# Two Dimensional Mapping of River Bathymetry and Power using Aerial Photography and GIS on the Brazos River, Texas

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## Abstract

*Effective management of river environments requires efficient means of gathering data on the rivers, including stream power and other hydraulic attributes. Traditional methods of data collection are spatially limited and can be restrictively expensive. This study utilizes hydraulically-calibrated aerial photography and GIS to calculate cross-sectional and mean stream power on a stretch of the Brazos River in central Texas. Field measured water depths are regressed against image brightness values to establish a highly accurate depth to reflectance curve. GIS-derived water surface slopes are then combined with estimated water depths to map fully two-dimensional hydraulic processes. This type of image-based river monitoring provides both an advance in measurement accuracy and in temporal monitoring.*

## Introduction

Water resources scientists, managers, and policy makers need accurate information about the properties of rivers they study and manage. However, traditional methods of obtaining this information may not be adequate to support the decisions made with it. Researchers have made many technological advances in river assessment, including those that utilize remotely sensed data and geographic information systems (GIS) for collection, management, and calculation of river properties. While these tools will never replace fieldwork, they can enhance and augment the quality of data available for research and decision making. The purpose of this project is to examine the effectiveness of utilizing remotely sensed imagery and GIS to perform a quantitative assessment of stream power.

Stream power is an important measure of river environments and influences sediment transport, erosional capacity, and flood dynamics. Two variations of measured stream power are cross-sectional stream power and mean stream power. Cross-sectional stream power is defined as the amount of work done per unit cross-section of a river and is important for quantifying sediment transport rates. Mean stream power is the amount of work done per unit area of a stream, and affects sediment competence and channel geometry (Fonstad 2000). Measuring stream power could enhance the analysis of river morphology and could also contribute to determining the impacts of human activity on river environments (Knighton 1999, Fonstad 2000).

Quantification of these stream power variables requires measurement of depth of the channel, slope of the water surface, velocity of the water, and width of the channel. Traditional methods of collecting these data involve making measurements along lateral cross-sections of the river. Downstream extrapolations are then made between these cross-sections to estimate the depth, slope, velocity, and width values between them (Winterbottom and Gilvear 1997). These measurements are both time consuming and expensive. Also, obtaining a time series of data for change analysis is difficult (Marcus 2002, Winterbottom and Gilvear 1997).

Researchers (e.g. Lyzenga 1981, Winterbottom and Gilvear 1997, Holden and LeDrew 2000) have demonstrated that depth measurements can be made with aerial photography. Also, many GIS tools are available for hydrologic modeling and representation. Remotely sensed data and GIS can provide the ability to make spatially continuous and relatively inexpensive stream power measurements.

The study area for this project is the Brazos River (Fig. 1) as it travels through central Texas below Whitney Dam to the USGS gage site near Aquila. The Brazos is relatively shallow and wide after it leaves Whitney Reservoir below Whitney Dam. The river in this section is ideal for this type of study because the conditions allow relatively accurate depth measurements. Also, much historical data is available for this area that could be utilized for future studies.

The purpose of this study was to integrate depth measurements made from aerial photography and channel width and slope measurements made within a GIS to calculate cross-sectional and mean stream power of the Brazos River from Whitney Dam to Aquila, Texas.

## Review of Prior Research

Stream power has implications for various features of rivers - channel shape, erosional capabilities and sediment capacities. Effective mapping and visualization of stream

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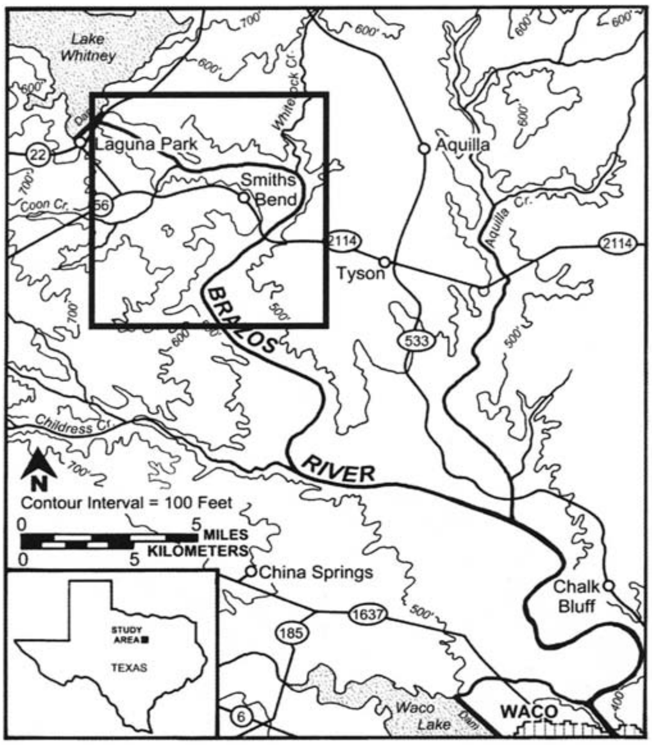

**Figure 1** The Brazos River study area from Whitney Darn to Aquila, Texas. Inset box shows area in Figure 2. Map courtesy of Karen Wynn Fonstad.

power could help river scientists and managers monitor and predict the effects of these phenomena. However, there have been few studies of the spatial characteristics of stream power (Knighton 1999). The measurement and accurate mapping of stream power could also be useful for determining the affects of human activities, including dam building (Fonstad 2000).

The goal of calculating stream power on the Brazos River with aerial photography and GIS can be subdivided into the tasks of calculating depth and integrating these data into a GIS with channel width, and slope measurements. We will first discuss remote sensing of water and how researchers have measured depth and then will discuss some hydrologic application of GIS. We will then relate how these previously developed methods were used in this project.

Measuring the depth of water with remotely sensed imagery is a difficult task. Many factors influence the radiation reaching the sensor from water, including substrate composition, water depth, turbulence, turbidity, and sun glint. The rapid absorption of visible wavelengths of light limits the maximum depth of water that visible light can penetrate, and therefore the maximum depth that can be measured (Lillesand and Kiefer 1994). According to Holden and LeDrew (2002):

> remotely sensed water depth cannot be interpreted directly as variation in water depth [ ... ] because the apparent signal is not uniquely and exclusively associated with any of these parameters. (300)

However, conditions at the time of data acquisition and the properties of the studied water body can be selected for optimal measurement of depth.

Researchers have performed many studies using remote sensing to produce bathymetric maps of coastal regions, but few have concentrated on rivers (Winterbottom and Gilvear 1997). Some studies have utilized hyperspectral imagery to map river conditions, but these often attempt to classify different habitats or water conditions (Wright, *et. al*. 2000, Marcus 2002).

Lyon, *et. al*. (1992) utilized hyperspectral imagery to map bottom type and depth in the St. Marys River, Michigan. Reflectances used for calculating water depth were normalized by bottom type and classed into five classes in the range of zero to ten meters. Accuracy of depth measurements using this method was around 85 percent.

Lyzenga (1981) introduced a method of measuring depth by subtracting the reflectance of a river pixel from the natural log of the reflectance of deep water pixels. Winterbottom and Gilvear (1997) compared the use of this method to measure depth on the River Tay in Scotland with hyperspectral imagery and aerial photography. The depth of the river in their study averaged 0.2 to 1.0 meters. The authors compared the remote-sensing based measurements to ground measurement and found that this method provided adequate depth measurements with aerial photography and multispectral imagery. A natural log transformation and a 3x3 smoothing kernel were applied to the image data. The analysis resulted in 206 depth values, and an $R^2$ of 55.2 as compared to depth measurements made on the ground. . They concluded that aerial photography is a viable resource for depth measurements. They also mentioned problems with the method they used to convert analog aerial photographs to digital format using a scanner and that contrast difference between images would be a problem.

Researchers have developed many tools for modeling hydrologic systems with GIS, and these have proven to provide beneficial information to water resources scientists. One common stream power related measurement often made is the stream power index. This is a basin-wide measure of erosional capability and is the product of slope and basin area. This index is created for the entire surface of a basin, including the land surface (Gurnell and Montgomery 2000). However, there have been few studies integrating remote sensing measurements of water properties into GIS.

As Winterbottom and Gilvear (1997) concluded, aerial photography is an adequate - not to mention cheaper - alternative to hyperspectral imagery for making depth maps of shallow rivers. However, many studies do not utilize this high resolution alternative that in many cases can provide high spatial and temporal coverage. Also, utilizing digital photography produced professionally from negatives can minimize errors in imagery produced by hard-copy scanning.

## Methodology

### Hypotheses

We hypothesize that aerial photography depth measurements of the Brazos River and the integration of these data with slope and channel width data in a GIS will provide a relatively accurate measurement of cross-sectional and mean stream power within the river. We believe, however, that there will be some limitations to the accuracy of these calculations because of the errors that data collection and data manipulation introduce. We believe that the representation of these data will be useful for creating visualizations of the distribution of stream power within the channel. Also, we believe that the relative ease of performing this type of study will allow for future accumulation of data measured at different discharge rates to gain a better overall picture of how the dynamics of the river vary. Because of the greater coverage capability and relative ease of use, we believe the methods used for this research will be useful for future stream power measurements.

### Study Area

The Brazos River is located in Texas and runs from the west-central panhandle southeast to the Gulf of Mexico. It is the third longest river in Texas with a length of 1516 kilometers. The Brazos drains approximately I 11,000 square kilometers (Huser 2000). Whitney Lake is located northeast of Waco and was created after the construction of Whitney Darn in 1947. The Brazos River beneath Whitney Dam to the town of Aquila (Fig. 1) is a relatively wide and shallow stretch of river with predominately agricultural and forested land uses along its banks. The substrate is dominated by sandy alluvium with some gravel-bed and bedrock substrate zones.

### Variables

The independent variables in this study were depth of channel, slope of water surface, and channel width. Depth will be obtained from aerial photography and will be measured in meters. From Lyzenga (198 1),

$$X_i = 1nL_i - Lw_i \tag{1}$$

where $X_i$ is the variable related to depth, 1, is the observed brightness, and Lwi is the deep water reflectance in the same band. The slope of water surface will be determined by measuring the ratio of elevation measurements to along-stream distance between elevation measurements

Image processing techniques allow channel width measurements to be made manually by counting the number of pixels along a line normal to the direction of flow. This method requires much effort and would not result in continuous coverage of the study area. This study utilized a GIS method whereby transects were created normal to a shapefile that defined the centerline of the river in the study area.

If the width of the water body is more than ten times its depth, then the hydraulic radius R is approximated by the mean depth (Rhoads 1987). By using this approximation, velocity (V) is a function of the depth and slope from Manning's equation (Goudie and Anderson 1990):

$$V=D^{2/3}S^{1/2}/n \tag{2}$$

where D is depth, S is slope and n is Manning's roughness.

The dependent variable estimated in this project is mean stream power, and several quantities must be measured in order to calculate this quantity. The equation for mean stream power is:

$$\omega = pgQS/w \tag{3}$$

where ρ is the density of water, g is the acceleration of gravity, Q is discharge, and w is channel width. By substituting the product of the hydraulic radius and velocity for discharge over width, the equation becomes:

$$\omega = pgRVS \tag{4}$$

where R is the hydraulic radius.. Using the hydraulic radius approximation as noted above gives:

$$\omega = pgDVS \tag{5}$$

Therefore:

$$\omega = pgD^{5/3}s^{3/2}/n \tag{6}$$

The equation for cross-sectional stream power is:

$$\Omega = pgQS \tag{7}$$

This equation becomes:

$$\Omega = pgwD^{5/3}s^{3/2}/n \tag{8}$$

when the discharge and velocity terms are substituted as in the cross-sectional stream power equations.

### Data

The digital aerial photographs for this project were provided by the Department of Geography at Southwest Texas State University. The aerial photography was acquired on 13 May 2001, and is comprised of red, green, and blue bands, and was in a proprietary compressed TIFF format. We obtained Digital Orthoquarter Quadrangles (DOQQ), digital topographic maps, and ancillary GIS data from the Texas Natural Resource Information System (TNRIS) via its public digital data download system (TNRIS 2002). The DOQQs and digital topographic maps data were in GeoTIFF format, and the GIS data were in shapefile format. We obtained various publicly available scripts and extensions (ESRI 2002, Jenness Enterprises 2002, Ryter 2002) to assist with data collection and calculation.

### Image Processing

The digital aerial photography provided by the Department of Geography was produced in a proprietary format by the company that took them. The images were converted from this proprietary format into GeoTIFF format with the RasTran program (Intergraph 1999). Images that contained little or no river pixel and those whose river pixels were too bright to effectively measure depth were discarded. The water on the eastern edge of most of the images exhibited some sun-glint. Of the images that were within the study area, we selected ten images based on the amount of sun-glint and the amount of overlap that could be used to cover sun glint on adjacent images. The selected images were then converted to the ERDAS Imagine (.img) format using the ERDAS Imagine Import function (ERDAS 2001).

The images had a spatial resolution of around 20 centimeters per pixel, producing files of approximately 900 megabytes (MB) per image. In order to reduce file size, we resampled the images to approximately 3 meters per pixel using the ERDAS Imagine Geometric Correction Affine algorithm. The resampled images were approximately 4 MB per image. In order to align images with each other in the image processing program and in subsequent images exported for use within the GIS, we assigned geometric information to the images using the ERDAS Imagine Geometric Correction 1st order polynomial transformation algorithm. The image containing the far eastern bend in the study required a 2nd order polynomial transformation because of the lack of ground control points near the edges of the image. Six or more ground control points were selected for each image from features that appeared both on the aerial photographs and on DOQQs. In order to eliminate the border of non-river pixels in the images, we subset them using the subset function in Imagine. Results of radiometric normalization attempts did not improve the contrast differences between the images enough to justify the benefits.

In order to more easily manipulate the images, we utilized the Imagine Mosaic function to combine the ten separate selected images into a single image (Fig. 2). The Mosaic function allows the user to select the order (top or bottom) and overlap of the images used for the mosaic. Image order was selected to minimize the sun glint and radiometric differences at the edges of the images.

In order to remove all non-river pixels from the image, we created an Area of Interest (AOI) polygon that included all river pixels on the mosaicked image. This AOI was then used to mask the image. We applied a 3x3 smoothing filter with zero-values excluded to minimize edge effects (Fig. 3).

We utilized field depth data collected during discharge conditions that were almost identical to the conditions when the photographs were taken to obtain a depth equation. Two transects were made and locations on the original image containing the area where the measurements were made were identified. One transect was used for equation generation, the second was used for accuracy assessment of the image depth measurements. Depth locations from the un-resampled, un-rectified image containing the transects were compared to the digital number of pixels on the mosaicked image. We then regressed the pixel values against the depth values and obtained a prediction equation for depth:

$$\text{Depth} = -0.0939\ (\text{Digital Number}) + 10.779 \tag{9}$$

The $R^2$ -value for the equation was 0.6994 (Fig. 4).

We utilized the ERDAS Imaging Model Maker, a graphical modeling interface, to apply the depth equation to each river pixel in the masked, smoothed image. We then exported the depth image to ESRI Grid format to facilitate analysis in the GIS.

### GIS Processing and Analysis

To place spatial constraints on the measurement of the depth data within the GIS, we created transects perpendicular to a stream centerline shapefile. We first modified a preexisting stream centerline shapefile obtained from TNRIS

**Figure 2** Mosaicked aerial photographs of the river reach downstream of Whitney Dam.

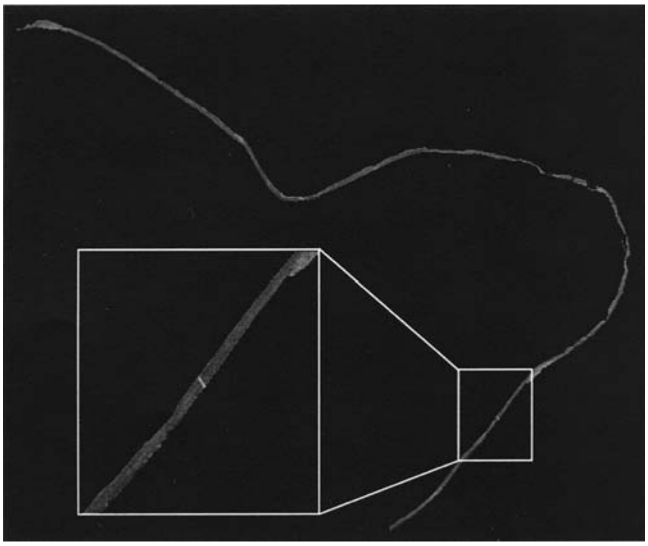

**Figure 3** Masked, smoothed image of the study area with inset box showing in-channel brightness details.

(2002) to decrease angularity and reflect any changes in the channel that occurred between the creation of the original shapefile and the date of photography. We also clipped the centerline shapefile to the extent of the study area. We then created a polyline shapefile that contained transect lines perpendicular to the digitized river centerline shapefile utilizing an Avenue script in ESRI ArcView 3.3 (ESRI 2002). Because the transects were created with a uniform length, we clipped the lines to the extent of a polygon created to reflect the outlines of the river in the masked river image. 3,416 transects were created in this process.

An estimation of the slope of the surface of the water was obtained by creating a point shapefile of locations where topographic lines on a digital topographic map crossed the river. A slope surface of these points was then created using ESRI Spatial Analyst. The resulting slope grid was clipped and converted back into a polygon shapefile to facilitate spatial joining with the transect shapefiles. Results of slope measurements taken from a 30-meter digital elevation model did not perform adequately because the slope equation within Spatial Analyst utilizes a 3x3 window. This, combined with the poor resolution of the DEM, creates steep slope values on the edges of and within the channel.

We estimated Manning's n to be 0.030 for the studied stretch of the Brazos River by comparing pictures and cross sections in the USGS Water-Supply Paper 1849 (Barnes 1967) to the river.

In order to obtain the average depth along individual transects, we utilized the “Surface tools for points, lines, and polygons” extension (Jenness Enterprises 2002), which calculates the average value of a grid theme along a polyline theme as well as the line segment lengths. The extension then joins the grid and length values to the theme's table. The average depth and slope values were then used to calculate cross-sectional strewn power for each transect using equation (6) with the Field Calculator function in ArcView.

Derek's Tools v1.1 (Ryter 2002) is a publicly available extension that has the capability of creating points along a polyline and assigning the value of an underlying grid theme to the points. We modified this extension to create equally spaced points along each transect polyline shapefile to be created (examples of transects and points along transects on depth grid shown in figure 5). The spacing was approximately the resolution of the depth grid, or three meters. Mean stream power was calculated with the Field Calculator using equation (8) for 67,402 points created. This process of 'serialization' allows downstream information to be visualized on a traditional I-dimesional graph.

### Data Analysis

A complete quantitative assessment of the accuracy of these stream power measurements is difficult because of their spatial extent, and the relative difficulty of obtaining accurate measurements in the field. However, the focus of this study was intended to be an exploratory, methodological approach to solving the problem of large scale stream power measurements without the necessity of extensive field work.

The accuracy of one quantity that plays a large role in determining stream power, depth, was assessed by comparing image-obtained depths to field measured depths. The data used for this analysis were taken from the second of two transects measured when river discharge levels were virtually identical to when the photographs were taken.

## Results

The results of an analysis of variance (ANOVA) are presented in table 1. The null hypothesis, that the two depth measurement groups are from different populations, is rejected. An F-value close to one indicates that the probability that the variation between the two samples is due to chance

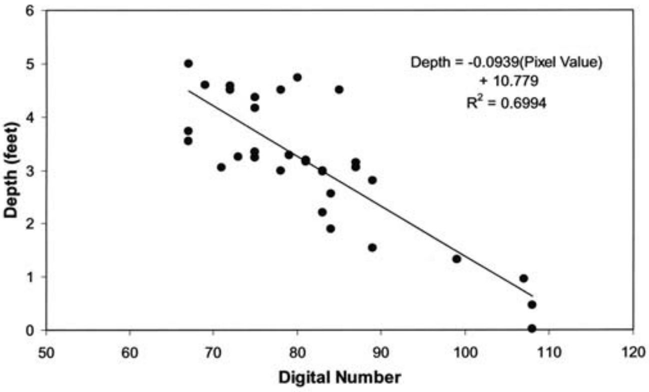

**Figure 4** Empirically determined field depth vs. image digital number relationship.

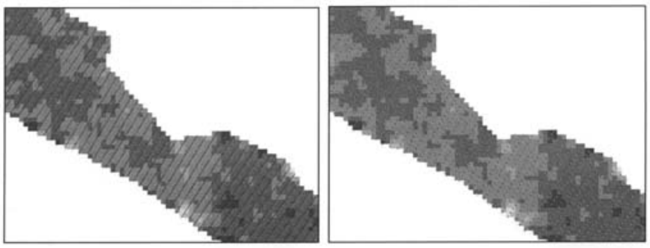

**Figure 5** Examples of GIS-produced transect lines (left) and points (right) underlain by depth grid.

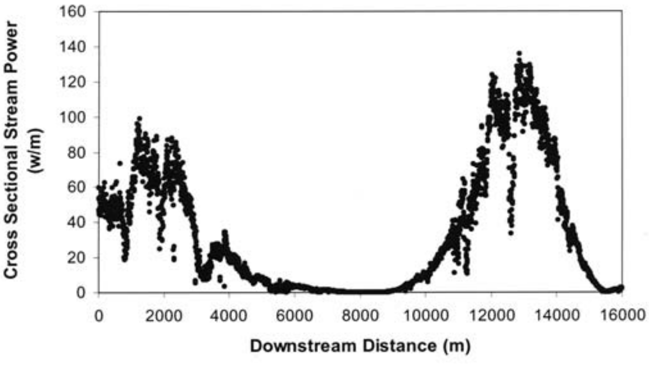

**Figure 6** Chart of cross-sectional stream power as a function of distance downstream.

**Table 1** Results of ANOVA between field and image depths.

**SUMMARY**

| Groups | Count | Sum | Average | Variance |
|---|---|---|---|---|
| Field Depth (ft) | 56 | 210.18 | 3.753214 | 0.326055 |
| Image Depth | 56 | 203.695 | 3.637411 | 0.304821 |

**ANOVA**

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *Fcrit* |
|---|---|---|---|---|---|---|
| Between Groups | 0.375493 | 1 | 0.375493 | 1.190387 | 0.277636 | 3.927397 |
| Within Groups | 34.69816 | 110 | 0.315438 | | | |
| Total | 35.07365 | 111 | | | | |

**Table 2** Descriptive statistics for depth, slope, transect length, and cross-sectional stream power

| | *Depth(m)* | *Slope (%)* | | *XSSP (w/m)* |
|---|---|---|---|---|
| Mean | 1.3 | 0.12 | | 30.7 |
| Standard Deviation | 0.3 | 0.1 | | 34.7 |
| Range | 1.9 | 0.32 | 135.5 | |
| Count | 3416 | 3416 | | 3416 |
| | *Depth (m)* | *Slope (%)* | *Transect Length (m)* | *MSP (w/m$^2$)* |
| Mean | 1.3 | 0.14 | 67.3 | 0.16 |
| Standard Deviation | 0.4 | 0.1 | 18.1 | 0.17 |
| Range | 2.8 | 0.32 | 138.3 | 3.97 |
| Count | 67402 | 67402 | 67402 | 67402 |

is low. Also, the P-value of 0.277 indicates that the probability that these two observation groups are from different populations is not significant.

Descriptive statistics of the two variations of stream power measured in the study are presented in Table 2. A graph of cross-sectional stream power as a function of downstream distance is presented in Figure 6. Downstream of Whitney darn, there is a general decrease in cross-sectional stream power, followed by a six kilometer high power zone in the Smiths Bend reach. This high power zone possibly corresponds to larger bedrock control on the channel width and bed. Figure 7 is a map of depth (in) and figure 8 is a map of percent slope along the Brazos River study reach. Both show the possible effects of the bedrock near Smiths Bend; the stream depths shallow considerably in the bend reach, and the bed slopes become greater. The spatial variation of cross-sectional stream power (W/m) and mean stream power (W/m$^2$) are shown in figures 9 and 10. In each of these figures, there is an increase in stream power downstream of Whitney Dam for the first ten kilometers, followed by a reduction in power in the Smiths Bend reach. Cross channel variations in mean stream power do not occur in any systematic pattern at the 3 meter resolution of our image-derived maps.

Cross-sectional and mean stream power measurements with aerial photography and GIS, as with every other quantitative measurement, rely on the input data. The data used for this study certainly have room for improvement, but the techniques utilized demonstrate that these two fluviogeomorphic measurements can be made in a comparatively efficient and cost-effective way. Some areas that could be improved to provide more accurate results include higher resolution imagery, better ground control for the depth equation generation, and higher resolution elevation data.

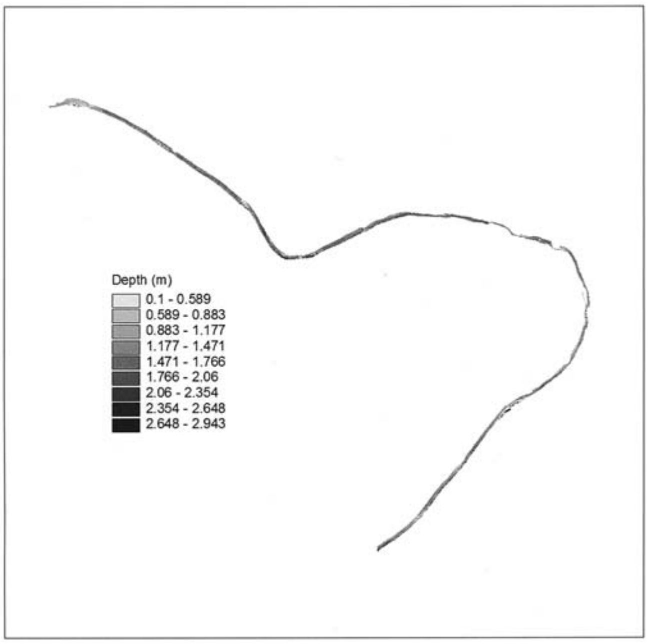

**Figure 7** Two-dimensional depth map of the entire Brazos study reach.

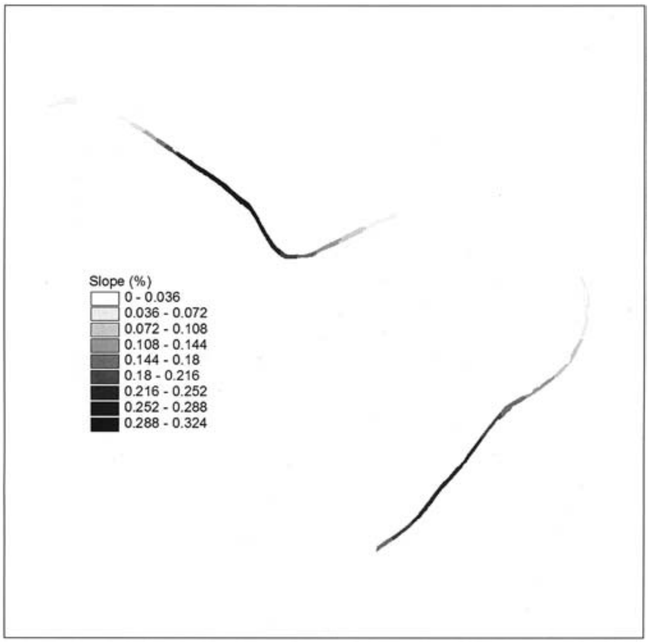

**Figure 8** Two-dimensional slope map of the entire Brazos study reach.

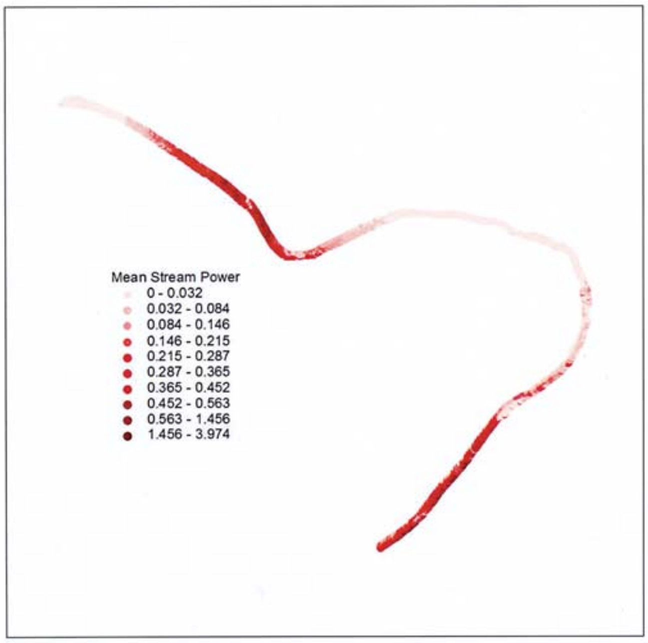

**Figure 10** Mean stream power map derived from depth and slope information and GIS analysis. The size of the points and their density causes the "widening" effect seen in the map.

As is the case with most remote sensing studies, much detail was lost when the images were resampled. However, because of computational and file size constraints, the image resolution used for this study was approximately 3 meters per pixel. Higher resolution imagery could provide more accurate depth measurements, partly because of the effects introduced in averaging process that occurs during resampling.

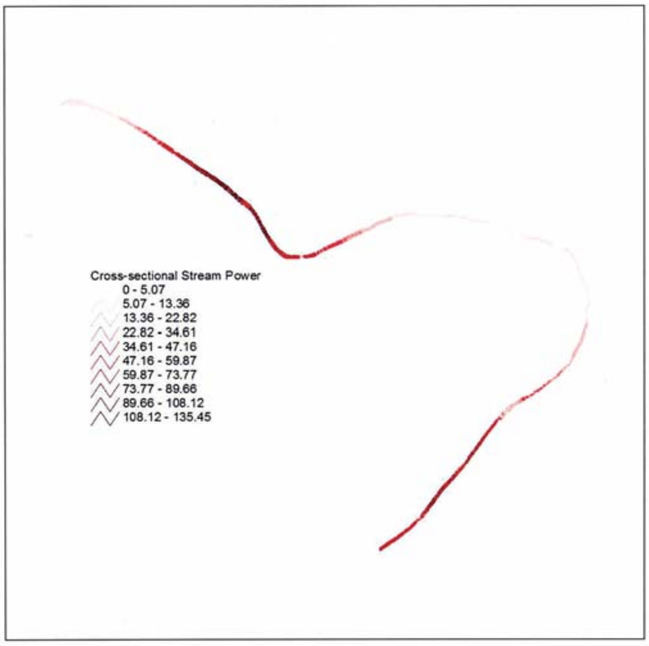

**Figure 9** Cross-sectional stream power map derived from depth and slope information and GIS analysis.

Ground control data for more than a single location would probably have improved the results of depth measurements. Because the depth measurement/digital number relationship was measured from one image, contrast differences between images could have introduced error into the results.

Slope measurements had a marked effect on the stream power calculations. Attempts to perform the calculations with a simple slope calculation made by dividing the difference in elevation by the length of the section of river between them resulted in obviously stepped values at the elevation measurement location. Higher resolution topographic maps and DEMs could improve these sources of error.

## Conclusions

These types of remotely sensed measurements are exactly the types of data that would be beneficial for the modeling of river characteristics within a dedicated GIS, such as one developed in the ArcHydro system (Maidment 2002). The channel modeling features of this package are suited for these types of measurements and could be used for improved visualization and integration with other types of data for the river system.

The purpose of this study was to explore the feasibility of utilizing aerial photography and GIS to calculate stream power. The scope of the study did not include extensive field data collection, therefore more data should be collected in the field to corroborate these types of studies in the future. This study did demonstrate that these types of geomorphic measurements are possible and could lead to better understanding of fluvial processes.

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