MEASURING MIXED BED LOAD TRANSPORT WITH AN ACOUSTIC DOPPLER CURRENT PROFILER

THESIS

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ABSTRACT

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The transport of sediment through a river as bed load helps to define the channel geomorphology. Measuring bed load is difficult and often problematic due to the high flow velocities of which they are often associated. A non-intrusive method of measuring bed load with an Acoustic Doppler Current Profiler (ADCP) in mixed-sized sediment Central Texas stream is proposed. Velocity data extracted from ADCP software combined with physical measurements of the channel bed composition can be used to determine a total bed load transport rate. Using this faster and safer measurement technique, it is the goal of this research to improve the collection and quality of available bed load data.

CHAPTER I

INTRODUCTION

When asked to describe a river, the common individual will probably describe the water flowing in the river, not the channel in which it flows. Just as a glass of water sitting on a nightstand is defined by the shape of the glass, the shape of the water in a river is defined by the channel. Unlike the glass on the nightstand, a river channel does have the power to evolve or change shape to better accommodate the river's flow regime through the processes of sediment erosion, transport, and deposition. As a river flows, the water is in constant contact with the sediment that comprises the channel bed and banks. Depending on the depth and slope of the channel, the flow in the river can mobilize different sizes and compositions of sediment (Baosheng et al. 2004). Very fine silts and clays can easily mobilize and be carried the full length of the river, while larger sands and gravels can be transported, re-deposited, and moved again from one high water event to another (Robert 2003).

The Colorado River Basin in Central Texas is an example of a stream system capable of transporting sediment (Figure 1). The Texas Colorado River Basin is monitored by 94 United States Geological Survey (USGS) stream gauges and over 200 stream and precipitation gauges managed by the Lower Colorado River Authority in Austin, Texas (USNWIS 2007; LCRA 2007). This dense number of gauges is required

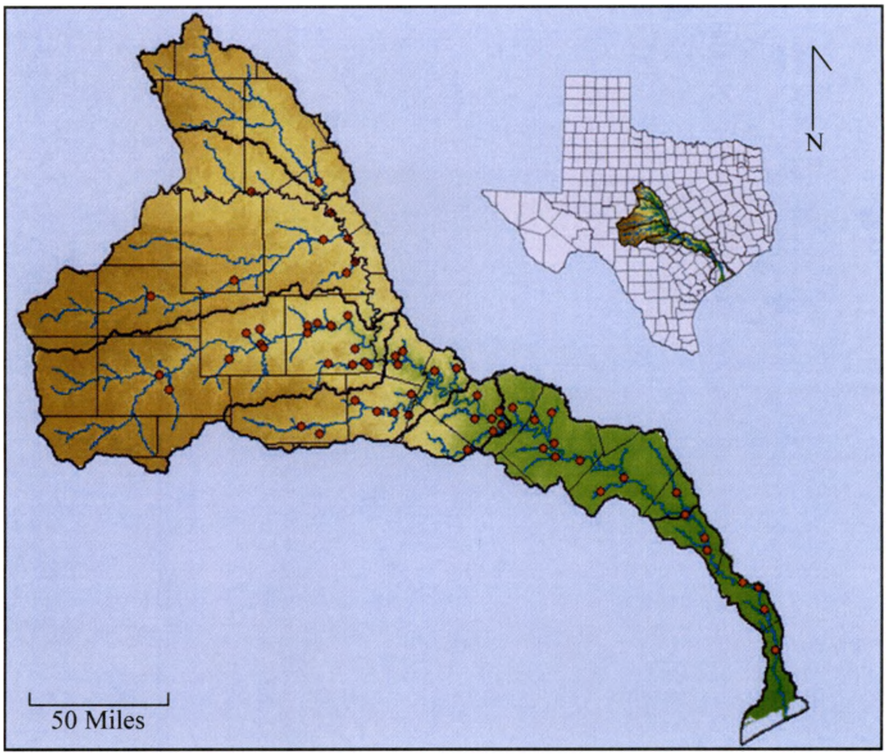

Figure 1. Location of the Lower Colorado River Basin in Central Texas.

to monitor the aggressive nature of floods in the area. Shallow soils overlying limestone or granite bedrock can quickly route the runoff from intense rain events common to the region through the relatively steep slopes of the local area streams. As an example, the Pedernales River near Johnson City, Texas, a tributary of the Colorado River, went from zero flow on September 9, 1952 to 441,000 cubic feet per second of flow on September 11, 1952, over 2.3 times the mean flow of the Mississippi River at St. Louis, Missouri. The Pedernales River near Johnson City, Texas has a drainage basin over 770 times smaller than that of the St. Louis gauge, yet was able to surpass the average flow of the Mississippi River in only two days (USNWIS 2007). Figure 2 is a side-by-side comparison of two aerial photographs taken before and after the September 11, 1952 flood on the Pedernales River. The after photo shows large amounts of bed and bank

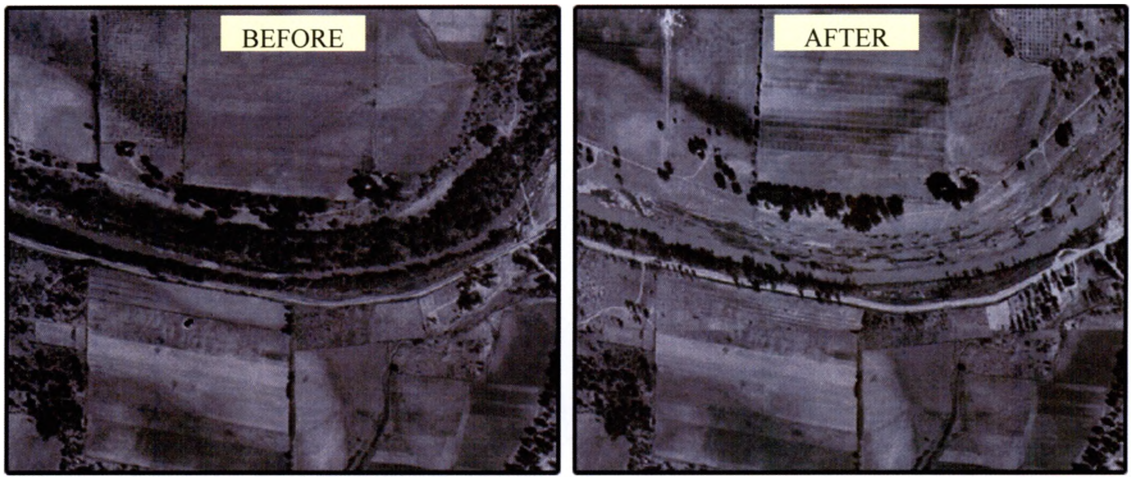

Figure 2. Before (1938) and after (1955) the September 11, 1952 flood on the Pedernales River in Central Texas illustration how a flood can remove large quantities of sediment (LCRA 2006). (Approximate scale 1 inch = 1000 feet)

erosion, which is evident by the missing groves of oak trees.

During any flood, the question of how much sediment will be mobilized, transported, and deposited becomes important. The connection between sediment transport and bank erosion is especially important for a river or creek that runs through an urban area. Common sense implies that building a summer home fifty feet from the edge of the Grand Canyon is not wise, but what does it say about building fifty feet from the small creek that runs through town. As urban infrastructure grows, the ground is covered with more impermeable concrete, asphalt, and structures. A city drainage system is designed to prevent local flooding of streets by swiftly routing precipitation runoff to the nearest natural drainage. If the natural drainage is the town creek, the increased quantity and intensity of flow from the city runoff will increase rates of sediment transport, forcing the stream channel to adapt to the new flow regime. An adapting or widening stream channel in an urban area has the potential to affect homes, bridges, or any other physical structure within its path. Knowledge of how and when sediment moves in a river allows for better planning and understanding of potential construction and engineering projects (Heitmuller et al. 2005).

The installation of dams, regardless of size, will have a major affect on the flow and sediment transport of a stream. A dam impounds both water and sediment, causing sediment to accumulate behind the dam, and sediment free water to be released below the dam. The accumulation of sediment behind a dam is an accepted process, and is one of the primary variables engineers use when planning the predicted life-span of a reservoir (Radoane and Radoane 2005). The water released from a dam has extra energy, as it does not have to support a sediment load. The water quickly expends the excess energy by mobilizing sediment from any source it comes in contact with causing the stream to erode below the dam. For the same reason it is important to understand how the town creek will adapt to a different flow regime, it is important to understand how much sediment the lake will accumulate, and how much sediment will erode from below the dam.

Sediment transport can be separated into two parts, suspended sediment and bed load. Suspended sediment is the sediment held in suspension, and bed load is the sediment that slides, rolls, or bounces (saltates) across the bottom of the channel. Suspended sediment measurements are made by taking water samples at different elevations in the water column and analyzing the sediment particles at a lab. The samples are relatively easy to collect, but do not inform about movement of the large sediment. The more difficult of the two types of sediment samples to obtain is bed load. As with suspended sediment, bed load is most active during floods or elevated flows when the river has more energy to move the larger sediment sizes on the bed. Because of the location of the sediment, samples must be taken from the channel bed. High water velocities and debris associated with flood flows makes it both difficult and dangerous to lower a sampling device to the channel bed. Because of the difficulties measuring bed load, data is scarce and at best marginal in quality (Rennie et al. 2002).

Stream flow measurements are required to calibrate the discharge ratings at stream gauges. Traditional methods of measuring discharge require that a mechanical current meter be used to sample twenty to twenty-five stations across the channel with multiple velocity measurements at each station (Sauer 2002). With the length of each velocity measurement comprising at least 40 seconds, some discharge measurements can take over three hours to complete. As with the bed load sampling, keeping equipment submerged in the water column during a flood is both difficult and dangerous due to large amounts of debris and high water velocities. With the flashy nature of the Texas Colorado River Basin, it is difficult to find a stream that will stay steady for three hours.

The introduction of acoustic Doppler instrumentation is changing the way surface water is measured and understood. Instruments based on the Doppler principle for measuring water velocity and computing discharge in a stream are commonly used by Government agencies, educational institutions, and private companies (Morlock et al. 2002). Over 40 percent of the discharge measurements made by the USGS in 2006 were made with acoustic Doppler equipment (Oberg 2007). At the forefront of Doppler measurement equipment is the Acoustic Doppler Current Profiler (ADCP). The ADCP is used to calculate discharge by measuring channel depth, width, and three-dimensional velocity across three acoustic beams emitted from a sensor suspended just below the surface of the water. Whereas traditional methods of making a flood discharge measurement could take over three hours, the ADCP can accomplish the same task in under 30 minutes. Because the ADCP is suspended just below the surface of the water, it is safer to use than traditional mechanical methods, as the likelihood of catching debris or losing submerged equipment diminishes.

The ADCP is also having an effect on suspended sediment measurement techniques. Velocity measurements from the ADCP are based on a change in emitted sonic frequency reflected off backscatter moving in the water column. The amount of backscatter in the water column is proportional to the amount of suspended sediment in the water. ADCP measured suspended sediment must be calibrated to traditional measurement methods on a stream by stream basis, but once a relationship is established, suspended sediment data can be extrapolated from an ADCP discharge measurement (Gartner 2004). With the ability of the ADCP to measure both flow and suspended sediment at the same time, the value of the instrument increases.

Data from the ADCP is now being considered as a possible method of extrapolating bed load information (Rennie et al. 2002; Kotaschuk et al. 2005). The term 'bottom-tracking' is used to describe the method by which the ADCP tracks its location across the channel by measuring the speed and direction of the sensor relative to the bottom of the channel. If the river bed sediment is mobile, bottom-tracking results will be biased, as the ADCP cannot accurately calculate boat location or velocity. When a moving bed is detected, the ADCP uses a differential global positioning system (DGPS) to correct for the moving bottom and calculate the boat speed and direction (Sontek 2000). A comparison of the DGPS calculated boat speed and direction verses the bottom-tracking boat speed and direction results in the mean speed and direction of the moving channel bed. If the magnitude and direction of the moving bed is known, a relationship between ADCP data and bed load data can be established on a stream by stream basis (Rennie et al. 2002).

The objective of this research is to establish a relationship between traditionally measured bed load and mean bed velocity from the ADCP. Lessons and suggestions learned from previous works (Rennie et al. 2002; Kotaschuk et al. 2005) will be used, and further discussed in Chapters Two and Three.

CHAPTER II

LITERATURE REVIEW

Traditional methods of bed load sampling have the reputation of being an extremely difficult process (Rennie et al. 2002). Real time fluctuations in the volume and velocity of bed load require a large number of samples to average out the variability to obtain meaningful results (Kotaschuk et al. 2005). The bed load sampling equipment is a disturbance to both the flow and mobile bed, which can bias results. Because bed load is most active during high flow, extracting samples from the bed is dangerous, requiring a great deal of physical work to lower and raise the heavy samplers (Figure 3).

Figure 3. Pictures of the 195 pound model 8075 cable-suspended Helley-Smith (Left), and the 210 pound model 404-030 US-TR2 cable-suspended Toutle (Right) bed load sediment samplers (Rickly 2007).

Despite all of these disadvantages the two devices shown in Figure 3 are the industry standard (Brunte et al. 2004). Bed load sediment sampling generally follows the same methodology as a stream discharge measurement with 20 to 25 samples across the channel with at least 40 seconds per sample. Results are totaled for each section, and a total mean bed load in volume or weight per unit time is recorded. Helley-Smith samplers range in size from 65 pounds to 195 pounds with either a 3 or 6 inch square opening.

The Acoustic Doppler Current Profiler (ADCP) is based on the principal of Doppler shift which states, "that if a source of sound is moving relative to the receiver, the frequency of the sound at the receiver is shifted from the transmit frequency" (SonTek 2000). Figure 4 is an illustration of the Doppler principal which

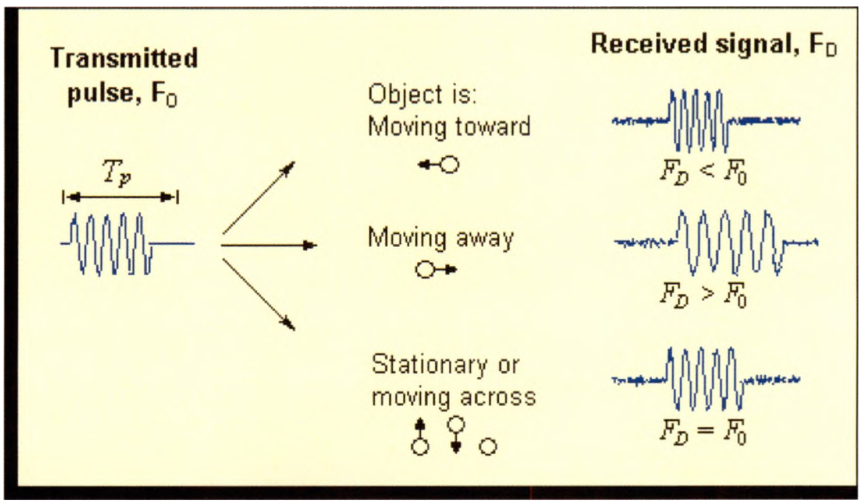

Figure 4. Illustration of the Doppler principal which shows how the transmitted pulse is shifted as an object is either moving away, towards, or stationary relative to the source (Sontek 2007).

shows how the transmitted pulse is shifted as an object is either moving away, towards, or stationary relative to the source.

For the purpose of the ADCP, the signal is not reflected off of the water, but rather the sediment, air bubbles, biological materials, or other suspended material in the water column. The ADCP, depending on the manufacturer, has three to four transducers that both send and receive the sonic signals (Figure 5). Each beam measures the

Doppler shift from the emitted signal to the received signal to calculate water velocity. The three beams are divided up into cells or bins, where a mean velocity and direction in Cartesian coordinates (X,Y,Z) are determined. Figure 6 shows how a three beam ADCP breaks the water column into cells, where a mean velocity and direction is calculated for each cell. Each transducer is set at an angle 25 degrees from vertical,

Figure 5. SonTek ADCP sensor head, and black controller box (SonTek 2007).

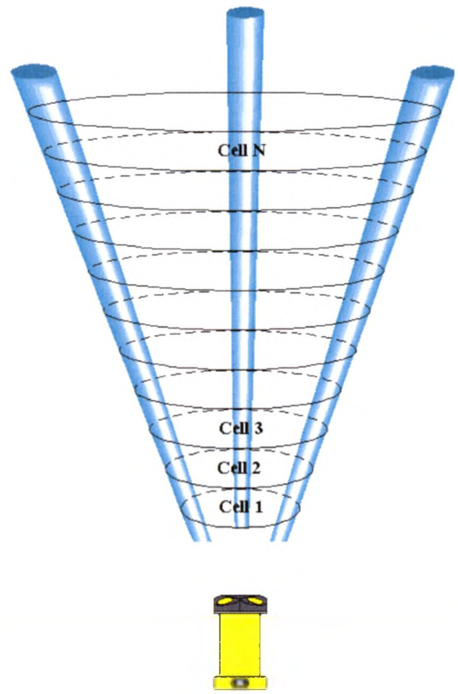

Figure 6. ADCP with a three beam setup, showing cell geometry (SonTek 2007).

meaning that in deeper water, the ADCP beams will be further apart, giving the ADCP signal a larger footprint on the channel bed. The total depth of the water is roughly equal to the total diameter of the signal footprint. One critical assumption that all ADCPs make, is that the water measured in each cell is the same across all three beams. If the water is turbulent, or violently mixing, the discharge calculations begin to break down and error is introduced to the measurement (SonTek 2000).

Figure 7 . SonTek ADCP mounted on an un-
manned tethered trimaran (SonTek 2007).

For a stream discharge measurement, ADCPs are generally mounted to a manned boat or smaller unmanned catamaran (Figure 7). In both situations, the transducer head of the sensor is suspended just below the water surface aimed vertically down at the channel bed. During the measurement, the ADCP, at a velocity slower than the water velocity, transverses across the channel. A total of four trips, or transects, across the channel are required by U.S. Geological Survey standards (Sauer 2002). The measurement is accepted when the calculated discharges from each transect are within five percent of each other. If the five percent standard is not met, more transects must be made.

During a transect, the ADCP transducers are constantly sending out sound waves at a specific frequency. Different manufactures offer different frequencies of ADCPs, all designed to work in a wide range of situations. As a rule, the lower the frequency, the further the signal can penetrate into the water column, and the deeper the ADCP can measure (Table 1). A high frequency SonTek 3.0 MHz ADCP has a range of up to 20 feet, while a 1.0 MHz SonTek ADCP can measure to depths of 115 feet. Table 1 lists

Table 1. List of frequencies, profiling ranges, and minimum cell sizes of SonTek Acoustic Doppler Current Profilers (SonTek, 2000).

Frequency (Housing)	Profiling Range	Minimum Cell Size
1.0 MHz (Mini)	0.75-35 m (2.5-115 ft)	0.25 m (0.8 ft)
1.5 MHz (Mini)	0.5-25 m (1.6-82 ft)	0.25 m (0.8 ft)
3.0 MHz (Mini)	0.3-6.0 m (1.0-20 ft)	0.15 m (0.5 ft)

the frequencies of SonTek ADCPs with the profiling ranges and minimum cell sizes. Lower frequency units can profile to greater depths, but in doing so must have a larger minimum cell size. Choosing the appropriate profiling range and cell size is critical when trying to determine which unit to use on a particular stream. If a stream has a maximum depth of eight feet, the 3.0MHz unit can measure more water at a 0.5 foot cell resolution verses the 1.0MHz or 1.5MHz units with larger cell sizes. Higher resolution data gives a better representation of the true flow patterns of the water, and will produce more accurate measurement results (SonTek 2000).

Along with recording the velocity and direction of the water, the ADCP accounts for the movement of the instrument during each transect. As the ADCP transects the river, the velocity is averaged using default five second intervals. These averaged sections of data are called profiles, where each profile is a collection of vertical cells in the water column. One transducer ping in every profile is reserved to calculate the speed and direction of the boat, which is termed bottom tracking. Bottom tracking, and the algorithms it uses, are a closely guarded secret amongst ADCP manufactures. In favorable conditions, bottom tracking is more accurate, and recommended over sub-meter Differential Global Positioning System (DGPS). With an accurate reading of the vessel speed and direction, an accurate measurement of the water speed and direction can be obtained (Rennie et al. 2002).

The bottom tracking method also holds the promise of being applicable to bed load sediment measurement techniques. Previous ADCP bed load measurement research on sand and gravel channels by Rennie et al. (2002) present a method by which velocities measured by a DGPS were compared to bottom tracking velocities of the same ADCP to estimate the bed load transport of the mixed sand and gravel bed Fraser River in British Colombia. Rennie et al. (2002) developed a relationship between traditionally measured bed load sediment samples and the moving bed velocity obtained from the ADCP (Figure 8). "Mean apparent bed load velocity correlated well (r^2 = *0.93*) with mean bed load transport rates measured using conventional samplers" (Rennie et al. 2002). With a strong correlation between bed load velocity and bed load transport, a calibration curve or rating can be developed.

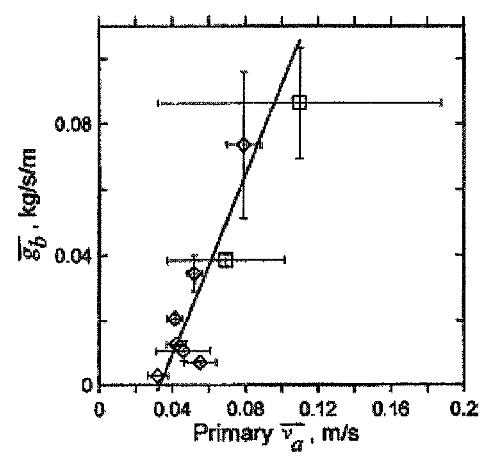

Figure 8. Bed load verses ADCP measured bed velocity plot from the Rennie et al. (2002) study.

Kotaschuk et al. (2005) are more critical of the ADCP and discuss the limitations and error associated with using the equipment to estimate bed load in a study area with a sand bed channel. Kotaschuk et al. (2005) state that "the most serious limitation of an

ADCP is in obtaining measurements near the bed. Beam geometry results in a large sampling diameter close to the bed that does not adequately capture variations in velocity, particularly vertical velocity, or sediment transport over complex topography" (p. 37). As previously illustrated in Figure 6, the ADCP divides the water column into cells, and makes the assumption that the same volume of water is measured across all three beams. A rough channel bed or the presence of bed forms can cause the three beams to sample three different volumes of water, violating this assumption and causing a breakdown in the ADCP velocity calculations. Because bottom tracking is independent of the water velocity calculations, it is not disrupted by the turbulence, but is still limited to returning a single velocity vector over the entire signal footprint. Kotaschuk et al. (2005) conclude that the ADCP technology looks promising in its ability to measure sediment load, but needs to be tested over a wide range of bed material over a wide range of flow rates.

One problem that both Kotaschuk et al. (2005) and Rennie et al. (2002) had was noise in the bed velocity data computed from bottom tracking. Both studies concluded that noise from the bottom tracking data proved to be their largest source of systematic error. Since bed load velocity and volume are highly variable, the default ADCP averaging interval of five seconds is too short, and needs to be increased to obtain reliable results. The physical process of operating a boat and transecting the channel so slowly that the averaging period can be lengthened during periods of high velocity is exceedingly difficult.

A recent release of new software from the ADCP manufacturer, SonTek, may help with the bottom tracking error. The SonTek Stationary software allows the ADCP to be used in a method similar to traditional current meter methods (Figure 9). The river is measured at 20 to 25 stations, and a mean velocity is calculated at each station across the channel. Where a traditional current meter is lowered to measure velocity at multiple places in the water column for at least 40 seconds at a time, the ADCP makes only one 40 second measurement from the safety of the water's surface. The ADCP also splits the water column into cells resulting in a more accurate velocity profile. Because an operator physically holds the ADCP in place, bottom tracking and DGPS are not required to calculate velocity, but the data is still collected. The 40 second averaging interval coupled with the 20 to 25 necessary stations gives a total measurement time of about 20 to 25 minutes. Bottom track data is also averaged during the 40 second intervals, and the data do not need to be compared to DGPS calculated

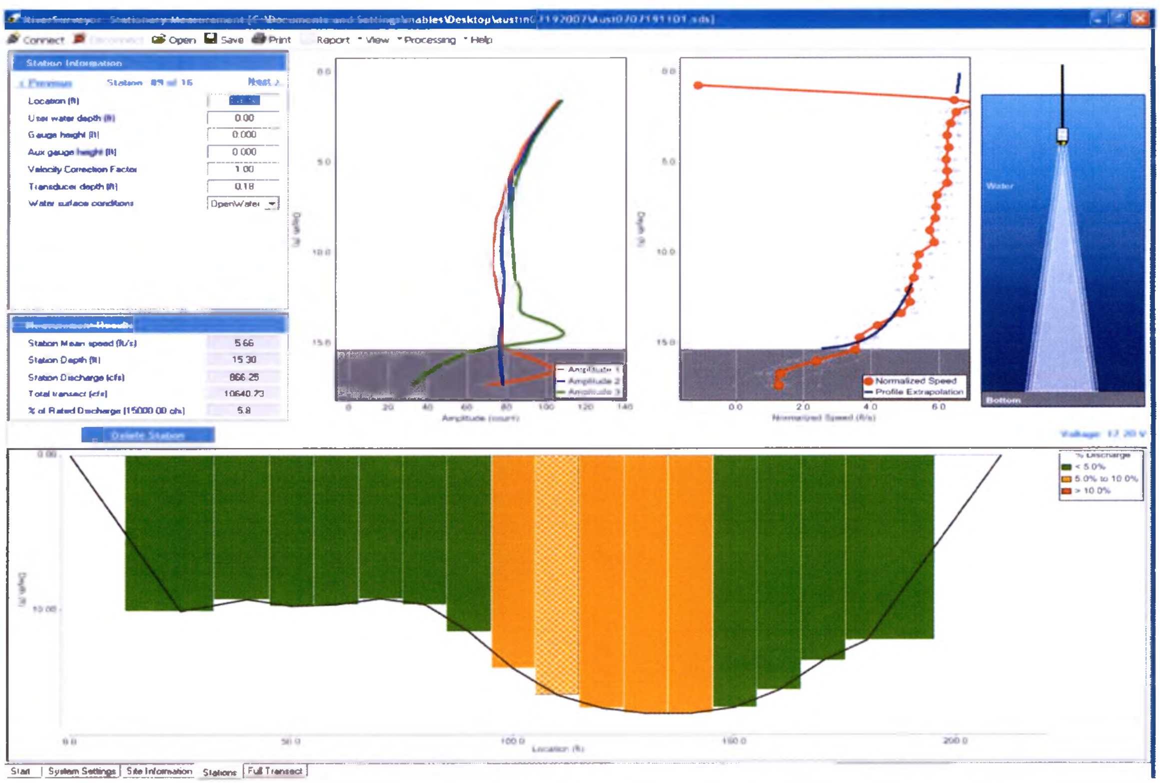

Figure 9. Output from the SonTek Stationary ADCP software illustrating the river channel separated into 20 to 25 sections in the lower image, with velocity profile and beam amplitude plots in the upper half (SonTek 2007).

velocities to obtain a mean bed velocity. Since the ADCP is stationary, any velocity measured by bottom tracking is the velocity of the channel bed, essentially the velocity of sediment moving through the channel. Sampling using stationary software is similar to the traditional bed load sampling techniques, and the two can be done side by side from the same vessel making the results comparable (Bunte et al. 2004).

CHAPTER 3

METHODOLOGY

Reach Selection

Identification of a suitable study reach along the Colorado River is dominated by the need for a controlled and fluctuating flow regime. This study requires periods of high and low flow, despite current weather conditions. The Colorado River at Austin USGS stream gauge has a 110 year discharge record, is a logical location, and represents the downstream boundary of the selected 1600 ft study reach (Figure 10). The site is less than two miles from where the necessary measurement equipment is stored, and daily releases of water from the upstream Tom Miller Dam for downstream irrigators provides a variable water level and flow. The bed composition is a mixture of sand and gravel that regularly displays signs of sediment mobilization and bed erosion.

Cross-Section Selection

Before a suitable measurement cross-section was selected, an extensive survey of the reach to find the areas of maximum potential bed load is needed. The site survey was comprised of two methods; one to look for channel bed movement, and the other to identify the areas of highest shear stress. The presence of a moving channel bed was identified through the same methods deployed by Rennie et al. (2002). During a period

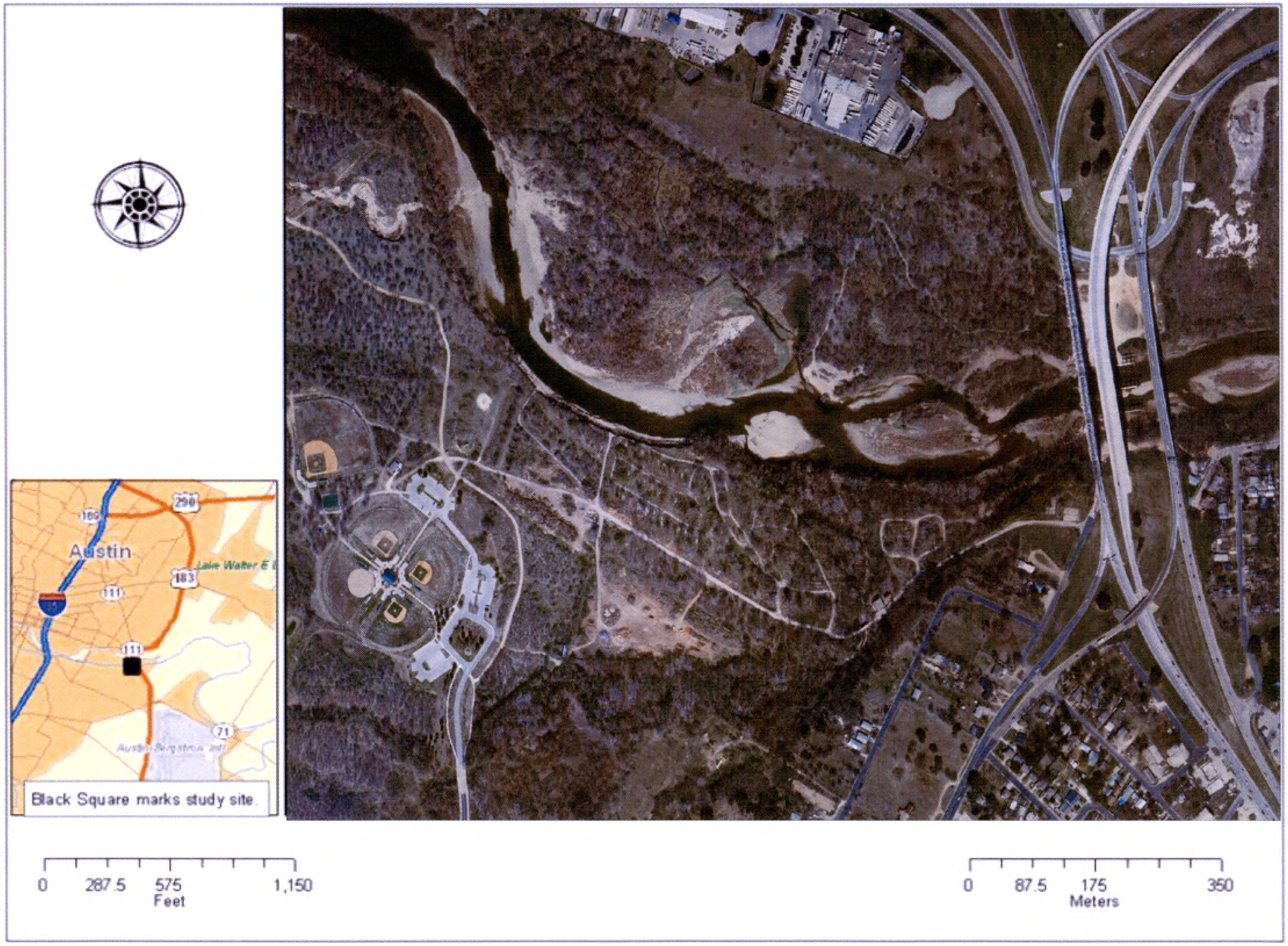

Figure 10. Map of the proposed study site near the Colorado River at Austin stream gauge.

of high flow, an ADCP with DGPS was deployed using the moving boat method, and multiple cross-sections were measured throughout the reach. A comparison of recorded bottom-track velocities with DGPS referenced velocities yields the areas within the reach where the ADCP records a moving bottom. In the second method, shear stresses identify the areas with the highest potential to transport sediment. The formula for shear stress, $\tau = \rho g h S$ requires two variables from the field, depth (h) and slope (S). Depths measured by the ADCP in the first method are used together with slope calculated from a surveyed water surface profile from the top of the 1600 ft reach to the USGS gauge staff plates. The product of the density of water (ρ) equaling 1000 kg/m^3, the gravity (g) constant of 9.81 m/s^2, the measured depths (h) in meters from the ADCP, and the surveyed water surface slope (S), returns the shear stress values in Pascals for each point measured in the first method. A cross-section was chosen by comparing the two methods and selecting the site with the highest probability of measurable bed load.

Sample and Measurement Methods

After identifying a suitable cross-section within the reach, the size and composition of the channel bed material was analyzed before, during, and after the bed load measurement. Wolman pebble counts (1954) and sieve analysis were used to measure changes in the channel bed composition and to identify what size and percentage of the channel bed sediment are moving. A gravelometer was used in the collection of a pebble count during low flow in the cross-section before the sediment transporting flows were released from the dam. During the high flow event, sediment samples were collected using a Helley - Smith suspended sampler with a 3x3 inch opening at 16 stations within the cross-section. The mass of each sample was measured and the grain size analysis performed through a combination of sieving and gravelometer measurements. After sediment transport ceased and low flows returned, a third and final pebble count was completed at the cross-section in the same manner that the first was collected.

Based on the manufacturer recommendations, both a 3.00 MHz and 1.0 MHz SonTek RiverCat ADCPs were used in this study, due to varying water levels (Table 1). The ADCP equipment was deployed using an unmanned tethered trimaran (Figure 7) attached to the side of a manned 16 ft aluminum tunnel-hull boat with a 70 horsepower outboard motor. The deployment to the side of the boat protected the ADCP from being damaged by the 65 pound Helley-Smith sediment sampler which was suspended by a crane off the front of the boat. SonTek's stationary discharge measurement software collected data at 16 stations across the channel, in sync with the bed load sediment samples. The boat was held in place at each station by a Kevlar tagline stretched across the channel, marking the cross-section.

Analysis Methods

Sediment and ADCP data were analyzed using descriptive statistics and regression analysis to establish a relationship between the measured bottom-track velocity versus the mass of collected sediment at each station. A comparison of sediment data collected before, during, and after the high flow event provides insight into which size fractions of sediment are mobile at the measured flows.

CHAPTER 4

RESULTS

Site Analysis

Initial site analysis began on May 29, 2007 when multiple cross-sections were measured with a 3.0 MHz ADCP and DGPS. Due to several minor rainfall events, the Lower Colorado River Authority was releasing a sustained 5000 cfs from Tom Miller Dam, resulting in a water elevation change of about 6 feet at the study site during the cross-section measurements (LCRA 2007). ADCP measured peak velocities were 6 ft/s $\pm$ 0.5 ft/s, with a mean velocity of 4ft/s. 250 profiles were collected in 5 second averaging intervals, as the boat and ADCP followed a zigzag path up the reach with one additional path directly down the thalweg. A comparison of the ADCP bottom track and DGPS referenced velocities using the Rennie et al. (2002) method revealed bed movement was most likely present in both the furthest upstream and downstream sections of the study site (Figure 11). A survey stake was placed on the right edge of water marking the water surface elevation in the upstream section of the reach. The water surface elevation at the downstream section of the reach was marked and recorded by the USGS staff gauge. A standard rod and level setup were used after the water receded to survey the water surface slope between the USGS staff gauge and the survey stake, resulting in a calculated slope of 0.0001. Figure 12 shows shear stresses

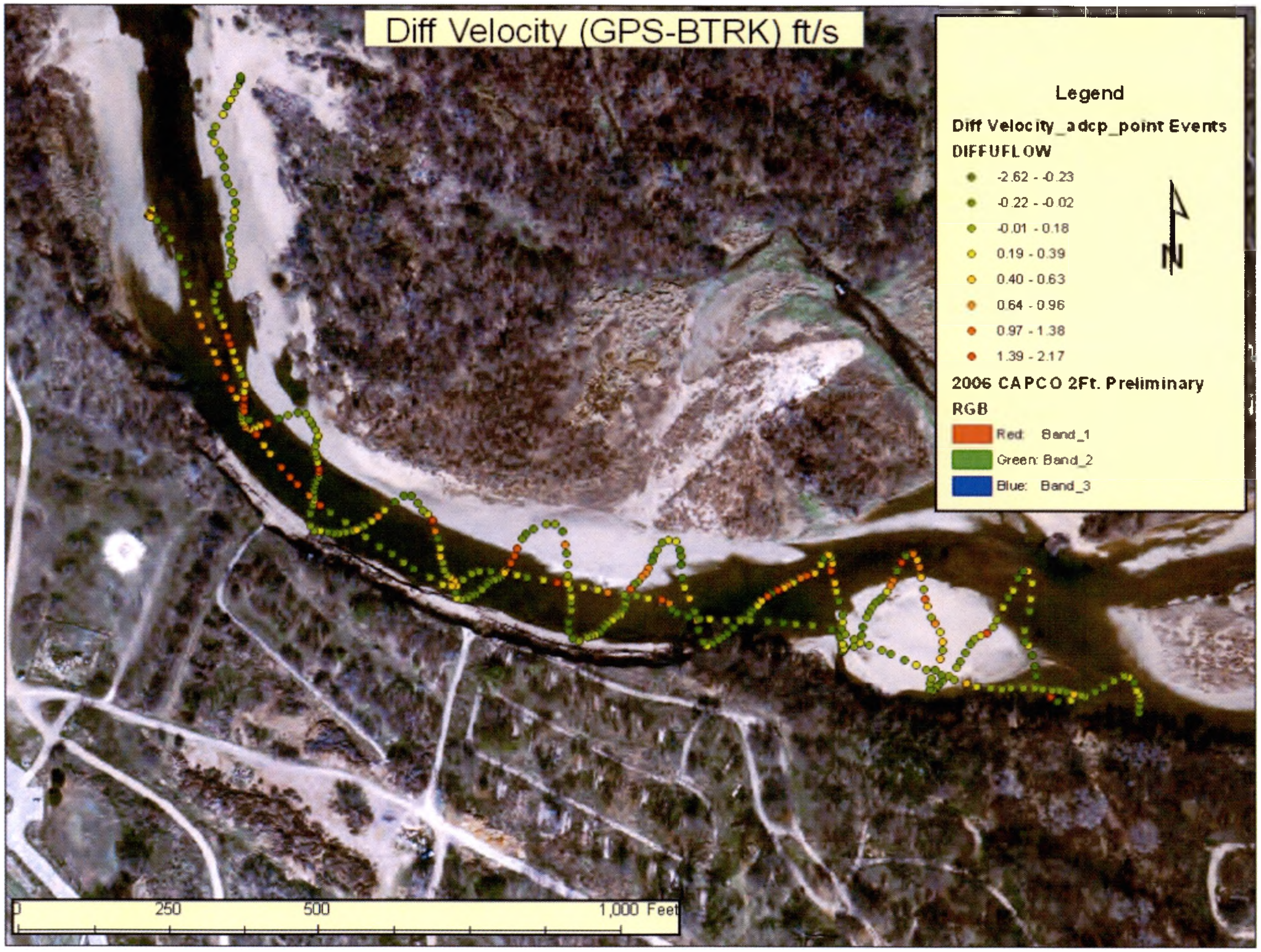

Figure 11. Aerial photo of the study site showing the ADCP path and bed load velocities (ft/s) using the Rennie et al. (2002) method.

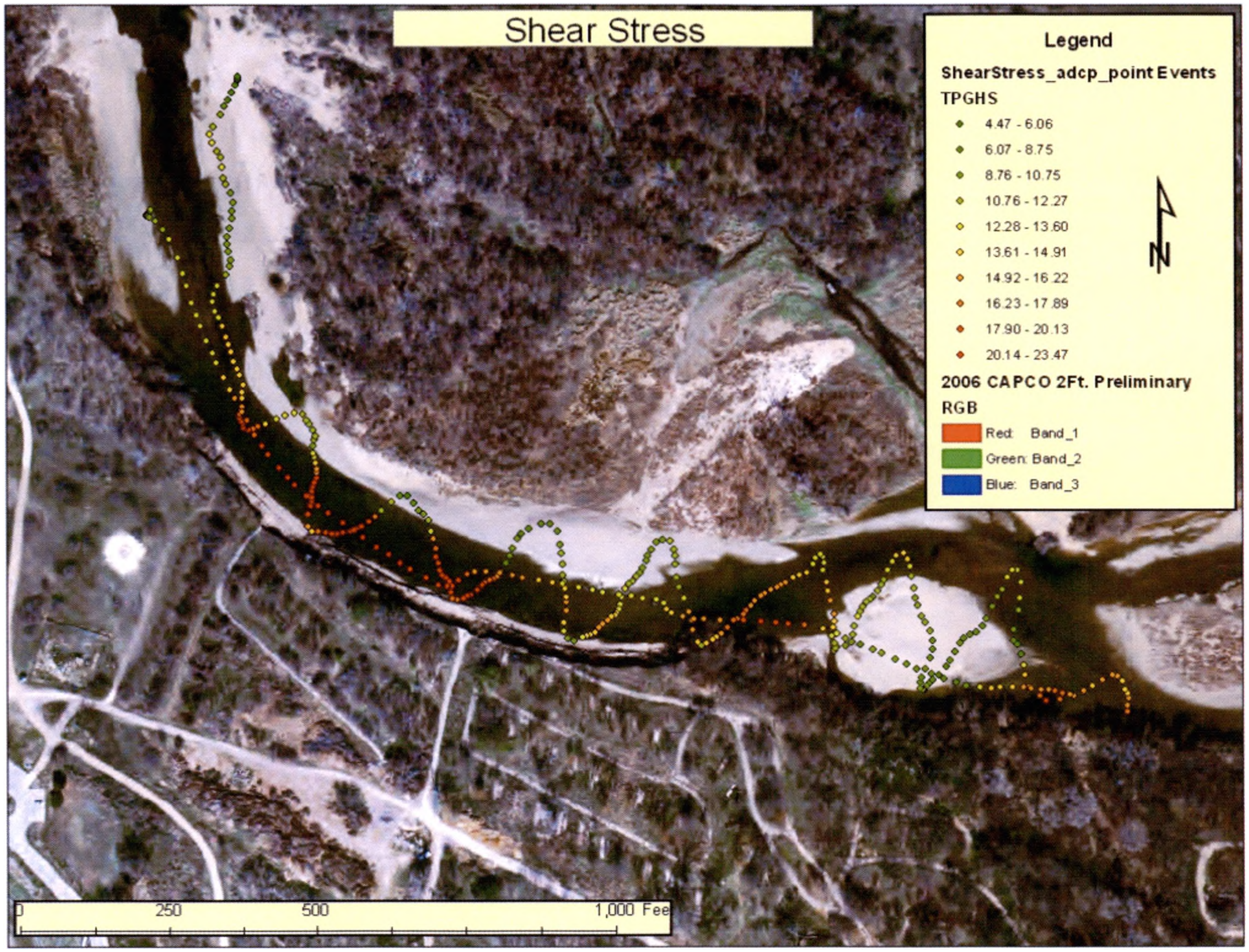

Figure 12. Aerial photo of the study site showing the ADCP path calculated shear stress in Pascals.

calculated using the depths obtained from the ADCP data and the water surface slope obtained from the survey. The highest values of shear stress were present in the upper sections of the reach, similar to the results given from the Rennie et al. (2002) method.

Cross-Section Selection

With the two methods in agreement, a cross-section was selected in the upstream section of the reach that had acceptable anchors for a tag-line on each side of the channel. Grain size analysis, after the high flows receded, using the Wolman pebble count method at the selected cross-section resulted in a mean bed surface grain size of 21mm and estimated at 10% sand.

On the night of 6/28/2007, over 18 inches of rain fell in 6 hours near the town of Marble Falls, about 90 miles upstream of the study site. Instantaneous inflows into the Lower Colorado River Authority reservoirs climbed from 200 cfs to over 250,000 cfs prompting floodgate operations and elevated flows at the study site. A total of two measurements were made during this event, one on 7/12/2007 and the other on 7/19/2007. Initial site investigations were made at the elevated flow conditions of 5,000 cfs, a change in water surface elevation of 6 feet. The rains from 6/28/2007 resulted in a peak flow at the study site of 28,700 cfs, and a sustained release from Tom Miller Dam of approximately 26,000 cfs, or a 20 ft rise over the next 20 days (Figure 14). Although discharges and water surface elevations were over four times those measured during initial site investigation, it was determined that the established cross-section was still a viable location for a measurement, and provided a relatively safe location in the fast turbulent water (LCRA 2007).

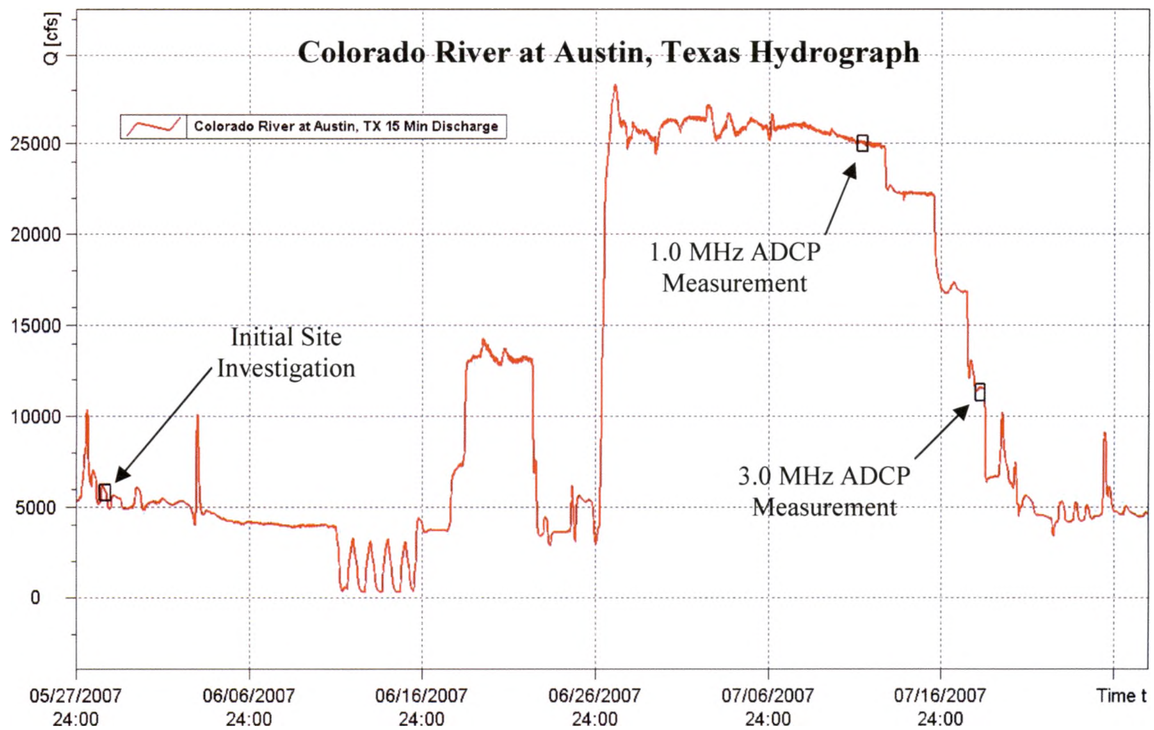

Figure 13. Hydrograph showing flood releases from the Lower Colorado River Authority at the study site due to heavy rains in the upper basin.

1.0 MHz ADCP Measurement

The first of two measurements was made on the morning of 7/12/2007. The water depths from the sustained 26,000 cfs exceeded the specifications of the 3.0MHz ADCP, and a 1.0MHz unit was used in its place. Total channel width during the measurement was estimated at approximately 800 feet, of which only about 40 percent was accessible. At this flow, the channel has flooded such that 60 percent of the channel width resided in a densely vegetated and shallow floodplain on the left side of the river. A 16ft boat with the ADCP and Helley-Smith sampler was secured to a 0.25 inch Kevlar tagline stretched 330 feet across the main channel area between two trees. With a three person crew consisting of an ADCP/boat operator, crane operator, and a sample collector, a total of 16 separate 40 second bed load samples and ADCP sections was made (Figure 14). Due to adverse conditions and safety concerns from the high velocities and flood debris, the standard 20 to 25 sections necessary for a discharge measurement were deemed unnecessary.

Mean vertically averaged velocities peaked above 7 ft/s with peak point

Figure 14. 16 ft boat and Helley-Smith sediment sampler setup with tagline during a measurement.

velocities near 10 ft/s in the thalweg (Table 2). The average depth was 16.2 feet with a maximum depth of 21.1 feet. Bottom track velocities ranged from –0.10 to 0.11 ft/s, with a channel mean of 0.02 ft/s. Bed load samples during the measurement were primarily gravel with a mean grain size of 5.6 millimeters. Of the 16 samples collected, quantities ranged from 0 to 458 grams, with a total bed load of 1,519 grams. Figure 15 is a plot showing how bottom track velocities, water velocities, and bed load vary throughout the cross-section. The plot illustrates how the bottom track velocities remained around zero throughout the cross-section, while a peak in bed load, consisting

Table 2. Summary table of data collected with the 1.0 MHz ADCP and Helley-Smith sediment sampler.

07/12/2007 1.0Mhz ADCP									
Station (ft)	Mean Velocity Water (ft/s)	Bottom Track Velocity (ft/s)	Water Depth (ft)	Area (ft^2)	Discharge (cfs)	Sample Time (sec)	Bed Load Sediment (g)	Sand (g)	Gravel (g)
0	0	0	0	0	0	0	0	0	0
50	1 19	-0 03	21 11	739	899	40	0	0	0
70	1 25	-0 04	19 79	396	509	40	0	0	0
90	2 28	0 04	18 63	373	834	40	0	0	0
110	3 35	-0 02	18 52	278	936	40	37	30	7
120	4 01	0 03	18 10	181	720	40	16 5	9 5	7
130	4 56	0 06	17 90	179	804	40	7	1	6
140	5 40	0 01	18 02	180	970	40	31 5	3 5	28
150	5 44	0 06	18 21	182	980	40	17	4	13
160	5 62	-0 10	18 51	185	1060	40	6	2 5	3 5
170	5 46	-0 05	18 52	185	1020	40	8	6	2
180	6 12	-0 02	18 00	180	1110	40	434 5	1 5	433
190	6 00	0 05	17 64	176	1050	40	458	62	396
200	7 03	0 02	18 04	180	1260	40	338	90	248
210	6 66	0 11	17 62	176	1150	40	62	14	48
220	4 92	0 07	16 11	161	781	40	30	30	0
230	5 83	0 05	16 25	894	5170	40	74	51	23
330	0	0	0	0	0	0	0	0	0

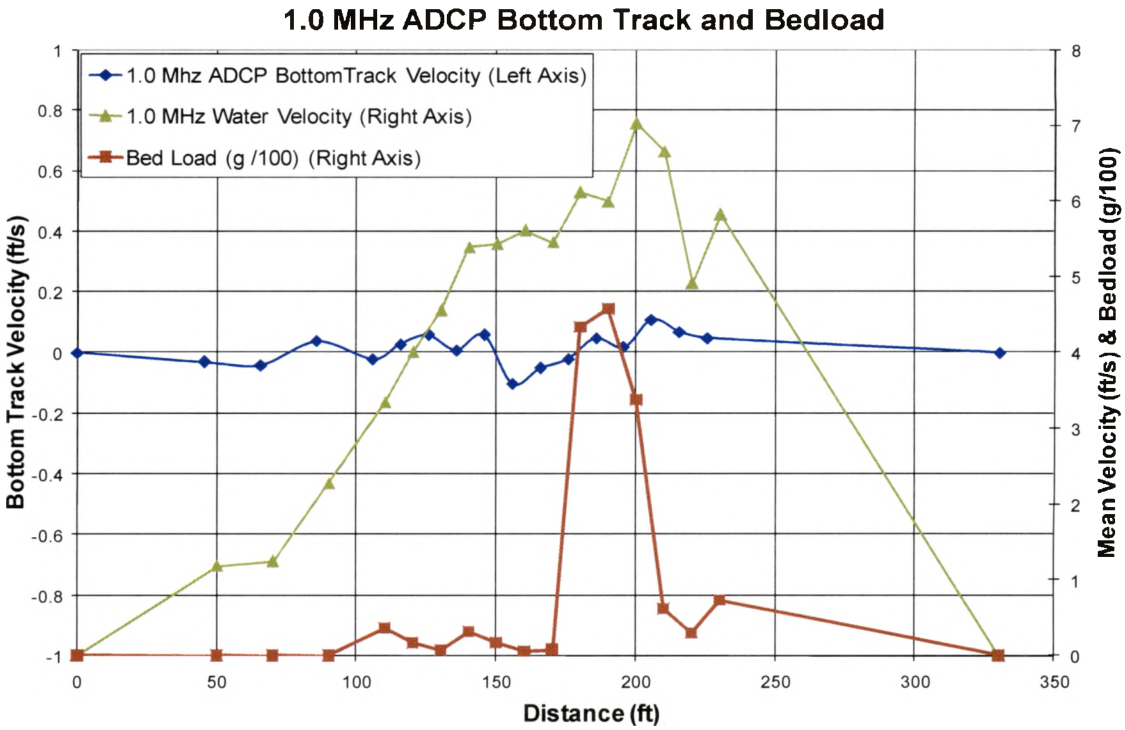

Figure 15. Chart showing how bottom track velocities, water velocities, and bed load varied throughout the cross-section during the 1.0 MHz ADCP measurement.

of three separate samples, is apparent in the thalweg.

3.0 MHz ADCP Measurement

On 7/19/2007, releases from the LCRA reservoirs had declined, and a second measurement was made at the same cross-section with a stage of 12 feet, and a discharge of 12,000 cfs. Just as in the first measurement, a tagline was stretched between two trees on either side of the channel to which the boat was secured. Water was still present in the floodplain to the left of the main channel, which remained inaccessible by boat. The 3.0 MHz ADCP was selected due to shallower depths, yet mean velocities near 6 ft/s with instantaneous velocities near 8 ft/s in the thalweg led to only 16 samples being collected due to safety concerns (Table 3). The average depth was 11.3 feet with a maximum depth of 16.5 feet. Bottom track velocities ranged from

Table 3. Summary table of data collected with the 3.0 MHz ADCP and Helley-Smith sediment sampler.

07/19/2007 3.0Mhz ADCP											
Station (ft)	Mean Velocity Water (ft/s)	Bottom Track Velocity (ft/s)	Water Depth (ft)	Area (ft^2)	Discharge (cfs)	Sample Time (sec)	Bed Load Sediment (g)	Sand (g)	Gravel (g)	Predicted Sediment (g)	%Diff
0	0	0	0	0	0	-	0	0	0		
25	3 57	0 01	10 05	201	716	40	207	23	185		
40	4 72	0 09	9 26	116	537	40	138	62	76		
50	5 53	-0 04	9 70	97	540	40	194	2	192		
60	5 59	-0 08	9 57	96	543	40	17	10	7		
70	5 71	0 02	9 19	92	523	40	215	62	153		
80	5 85	-0 02	9 60	96	563	40	91	12	79		
90	5 38	-0 02	11 31	113	610	40	12	5	7		
100	5 54	0 18	13 63	136	731	40	320	101	219	295	-7 92
110	5 66	1 20	15 30	153	683	40	1478	703	775	1500	1 51
120	5 46	1 18	16 08	161	688	40	1531	1104	428	1477	-3 11
130	5 22	0 03	16 45	165	854	40	175	26	149		
140	4 86	0 09	16 43	164	784	40	64	14	50		
150	4 39	0 05	16 07	161	698	40	49	7	42		
160	4 24	-0 05	14 96	150	641	40	11	10	1		
170	3 41	0 04	13 14	131	443	40	13	6	7		
180	2 82	0 03	11 83	237	661	40	8	7	1		
210	0	0	0	0	0	-	0	0	0		

–0.05 to 1.20 ft/s, with a channel mean of 0.17 ft/s. Bed load samples collected ranged from 8 to 1,531 grams, with a total bed load of 4,523 grams. In a similar pattern as the 1.0 ADCP measurement, a peak in bed load, comprised of three separate samples, is apparent near the thalweg (Figure 16). However, bottom track velocities in the 3.0 MHz ADCP measurement were significantly different from the first measurement, in that they also peak near the thalweg.

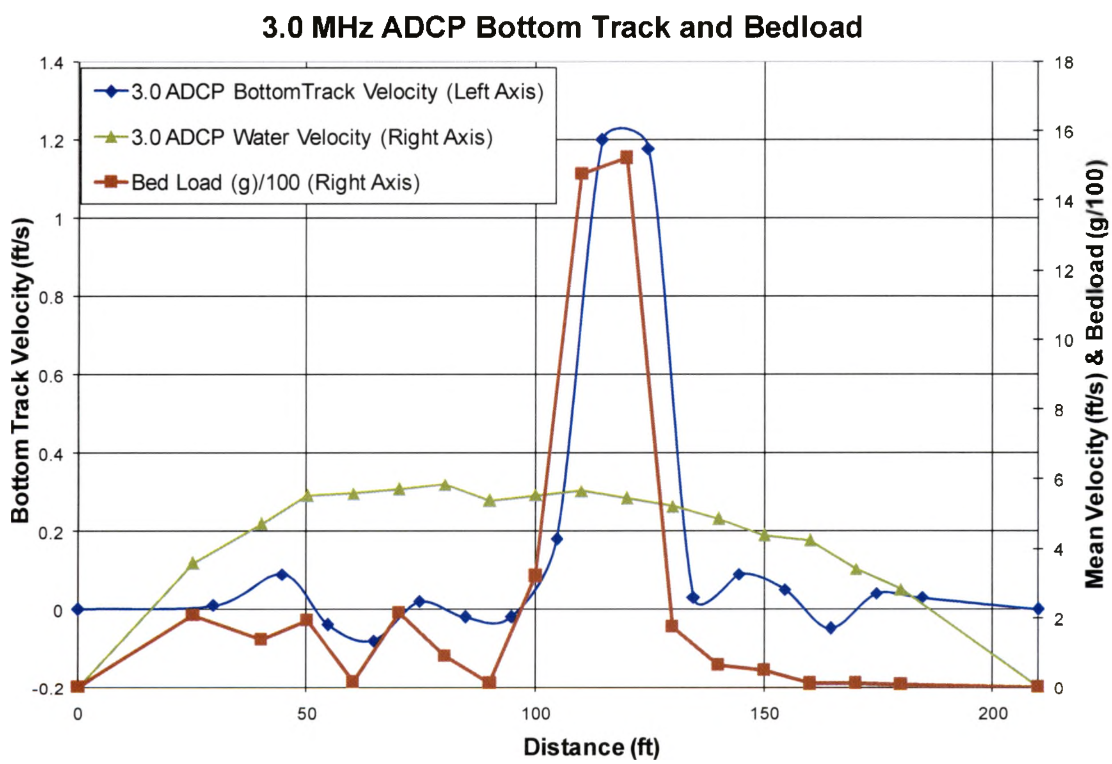

Figure 16. Chart showing how bottom track velocities, water velocities, and bed load varied throughout the cross-section during the 3.0 MHz ADCP measurement.

Grain Size Distributions

Bed load samples collected with the Helley-Smith during each measurement were analyzed and compared to grain size distributions gathered before and after the flood event (Figure 17). Samples from both measurements were separated through sieve analysis into sand (< 2 millimeters) and gravel (>2 millimeters) fractions. The sand and gravel for each sample was then weighed to establish a percent sand. Wolman pebble counts (1954) were completed on each gravel sample to complete the grain size distribution. Because sand was not further separated, each grain size distribution shown in Figure 17 is truncated below 2 millimeters, and represents a total of the 16 samples collected. Therefore, the value of each curve at the 2 millimeter mark is the measured percent sand for that distribution. With mean grain sizes ranging from 21 millimeters pre-flood, to only 2.5 millimeters during the 3.0 MHz ADCP measurement, large differences are apparent between each of the samples. The D50 for the 1.0 MHz ADCP measurement is 5.6 millimeters, illustrating the larger amounts of gravel present in the

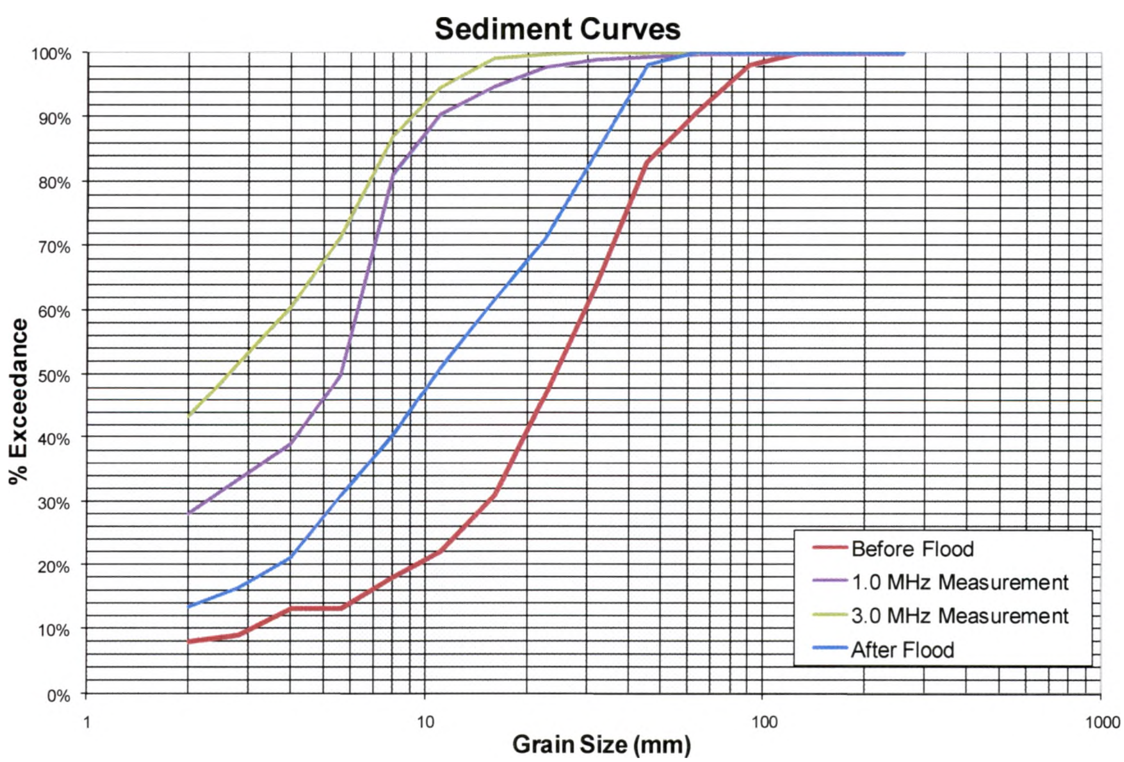

Figure 17. Grain size distributions from before the flood, the average for each of the two measurements during the flood, and post flood.

samples. Almost half of the sediment caught in the second measurement was sand sized, with sand making up more than 70 percent of the largest sample. After the floodwaters receded, and dam operations were back to normal, an additional Wolman pebble count (1954) was done at the measurement site. With a D50 of 11 mm, the post flood grain size distribution fell between the pre-flood and flood measurement distributions.

Figure 18 shows the sand and gravel fractions, and how each varies with bottom track velocity. The 3.0 MHz ADCP appears to track well with both sand and gravel. Simple linear regression analysis of the bottom track velocities and bed load samples

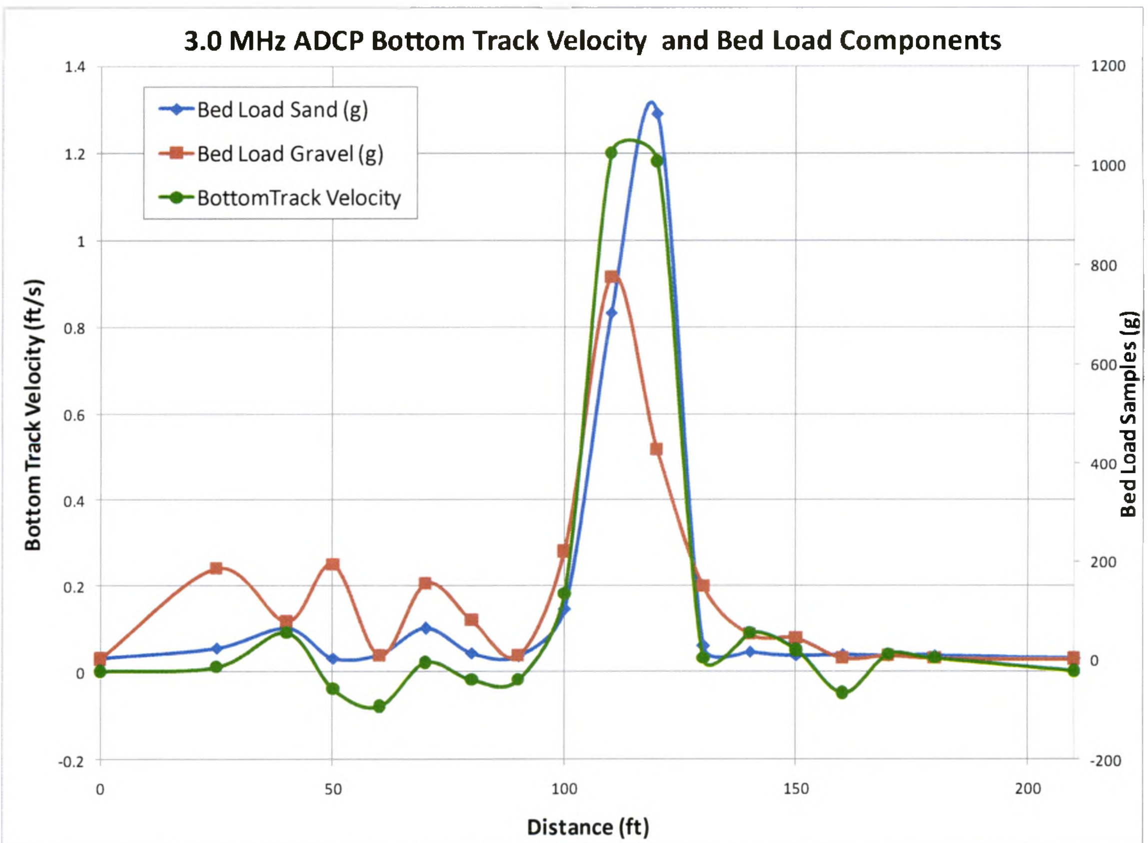

Figure 18. Chart showing how the different bed load components of gravel and sand varied with bottom track velocities throughout the cross-section during the 3.0 MHz ADCP measurement.

from the two measurements differed greatly. The 1.0 MHz ADCP from the first measurement did not record any significant bed velocities, most of which fell between –0.1 and 0.1 with a mean of 0.015 ft/s. A simple linear regression line was not able to fit the data, and therefore no relationship could be established. Measurement two, made with the 3.0 MHz ADCP, regression analysis yielded better results. As with the first measurement, some small amount of particles were captured in all bed load samples, and most of the bed velocities were between –0.1 and 0.1 ft/s. However, the three stations that recorded both significant amounts of bed load and bottom track velocities correlate well, as shown in Figure 19. The sand fraction of the bed load samples returned a more significant relationship (r^2 = 0.93) than the gravel fraction (r^2 = 0.79),

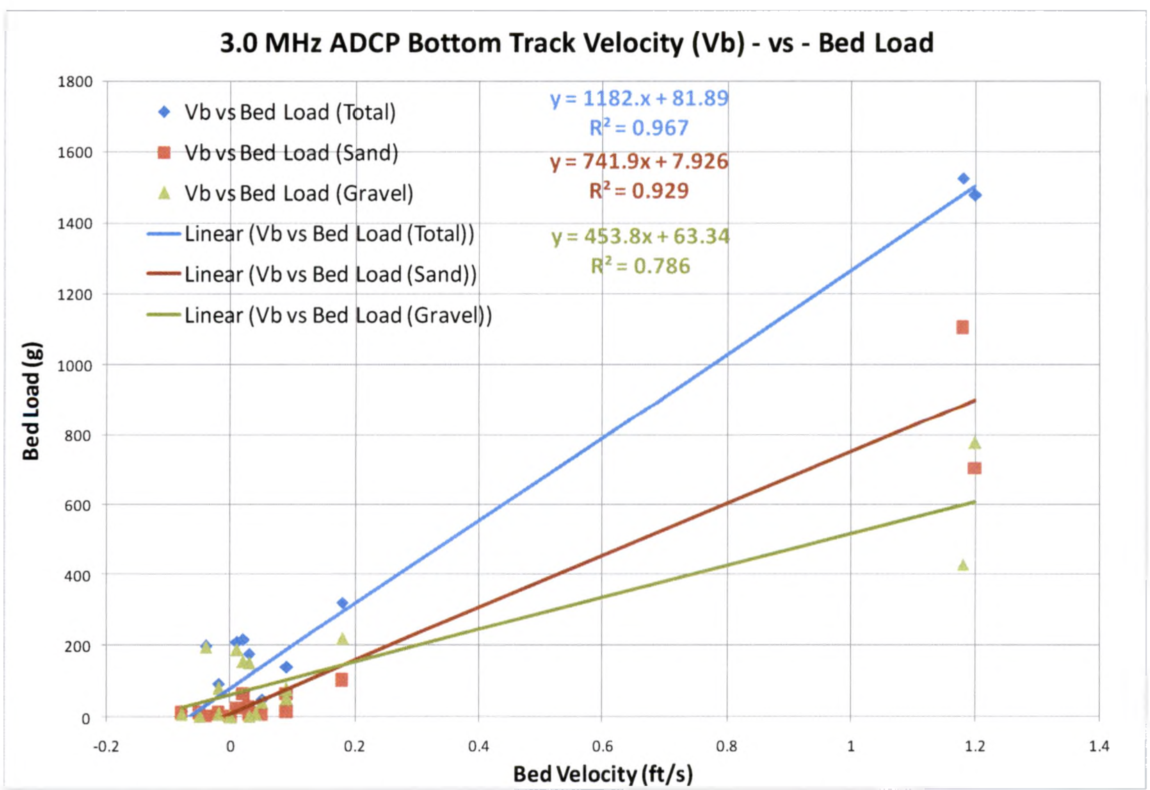

Figure 19. Linear regression lines demonstrating the relationships between the sand and gravel components of bed load captured during the 3.0 MHz ADCP measurement relative to bottom track velocity.

yet the strongest relationship is seen when the sand and gravel components are combined (r^2 = 0.97). Equations developed from regression analysis predict bed load transport from bed load velocity to within 8 percent when above a 0.10 ft/s minimum bed load velocity.

CHAPTER 5

CONCLUSIONS

Discussion

Results from the 1.0 MHz ADCP showed no relationship, as no bed load velocity was detected by the instrument. Although the two measurements demonstrated similar bed load patterns, only the 3.0 MHz ADCP results indicate that there is a linear relationship between bed load velocity and bed load transport rate at the study site. Although different methods, software, and brands of ADCPs were used, the results from the 3.0 MHz ADCP agree with those reported by Rennie et al. (2002). However, the use of the stationary method eliminated the error and cost associated with DGPS. It is uncertain if equations developed from the 3.0 MHz ADCP data are site specific, or can be used at sites with different grain size distributions.

Measurement Error

Years of experience and proper preparation for field work can reduce error in measurements, but can never eliminate or account for unforeseen problems that often arise. However, systematic error, or error associated with a particular method, can be accounted for and addressed. The goal of the proposed method is to expand on the Rennie et al. (2002) methodology and eliminate the systematic error associated with the use of DGPS. SonTek's Stationary software effectively eliminated the need for DGPS, making it the responsibility of the operator to hold the ADCP steady during each 40 second sample. For both cross-section measurements in this study, stability was achieved through the use of a tagline holding the boat relatively stable. The high velocities associated with each measurement pulled the boat in the downstream direction to the full extent of the tagline, which allowed for minimal drift. However, some side to side movement of the boat was observed near the left edge of water due to turbulence. It is believed that the 40 second averaging interval at each station reduces the error associated with subtle movements of the boat, but does not eliminate it. Boat drift cannot be eliminated, but with the SonTek Stationary method, it is not compounded by drift in the DGPS data. In both measurements, when significant bed load was not present, measured bottom-track velocities were between -0.1 and 0.1 ft/s. Natural fluctuations in bed load transport could be partially responsible, but slight movements in the boat during the measurement are also partially responsible for this 'noise' in the velocity. Because of this noise, a conservative estimate of 0.15 ft/s precision is given to the stationary method.

One source of error associated with all ADCPs used to measure bed load is the large footprint of the three acoustic beams. The three transducers of the ADCP are angled at 25 degrees from vertical, which roughly translates to a 1 to 1 ratio of water depth to sample diameter at the channel bed. More simply stated, if the mean depth was 18.2 ft, then the mean ADCP sampling footprint is also approximately 18 ft in diameter. While the Helley-Smith is sampling the channel bed directly below the boat, each of the three beams of the ADCP are sampling at a distance of approximately 9 feet out from the center of the transducers. In a large homogeneous stream, this error may be minimal, but in a deep narrow channel, this kind of error could dominate the measurement.

The assumption that the Helley-Smith is sampling directly below the boat may also be a misconception in higher velocities. During the 1.0 MHz ADCP measurement, instantaneous point velocities were in excess of 10 ft/s, which drug the 65 pound sampler downstream. Efforts to get the sampler to the channel bed as fast as possible helped, but in the highest velocities, the sampler was pulled more than 10 feet downstream. While still contained within the ADCP footprint, the sampler could scoop sediment from the bottom as it was drug back upstream, resulting in higher amounts of recovered sediment, and false bed load.

Initial site analysis and selection of a suitable cross-section were done during a period of moderately elevated flows, in comparison to the high discharges recorded during the two measurements. For this reason, the location of the selected cross-section may not have been the best location for sampling, but was still believed to be representative of the selected reach. A moving bottom was detected during initial site analysis at 5,000 cfs, and can be assumed present at higher flows. However, the larger amounts of shear stress generated by discharges in excess of 4 times the initial analysis are capable of moving the larger grain sizes. Grain size distributions done before the high water had a D50 of 21 millimeters, with grain sizes of 90 and 128 millimeters present. Due to equipment limitations, the Helley-Smith sampler used had a 76 x 76 millimeter opening. With a smaller opening than the potential sediment present, collected samples could be biased to smaller grain sizes.

Preliminary investigations into using the SonTek Stationary software to estimate bed load transport from bottom-track velocity were partially successful. Further analysis and multiple measurements at multiple sites are required before any definitive decision can be made about the success of the method.

Conclusions

The use of ADCPs to measure bed load is a promising and necessary technology. Central Texas rivers and streams are prone to violent, short duration floods which make it difficult to gather bed load data. If a more efficient method can be established, more data can be gathered to aid in the future development of water resources. The technique presented developed a strong correlation between bottom track velocity and bed load transport. With more measurements at different flow regimes, with variable grain size distributions, it is proposed that a calibration curve between ADCP measured bottom track velocity and bed load could be developed.

REFERENCES

Baosheng Wu, Albert Molinas, and Pierre Y. Julien. 2004. Bed-Material Load Computations for Nonuniform Sediments. *Journal of Hydraulic Engineering* 130(10): 1002-1012.

Bunte, Kristin, Steven R. Abt, John P. Potyondy, and Sandra E. Ryan. 2004. Measurement of Coarse Gravel and Cobble Transport Using Portable Bed load Traps. *Journal of Hydraulic Engineering* 130(9): 879-893.

Gartner, Jeffery W. 2004. Estimating Suspended Solid Concentrations from Backscatter Intensity Measured by Acoustic Doppler Current Profiler in San Francisco, California. *Marine Geology* 211(3-4): 169-187.

Heitmuller, F.T, W.H. Asquith, Xing Fang, D.B. Thompson, and Keh-Han Wang. 2005. Literature review for Texas Department of Transportation Research Project 0–4695—Guidance for design in areas of extreme bed-load mobility, Edwards Plateau, Texas: USGS Publishing Network-Online Only. http://pubs.usgs.gov/of/2005/1234/pdf/ofr2005-1234.pdf. U.S. Geological Survey Open-File Report 2005–1234.

Kostaschuk, Ray, Jim Best, Paul Villard, Jeff Peakall, and Mark Franklin. 2005. Measuring flow velocity and sediment transport with an acoustic Doppler current profiler. *Geomorphology* 68: 25-37.

Lower Colorado River Authority (LCRA). 2007. River Operations Center Hydrologic Data. Lower Colorado River Authority. http://hydromet.lcra.org. Accessed 04/20/2007.

Lower Colorado River Authority (LCRA). 2006. Historical LBJ Ranch Photos. Lower Colorado River Authority Photo Archives. Contact: 1-800-776-5272.

Morlock, Scott E., Hieu T. Nguyen, and Jerry H Ross. 2002. Feasibility of Acoustic Doppler Velocity Meters for the Production of Discharge Records from U.S. Geological Survey Streamflow-Gaging Stations. Indianapolis Indiana. U.S. Geological Survey Water-Resources Investigations Report 01-4157.

Oberg, Kevin. 2007. Hydroacoustics in the U.S. Geological Survey (USGS). Keynote Address of the 2007 USGS Surface-Water Conference and Hydroacoustics Workshop. St. Louis, Missouri. Meeting Notes April, 4 2007.

Quinn, Michael. 2002. Colorado River From Nankoweap. U.S. National Park Service. http://www.nps.gov/grca/photosmultimedia/photogallery.htm? id=128398&aid=108&root_aid=108&sort=title&startRow=1. Accessed 04/20/2007.

Radoane, Maria, and Radoane, Nicolae. 2005. Dams, sediment sources and reservoir silting in Romania. *Geomorphology* 71(2005): 112-125.

Rennie, Colin D. Robert G. Millar, and Michael A. Church. 2002. Measurement of Bed Load Velocity using an Acoustic Doppler Current Profiler. *Journal of Hydraulic Engineering* 128(05): 473-483.

Rickly. 2007. Bed load. Rickly Hydrological Company. http://www.rickly.com/ss/ bedload.htm. Accessed 04/20/2007.

Robert, Andre. 2003. River Processes An Introduction to Fluvial Dynamics. New York, Oxford University Press: 51-90.

Sauer, V.B. 2002. Standards For the Analysis and Processing of Surface-Water Data and Information Using Electronic Methods. Reston, Virginia. U.S. Geological Survey Water-Resources Investigations Report 01-4044: 1-91.

Sontek. 2000. Acoustic Doppler Profiler (ADP) Principals of Operation. SonTek ADP Users Manual. San Diego, California. SonTek/YSI.

Sontek. 2007. ADCP Principals of Operation. SonTek/YSI http://www.sontek.com/ princop/adp/adppo.htm. Accessed 04/20/2007.

U.S. National Park Service (USNPS). 2007. Grand Canyon National Park - Nature and Science .U.S. National Park Service. http://www.nps.gov/grca/naturescience/ index.htm. Accessed 04/20/2007.

U.S. National Water Information System (USNWIS). 2007. National Water Information System - U.S. Geological Survey Real-Time Data for Texas Stream Flow. http://waterdata.usgs.gov/tx/nwis/current/?type=flow. Accessed 04/20/2007.

Wolman, M.G. 1954. A method of sampling coarse river-bed material: Transactions of the American Geophysical Union (EOS), v. 35, p. 951-956.

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