a stream that allows water conveyance without increasing the BFE by more than 1 foot. Development in a watershed diverts flow into the main channels. This results in an increasein velocity and water depth. The purpose of floodways is to reduce the increase in depth and velocity in the main channel. HECRAS is one of the hydraulic models approved by the NFIP to perform floodway modeling. HECRAS hydraulic modeling involves placing cross-sections along a reach (or stream) where the program outputs water surface elevations to be used in mapping. Floodway extents are identified using HECRAS encroachment methods modeling (USACE 2008). HECRAS encroachment methodology is an iterative process where the modeler constricts flow at each cross-section and ensures that the BFE increase is less than 1 foot at all cross-sections. Floodway encroachment stations are identified on both sides of the reach at each cross-section that enables constricted flow between them. Selvanathan and Dymond (2009) have documented a method to automate the iterative process to produce an initial floodway.

Floodway modeling follows floodplain modeling in the sequence of steps undertaken to produce Digital Flood Insurance Rate Maps (DFIRMs). DFIRMs show the floodway and floodplain boundaries, and the BFEs estimated by hydraulic modeling. 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.

Geographical Information Systems (GIS) has been used increasingly in hydrologic and hydraulic (H&H) modeling workflow for calculating flows, water surface elevations and delineating floodplain boundaries. The key is to integrate or link H&H systems with GIS that would definitely improve model input/output accuracy and hence, the quality of maps produced from it.

The floodway boundary for NFIP purposes follow FEMA guidelines as stipulated in the Code for Federal Regulations. Transforming 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. It is a challenge to map a floodway between each HECRAS cross-section while satisfying FEMA requirements and recommendations. Some of the characteristics of a floodway modeled for NFIP purposes include:

1. The increase in BFE (termed as “surcharge”) should not exceed 1 foot. Negative surcharges (elevation less than the BFE) are also not desired.
2. FEMA recommends a consistent floodway topwidth (width of the floodway) along the stream for DFIRMs.

3. The encroachments should be placed between the channel banks and floodplain extents.
4. At each cross-section, the floodway extent should match the encroachments modeled by HECRAS.

GIS and Hydraulic Modeling

GIS and H&H modeling have developed as parallel technologies since the 1960s. There has been a constant push in acquiring superior spatial data, thanks to advancements in technology like remote sensing and photogrammetric methods in the 1980s. Areas for improving GIS analytical capabilities for hydrologic modeling (Fotheringham and Rogersen 1994 and Goodchild *et al.* 1992) have been identified in the 1980s. Goodchild *et al.* (1993) and Goodchild *et al.* (1996) provide a good compendium of articles for performing environmental modeling (including hydrologic modeling) using GIS. They also describe the capabilities and limitations of GIS for such applications. Demand for high resolution terrain models (Clark 1998, Singh and Fiorentino 1996, Tate *et al.* 2002) has further influenced efforts in 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). Geodatabase models like ArcHydro (Maidment 2002) have also been developed for linking GIS with hydrologic 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 AVRAS processor (Griva *et al.* 2003) which linked HECRAS with ArcView software. In addition to ArcHydro, the Center for Research in Water Resources (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. Selvanathan and Dymond (2010) have developed a tight-coupling system called FloodwayGIS with Environmental Research Systems Institute's (ESRI) ArcGIS and HECRAS to perform hydraulic floodway modeling. In FloodwayGIS, ArcGIS and HECRAS interact with each other through libraries and functions that facilitate executing the HECRAS model from within ArcGIS. The final output from FloodwayGIS is a smoothed floodway boundary for FEMA's DFIRMs. It should be noted that the boundary has to be checked by the modeler and some fine-tuning will be required.

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 ESRI's Terrain data models have improved floodplain delineation. The floodplain delineation methods using DEMs have since 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 using spatial interpolation algorithms. Such interpolation techniques generate smooth surfaces which have been well documented in the 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.

Differences between Floodplain and Floodway Delineation

Common floodplain delineation strategy is to create two surfaces – one that represents the underlying topography and another that represents the water surface elevation. The water surface elevation values come from hydraulics model output. The topographic terrain is typically generated from LiDAR data. The goal is identify flooding areas where the water surface elevations will be higher than the underlying terrain. A mathematical intersection between the two surfaces will yield locations where the elevations match which can be joined to form the floodplain boundary. ESRI's ArcGIS provides functionalities to perform such an intersection resulting in a polygon representing the floodplain. Adapting a similar methodology to delineate floodways was found to be challenging.

Floodway mapping and delineation has largely been a manual process contingent upon maintaining the desired surcharge at each of the cross-sections used in the engineering model. Floodway extents are based on a multitude of factors unlike in floodplain delineation.

Some of the factors include surcharge, floodway top width, landuse and local community factors. The location of the floodway extent is fixed at the cross-sections, but the shape of the floodway boundary between cross-sections is left to individual modelers' experience in mapping floodways based on the factors listed above.Hence, the biggest challenge is to produce an acceptable floodway extent between cross-sections in a study reach. We have proposed some floodway mapping methodologies based on spatial mathematical transformation and surface intersection capabilities available in ESRI ArcGIS.

Mathematical Transformations for Floodway Mapping

Floodway mapping involves creating a smooth boundary around the river centerline that maintains the floodway topwidth at each cross-section as modeled by HECRAS. 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. The transformation techniques assist in spatially adjusting the geometry of lines and polygons to suit floodway mapping requirements.

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. They can also be used to convert projection units within a given projected coordinate system. The general principle behind transformation is shown in Figure 1. Based on the method used, the shape may be preserved or skewed, followed by rotation and translation. The source and the

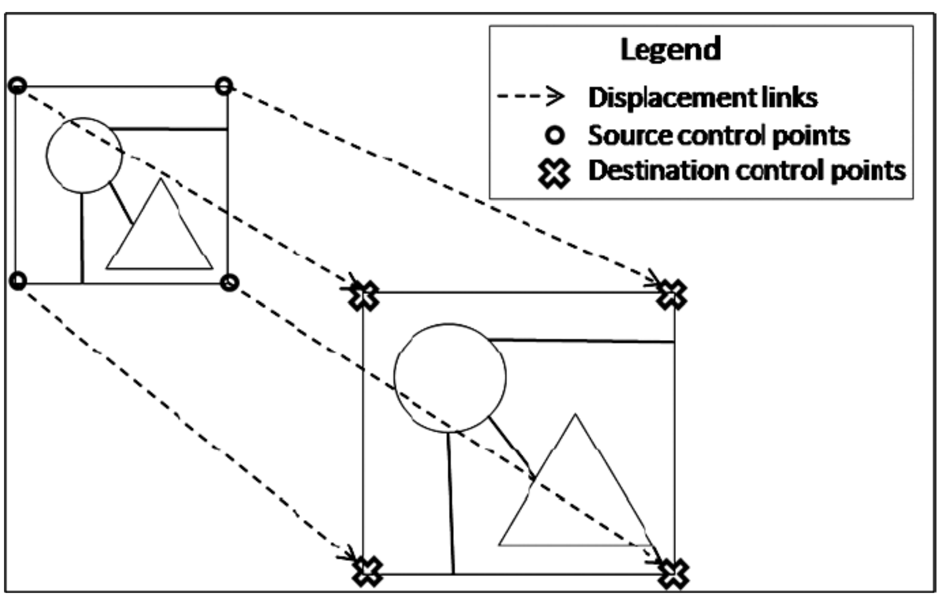

Figure 1: Principle behind transformation techniques (adapted from ArcGIS help documentation)

destination control points are identified and connected as displacement links. Displacement links are lines (or links) joining the source and destination points used in the transformation.

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. These ArcGIS spatial techniques can be successfully employed for floodway mapping.

2. METHODS

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. In addition to interpolation technique, the mapping methods also depend on mathematical transformations for deciding the geometry of the floodway boundary. Each of the three methods is described in the following section. Each is then utilized in real floodway mapping scenarios to gauge their effectiveness.

Method 1 – Stream Morphing

The stream morphing method is a simple rubbersheeting technique based on the shape of the river centerline. The river centerline is mathematically transformed to fit on both sides such that it passes through the HECRAS encroachment points. The source control points are defined along the river centerline where it intersects with the cross-sections. The destination points are the points of floodway encroachments at the cross-section on one side of the river centerline. In other words, the displacement links are drawn from the point of intersection of the river centerline with the cross-section to the encroachment station on each cross-section. Rubbersheeting stretches the surface using a piecewise transformation method preserving the linear portions. Thus, this method offsets and transforms the river centerline between two cross-sections in such a way that the floodway boundary passes through the encroachment stations at each cross-section. Figure 2 shows the output from

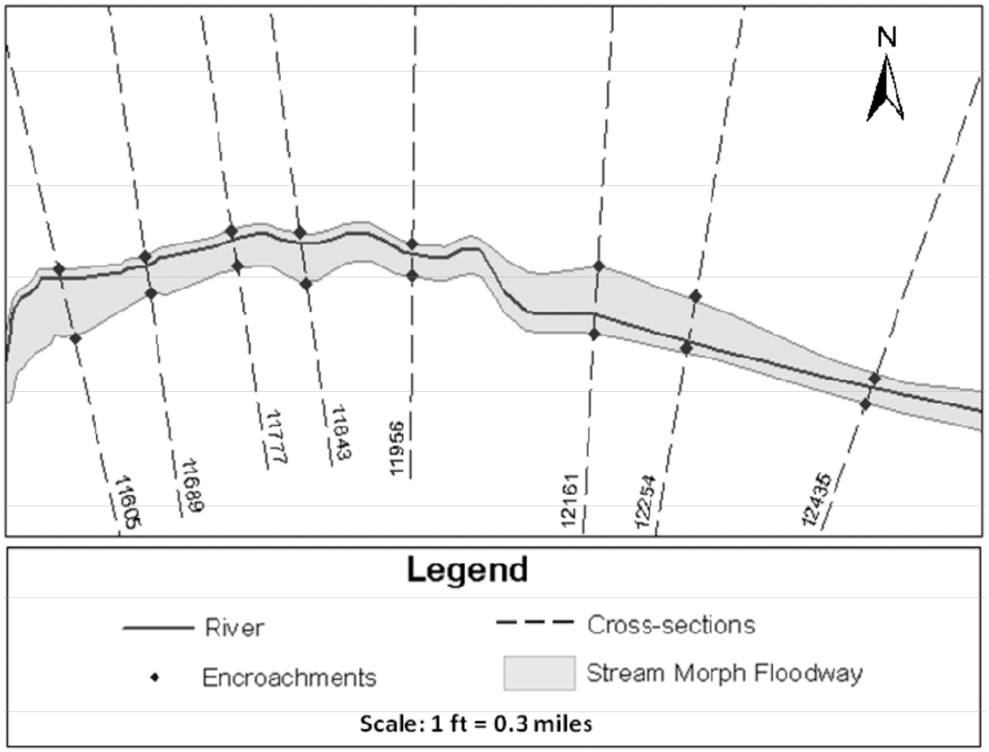

Figure 2: The stream morph mapping method. This method rubbersheets the shape of the river on either side based on the encroachment station points at each cross-section

the stream morph method. The main advantage of the 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.

Method 2 – Normal Distances Method

The 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 3. The triangles are the locations identified by the normal lines. The dotted line is the interpolated floodway between the two cross-sections generated by connecting all the triangle points into a line. The normal distances should be computed separately for each side of the river. Figure 3 shows the interpolated floodway being identified on the right side of the river.

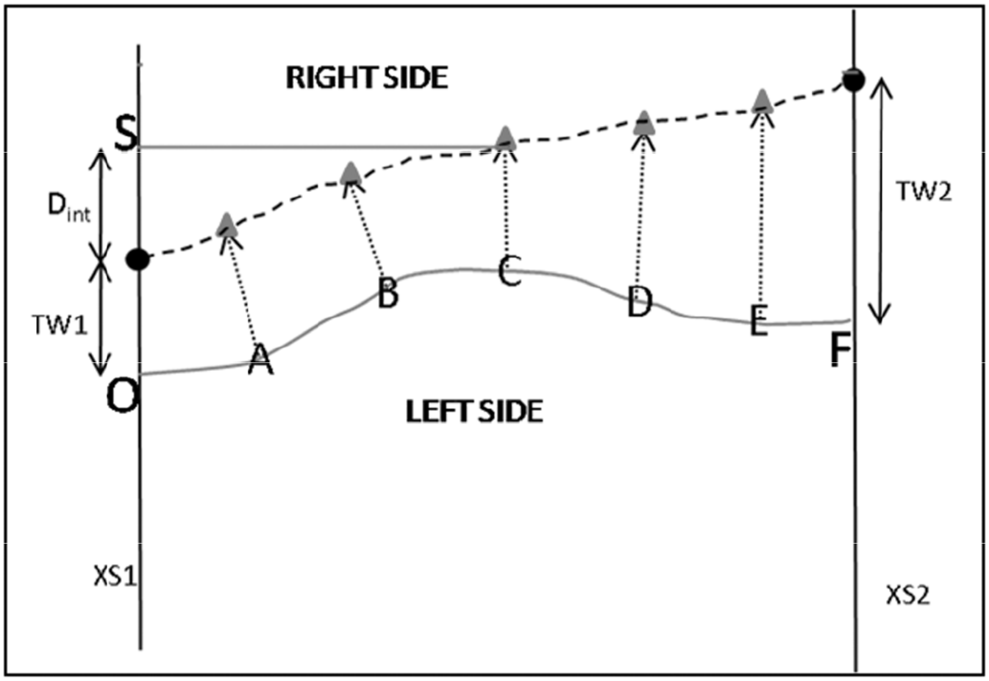

Figure 3: Schematic of the normal distances method. The method is based on plotting floodway boundary by intersecting the normal lines at each vertex to the interpolated width line

The normal distances method calculates interpolated topwidths between two consecutive cross-sections. The difference between the two topwidths indicates if the section is an increasing section or a decreasing section. A, B, C, D and E are vertices on the river centerline between two cross-sections XS_1 and XS_2. The proportional distance of a vertex along the river centerline between the two cross-sections is used to compute the interpolated floodway width at that vertex. An example calculation is shown below. For vertex C,

$$D_{prop} = \frac{OC}{OF} \tag{1}$$

Where,

D_{prop} = proportional distance of vertex C from XS_1 along the river centerline

OC = Distance of vertex C from XS_1 along the river centerline

OF = Distance between XS_1 and XS_2 along the river centerline

The interpolated floodway width (or the normal distance) at vertex C is given by

$$D_{int} = D_{prop} * (TW2 - TW1) \tag{2}$$

Where,

D_{int} = Interpolated floodway width between XS_1 and XS_2

TW_1 = Width of the floodway at XS_1 on right side of the river

TW_2 = Width of the floodway at XS_2 on right side of the river

The point of intersection of the horizontal line from S to the normal line at vertex C identifies the interpolated floodway width at vertex C. The same process will be repeated for other vertices on both sides of the river.

The normal distances method considers the vertices between the cross-sections; hence, it provides 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.

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, the floodway top widths on either side of the river are used to generate TINs. Multiple concentric buffer rings of the river centerline are generated, where the width of the closest and farthest rings are governed by the minimum and maximum floodway topwidths. A TIN of these rings (BufferTIN) is created. Figure 4 shows the floodway buffer rings on either side of the river used to construct the BufferTIN. In the figure, ten buffer rings are created at equal intervals, widths ranging from 2 ft to a maximum of 146 ft (not shown). Thus, the BufferTIN values represent the distances from the river centerline. Figure 4 also displays the left and right floodway topwidths at cross-sections 156, 179 and 209. The extent of the BufferTIN is such that the encroachments at each cross-section are covered.

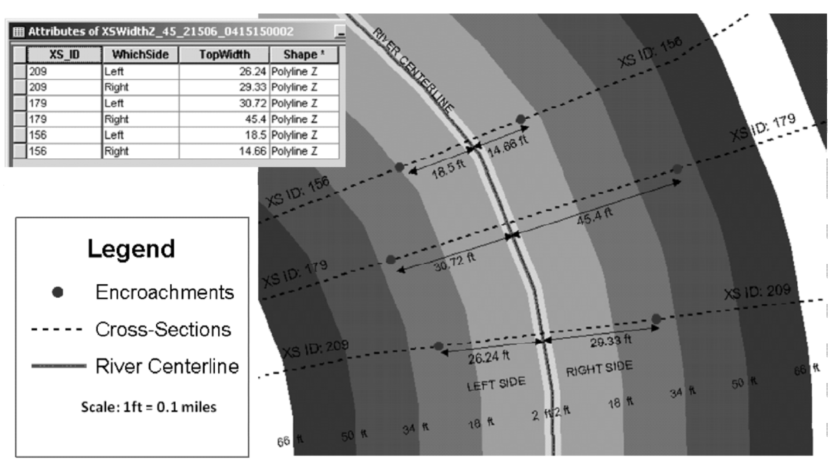

Figure 4: Concentric buffer rings between cross-sections 156 and 209. The width of each concentric ring is shown at the bottom. The width is same on the left and right side of the river centerline. These rings are converted into a TIN to create the BufferTIN.

The cross-sections along the river are split into a left and right side at their point of intersection with the river centerline. These cross-sections are converted into three dimensional cross-sections with floodway topwidths being the third dimension. The floodway topwidths are a distance measured from the river centerline along each cross-section. A TIN (XSTIN) is generated using these topwidth-based 3D cross-sections. The XSTIN values represent the interpolated floodway topwidths. The values are linearly interpolated between two successive cross-sections. The BufferTIN and the XSTIN are intersected and the difference between them yields the floodway boundary.

The BufferTIN and the XSTIN values represent widths based on distance from the river centerline. The TIN intersection output represents points on the TINs where the widths match. These points are connected to generate a topwidth-based floodway boundary. Figure 5 shows a schematic of the TIN intersection using contours between cross-sections 1386 and 1514. The contours range from 73ft to 31ft indicating the linear interpolation between the two cross-sections. When the two TINs are intersected, the points of intersection represent the vertices of the generated floodway boundary.

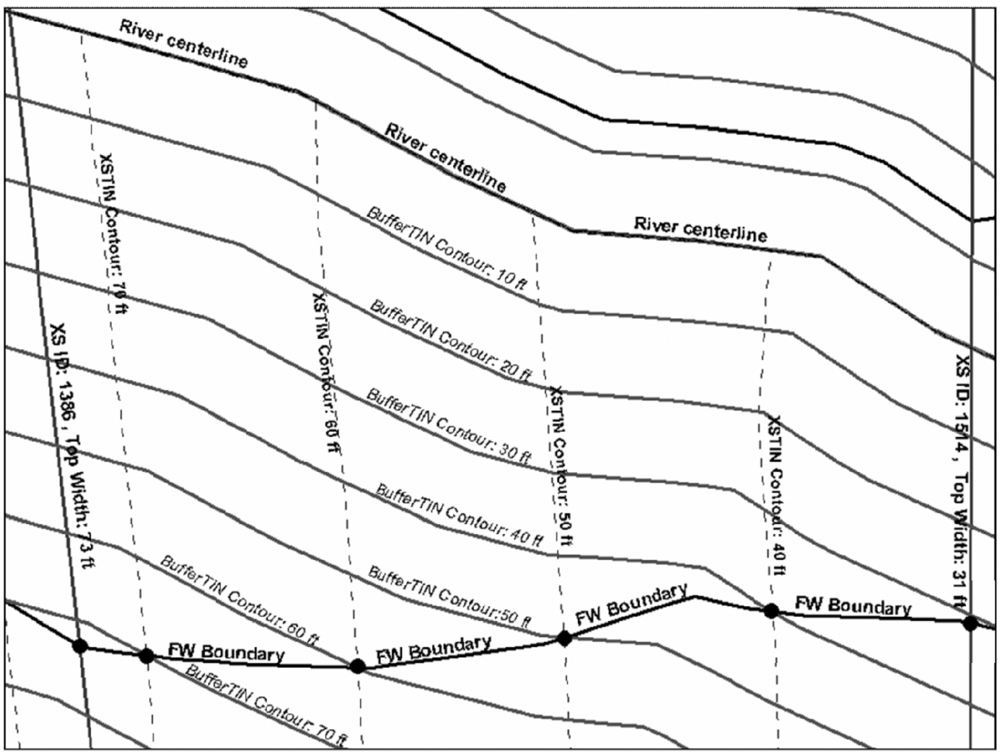

Figure 5: Overlay of the BufferTIN and XSTIN contours showing the points of intersection that forms the raw floodway boundary. The linear interpolation of floodway topwidths between cross-sections is indicated by the contours derived from XSTIN

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 6 shows the difference in floodway delineation as mapped by the buffer floodway technique and the stream morph method. Tests indicated that the buffer floodway method produces the most desirable output for DFIRM mapping purposes. The buffer floodway method based on the topwidths enables a quick way to map the floodway boundary across the entire length of the stream. The advantages of using the buffer floodway method include:

1. The river buffer helps to maintain the sinuosity of the river, especially at cross-sections where 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 XSTIN is created from topwidth-based three dimensional cross-sections, 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.

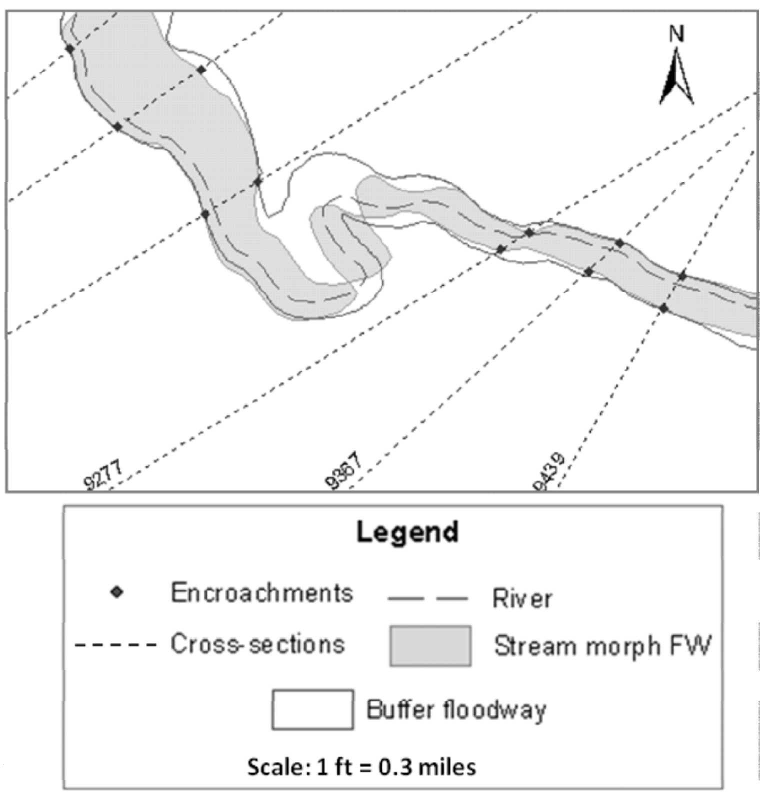

Figure 6: Map showing buffer floodway method vs. Stream morphing method

3. RESULTS AND DISCUSSION

The three proposed mapping strategies are expected to provide a good first cut of the floodway extents. The stream morphing method was found to produce helix patterns especially in areas where the river was sinuous with no cross-sections in between (Figure 7). Since there are no displacement links in the sinuous section between two cross-sections shown in the figure, the transformed curves on the left and right side of the river intersect the river centerline causing helical patterns. The floodway boundary output is unacceptable in this situation.

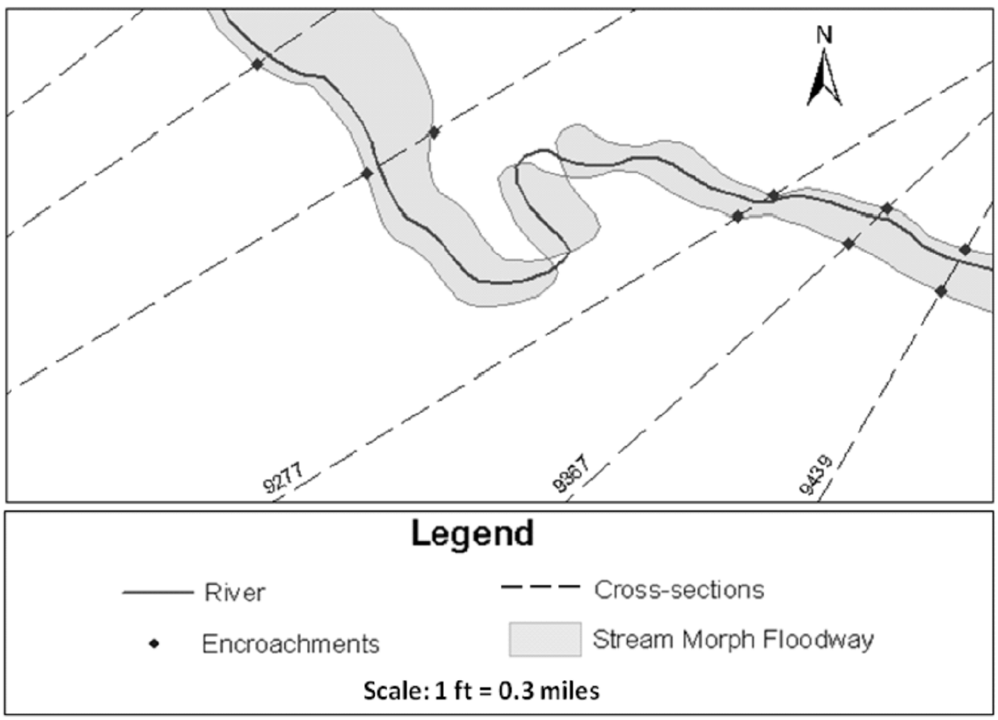

Figure 7: Helical patterns in the stream morph method. Such patterns cannot be avoided at the meanders where there are no cross-sections

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 8). Figure 8 shows an area where river meanders in such a way that the interpolated floodway width (D_{int}) on the right side of the river intersects with the normal line on the left side of the river. 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 all points on the meandering portions of the stream. Lack of definition at the meanders would result in the floodway boundary being clipped. The mapping method can be improved if a

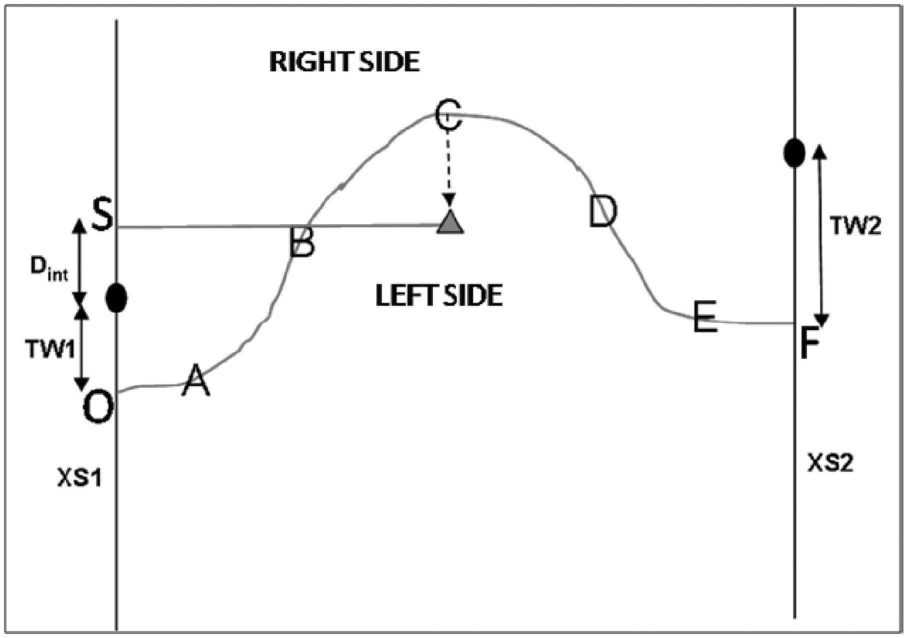

Figure 8: Problem with the normal distances approach. At narrow topwidth cross-sections, the intersection point will be identified on the wrong side of the river centerline

buffer of the river centerline is used to 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.

While the buffer floodway method produced a pleasing result of the floodway extents, it had its own set of limitations, including:

1. The floodway boundary does not match the encroachment stations at all the cross-sections. Due to the linear interpolation in ArcGIS TIN generation and the inherent generalization in TIN difference output (a polygon), the generated floodway boundary does not match the encroachments stations at all the cross-sections. This is a FEMA requirement for floodway boundaries. Hence, some post-processing is required to finalize the floodway.
2. The buffer rings get more generalized farther away from the stream centerline. Those rings do not follow the shape of the river centerline as much as the rings that are closer to the river. Hence, at cross-sections with very wide topwidths, the distance measured from the river centerline to a point on the farthest ring will not match the buffer width of the ring. This results in the floodway boundary getting mapped wider or narrower 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.

Regardless of these issues, the buffer floodway method shows the most promise insemi-automating the floodway mapping process.The buffer floodway method failed in portions of the reach around the structures. This can be attributed to the fact that the hydraulics of structures cannot be captured by spatial strategies that does not consider conveyance characteristics.

POST-PROCESSING ISSUES

The buffer floodway method produces a floodway which is essentially a product of TIN intersection. 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 of a test like the Root Mean Square (RMS) error of the fitted curve was not considered.

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 9 shows the difference between the rubbersheeted boundary and the raw floodway from TIN intersection.

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 sub-curves 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 10). 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.

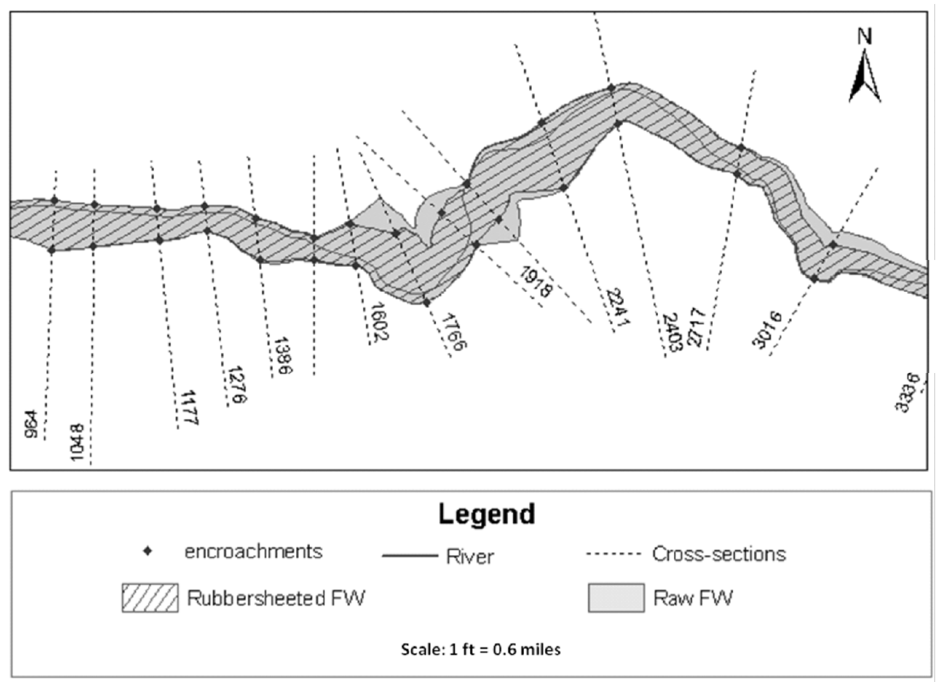

Figure 9: Comparison of the raw floodway and rubbersheeted floodway

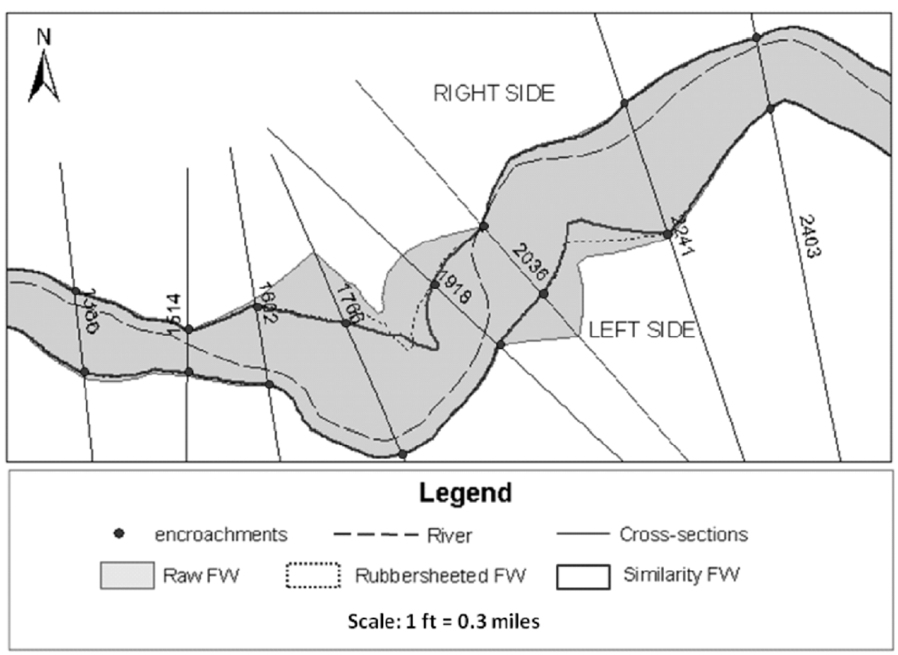

Figure 10: Localized similarity transformation comparison with rubbersheeted floodway

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 10, the fitted rubbersheeted boundary cuts the river centerline on the right side between cross-sections 1918 and 2241 near cross-section 2036. 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.

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 topwidth 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. Numerous challenges were overcome and modifications implemented 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 converted to topwidth-based three dimensional cross-sections. This preprocessing of the cross-section was necessary to generate accurate TINs on both sides of the river centerline.

2. The TIN interpolation process is expected to produce long, near-linear striations between two cross-sections. However, lack of sufficient intermediate vertices on cross-sections affected the TIN triangulation patterns as shown in Figure 11 (left). The figure illustrates that the TIN interpolation bands between two consecutive cross-sections is not smooth. Such triangulations are not desirable while interpolating between two cross-sections. Hence, the cross-sections were densified in order to eradicate abnormal triangulation patterns. The TIN interpolation bands between cross-sections 7617 and 8797 improved vastly after densification (Figure 11, right). There is a smooth linear transition in elevation from one cross-section to the next.

3. Since the cross-section lines were split at their points of intersection with the river line before generating three dimensional lines (based on topwidths) and eventually the XSTIN, the TIN triangulations on one side of the river influenced the triangulation on the other side. This 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

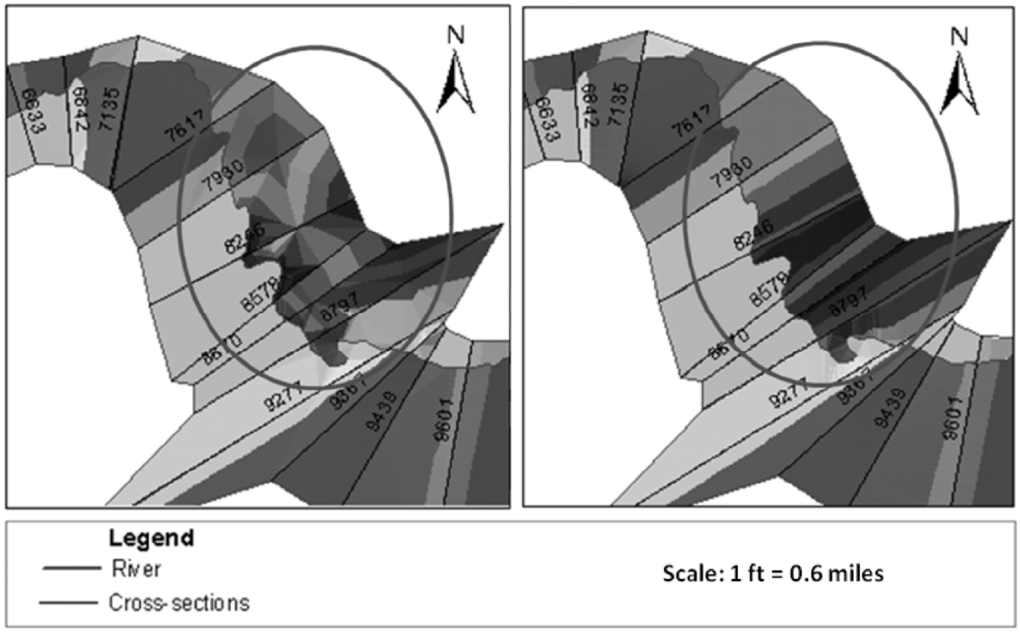

Figure 11: Improvements in TIN triangulation due to densification. Improper triangulation due to lack of definition (left) and improved triangulation after densification (right)

12 shows a perspective view of the elevated ‘wall’ near the river centerline, which act like a hard breakline in TIN creation. The elevation wall prevented triangulation from crossing to the other side of the river centerline.

4. Any area outside of the cross-section limits should not be used in the TIN intersection method. Hence, a three dimensional 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 XSTIN creation process.

4. 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. Three algorithms that perform floodway smoothing were evaluated and issues that affect or influence the floodway boundary were highlighted. Preprocessing the data (densification and elevated wall) is vital to the success of the recommended buffer floodway algorithm.

The preferred 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

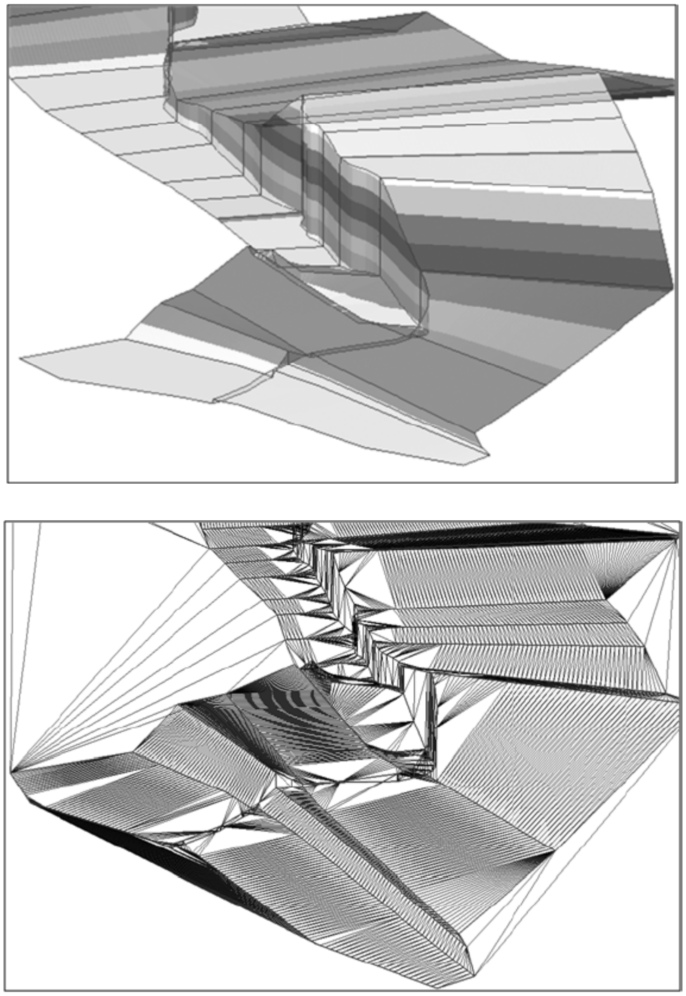

Figure 12:Elevation 'wall' along the river centerline. The widths of the floodway are larger on the right side than the left side. Hence, the XSTIN indicates lower values on the left side compared to the right side of the river (Top). The TIN triangulations show the vertical TIN faces along the river centerline which prevents triangulations from one side of the river from affecting the other side (Bottom)

very good floodway boundary for the modelers to fine-tune manually. The TINs form the building blocks in determining the floodway boundary. The buffer floodway method is a hybrid approach performing a "force-fit" mapping at the cross-sections matching the extents defined by the hydraulic model and a "form-fit" mapping between the cross-sections that results in an acceptable floodway boundary based on engineering judgment and local topographic criteria. The DFIRM production mapping scales should also be considered. There is still room for improvement in this algorithm. For example, the localized rubbersheeting provided better results in some locations. Alternatively, the outputs from various transformation methods can be provided in order to 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.

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