A GIS framework for describing river channel bathymetry

by

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Abstract

Detailed bathymetry data are collected on short reaches and are usually not available for the entire stream network at a regional scale. By using the field data collected for a reach along the Brazos River in Texas, a geographic information system (GIS) framework for describing river channel bathymetry at regional-scale is presented. The framework is based on deriving relationships among different channel characteristics such as the channel planform, the thalweg location, and the cross-sections. Thus, using only the channel planform, in conjunction with the derived relationships, it is possible to create a three-dimensional mesh that comprises a series of cross-sections and profile-lines (lines parallel to the flow). The three-dimensional mesh provides a mean surface for the channel bed. The suitability of this approach is verified by it applying to a short reach upstream of the study area to create a three-dimensional channel description.

Keywords: geographic information systems (GIS), river channels, bathymetry, thalweg, radius of curvature, beta probability density functions.

Introduction

Unlike land surface terrain and river network hydrography, there is no standardized three-dimensional geospatial representation of river channel morphology. Detailed bathymetry and river cross-section data are collected only on short reaches so they are not available at a regional scale. A geographic information system (GIS) framework for three-dimensional description of river channels is developed. This framework inter-relates channel characteristics, such as the channel planform, the thalweg location, and the cross-sections, with each other. The channel planform and cross-sections are characterized by analytical functions. Therefore, by knowing only the planform of the channel, the cross-sections can be described in three-dimensions. The three-dimensional description of the channel provided by the framework defines a mean surface for the channel bed.

The channel bathymetry, which provides a description of channel bed form, is an important dataset for hydrodynamic modeling. The methods currently used for dense mapping of land surface terrain such as LIDAR (Light Detection and Ranging) cannot penetrate the water, and therefore cannot detect the channel bed form. The channel bed form is measured by other means such as the traditional cross-section surveys or by using a depth sounder combined with GPS (global positioning system). The depth sounding technique which measures the channel bathymetry in the form of (x,y,z) points provides more information compared to the traditional cross-section surveys. The depth sounding data are, however, limited to short channel reaches because of resource limitations; they require a considerable amount of time expended by trained personnel. Due to this, the hydrodynamic modeling studies, which use the depth sounding data are also limited to short reaches. The results from these short representative reaches are, however, used to make decisions at regional scales. For example, decisions related to instream flow, contaminant transport and soil erosion modeling fall into this category, and such regional decisions based upon local studies are open to arguments (Van Winkle et. al., 1998; Addiscott and Mirza, 1998; Renschler and Harbor; 2002). If additional bathymetry data are available, then these data can be used to verify the decisions made based upon studies on the representative reaches. Therefore, the ability to acquire bathymetry data over large spatial domain is a key to regional scale studies.

The availability of remotely sensed satellite data, such as LIDAR, has proven to be a very useful for regional scale studies, but their inability to penetrate *deep and turbid* water limits their use in river channel studies. Other commonly available regional datasets in hydrology are the NED (National Elevation Dataset) and the NHD (National Hydrography Dataset). The NED provides digital elevation models for the entire United States and has a resolution of about 30 meters. The NHD provides a nationwide coverage of millions of features, including waterbodies such as lakes and ponds, linear water features such as streams and rivers, and point features such as springs and wells. Although NED and NHD are used extensively in hydrologic studies, they are not useful for studying the detailed hydrodynamics of river channels. NHD, for example, provides only the location of the centerline of the river channels. The present study is an attempt towards providing a regional description of river channels in hydrology.

Objective

The channel bathymetry can be considered as an analytical model described by a function

$$\boldsymbol{b}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) = \boldsymbol{b}'(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) + \boldsymbol{b}''(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) \qquad (1)$$

Where $\boldsymbol{b}'(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$ is the mean surface for the channel bed and $\boldsymbol{b}''(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$ are the departures from the mean. Developing an analytical model for channel description is useful because the model can then be used to describe the channel bathymetry at locations where there are no data. Both $\boldsymbol{b}'$ and $\boldsymbol{b}''$ in equation (1) are equally important to provide a meaningful description of channel bathymetry. However, due to the complex nature of the problem, and to explain the approach in sufficient details, only the first term (the mean surface) is discussed in this paper. The objective of this paper is therefore to develop a framework for describing the mean surface of the channel bed in an analytical form.

Related work

The study of river channels is of interest to both geomorphologists and water resources engineers. Geomorphologists are mainly concerned with the evolution of river channels over time, whereas water resources engineers are concerned with the hydrology of the catchments and the hydrodynamics within the river channels. Although both disciplines have different interests, they share common datasets and computing tools. Datasets such as topographic maps, satellite imagery, and digital elevation models (DEMs) are shared by geomorphologists and water resources engineers. Similarly computer models for rainfall-runoff modeling, hydraulic routing, and sediment transport are common between the two disciplines. The sharing of common data and computer tools is bringing the two disciplines on a converging path. The proposed study attempts to bring the two disciplines even closer by using the geomorphologic concepts to build a GIS dataset that is useful for engineering applications.

The traditional approach to the evolution of river channels involves comparison of the present morphology with that recorded by previous measured sources. The change in morphology is then related to field indicators such as vegetation and urbanization. The studies involving cross-sections and topographic maps are localized in extent due to the unavailability of extensive data at a watershed scale (Gregory et. al., 1992). With the availability of aerial photographs, image processing tools and GIS, morphological comparisons are now carried out using aerial photographs and satellite-based remotely sensed data (Leys and Werritty, 1999; Winterbottom, 1999). In addition, satellite remote sensing offers the possibility of studying spatial and temporal variations in geomorphology from the fine scale of mapping pebbles to the regional scale of a single catchment to the global scale of the world's topography (Mertes, 2002). Yang et. al., (1999) is an example of regional scale study that involved examining the spatio-temporal changes of river banks and channel centerlines in the active Yellow River Delta, China. Stein et. al., (2002) is an example of continental scale study that involved assessing anthropogenic river disturbance in Australia.

Water resources engineers use GIS data for hydrologic modeling and to model the hydrodynamics in river channels. GIS is used for data pre-processing, post-processing, and visualization. GIS plays an important role in the distributed hydrologic modeling approach where the model is distributed based on the resolution of the input dataset. The area can be sub-divided into a number of cells in the case of a DEM or remotely sensed satellite data (Schultz, 1993; Biftu and Gan, 2001). Radar-based flood warning has emerged in recent years with the availability of next generation radar (NEXRAD) rainfall data and other sources such as the WSR-88 (Weather Surveillance Radar-1988 Doppler) from the National Weather Service (Giannoni et. al., 2003; Bedient et. al., 2003). The flow from the hydrologic model is used to simulate the hydrodynamics in the river channel to map the floodplain using GIS (Townsend and Walsh, 1997; Tate et. al., 2002).

Hydrodynamic models are also used to model the transport phenomenon and the spatial distribution of fish habitats (Karpik and Crockett, 1997; Austin and Wentzel, 2001). The data for hydrodynamic modeling, however, comes from other sources such as the traditional cross-section surveys or depth sounding measurements. The quality of bathymetry data plays a major role in hydrodynamic modeling, and depending on the available data, different numerical schemes are used (French and Clifford, 2000). The most commonly used datasets in hydrodynamic modeling, TIN and raster grids, are not flow oriented (aligned with stream channel), which adds some computational inefficiency. However, this computational inefficiency can be overcome by using the data suitable for boundary fitted curvilinear methods (Hodges and Imberger, 2001; Ye and McCorQuodale, 1997). Besides hydraulic and hydrodynamic modeling, GIS datasets are also used for non-point source pollutant modeling and sediment transport (Wicks and Bathurst, 1996; Joao and Walsh, 1992).

Hydrologic models estimate the discharge at the drainage outlet, and the discharge controls the river geometry. This interdependence between the flow and river geometry is the underlying principle of the hydraulic geometry approach. The hydraulic geometry approach assumes that discharge is the dominant independent variable, and the dependent variables (channel width, mean depth, velocity) are related to it in the form of simple power functions (Knighton, 1998). Besides the traditional approach of using cross-section surveys, the use of GIS has emerged in investigating the relationships between the channel morphology and watershed characteristics (Miller et. al., 1996; Harman et.al, 1999). The morphological variables include channel width, radius of curvature, meander wavelength and mean depth, while the watershed characteristics include drainage area, maximum flow length, stream order, and relief. The ability of GIS to easily compute the above listed variables has made it popular in hydraulic geometry studies.

The importance of GIS, along with the fact that the GIS data are being shared by different applications, has led to the development of Arc Hydro (Maidment, 2002). Arc Hydro is a geospatial and temporal data model for water resources that operates within the ArcGIS environment, which can be used for integrating hydrologic simulation models. Arc Hydro divides water resources data into five components: network, drainage, channel, hydrography, and time series. The channel component of Arc Hydro includes three-dimensional description of river channels in the form of cross-sections and profile lines.

In summary, GIS is widely used to understand and model the watershed processes and how these processes influence river morphology. The network, drainage and hydrography components of Arc Hydro can be populated by using widely available GIS data such as the National Elevation Dataset and the National Hydrography Dataset. The channel component, however, requires separate data collection that is restricted to short reaches. The framework that is proposed here provides a three-dimensional description of river channels using an analytical form, and the parameters are related to the flow. The output comprises a series of cross-sections and profile lines that can be incorporated into the channel component of Arc Hydro. The three-dimensional channel data is flow oriented, which is useful for a boundary fitted curvilinear orthogonal numerical scheme in modeling the hydrodynamics of river channels.

Study area and data

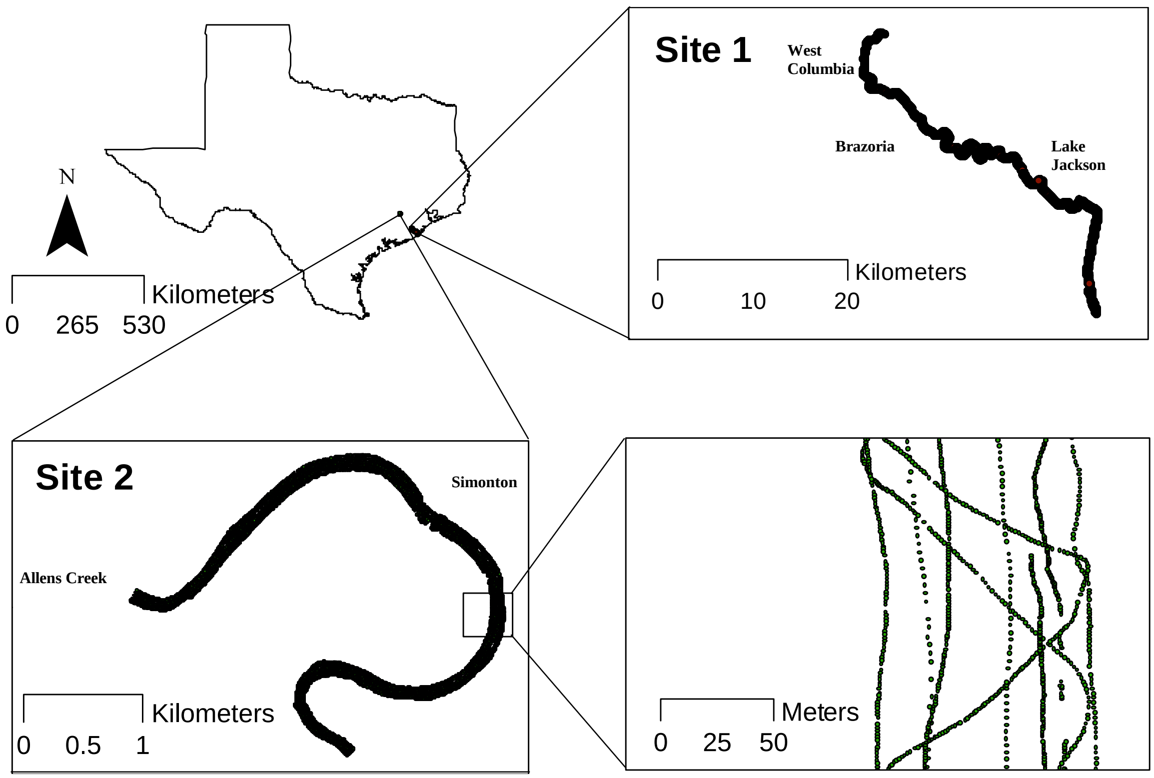

Figure 1. Study area and data. (a) Texas; (b) Bathymetry data (Site 1); (c) Bathymetry data (Site 2); (d) Small section of the Brazos river showing bathymetry points. Each (*x*,*y*) point has depth (*z*) associated with it.

The study area is the Brazos River in Texas as shown in Figure 1. The data are in the form of (*x*,*y*,*z*) bathymetry points collected by the Texas Water Development Board (TWDB). The data are collected using a depth-sounder and a GPS unit, both mounted on a boat. The data for two reaches are used in the current study. The first reach (Site 1 in

Figure 1), which is near the coast, is about 50 kilometers long, and has 46, 770 bathymetry points (@ 1 point /100 m^2). The second reach (Site 2 in Figure 1), which starts at the confluence of Allens creek, is about 6.9 kilometers long. Site 2 is located due NE of Wallis County in Texas just south of Simonton town, and it has 37, 290 bathymetry points (@ 5 points/ 100 m^2).

Methodology

A framework is developed to describe the mean surface for the channel bathymetry. The framework inter-relates channel characteristics, namely the thalweg location and the cross-sectional shape, with the channel planform. Looking downstream, the thalweg location refers to the distance of thalweg from the left bank of the channel. The framework is based on a conceptual model that is explained with reference to Figure 2.

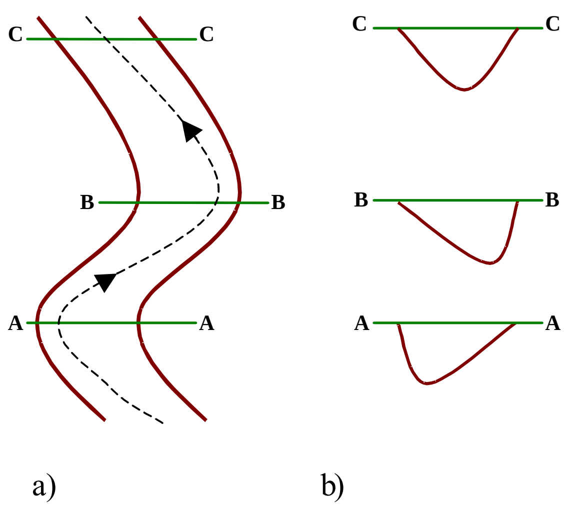

Figure 2. Conceptual model for the GIS framework. (a) Channel planform and thalweg; (b) cross-sectional forms for different thalweg locations.

The conceptual model is based on following characteristics about meandering channels:

- The thalweg has a typical pattern that follows the channel planform (Figure 2a). For example, at the meandering bend, the thalweg is close to the bank, while the thalweg is more or less in the center when the channel is straight (not meandering).
- Depending on the thalweg location, the cross-sections have asymmetric or symmetric forms (Figure 2b). For example, when the thalweg is close to the bank, the cross-sections have asymmetric form. If the thalweg is more or less at the center of the channel, the cross-sections have a symmetric form.

In summary, the direction of channel meander defines the thalweg location, which in turn dictates the channel symmetry. Therefore, if the knowledge about the channel planform is available, it is possible to describe the cross-sections. This conceptual model is simple, and there are exceptions to it. For example, as shown later in the results, the thalweg does not always lie in the center when the channel is straight. However, the idea is to build a framework based on a simple model, and then modify it to incorporate additional information. The framework is calibrated by using the data for Site 1 of the Brazos River, and is then verified by applying it to Site 2 of the Brazos River (Figure 1). The framework is applicable only to meandering channels with alluvial bed, and it does not take into account the effect of tributaries. The development of the framework is described step by step in the following sections.

Locating the thalweg along the channel

A GIS procedure is developed to locate the thalweg using the discrete (x,y,z) bathymetry points. The procedure requires the bathymetry points, the channel boundary, and an arbitrary centerline as an input. The bathymetry data are available and the channel boundary is defined by using the digital orthophoto quadrangle (DOQ) for the study area with slight modifications to incorporate recent changes, as the DOQ is five years old. The detailed description of the procedure to locate the thalweg can be found in Merwade et. al., (2003). However, some of the key points are mentioned here:

- Bathymetry points are interpolated to create a continuous surface (raster grid) for the channel bed.
- The channel bed is used to create three-dimensional cross-sections along the arbitrary centerline.
- For each cross-section, the deepest point is located.
- The deepest points along each cross-section are joined to get the thalweg.

The result is a three-dimensional line derived from bathymetry data that follows the deepest part of the river channel bed.

Data transformation and normalization

The framework developed in this study involves dealing with different locations and different scales. To make this process generic, the data are handled in a system that is independent of location and scale. After processing, the data can be transformed back to their original form. To make the data independent of location, the first transformation involves converting the data from Cartesian coordinates (x,y,z) to orthogonal rectilinear coordinates (s,n,z) (Wadzuk and Hodges, 2001; Merwade et. al., 2003). The (s,n,z) coordinate system references the data with respect to the flow in the river channel. In this coordinate system, s is the distance along the channel from the origin (upstream end of the channel) and n is the perpendicular distance from the thalweg. Looking downstream, the data to the left hand side of the thalweg have negative n coordinates and the data to the right hand side of the thalweg have positive n coordinates. In the (s,n,z) coordinate system all the river channels are therefore straight, irrespective of their location and planform in the Cartesian coordinate system.

In this study, data normalization refers to making the data independent of scale. This is accomplished by converting the data to a non-dimensional form, in which the width and the depth of the channel are unity. For example, Figure 3 shows a typical cross-section with regular (s,n,z) coordinates. In Figure 3, looking downstream, n_L is the n coordinate at the left bank with a negative sign, n_R is the n coordinate at the right bank with positive sign, and Z is the bank elevation with respect to the mean sea level. The s coordinate is a measure along the channel, and it is the same at any location for a given cross-section. After transforming the data to normalized domain, the n coordinate for any point becomes n^*, which is zero at the left bank and is equal to one at the right bank. Similarly, the z coordinate for any point becomes z^*, which is zero at the banks and is equal to one at the thalweg. The data are transformed using equations (2) and (3) as shown below.

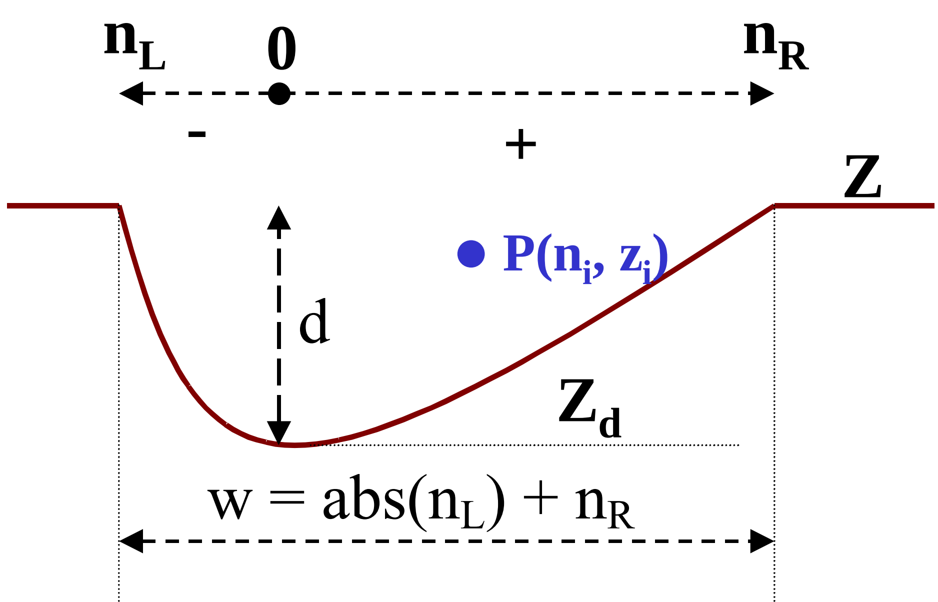

Figure 3. A typical cross-section with (s,n,z) coordinates.

With reference to Figure 3, for any bathymetry point P(n_i,z_i), the non-dimensional coordinates are:

$n_i^* = (n_i - n_L)/w$ (2)

$z_i^* = (Z - z_i)/d$ (3)

Where

w = width of the channel

d = maximum depth (thalweg)

Similarly, if t is the thalweg location (distance from left bank to the thalweg), then t^* (thalweg location in normalized domain) is calculated as

$t^* = |n_L/w|$ (4)

The conversion of bathymetry data to a normalized form can be carried out in two different ways: global and local. Here the term global refers to the entire channel, and local refers to a short reach within the channel. In the case of global conversion, the widest section and the deepest point in the river channel are used for w and d in equations (1) and (2), respectively. The global conversion process is undesirable because the deepest point in the entire channel may be several times deeper than the rest of the bathymetry data. This makes the entire channel in non-dimensional form relatively flat compared to the deepest point. Therefore, local conversion is used. In the case of local conversion, the channel is divided into a number of short reaches, and the data are converted for each reach individually. Finding a reach length for local conversion depends upon the density of the bathymetry data. An optimum reach length that captures enough data points to define a cross-section adequately must be determined. Reaches ranging from 25m to 300m were analyzed, and a 200m long reach was found satisfactory for site 1. For site 2, which has a higher density of bathymetry data, a 50m long reach was found satisfactory for normalization. Figure 4 shows the data for a reach (Figure 1d) along the study area in the original form and in the non-dimensional form. The conversion only changes the scale while preserving the original shape of the cross-section.

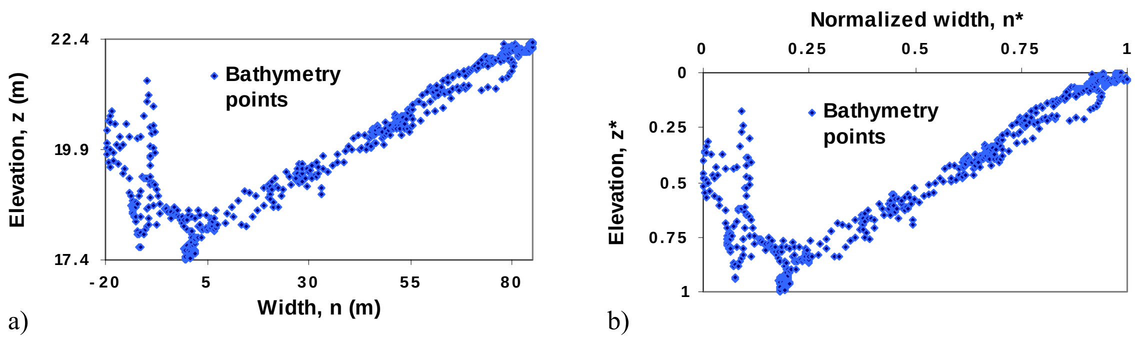

Figure 4. Data normalization. (a) Bathymetry data in original coordinates for a section shown in Figure 1d; (b) Bathymetry data in normalized coordinates.

Relationship between the thalweg location and the channel planform

Looking downstream, thalweg location refers to the distance of the deepest point (thalweg) along a cross-section from the left bank of the channel. The thalweg location can also be calculated using the right bank. In this study, however, the left bank is used because it has the least n coordinate in the (s,n,z) coordinate system. In the normalized form, where the width of the channel is unity, the thalweg location is always between zero and one. The thalweg location dictates the asymmetries in the cross-sectional forms, and these asymmetries have been related to flow by Knighton (1981; 1982; 1984). The main goal of Knighton's work was to develop asymmetry indices to study the adjustment of channel form over time, and these indices were based on extensive field measurements. In the present study, however, the radius of curvature of the left bank, which is easy to compute, is used to quantify the cross-section asymmetry. The radius of curvature, which is used as an indicator for the channel planform, is related to the thalweg location (t^*). With reference to Figure 2, if the radius of curvature of a particular reach is small, the thalweg is close to the bank with an asymmetric cross-section. If the radius of curvature is large, the thalweg is more or less at the center of the channel with more or less symmetric cross-section. A GIS procedure is developed to establish a relationship between the radius of curvature (channel planform) and the thalweg location.

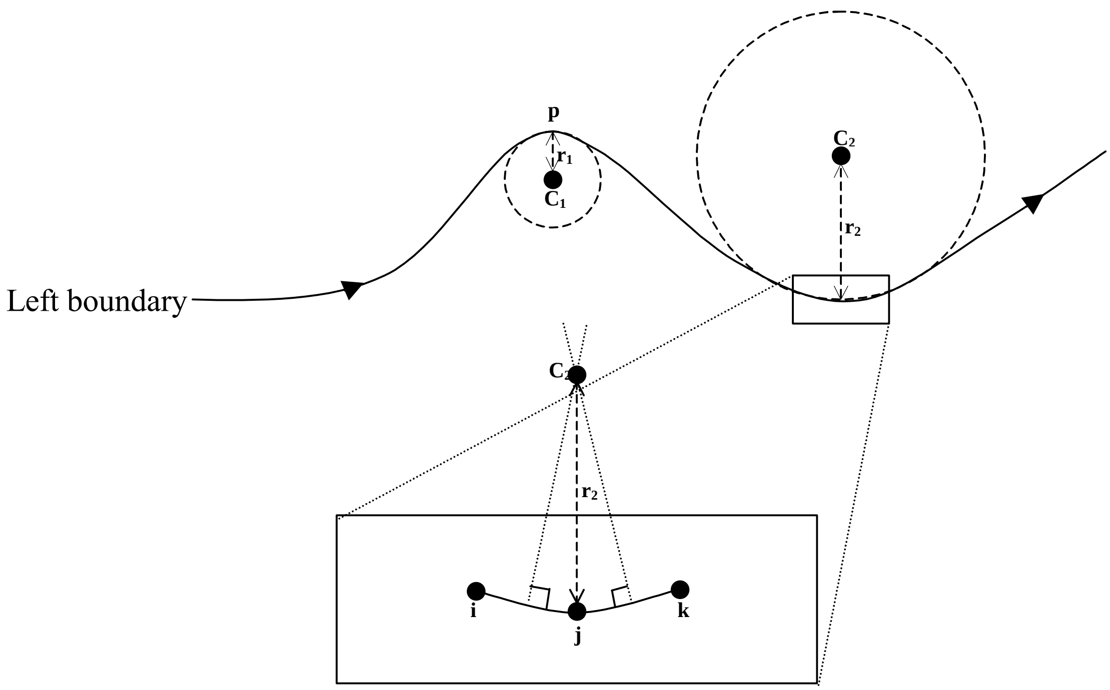

Figure 5. Radius of curvature calculations to quantify the meandering shape of the channel

The boundary of the channel is split into two banks, with only the left bank (looking downstream) used in computations. The left bank is divided into a number of segments such that the length of each segment is approximately equal to the meander wavelength, which is 10-14 times the width of the channel (Knighton, 1998). The average width of the channel is about 60m, and the average length of the segments is about 650m. The bank is divided manually to make sure that each segment does actually represent a bend. The locations of segments that are used for computing the radius of curvature are shown in Figure 6.

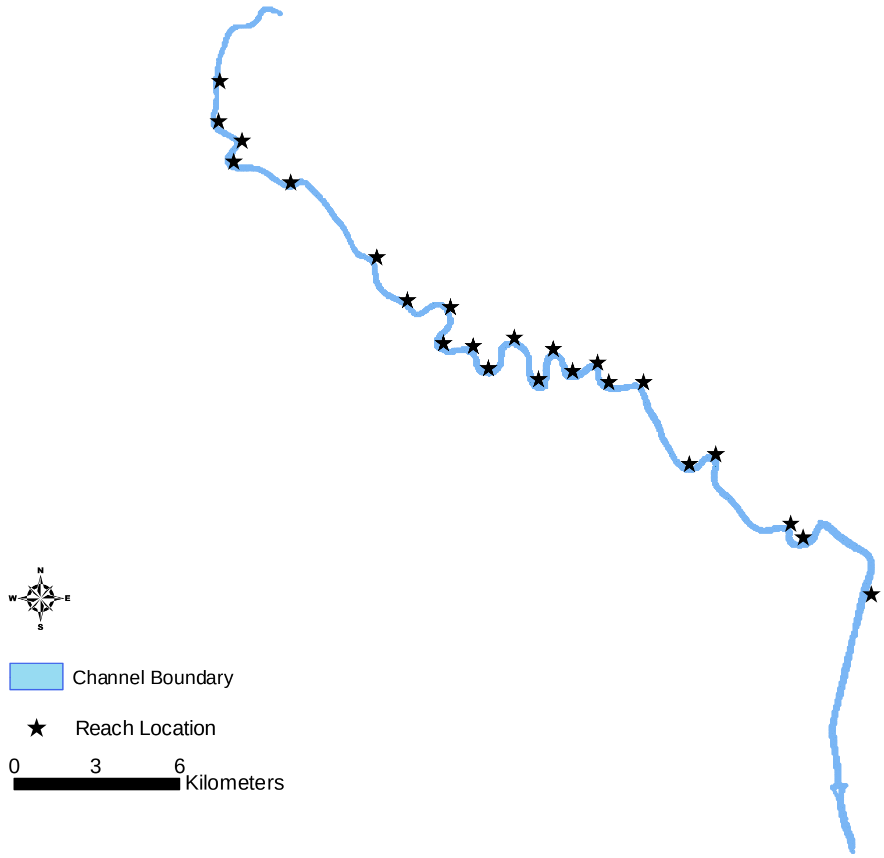

Figure 6: Locations of segments used for computing the radius of curvature.

For each segment, two items are computed: 1) the radius of curvature and 2) the distance from the midpoint of the segment to the thalweg. For each segment, the circle of curvature is computed using the two end points (*i* and *k* in Figure 5) and the mid point (point *j*). The point of intersection of the perpendicular bisectors of sub-segments *ij* and *jk* defines the center of the circle of curvature (c_2), while the radius of this circle is the radius of curvature (r_2) for that particular segment. Looking downstream, if the center of curvature is to the right hand side of the segment (circle c_1), the radius of curvature is assigned a positive value, and the radius of curvature for circle c_2 is assigned a negative value. Therefore, a positive radius of curvature means the channel is meandering to the left, and a negative radius of curvature means the channel is meandering to the right. Thus, the radius of curvature not only quantifies the meandering channel planform, but also indicates whether the channel is meandering to the right or left. For each segment, the radius of curvature and the thalweg location (t^*) are computed. Figure 7 shows the results that relate the radius of curvature and the thalweg location.

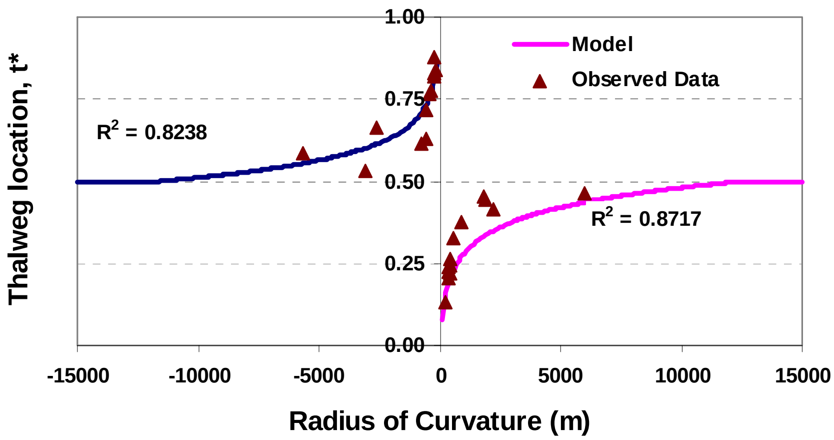

Figure 7: Relationship between thalweg location and radius of curvature for site 1 on the Brazos River.

Figure 7 has two relationships:

$t^* = -0.076*ln(r) + 1.21$ (5)

$t^* = 0.087*ln(r) - 0.32$ (6)

Where, t^* and r are thalweg location and radius of curvature, respectively.

For the negative values of radius of curvatures (looking downstream and the channel meandering to the right), the thalweg location is between 0.5 and 1.0. For the positive values of the radius of curvature (looking downstream and the channel meandering to the left), the thalweg location is between zero and 0.5. Equations (5) and (6) can be used to locate the thalweg by knowing the channel planform.

Relationship between the thalweg location and the cross-sectional form

To develop a mathematical form, the channel planform is indexed by the radius of curvature. Likewise, the cross-sectional shape has to be quantified with an analytical form. The concept of fitting an analytical form to cross-sections is not new. Attempts have been made to fit analytical forms to glacial valley cross-sections. For example, James (1996) compared power functions and second-order polynomials for glacial valley cross-sections in three Sierra Nevada valleys. For the present study, several analytical forms including power functions, polynomials, splines and probability density functions (Gamma and Beta), were considered for fitting the channel cross-sections. A beta probability function was found to be feasible among all the candidates for two main reasons:

1. The beta pdf belongs to a family of continuous distributions and is bounded by a finite interval (0,1). Since the width of channel in the normalized domain is also bounded by zero and one, the beta pdf offers a simple solution to model the cross-sections.

2. The shape of the function is controlled by only two parameters (α, β). The relative values of α and β dictate the shape of the function. For example, the function is skewed to the left when $\alpha < \beta$, skewed to the right when $\alpha > \beta$, and is symmetric

when α = β.

Therefore, the cross-sectional form of the channel is quantified using the beta pdf. The beta pdf is indexed by two parameters (α,β) and is given as:

$$\boldsymbol{beta}(\alpha,\beta) = \boldsymbol{f}(\boldsymbol{x}\,|\,\alpha,\beta) = \frac{1}{\boldsymbol{B}(\alpha,\beta)}\boldsymbol{x}^{\alpha-1}(1-\boldsymbol{x})^{\beta-1}, \quad 0<\boldsymbol{x}<1, \quad \alpha>0, \quad \beta>0, \qquad (7)$$

where $B(\alpha,\beta)$ denotes the beta function,

$$\boldsymbol{B}(\alpha,\beta) = \int_0^1 \boldsymbol{x}^{\alpha-1}(1-\boldsymbol{x})^{\beta-1}\boldsymbol{dx} = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)}, \qquad (8)$$

where Γ(.) is a standard gamma function given as

$$\Gamma(\alpha) = \int_0^\infty \boldsymbol{x}^{\alpha-1}\boldsymbol{e}^{-\boldsymbol{x}}\boldsymbol{dx}. \qquad (9)$$

To fit the beta pdf to a cross-section, x can be replaced by n^* and beta (α,β) can be replaced by z^* in equation (7). A single beta pdf, however, has two disadvantages:

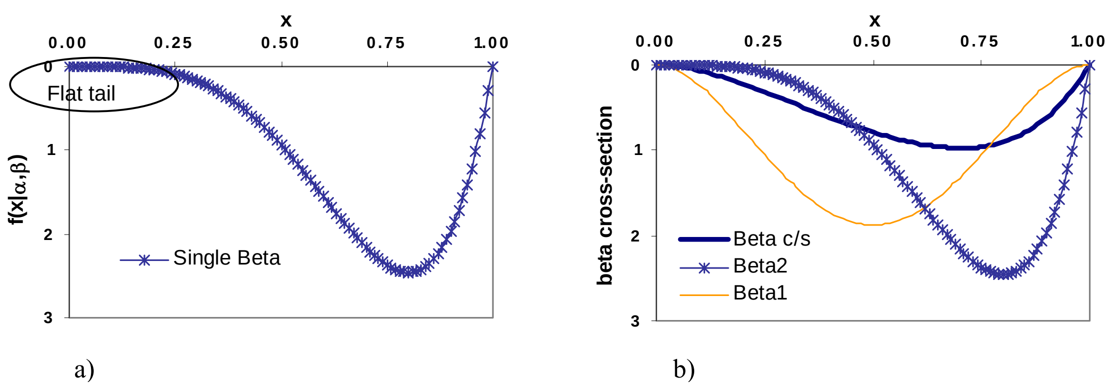

Figure 8. Beta probability density function. (a) Single beta pdf with α > β; (b) Combination of two beta pdfs. α = β for Beta1, α > β for Beta2.

1. The beta pdf, as shown in Figure 8a, is relatively flat at one of the tails. A flat tail is undesirable because it indicates zero cross-sectional area towards the end of the river channel cross-sections (Figure 8a).
2. In the normalized domain, $z^* \leq 1$. This condition is violated with a single beta pdf because the area under the curve has to be equal to one (Figure 8a).

These disadvantages are overcome by combining two beta pdfs (Figure 8b). A symmetric beta ($\alpha = \beta$) is added to an asymmetric beta ($\alpha \neq \beta$) and multiplied by a factor (*k*) to maintain $z^* \leq 1$. The combination of two beta pdfs is designated as a beta cross-section, and is calculated as:

$$\text{Beta cross-section} = \{B(\alpha_1,\beta_1) + B(\alpha_2,\beta_2)\}*k, \text{ where } \alpha_1 \neq \beta_1 \text{ and } \alpha_2 = \beta_2. \quad (10)$$

Since $\alpha_2 = \beta_2$, the combination of two beta pdfs adds two more parameters to the model, α_2/β_2 and *k*. Even with four parameters, the beta pdf is still considered a preferable model because of the (0,1) bound and its simple form. To compute beta cross-sections, the bathymetry points are selected manually for nine different thalweg locations and beta parameters estimated. The nine different thalweg locations are 0.1 to 0.9 in the increments of 0.1 units, and they are selected from the same reaches that are used for the radius of curvature computations (Figure 6). So, for example, if the thalweg is located at about 0.3 units from the left bank, then the bathymetry points covering one reach length (200m) are selected manually for one computation. This will give a beta cross-section for a thalweg location that is 0.3 units from the left bank. This process is repeated for all nine thalweg locations. The Netwon-Rhapson optimization technique available with the Microsoft Excel Solver is used to estimate the beta parameters. If two or more reaches have the same thalweg location, then the reach that gives a best fit (least sum of squares of residuals) is used for estimating the beta parameters. The beta parameters estimated for different thalweg locations are summarized in Table 1.

Thalweg location	$\alpha 1$	$\beta 1$	$\alpha 2$	$\beta 2$	*k*
0.1	1.5	8	2.5	2.5	0.2
0.2	2.25	7.5	2.25	2.25	0.225
0.3	3	6	2	2	0.24
0.4	3.75	5	1.75	1.75	0.25
0.5	3.75	3.75	1.5	1.5	0.275
0.6	5	3.75	1.75	1.75	0.25
0.7	6	3	2	2	0.24
0.8	7.5	2.25	2.25	2.25	0.225
0.9	8	1.5	2.5	2.5	0.2

Table 1. Beta cross-section parameters for different thalweg locations.

The parameters for all other locations are linearly interpolated by using the values shown in Table 1.

Rescaling the normalized data

To create a three-dimensional description, the cross-sections that are developed in the normalized domain (s, n^*, z^*) should be rescaled and transferred back to the original coordinate system (x,y,z). River channel cross-sectional form adjusts over time through the process of erosion and deposition to accommodate the varying flow. Since the discharge increases downstream, the width and depth of the channel should similarly vary (Knighton, 1998). This is the underlying principle of hydraulic geometry relationships. It has been a common practice to describe the spatial variability of channel-width and mean channel depth using the flow data (Moody and Troutman, 2002; Harman et. al., 1999; Miller et.al., 1996). The same approach is used here to rescale the normalized data by developing hydraulic geometry relationships. Hydraulic geometry relates the independent variable (flow) to dependent variables (channel-width, mean depth, and mean velocity) through simple power forms as shown below:

$w = aQ^b$ (11)

$d = cQ^f$ (12)

$v = kQ^m$ (13)

where w, d, v, and Q are respectively width, mean depth, mean velocity and discharge.

The United States Geological Survey (USGS) is the primary source of data on all the rivers in the United States. The data include time-series of stream levels, steamflow, and cross-section measurements for more than 850,000 gaging stations. The criteria used in the selection of gaging station rarely takes into account the data quality requirement for hydrologic studies, and this introduces some bias in the cross-sections surveyed at the gaging stations. For example, the cross-sections at gaging sites are less susceptible to erosion and deposition. However, hydraulic geometry relationships have been developed using gaging station data (Harman, et. al., 1999; Dodov and Efi, 2003). In addition, as will be shown later, these data are found adequate for the current study. To develop the hydraulic geometry relationships for the Brazos River, flow data and cross-section measurements are downloaded from the USGS website. USGS performs cross-section measurements, which include channel-width, mean cross-sectional area and mean velocity, to update the rating curves for the gaging stations. A typical relationship between average depth (d) and the flow (Q) for a gaging station at Richmond (# 08114000) is shown in Figure 9. The parameters obtained from this relationship are c and *f* in equation (12).

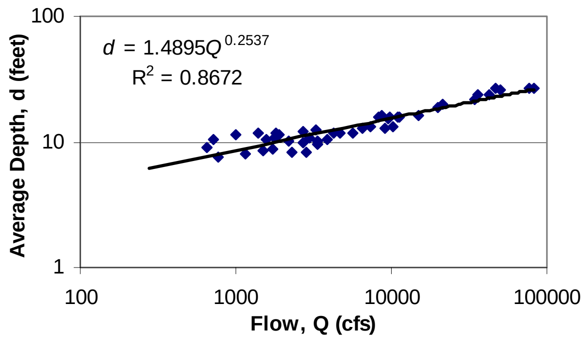

Figure 9: Hydraulic geometry relationship between average depth and flow at Richmond.

Hydraulic geometry relationships are developed for ten gaging stations using the measurement data from the USGS, with the results summarized in Table 2. The parameters in Table 2 can be used to predict *w*, *d*, and *v* for any given flow at the gaging stations listed in the table. For any point along the river that does not lie exactly at any of the gaging station locations, the parameters presented in Table 2 can be linearly interpolated with respect to the upstream watershed area to predict *w*, *d* and *v*. The results (channel-width and depth) can then used to rescale the normalized cross-sections developed in the previous section. After rescaling, the data can be transformed back to their original (*x*,*y*,*z*) coordinate system.

Gaging station number	A (km^2)	a	b	c	f	k	m
08089000	36894.38	17.822	0.3267	0.1686	0.3759	0.4029	0.2743
08090800	40587.70	24.632	0.3209	0.2521	0.3495	0.2038	0.2912
08091000	42092.48	21.369	0.3614	0.1692	0.3753	0.364	0.2356
08093100	45785.81	54.609	0.1963	0.1403	0.4513	0.1304	0.3526
08096500	51781.63	20.746	0.3333	0.134	0.5017	0.2568	0.2344
08098290	54053.05	189.41	0.0747	0.0364	0.5668	0.1363	0.3636
08108700	76360.62	97.624	0.1135	0.4878	0.3535	0.0246	0.5126
08111500	88872.85	120.33	0.1026	0.3727	0.3944	0.0232	0.4917
08114000	92050.76	95.654	0.1206	1.4895	0.2537	0.0094	0.5894
08116650	92651.64	60.153	0.1572	0.0652	0.5822	0.2413	0.2716

Table2. Hydraulic geometry parameters for Brazos river. *A* is drainage area obtained from USGS; a, c, k, and b, f, m, are the coefficients and power terms of equations (11), (12), and (13), respectively

Creating profile-lines using cross-sections

To generate profile lines, all the cross-sections are processed individually. In other words, to generate a profile line at a particular elevation, a point is established for that elevation on each cross-section. The points on all the cross-sections are then joined to create a profile line. Profile lines can be generated using two different approaches: 1) depth-based approach and 2) area-based approach. The depth-based approach divides the cross-section into regions with equal depths. If a cross-section that is 10m deep (from banks to the thalweg) has to be divided into two regions, the depth-based approach will introduce the profile lines at d/2 on each side. On the other hand, the area-based approach will divide the cross-section into regions with equal areas.

Results

The results from application of the framework to Brazos River site 2 (Figure 1c) are presented. The application of the framework involves starting with a blue line (centerline) obtained from the NHD (National Hydrography Dataset), and then converting this blue line into a three-dimensional description of a river channel through the following steps:

1. Using equations (11), (12) and (13), predict the average depth (*d*) and width (*w*) for a particular flow in question. Since the bathymetry data available at site 2 correspond to a flow of about 9700 cfs, *d* and *w* are predicted for the same flow. The parameters listed in Table 2 are interpolated based on the drainage areas of upstream (USGS # 08111500) and downstream (USGS # 08114000) gaging stations to get *d* and *w* at site 2.

2. Offset the blue line obtained from the NHD by a distance of $w/2$ on each side to establish the channel boundary. The channel boundary is modified to accommodate additional information (if any) from aerial photographs.

3. Looking downstream, use the left bank, created in step 2, to calculate the radius of curvature. Using the radius of curvature and the radius of curvature-thalweg relationship (Equation (5) and (6)) to locate the thalweg.

4. Using the thalweg, created in step 3, generate beta cross-sections using the parameters given in Table 1.

5. Using *w* and *d* obtained in step 1, rescale the cross-sections created in step 4. Rescaling the transfer the data from (s,n^*,z^*) to (s,n,z) coordinates, which in turn

are transferred back to original (x,y,z) coordinates.

6. Create profile lines using the cross-sections created in step 5.

Except step 1, all the steps are carried out inside GIS. The required data are blue lines from NHD and aerial photographs, both for step 2. The outputs are profile lines and cross-sections created in step 6. Using the procedure listed in step 1, the values for d and w corresponding to a flow of 9700 cfs are predicted to be 4.25m and 94m, respectively. The thalweg identified by the framework using equation (5) and (6) for site 2 on the Brazos River is shown in Figure 10.

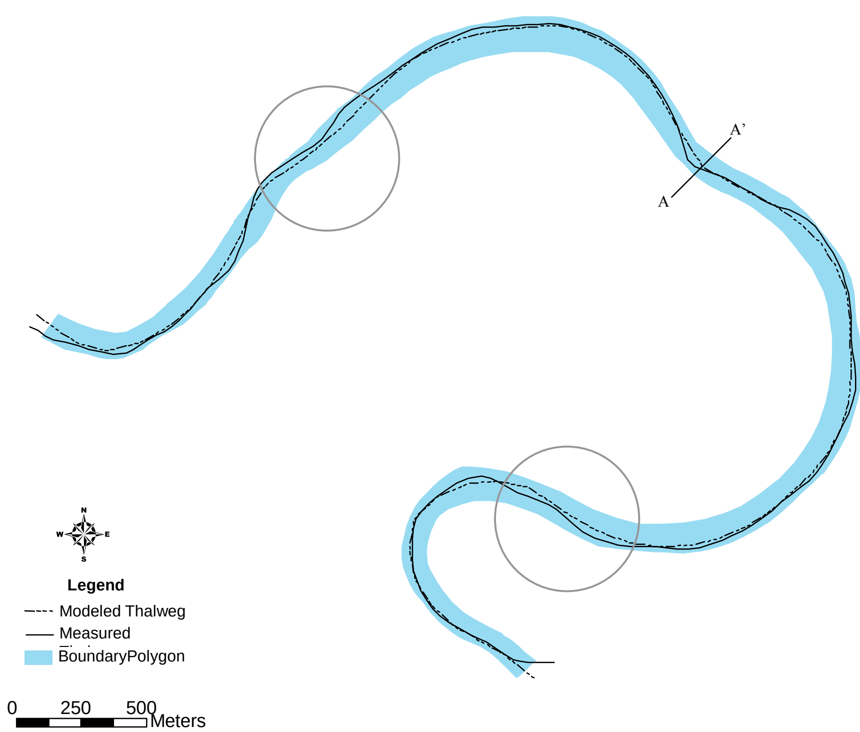

Figure 10: Thalweg prediction using the radius of curvature and thalweg location relationship.

As shown in Figure 10, the model predicts the thalweg location well for most of the reach. However, there are locations (circled on Figure 10), where the model result is not in agreement with the observed data. The main reason for such deviation is the model's behavior to locate the thalweg close to the center of the channel when the channel is straight. The model needs to be modified to incorporate additional information when the reach is straight.

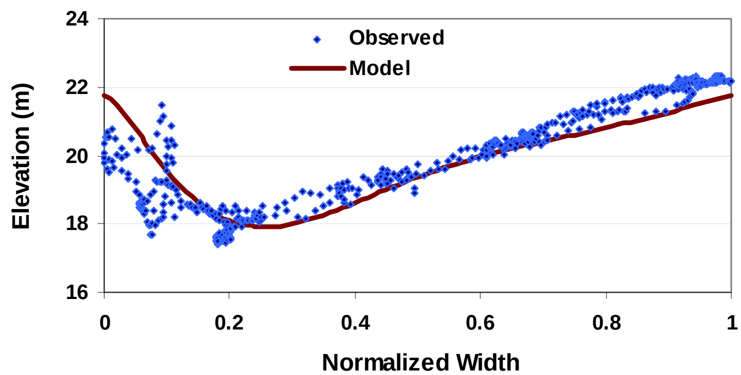

Figure 11. Cross-section described by the GIS framework along the reach shown in Figure 1d.

Figure 11 shows a resulting cross-section from the model at location shown in Figure 1d. As shown in Figure 11, the cross-section fits well to the observed data at this location. However, this is not true at all the locations. For example, at cross-section A-A' shown in Figure 10, the model does not agree completely with the observed data (Figure 12).

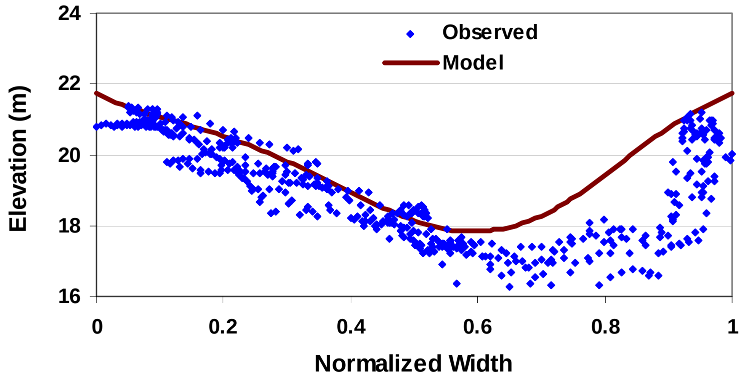

Figure 12. An example of cross-section where the GIS framework fails to describe the cross-section precisely.

The disagreement between the model and the data at cross-section A-A' is a result of an abrupt change in the bathymetry just upstream. Cross-section section A-A' is located just downstream of a big dip in the channel bed, and the bathymetry at this location is not as smooth compared to rest of the channel. The thalweg is in an abrupt transition from the right bank (looking downstream) towards center of the channel. The analytical model does not take into account such abrupt changes in bathymetry.

The current framework only provides a mean surface for the channel bed, and it is obvious to expect some deviations of the observed data from the mean surface. Figure 12 provides one example of the drawback of the current framework. Finally, after the cross-sections are generated, profile lines are generated to get a three-dimensional mesh as shown in Figure 13:

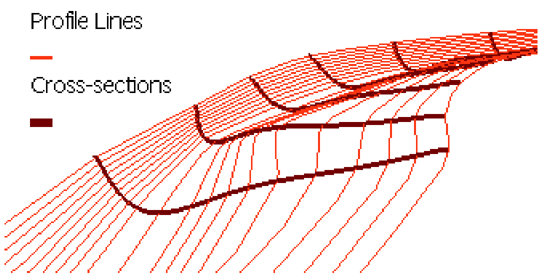

Figure 13. Three-dimensional description of river channel in the form of cross-sections and profile lines.

The three-dimensional mesh can be used to create a triangular irregular network (TIN) for the channel-bed.

Conclusions

A GIS framework is presented that uses the detailed bathymetry measurements made on short reaches to describe the river channel upstream or downstream. The framework is applicable only to meandering channels with alluvial bed, and it does not take into account the effect of tributaries. The framework is based on inter-relating the channel planform, the thalweg location and the cross-sectional form with each other. Therefore, by knowing only the channel planform, the three-dimensional form of the channel can be described. The resulting three-dimensional description is an analytical model in the form of cross-sections and profile lines. As an example, a short reach on the Brazos River is described using the detailed bathymetry data downstream.

The framework is developed in a domain that is independent of location and scale. In this normalized domain, the cross-sectional form (beta cross-section) is a function of the meandering channel planform. The cross-sections are re-scaled to the original form using the hydraulic geometry relationship, which relates the width and the depth of the channel to the upstream watershed area. Therefore, the resulting cross-sections are functions of both the channel planform and the upstream watershed area. The cross-sections are then used to generate profile lines, which are described using Bezier curves. The result from the framework, a mesh of cross-sections and profile lines, is an analytical model. This analytical model can be used to describe the three-dimensional form of the river channel, irrespective of location and scale.

The data on the channel planform are available as blue lines from the National Hydrography Dataset, and the upstream watershed area at any location along the river channel can be calculated using GIS. The framework thus provides a procedure to describe the river channels in three dimensions over large spatial domain. Bathymetric data on river channels are not available over large spatial domains, and thus the framework is a useful tool for large-scale regional studies. In addition, the three-dimensional mesh of profile lines and cross-section provided by the framework is flow-oriented. The flow-oriented mesh may be a useful dataset for hydrodynamic modeling simulations that use a orthogonal rectilinear coordinate system.

The current framework is based on a simple conceptual model (Figure 2), which is not universal. River channels are complex systems and it is not possible to capture all the details of river morphology. However, the current framework can be modified to accommodate additional information. For example, the thalweg location is not always in the middle of the channel along straight reaches, as used in the current model. Therefore, additional information such as bed material type may be used to study the behavior of the thalweg along straight reaches. In addition, the current framework provides only the mean surface. The possibility of incorporating some geomorphologic features such as pools and riffles will be explored in future.

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