METHODS FOR SEDIMENT BUDGETING

ALONG THE MIDDLE TRINITY RIVER

By

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Submitted to the Graduate Faculty of the
College of Science and Engineering
Texas Christian University
In partial fulfillment of the requirements
for the degree of

Master of Science

May 2008

ACKNOWLEDGEMENTS

Field work was accomplished with thanks in part to Lee Todd, Matt Patyk, Stephanie Eady and Dr. Michael Slattery. I would like to thank Dr. Rhonda Hatcher for reference. Thanks also to Dr. Michael Slattery and Dr. Noel Donovan who mentored me and encouraged me to attend graduate school as well as to focus on the Trinity River for my thesis. I have eternal gratitude to Dr. Joe Kuban for giving me the inspiration to be a steward for our planet Earth. Dr. Kuban’s example has changed many lives, including mine. Last but not least, I would like to thank my family and loving wife for all of their support and most importantly patience.

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INTRODUCTION

Fluvial systems are highly complex and dynamic. This is especially true of alluvial river systems, where channels continually move across floodplains, eroding and reworking sediment, resulting in new areas of channel as well as deposition in the form of bars and overbank deposits. The controls of alluvial river systems are not fully understood, but the geomorphic effects of these systems are far-reaching. For example, bank erosion and channel shifting causes land loss to residents and channel scour damages and destroys boat ramps and bridge crossings, necessitating repairs and replacements.

One of the least understood components of fluvial systems is sediment flux. This is partially due to the paucity of sediment transport data. It has been estimated that less than 10% of the world's rivers have been monitored for sediment delivery to coastal regions (Syvitski et al., 2005). Another challenge with quantifying sediment flux relates to the location of sediment gaging stations. Phillips and Slattery (2006) noted that sediment delivery to the coast is frequently overestimated because sediment data is often only available from monitoring stations that are far inland and well upstream of potential storage zones. These data are not reflective of the low slope, low stream power reaches typical of coastal plain rivers. In the Sabine, Neches, Trinity, Brazos, and Colorado Rivers on the Texas coastal plain, for example, the gaging stations used to measure or estimate sediment loading to the coast range from 54 to 98 km upstream of the river mouth. As illustrated by the case of the Trinity (Phillips et al., 2004; Phillips and Slattery, 2006) sediment transport monitoring which does not represent the lower reaches of coastal plain alluvial rivers will result in overestimation of sediment flux to the sea in a contemporary sense. This raises questions as to how much upland sediment is really being delivered to bays and estuaries in the coastal zone.

Notwithstanding the difficulty in monitoring sediment flux, particularly at large scales, land-to-ocean sediment flux is vast. Syvitski et al. (2005), for example, estimate that 12.6 billion tons are transported from interior basins to the coastal zones globally. Identifying the source area(s) of this terrestrial sediment, and understanding how it is delivered from source to sink, is an important yet difficult task. One approach to accomplish this is through the construction of sediment budgets. A sediment budget is defined as "… an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from the drainage basin" (Reid and Dunne, 1996). Conceptually, sediment budgets can be written as:

$$I - O = \Delta S$$

where I is sediment entrained within and entering the drainage basin, O is sediment released from the system, and ΔS the change in the sediment stored in the drainage basin. This equation captures sediment production and sediment losses, as well as changes in river sediment storage. Generally speaking, quantifying output is relatively straightforward and requires long-term sediment monitoring at gaging stations and the construction of sediment rating curves. Measuring sediment input to a fluvial system is more difficult, especially at larger scales, and is generally accomplished through simple empirical sediment transport equations, such as the Universal Soil Loss Equation (USLE). Quantifying sediment storage, however, remains the most difficult task.

The rate at which sediment is stored within fluvial systems is controlled by a number of interrelated factors. An alteration in bed topography of braid bars and point bars can decrease stream power and consequently increase the amount of deposition. Bank erosion typically happens along the outer bends of the channel where the flow is moving the fastest. Deposition of channel bars occurs to the inside of channel curves because the flow is least erosive and secondary flow cells break down. Cutting of new channels, enlarging existing channels, and abandonment and filling of others is also involved in alluvial river systems as they move across the floodplain. The main influence of alluvial river systems with respect to sediment storage is the flow regime. High magnitude flows flush the available channel sediment downstream and increases erosion. However, if more sediment is entering the system than leaving it, this is referred to as sediment sink. This occurs frequently in areas with low gradient such as wetlands and extremely sinuous river systems. Conversely, more sediment leaving than added to a system is called a sediment source. This takes place in upland areas and other places where erosion and sediment transport dominate.

This thesis focuses on the issue of sediment delivery and storage within fluvial systems, specifically, the question as to how researchers can make rapid, yet still meaningful, estimates of storage along the sediment conveyance route. The work is conducted along a reach of the middle Trinity River in Texas. The goal of the study was not to construct a sediment budget per sé. Rather, the over-arching aim of this work is to provide an assessment of the methods used to quantify the storage component of a sediment budget and the types of data that can be generated using fairly rapid and straightforward estimation techniques. Recommendations on ways to refine aspects of the sediment storage component in future work are also made.

BACKGROUND

The Trinity River, which originates in north central Texas just west of Fort Worth, drains 46,000 km^2 as it travels south and east toward its delta on Galveston Bay on the Gulf of Mexico (Figure 1). Land use along the upper Trinity River is primarily urban in nature. The middle Trinity River passes through rural and forested land adjacent to the channel. The lower Trinity River travels through forested land and transitions to coastal marshlands (Figure 2). The majority of the basin has a humid subtropical climate. In the North Central Texas area where the Trinity River originates, the annual average rainfall ranges from 27 inches in the west to about 33 inches in the east.

Figure 1: Trinity River basin showing major gaging stations. The study reach is located between Crockett and Lake Livingston

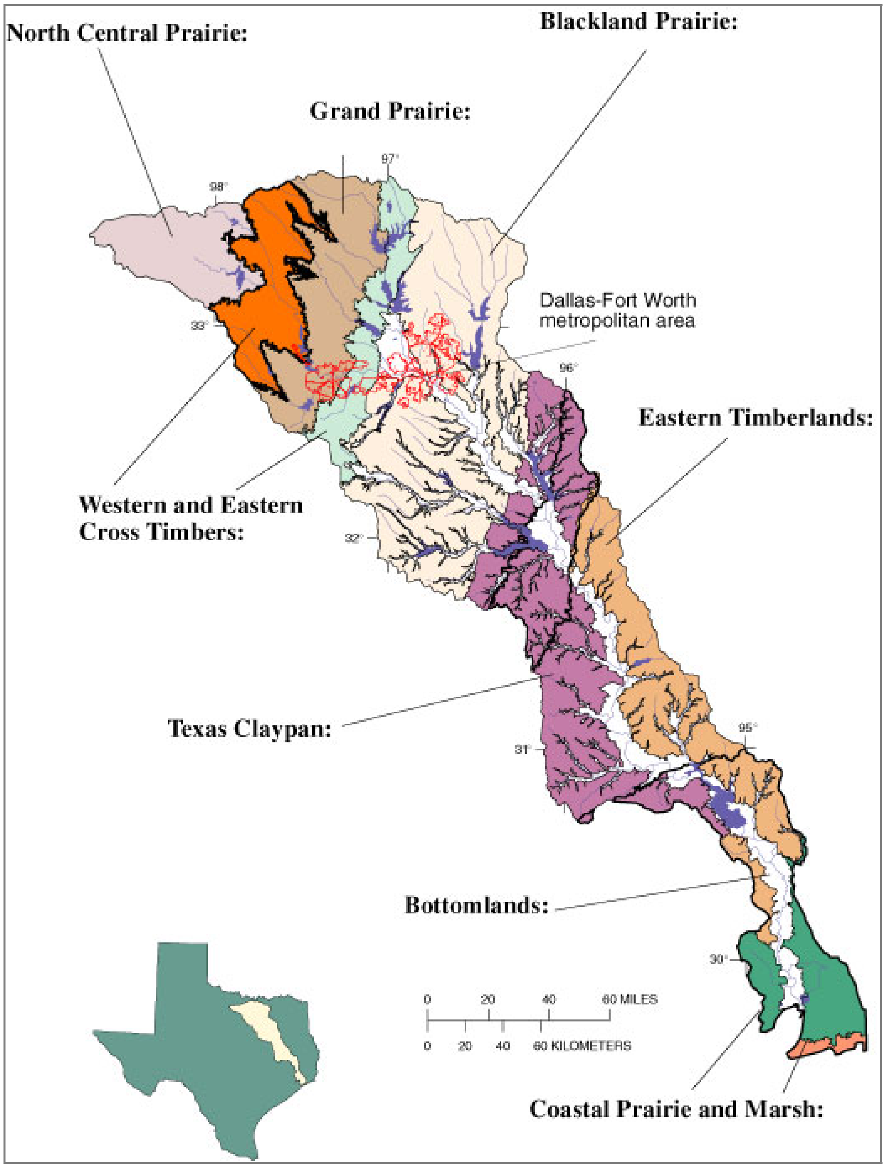

Figure 2: Trinity River basin showing major ecological environments

Soils on stable upland sites are mostly Alfisols and Ultisols. Deep to shallow clay and clay loam dominate the upper reach while clay and sandy loam reside in the lower part of the basin below Lake Livingston. The channel itself is characterized by finer grained sediments over bedrock. The river follows a gentle sloping gradient towards the Gulf of Mexico where it empties first into Trinity Bay and then Galveston Bay.

The main channel of the Trinity River is meandering, and it is clear there has been lateral and vertical channel movement in the recent past as evidenced by abundant meander scarring and oxbow lake development (Figure 3). Rising Holocene sea levels and Quaternary climate change, as well as major impoundment and water withdrawals in recent years, have been thought to influence this river in terms of flow and sediment transport (Phillips et al., 2005). Twenty-nine dams are in operation in the basin, most of which are grouped near the major metropolitan areas, such as the Dallas-Fort Worth Metroplex to the north and Houston and Galveston to the south (Figure 4).

Figure 3: 1995 DOQQ of the lower Trinity showing meanders, oxbow lakes, and meander scrolls. The Romayor gaging station is also shown.

Figure 4: Trinity River and nearby populated areas.

Relatively little is known about the sediment transport regime of the middle Trinity River. However, the lower reach of the Trinity, defined here as the basin below Lake Livingston, has been the focus of a number of studies mostly centering on the effect of impoundment on sediment transport (Phillips et al., 2004; Phillips et al., 2005; Wellmeyer et al., 2005; Phillips and Slattery, 2006; Dollar, 2005). Several key themes have emerged from this work. First, the effect of Lake Livingston reservoir on the overall sediment delivery to the coast has been found to be small. Although the reservoir is an efficient trap for sediment being delivered from upstream, loads in the Trinity 50-60 km below the dam (i.e., at the Romayor station, see Figure 3) approximate those in the middle reaches. The sediment budget constructed by Phillips et al. (2004) showed that Livingston Dam has not reduced sediment delivery to Trinity Bay. They concluded that alluvial storage in the lower Trinity River is extensive, dwarfing sediment yield and that this is due to low stream power controlled by low energy gradients rather than trapping in Livingston dam.

Hungry water was one consideration pertaining to the impact of impoundment on the Trinity River. As Kondolf (1997) explained, all bedload sediment and all or part of the suspended load is deposited in the quiet water of the reservoir. Downstream, clear water is released from the dam that contains little or no sediment load. This water possesses the energy required to erode and transport sediment. Hungry water plays a part in channel incision and channel geometry immediately downstream of the dam. Phillips et al. (2005) suggested that the channel response to impoundment would occur in about 35 years or less. They found, however, no evidence that the scour from the dam to Romayor is abating.

Phillips et al. (2004) concluded that dam-related sediment starvation effects are evident for approximately 50-60 km downstream, and the sediment budget suggests that a majority of the sediment in this reach is likely derived from channel scour and bank erosion. Since the river is at or near bedrock from the dam to Romayor, additional downcutting will most likely be quite slow (Phillips et al., 2004). This indicates that lateral channel migration may be expected to increase. The extensive alluvial storage in the lower Trinity, however, essentially buffers Trinity Bay from the effects of fluctuations in fluvial sediment dynamics.

A major finding of the work conducted on the lower reach of the Trinity is that of basin decoupling. Phillips et al. (2004) and Phillips and Slattery (2006) both showed that the lowermost river segments are essentially decoupled from the upper basin in the sense that very little upper-basin sediment reaches the lower river, independent of the dam. These lower reaches of the river, just downstream of the Romayor gaging station (see Figure 3), are dominated by responses to downstream forcing (sea level rise) that increase sinuosity, reduce channel slope, and result in extensive sediment storage and reduced conveyance capacity. This notion of basin decoupling was further confirmed by Wellmeyer et al. (2005) after analysis of historical air photos. These photos were studied for the purpose of determining rates of channel change and activity both before and after impoundment. The photographic analysis in the study concluded that the river seemed to be adjusting to the dam and other modern engineering impacts no differently than it accommodates other environmental changes and stresses through expected behaviors characteristic of alluvial rivers (Wellmeyer et al., 2005).

Channel decoupling is not just characteristic of the Trinity River. Decoupling has also been observed in other lower gradient coastal river systems including North Carolina, New Zealand, Australia, and Texas (Fryirs and Brierly, 1999; Phillips, 1991; Phillips et al., 2004; Phillips and Gomez, 2007). This means that changes in sediment delivery to the coast are associated with lower basin sediment dynamics and not, as is commonly inferred, through changes in sediment delivery from upper reaches of the basin. Overall, no work has been done on quantifying sediment delivery and storage within any reach of the middle Trinity River.

METHODOLOGY

Historical Flow Gage Data

Mean daily discharge data in cubic feet per second from 10 different gaging stations along the Trinity River and various tributaries was used for flow and sediment analysis (Table 1, see Figure 5). This data is available from the United States Geological Survey at http://waterdata.usgs.gov. Flow duration curves were then created and analyzed from the historic record.

Table 1: List of gaging stations

Gage	Location	Start Date	End Date	# of Observations
USGS 08063800	Bardwell	10/01/63	12/31/05	15433
USGS 08065350	Crockett	01/01/64	12/31/05	15341
USGS 08063100	Dawson	10/01/60	12/31/05	16528
USGS 08062800	Kemp	01/01/63	12/31/05	15706
USGS 08065000	Oakwood1 @ Trinity Rvr	10/01/23	12/31/05	30043
USGS 08065200	Oakwood2 @ Keechi Crk	05/01/64	12/31/05	15951
USGS 08064100	Rice	10/01/83	12/31/05	8128
USGS 08062500	Rosser	08/01/24	12/31/05	29738
USGS 08064700	Streetman	04/01/68	12/31/05	13789
USGS 08062700	Trinidad	10/01/64	12/31/05	15067

Flow duration curves compare the frequency and magnitude of flow events for a single point along a channel. Creating a flow duration curve, or discharge exceedence frequency distribution, is a very helpful technique for determining the temporal variability in a discharge record. This has a substantial bearing on sediment flux as well as channel and floodplain development. Ultimately, these curves relate any mean daily discharge value to the percentage of time that it is equaled or exceeded. This means that, from any station, the lowest discharge value will be equaled or exceeded 100 percent of the time. On the other hand, the largest flow will be equaled or exceeded only once out of the entire number of days in the sample. The percentage value it is given is slightly greater than zero.

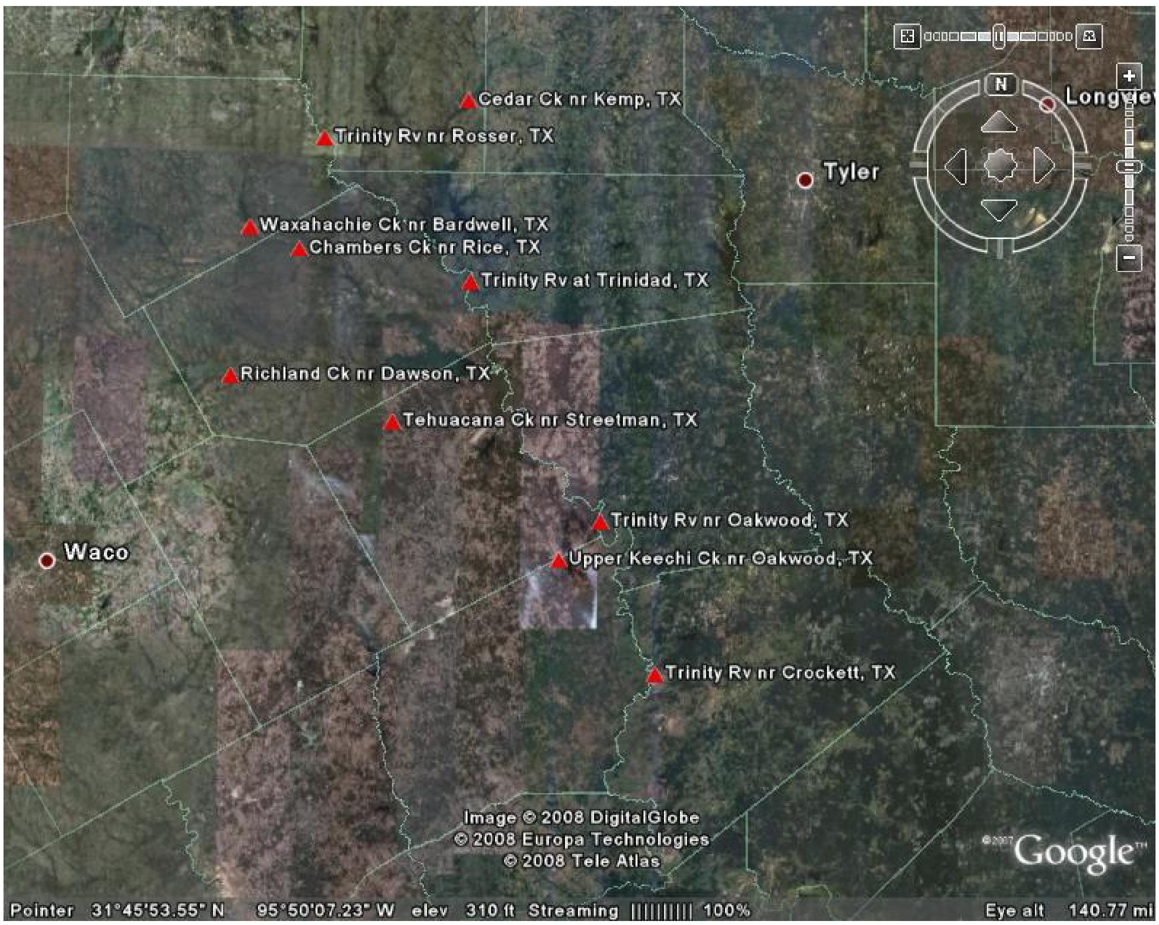

Figure 5: Overhead view of the gaging stations used in the flow duration analysis.

In this study, the Weibull plotting method was performed on the dataset (Sugiyama, 2003). This is a common way of plotting discharge data against exceedence probability. The first step in constructing the flow duration curve is to rank average daily discharges. This was done for the period of record from the largest value to the smallest value resulting in a total of *n* values. Next, each discharge value is given a rank (M), starting with 1 for the largest daily discharge value. After ranking the average daily discharges the exceedence probability (P) is calculated by:

$$P = 100 * [M / (n + 1)]$$

The mean daily discharge on the y-axis was plotted against the exceedence percentage as a scatter plot. The mean daily discharge on the y-axis was then logged.

Flow duration curves characterize the ability of the basin to provide flows of differing magnitudes. The shape of the flow duration curve is indicative of the flow regime at that point in the watershed. This is particularly true for the lower and higher magnitude flows. The high-flow region of the curve shows what type of flood regime the basin is likely to have. On the other hand, the low-flow region of the curve characterizes the ability of the basin to sustain low flows during the dry season.

Historical Sediment Gage Data

Sediment data is extremely sparse along the Trinity River, with only two USGS gaging stations having long-term suspended sediment information: Crockett (08065350) and Oakwood (08065000). At Romayor (08066500), 52 km below Lake Livingston, the historic sediment record goes back to 1934 and has been updated by contemporary turbidity readings at the gage (Phillips et al., 2004). At Crockett and Oakwood, however, the data are derived from depth-integrated samples collected by the USGS, a record that was stopped in 1981. Despite the paucity of data along the Trinity, the Crockett and

Oakwood record does allow in-stream sediment transport and yields to be computed for that section of the Trinity River.

The suspended sediment concentration, expressed in Mg per day, was plotted against discharge and a power function trendline fitted to the dataset. The equation of the trendline was then used to calculate the mean tons/year sediment yield. Mean daily discharge (Q) from the flow duration dataset of progressively higher increments, from 0.02 to 99.8% exceedence frequency, were inserted into the trendline equation for suspended sediment concentration. This resulted in instantaneous sediment discharge (Q_S), expressed in tons/day, for each discharge value. In order to arrive at mean tons/day, the Q_S is multiplied by the change in time increment (Δt) and divided by 100:

$$(Q_S * \Delta t) / 100 = \text{mean sediment Q for time increment}$$

For each time increment, mean sediment discharges are added to arrive at the mean annual tons of sediment traveling through the gaging station on an annual basis.

The Trinity River gaging station at Oakwood had to be handled differently. When the flow rate approached approximately 15,000 cfs, there was a noted decrease in sediment production and, therefore, a different line equation had to be generated. The data was calculated using one equation for flow that exceeded 15,000 cfs and a second equation for flow rates less than 15,000 cfs. These were than added together to result in a true representation of the suspended sediment moving past the Oakwood gaging station.

The sediment rating curves described above do not take into account bed load transport. Phillips et al. (2004) noted that bed load usually accounts for less than 10% of a river's sediment load. In this study, conducted in the lower reach of the Trinity below Lake Livingston, bed load represented 1.4% to 21.4% of total sediment load, with a mean of 9.7%. Although sediment budgets constructed using only suspended sediment measurements may significantly underestimate sediment flux, this appears to be less of a problem in the Trinity, where bed load is a relatively small component of the overall load.

GIS Analysis

GIS-based methods were used in an attempt to quantify sediment stored along the main channel of the Trinity River. Vertical DOQQ's (digital orthoquads) of the Trinity River channel were digitized in order to compute area of sand bars. ArcView GIS v9.2 was the program utilized for this study. This program incorporates multiple layers of data into one combined view that easily enables the display and presentation of data in map view. Digital orthoquads were downloaded from TNRIS (Texas Natural Resource Information System) at http://www.tnris.state.tx.us. The pictures chosen were high resolution, 1 square meter pixel resolution, for more accurate digitization and taken in 2004 (see Figure 6). All computed areas were then summed to give an estimation of total visible sand bar area along the Trinity River.

Figure 6: Example of digitized sand bar along the Trinity River.

The next step in the analysis of sediment storage was to compute average sand bar thickness. This is clearly a difficult task as deposition along an alluvial channel is highly variable, both in time and space, and sedimentary “packages”, in the form of bars and overbank deposits, are mobile and continually being re-worked. Measurements taken in the field with soil augers (see discussion below) suggested that sediment thickness varied between one and four feet, on average, and these measurements were then used as lower and upper bounds to the storage calculations. The resulting volume is then used to estimate the overall storage within the channel. This storage volume does not include bed load or sediment entrained in the water column.

GIS digitization was also attempted through aerial photography taken during low-level flights along the main channel. A private plane was chartered and flown at an altitude of 1,500 feet. The flight path was from Rosser to south of Trinidad (see Figure 5). The objective was to obtain photographs that were as vertical as possible but that gave good spatial coverage of depositional features. These photographs were taken with a digital camera and the coordinates of each picture were noted. The pictures were compared in Google Earth to the segment of the river in the vicinity of the coordinates to verify location.

Once the exact locations of the pictures were obtained they were imported into ArcView. The same Digital orthoquads in high resolution from TNRIS were used. The photos were georeferenced using roads and bridges as suitable control points. The images were then warped via quadratic rectification and finally projected as individual GeoTiff image files.

Field Measurements

Detailed field measurements were taken at two sites in order to determine the general depth of lateral bar deposits and bank storage. The sites were chosen due to their proximity to roads across the Trinity River, accessibility, and overall "representativeness" of deposits along the middle reach. A standard 18 mm diameter hand-held soil auger was used with the intention of measuring the depth from the top of the sand bar to the transition from channel sediment to fine-grained clay. The first site (Site A, Figure 7) was 90 meters north of highway 287 near Cayuga, TX on the west bank of the channel. The bar was approximately 57 meters long and 12 meters wide at the most. At Site A, transects were spaced 12 meters apart and cores were taken every 2 meters. The second site (Site B, Figure 8) was north of highway 79 near Long Lake, TX on the west bank of the channel. The bar was approximately 185 meters long and 21 meters wide at the most. At Site B, transects were spaced approximately 30 meters apart and cores were taken every 3 meters because of its size. It should be noted that this measurement strategy underestimates sand bar volume because the cores were taken up to the waters edge, which disregards sediment deposited under the water level.

Figure 7: Overhead view of Site A.

Figure 8: Overhead view of Site B.

After field measurements were completed the volume of each sand bar was calculated. The sand bar was broken up into rectangular solids and two different formulas were used. These different formulas were used because transects for the two sites were spaced at differing intervals. For Site A:

$$V = 5\,(a + b + c + d)$$

For Site B:

$$V = {}^{15}/_{2}\,(a + b + c + d)$$

where a, b, c and d are the four depths at the corners of the area. All of these volumes were added up to result in the total volume of the individual sand bars. After the volume was calculated, the overall mass was calculated by multiplying the volume with the bulk density of the sediment. For the purposes of this preliminary study, a bulk density of 1.4 $Mg\ m^{-3}$ was assumed following Phillips et al. (2004).

RESULTS AND DISCUSSION

Historical Flow Gage Data

The flow duration curves for gaging stations along the Trinity River and key tributaries are shown in Figure 9. From these data it is clear that the tributaries are relatively minor contributors to the flow in the main channel. The gages on the main channel of the Trinity (Rosser, Trinidad, Oakwood, and Crockett, see Figure 5) have flow rates that are, generally, orders of magnitude greater than the tributaries (Table 2).

Table 2: Flow rates for five exceedence probabilities at study gaging stations (cfs)

Exceedence	Oakwood2	Bardwell	Dawson	Streetman	Kemp	Rice	Rosser	Trinidad	Oakwood1	Crockett
0.01	1200	1320	1830	2250	2490	6470	26200	34000	44200	40800
0.04	425	746	1310	504	1030	2250	14200	19900	23800	26400
0.1	143	338	678	76	270	1190	8710	12300	14900	18800
0.5	13	1.6	3.3	2.6	9.1	60	975	1330	1530	2340
0.95	0.12	0.02	0.08	0.03	0.07	0.17	148	449	176	620

The Oakwood gaging station on the Trinity (Oakwood1) has higher flows than Crockett approximately 100 km downstream, specifically for the 100 year flood. This anomaly can be explained by the fact that the Oakwood1 gaging station has been operational since 1943 while the Crockett gaging station has only been operational since 1964. The 1940s happened to be the wettest decade for the Trinity River basin since flow gaging began in 1904. The high magnitude flows observed at the Oakwood1 gaging station consisted mostly of readings from the 1940s. This, in turn, raises the exceedence values above those of Crockett where the wet decade of the 1940s is not incorporated into the hydrologic record. Moreover, according to Dr. Richard Browning of the Trinity

River Authority, there was 1.25 million acre feet of flood storage in service by 1965 that did not exist in the 1940s (personal communication, March 17, 2008). That being said, flow rates along the Trinity River and its tributaries are typical of low-gradient, coastal plain rivers heading toward the coast in a sub-humid environment.

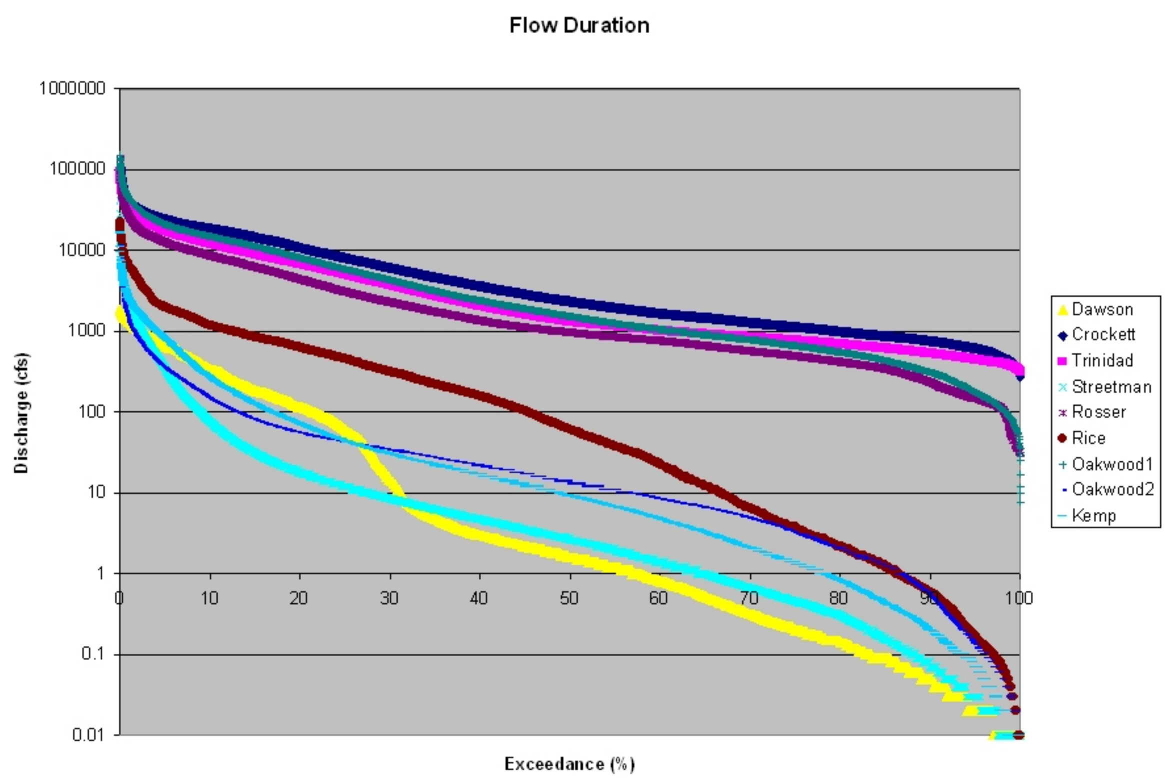

Figure 9: Flow duration curves of gaging stations.

Historical Sediment Gage Data

The suspended sediment rating curves for the Oakwood and Crockett stations along the Trinity River are shown in Figures 10 and 11 (the flow duration curves used to construct the sediment-discharge relationships are those shown in Figure 9, above). The computed sediment yields for each discharge interval at each station are given in Appendix B.

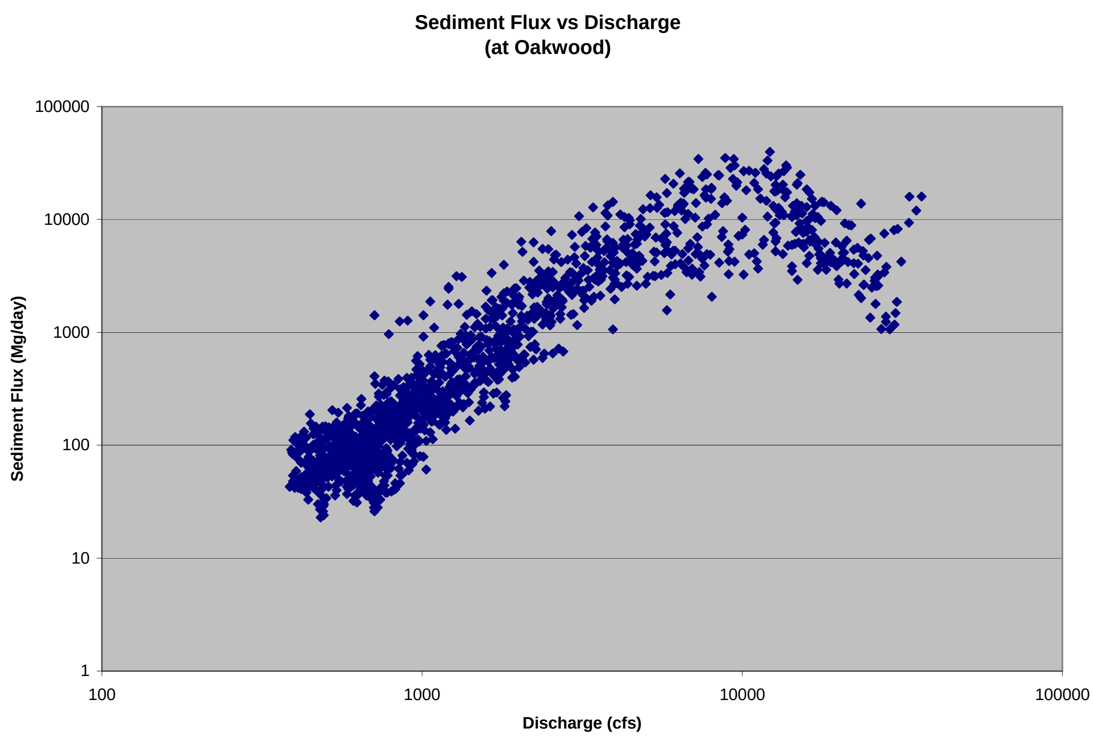

Figure 10: Sediment rating curve at Oakwood.

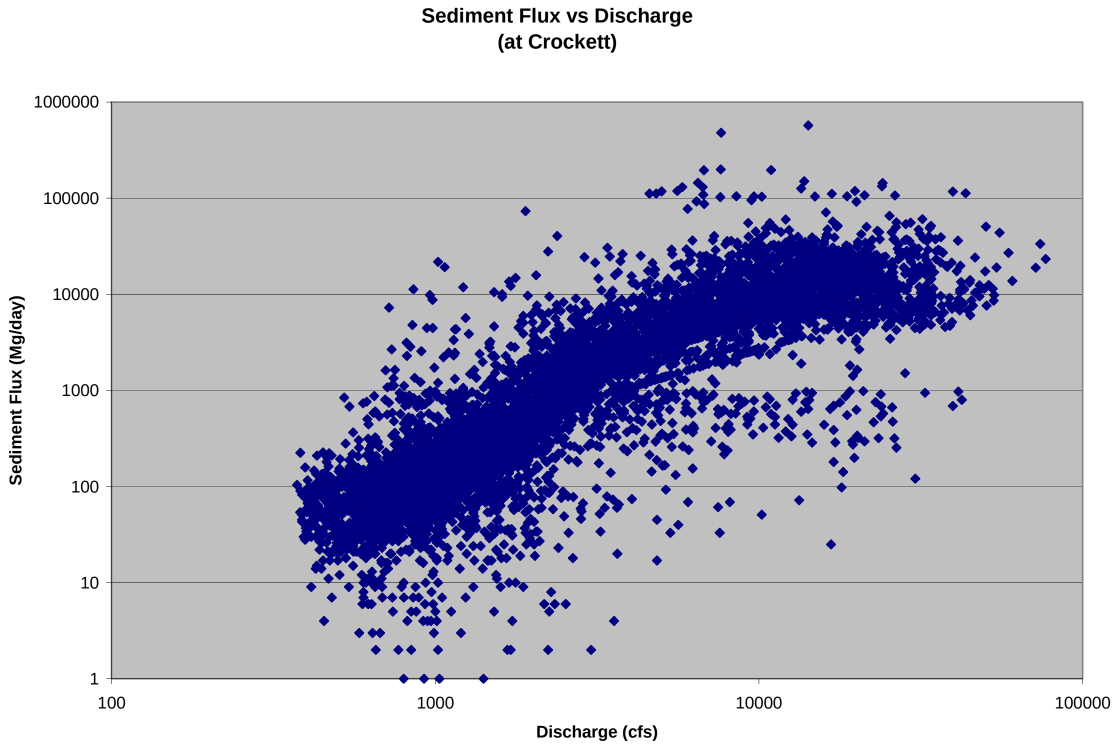

Figure 11: Sediment rating curve for Crockett.

Sediment yield at Oakwood was computed at *c.* 4,000 Mg day^{-1}, or *c.* 1,500,000 Mg $year^{-1}$. When discharge is below 15,000 cfs, sediment concentrations are directly proportional to the flow. Above 15,000 cfs, however, the sediment-discharge relationship reverses, with sediment concentration decreasing in the channel with increasing flow. This sediment transport/discharge anomaly is most likely the result of overbank flooding at these flows. At the Oakwood gaging station, bankfull discharge occurs at a stage of 35 feet, or approximately 18,000 cfs. At these discharge values, flow in the main channel breaks its banks and the stage-discharge relationship breaks down. In effect, the river becomes a transport-limited system (Figures 12 and 13), with sediment becoming sequestered in the floodplain at increasingly higher flows.

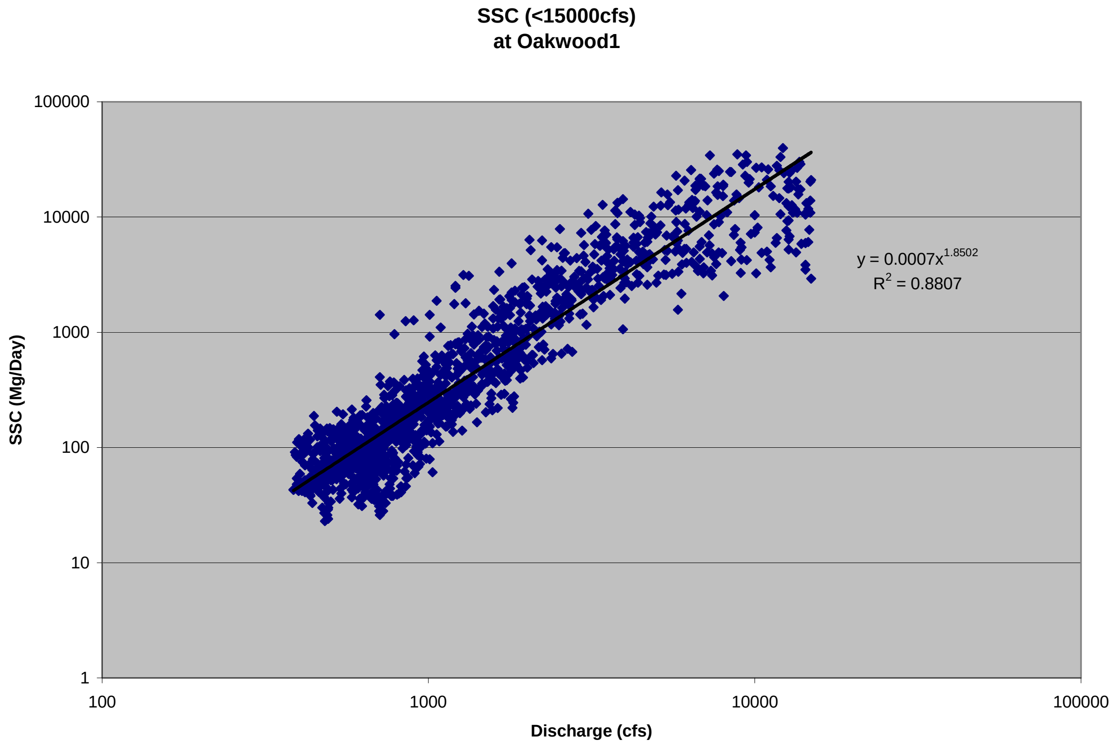

Figure 12: Suspended sediment concentration at Oakwood1 below 15,000 cfs.

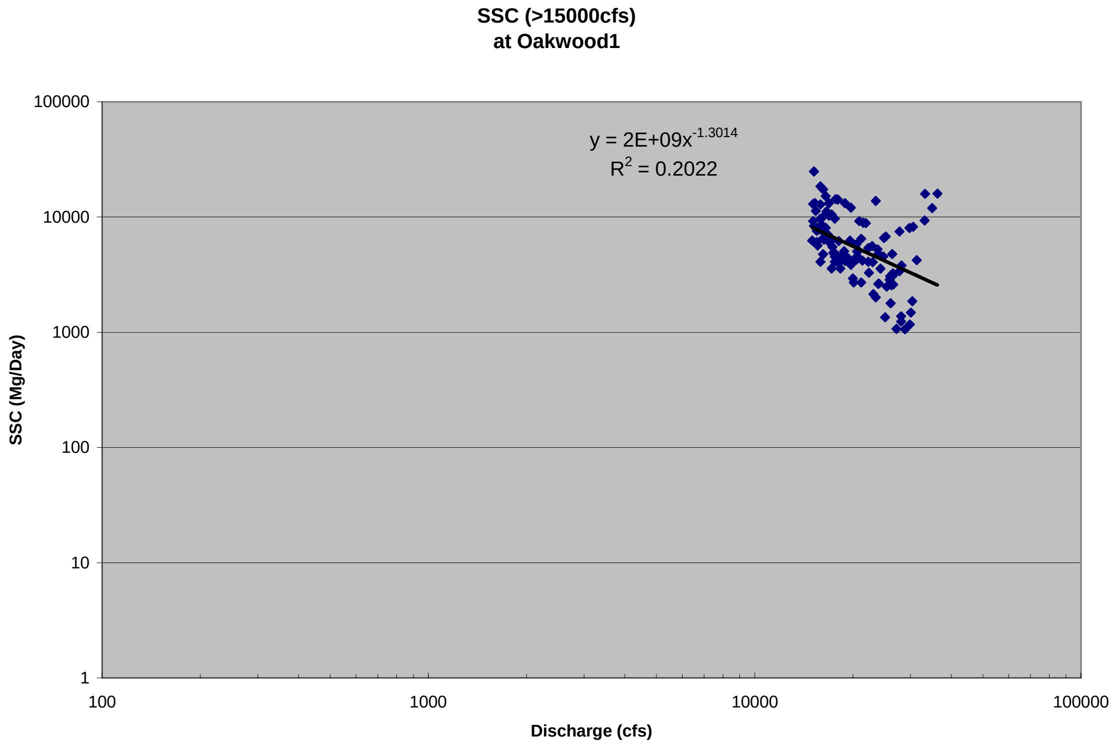

Figure 13: Suspended sediment concentration at Oakwood1 above 15,000 cfs.

At the Crockett gaging station the sediment flux-discharge relationship is proportional, with sediment transport increasing with flow. Mean daily sediment discharge was computed at 5,000 Mg day^{-1} or 1,900,000 Mg year^{-1}. This increase downstream suggests that the area between the Oakwood and Crockett gaging stations is acting as a sediment source. The difference in the sediment yield between the two gaging stations shows a net surplus of 1,000 Mg day^{-1} or 400,000 Mg year^{-1} at the downstream reach.

The sediment rating curves for Oakwood and Crockett were fitted with hysteresis loops (see Figures 14 and 15). Hysteresis loops show the phase relationship between sediment transport and discharge at the gaging station. In general, the hysteresis loops showed are clockwise, or positive, in direction. This is common for most rivers and indicates a depletion of sediment through time, either on a storm-by-storm basis or between storm events, as happens on the Trinity. Positive hysteresis is also indicative of sources proximal to the stream channel, such as in-stream bar deposits and sediment stored along the channel banks. Counterclockwise hysteresis loops occur much less frequently and happen when the sediment source is much more distant or, for example, when a valley slope forms the most important source.

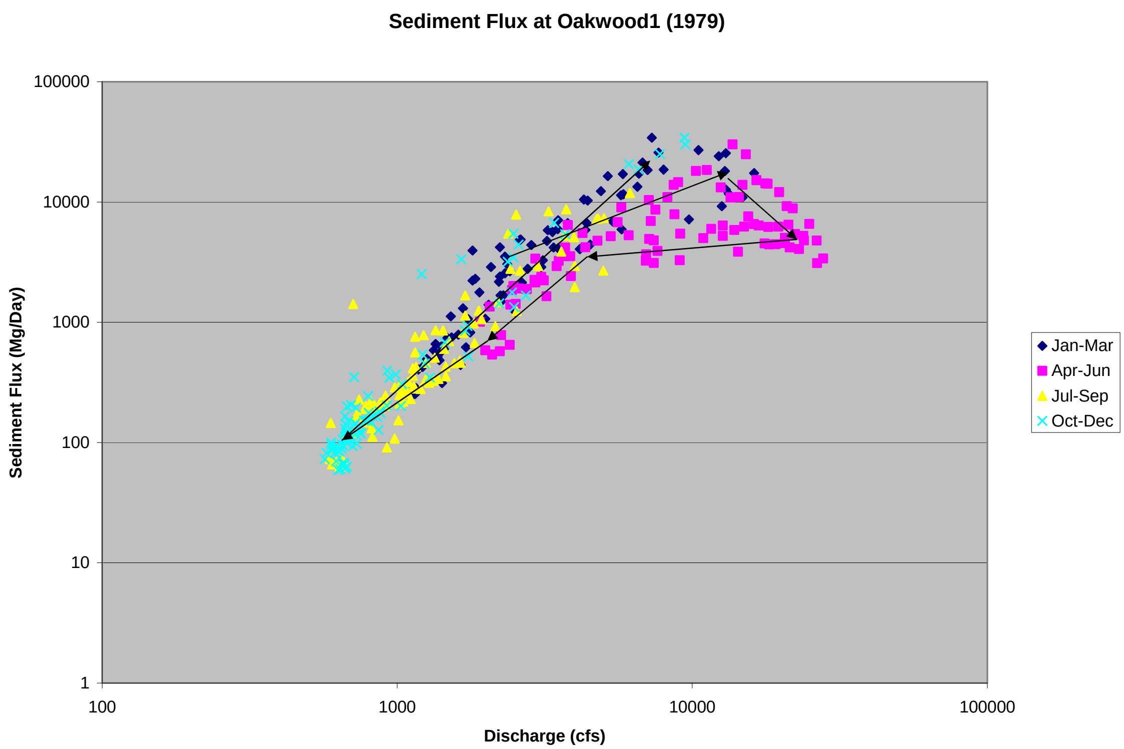

Figure 14: Hysteresis loop at Oakwood1.

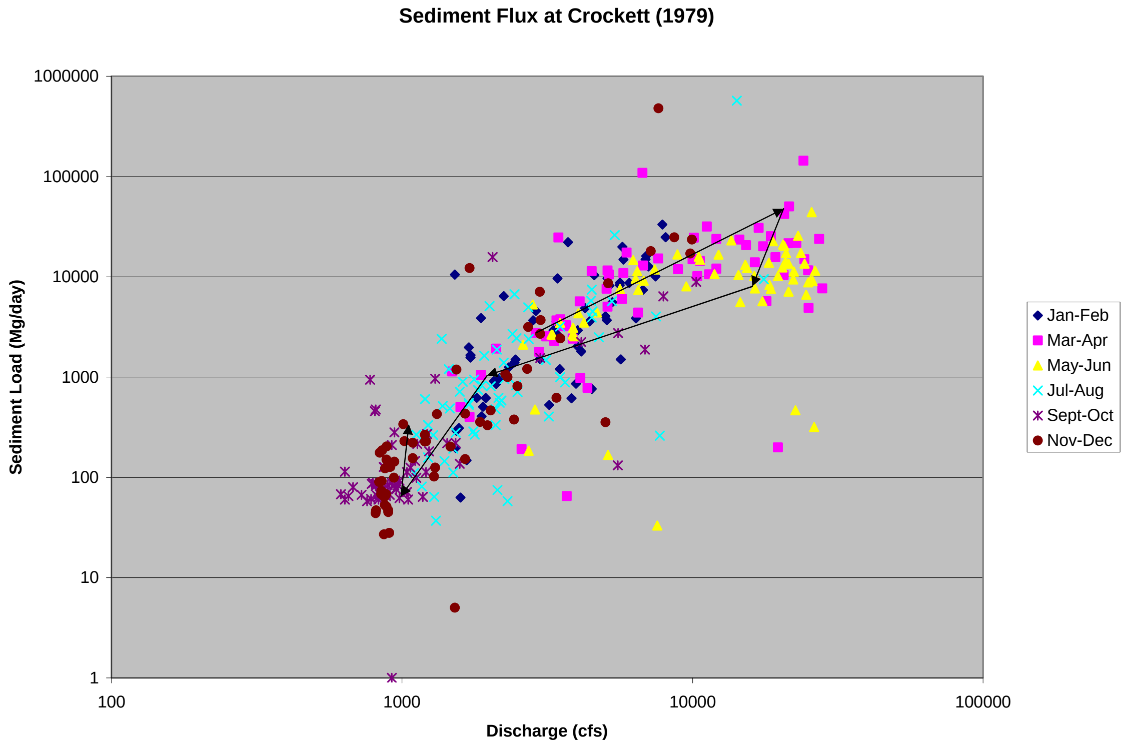

Figure 15: Hysteresis loop at Crockett.

The nature of sediment production and delivery in this reach of the Trinity is complex. Mean annual sediment yields at Oakwood and Crockett were computed at 45 t km^{-2} $year^{-1}$ and 53 t km^{-2} $year^{-1}$, respectively. Although there are no tributary sediment data between Oakwood and Crockett, previous work on tributary loadings in the lower Trinity and middle and upper Brazos (Slattery, 2007) show average sediment loadings of 145 t km^{-2} $year^{-1}$ (σ = 238 t km^{-2} $year^{-1}$). It should be emphasized that this is *estimated* sediment delivery because, as Slattery (2007) notes, the historic record on these streams is relatively short and does not cover the full range of flow conditions. The specific sediment yield data reported are, therefore, broad estimates of sediment transport to the main channel rather than precise calculations.

Independent estimates of sediment delivery to coastal plain streams in Texas were made from reservoir surveys conducted by the Texas Water Development Board (Phillips et al., 2004). These authors documented changes in reservoir capacity, which are assumed to be the result of sedimentation. Dividing the capacity change by the number of years between surveys gave a volume of sediment accumulation per year. This was further adjusted for drainage areas to produce a virtual rate in $m^3 km^{-2} year^{-1}$. Data were averaged for 27 lakes in east and central Texas, in the same land resource areas as those encompassing the middle Trinity. The lake surveys indicated sediment yields of 6 to 1002 $t\ km^{-2} year^{-1}$, (assuming an average bulk density of 1.0 $Mg\ m^{-3}$), with a mean of 315 $t\ km^{-2} year^{-1}$ (σ = 331 $t\ km^{-2} year^{-1}$, Appendix A). These tributary and lake data provide an important context for the present study. As noted above, approximately 400,000 tons of sediment is being sourced between Oakwood and Crockett. Using both the tributary and lake loading estimates from Phillips et al. (2004) gives a minimum and maximum local input and, by extension, a lower and upper estimate for maximum storage within the reach. This estimate of maximum storage for the reach is based on upstream input plus sediment produced in the drainage area between the upstream and downstream ends of the reach (estimated at 145 $t\ km^{-2} year^{-1}$ using tributary loadings and 315 $t\ km^{-2} year^{-1}$ using lake loadings), minus downstream output. The data show that, based on minimum local input, this reach of the Trinity is essentially a throughput reach, with negligible storage. However, the lake loading data suggest that approximately half of the sediment potentially delivered to the Trinity between Oakwood and Crockett goes into storage (*c*. 480,000 tons; see Appendix A).

It is difficult to know, at this scale, the precise source of the sediment transported along this reach of the Trinity. In a recent study, sediment production rates in sub-basins of the Trinity watershed were calculated by Muttiah (2007) by incorporating National Resources Inventory (NRI) erosion rates into a GIS. The NRI provides nationally consistent statistical data on erosion resulting from water (sheet and rill) on cropland for the period 1982 to 1997. Erosion rates computed from NRI data are estimates of average annual (or expected) rates based upon long-term climate data, inherent soil and site characteristics, and cropping and management practices. These estimates come from USLE-based factors that are determined for the portion of the field associated with an NRI sample site that is under cropland, pastureland, or land enrolled in the Conservation Reserve Program. Muttiah (2007) used 1997 USLE-based soil loss estimates by broad land use (cultivated, uncultivated land, pasture land) made from several thousand NRI observations in 21 counties in the middle Trinity basin. Land cover/use was determined for each 12-digit HCU (Hydrologic Cataloging Unit) in the middle Trinity using the USGS National Land Cover Dataset (NLCD) for 1992 incorporated into the GIS. The USLE soil loss (land cover/use by county) estimates were then incorporated into the GIS dataset to determine soil loss by 12-digit HCU (see Figures 16 and 17). Interestingly, the USLE-based estimates of the sediment delivery using the NRI suggest sediment yields of 55 to 485 t km^{-2} $year^{-1}$, with a mean of 197 t km^{-2} $year^{-1}$. Highest yields occur in sub-basins draining into Richland Chambers Creek Reservoir. However, the majority of sub-basins adjacent to the Trinity indicate yields of between 145 and 220 t km^{-2} $year^{-1}$. Based on these data, sediment loading within the Trinity basin is estimated at 200 t km^{-2} $year^{-1}$, remarkably in line with the tributary and lake survey data. These data show sediment storage to be on the order of 160,000 tons $year^{-1}$.

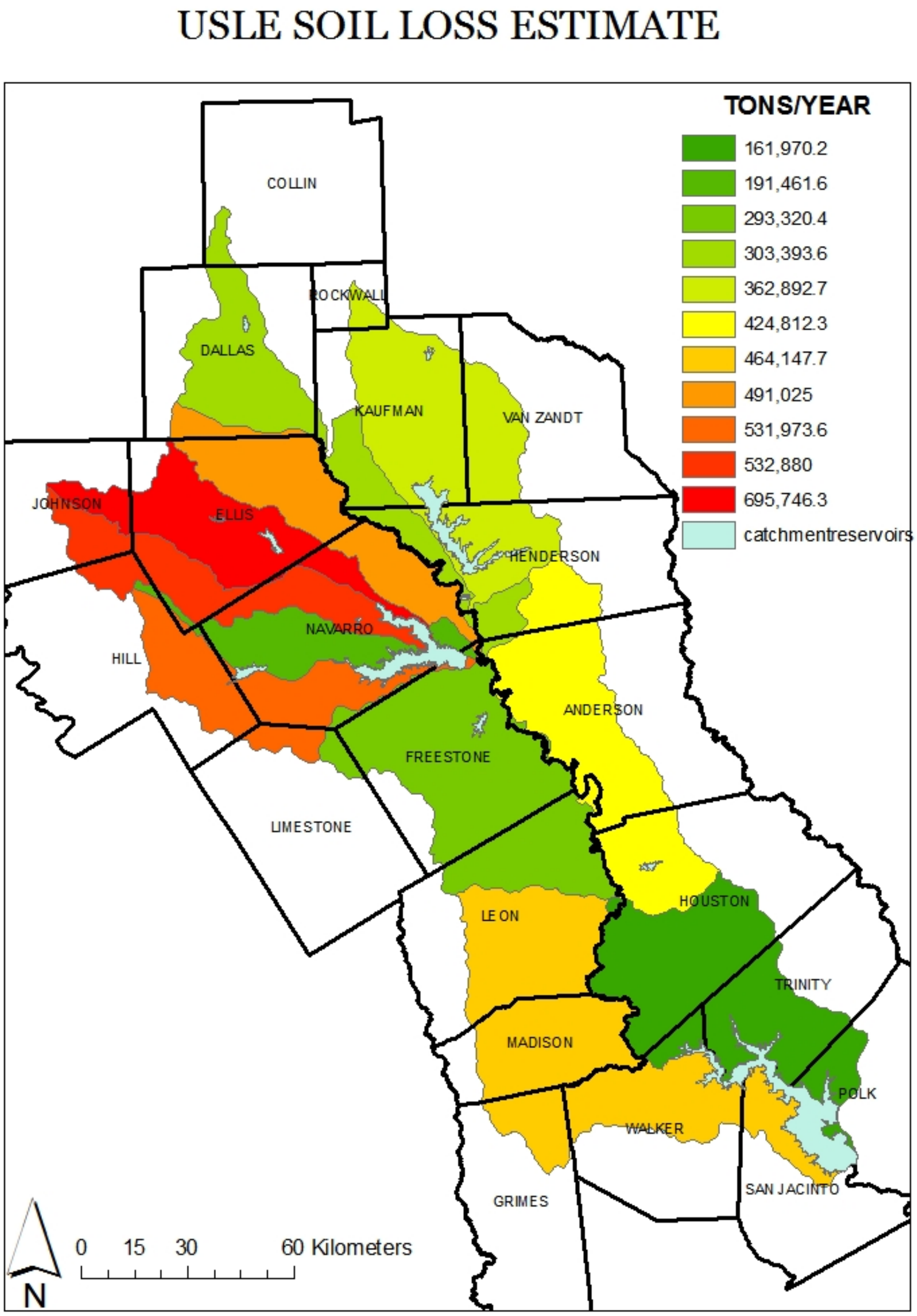

Figure 16: USLE soil loss estimate based on GIS analysis in tons per year.

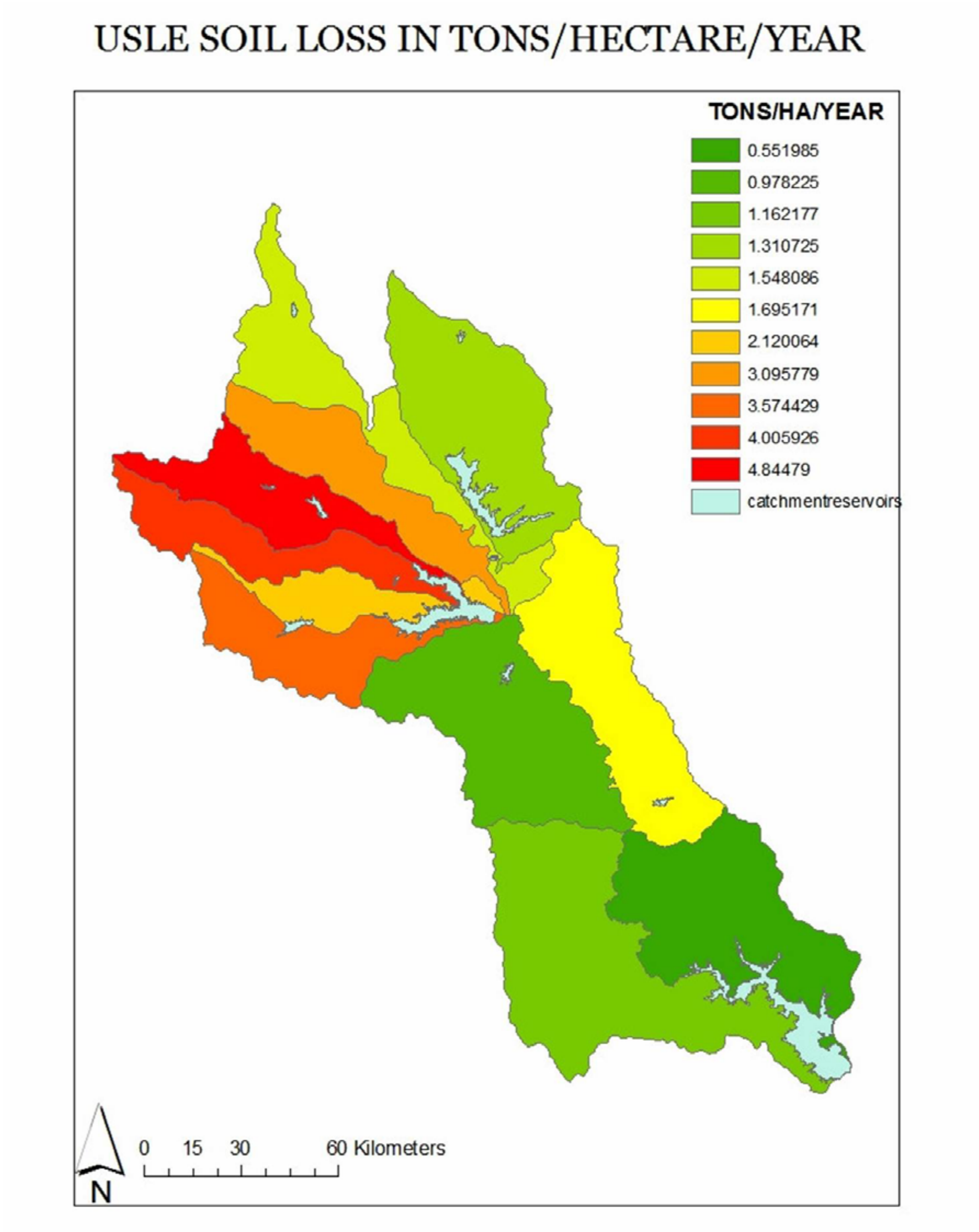

Figure 17: USLE soil loss estimate based on GIS analysis in tons per hectare per year.

The analysis and discussion above suggests that there is potentially enough sediment delivered from the sub-basins to the main channel to account for the *c*. 400,000 tons of material being transported past the Crockett station. However, the Trinity is an active river and has been throughout the Holocene. Lateral migration of the channel across the floodplain undoubtedly provides additional sediment to the overall sediment load. In a previous study, by Wellmeyer et al. (2005) mainstem bank erosion rates were computed along a 75 km length of the lower Trinity River between Romayor and Liberty. Using digitized aerial photography, this work established that there is significant channel movement along the Trinity River and that contributions from channel erosion are significant, even dominant. For the lower Trinity, rates of floodplain erosion ranged between 10.7 and 42.0 ha $year^{-1}$, with mean annual channel erosion calculated at 30.2 ha $year^{-1}$. Using an average channel depth of 7 m and a mean bulk density of 1.4 Mg m^{-3} yielded a possible 2.96 x 10^6 Mg of sediment per year, equivalent to 87.6% of the annual sediment load measured at Romayor. If channel migration in the middle reach upstream of Lake Livingston is similar in magnitude to that below the dam, and there is no reason to believe it wouldn't be, then channel erosion could supply approximately 39,500 tons of sediment per linear kilometer of stream channel. This most likely is a high estimate, but illustrates the potential of channel banks to supply sediment independently of surface erosion and delivery within the basin.

There are two different ways sediment is potentially being supplied to the main channel of the Trinity. The first is sediment being provided by erosion within the sub-basins. This is evident in the tributary study, the lake survey data, and the GIS analysis. The second is the potential for sediment to be provided by lateral migration of the main channel itself. It cannot be confirmed at this stage which source(s) dominate, but it is likely a combination of the two in this particular reach. Further study is needed that is focused on sediment sourcing from the sub-basins.

The primary challenge this study faced when analyzing the historical sediment data in the Trinity River was the overall lack of suspended sediment concentration data. Along the 275 km stretch of the river that was studied, including its tributaries, there were only two gaging stations that had historic sediment data. These two gaging stations were only 70 kilometers apart. This presents a problem when analyzing the sediment data and increases the margin of error of the results. Augmenting the historic record with either manual measurements or the use of turbidity probes (as has been done on the lower Trinity in previous work; see Slattery, 2007) is possible, though doing so increases the time (and cost) required to construct the sediment budget. Notwithstanding, future work involving suspended sediment along the Trinity River (or other Texas rivers, for that matter) would need to include more gaging stations.

GIS ANALYSIS

Figure 18 shows the length of the Trinity and areas where sand bars were digitized. Analysis of the digitized sand bars along the main channel of the Trinity River yielded a total sand bar area of *c.* 120,000 m^2. This total is from 180 sand bars along the Trinity River from Rosser to Crockett. Depth of the sand bars was found to range between 1 and 4 feet based on field augering. This gives a total volume of between *c.* 52,000 m^3 and *c.* 145,400 m^3. Assuming a bulk density of 1.4 Mg m^{-3}, the resulting sand bar storage ranges between *c.* 72,000 Mg and *c.* 205,000 Mg.

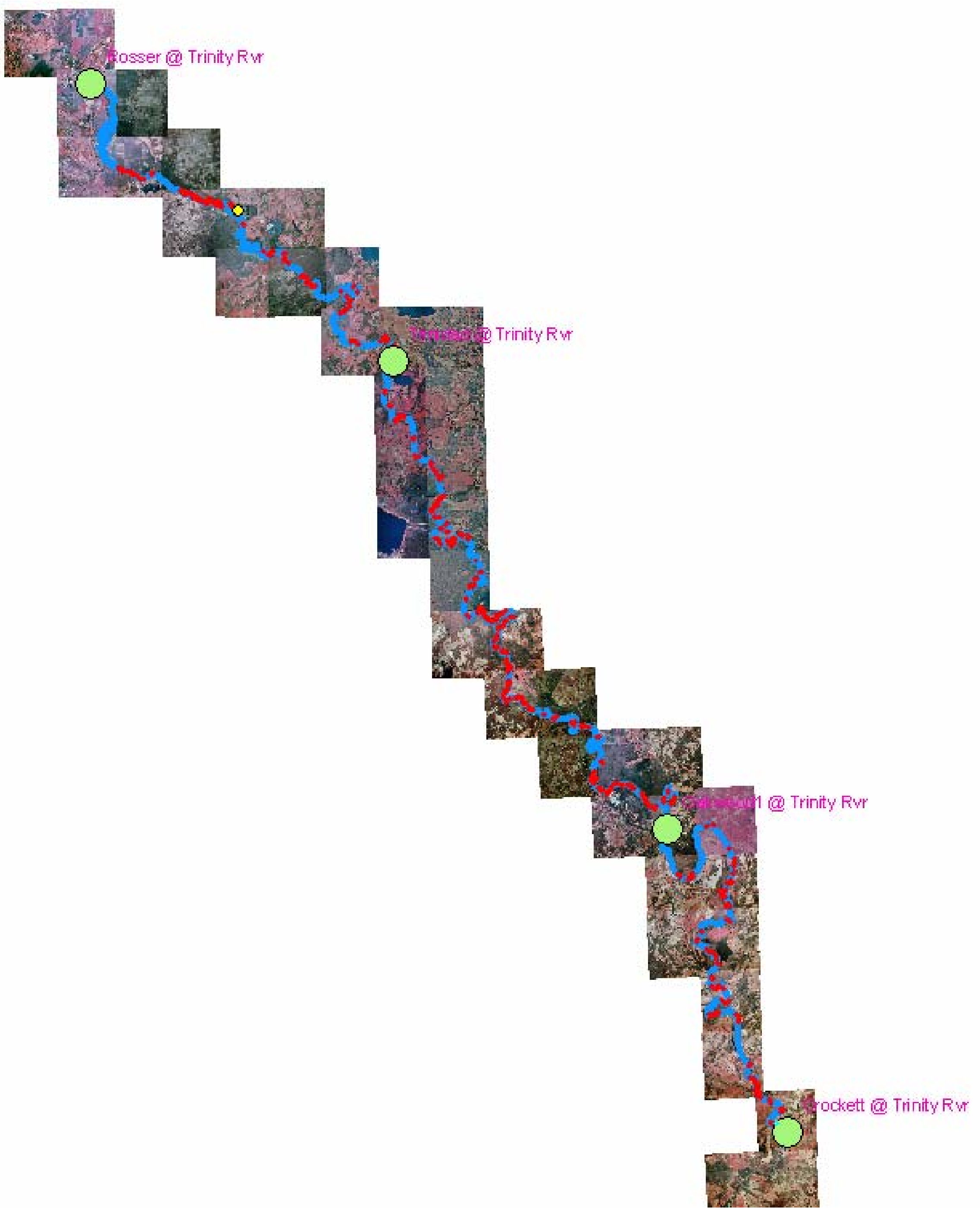

Figure 18: Overhead view of Trinity River in GIS with digitized sand bars in red.

GIS analysis of the bars in the channel visible from above is valuable in generating a rapid estimate of the storage in the Trinity River, but it does have drawbacks. The primary problem with GIS analysis of Orthoquad photos is the temporal variation between photos. This is problematic because discharge varies with time and flow in the channel and can be very different between the times photos have been taken. This undoubtedly affects storage numbers. The river can experience high flows and obscure the sand bars or flush a large amount of sediment out of the system during major storms. Another challenging issue with utilizing GIS for Orthoquad photo analysis is how much sediment up the tributaries to count towards sediment storage in the main channel. Some sediment deposits can start in a tributary and grow into the main channel. Additionally, sediment can be deposited on the side of the main channel where trees have begun to grow. Multiple trees in the channel reduces the velocity of the water and sediment drops out of the water column. This presents a particular problem with aerial photo analysis because it is difficult to ascertain where the bank is under the tree cover.

When analysis of aerial photos we was attempted, there were problems encountered that affected the ability to digitize the sand bars. The aerial photos were taken at an angle out of the airplane. This created two problems. First, the surrounding area provided an inadequate amount of control points in order to georeference the pictures. The majority of the pictures contained only the river channel and vegetation in the frame. When georeferencing of these pictures was attempted, the Orthoquad it was being georeferenced to could have been taken up to 4 years prior. The vegetation and channel geometry can vary greatly in that amount of time. Suitable ground control points such as bridges and roads rarely appeared in the photographs. The second challenge encountered was that the angle at which the pictures were taken altered the measurements of the sand bar. Even if there were suitable ground control points, if the picture was taken at too much of an angle, the sand bar would be warped to a degree that would not represent the total area in reality (Figure 19 and 20).

In order to use oblique aerial photographs, it would be helpful to mount a camera on the underside of the airplane. If that is beyond the resources available, it is recommended that just the Orthoquads available online are used for GIS analysis.

Figure 19: Aerial picture taken on private airplane flight.

Figure 20: Vertical picture of the same sand bar in Google Earth.

Field Measurements

The analysis of the bar deposit in the channel near Cayuga (Site A) resulted in a volume of 65.6 m^3. The storage of the entire bar was calculated as 91.8 Mg, again using a bulk density of 1.4 Mg m^{-3}. Analysis of the bar deposit along the channel bank near Palestine (Site B) resulted in a volume of 1,296 m^3. This produced sediment storage at that point of 1,815 Mg. Both sites are near bridge pads in the river and occur in a segment of the river with similar sinuosity. While it can be hypothesized that sediment storage is increasing down river, this data is merely anecdotal and is not statistically significant.

The difficulty with utilizing this type of technique when assembling a sediment budget is a matter of temporal variation in sediment dynamics and river access.

Temporal variation is an issue because of the changes in instantaneous sediment storage that can occur in the river between flow events. The abundance of privately owned land throughout the middle Trinity River makes it exceedingly difficult to conduct a proper field evaluation of the bar deposits along the channel. Furthermore, only five suitable crossover points exist along this stretch of the Trinity, all between 25 and 90 kilometers apart. There are even fewer crossover points fitting for field study due to a lack of substantive bar deposits along the channel. This makes gathering a statistically significant dataset challenging. These challenges notwithstanding, some estimate of storage along the length of the channel can be made with certain assumptions. First, if this channel bank material along the 180 meters is representative of deposition and storage patterns along the entire length of the channel, then we can estimate that *c.* 10.1 Mg of sediment per meter of channel length is stored along the reach. If we then assume that deposition and erosion alternates along the reach, as fluvial theory suggests, then *c.* 707,000 Mg of sediment is in storage along the 70 river kilometers between Oakwood and Crockett. This probably represents a high estimate of sediment storage, but does illustrate the point that considerable material along the conveyance route is in storage at any given time.

CONCLUSIONS AND RECOMMENDATIONS

This thesis had the primary objective of evaluating several methods for estimating sediment delivery and sediment storage along a reach of the middle Trinity River, Texas. In terms of in-stream sediment transport, the reach between two major gaging stations, namely Oakwood and Crockett, was found to be acting as a sediment source. Sediment yields calculated at Oakwood (*c.* 1,500,000 Mg $year^{-1}$) and Crockett (*c.* 1,900,000 Mg $year^{-1}$) resulted in *c.* 400,000 Mg $year^{-1}$ of sediment being sourced and delivered to the lower reaches of the Trinity River. Mean annual sediment yields at Oakwood and Crocket were computed at 45 t km^{-2} $year^{-1}$ and 53 t km^{-2} $year^{-1}$, respectively.

Sediment delivery *to* the Trinity River was estimated using three different methods in order to provide a range of possible sediment production values. Tributary data showed sediment delivery of 145 t km^{-2} $year^{-1}$, an estimate based on a relatively short historic record that does not include all flow scenarios and very few streams. Surveys of multiple lakes in the general area noted the change in reservoir capacity due to sediment input and estimated a mean sediment loading of 315 t km^{-2} $year^{-1}$. Finally, a GIS model was created using erosion rates and USLE-based factors to calculate sediment traveling to the Trinity River at 200 t km^{-2} $year^{-1}$. Using these methods, sediment storage *within* the Trinity reach was computed and ranged from essentially zero on an annual basis (using the tributary delivery rates) to *c.* 480,000 Mg per annum (based on lake loadings).

The analysis presented here suggests that there is easily enough sediment potentially delivered from the sub-basins to the main channel to account for the *c.*

400,000 Mg $year^{-1}$ of material being transported past the Crockett station. The question that arises is whether this reach is essentially a sediment through-flow system (i.e., no net storage over the longer term) or whether in fact the *c*. 480,000 Mg $year^{-1}$ is going into net storage and if so, where? This maximum storage number, based on lake loadings, does make sense in a broader context when sand bar storage is included. The digitized bars, when assuming a bulk density of 1.4 Mg m^{-3}, indicate in-stream storage of between *c*. 73,800 Mg and *c*. 205,000 Mg of material. The sediment deposited and draped along the channel banks suggests that *c*. 707,000 Mg could be in storage along the reach which would certainly be re-worked and re-mobilized on an event time frame.

In terms of quantifying sediment storage, the GIS based approach of digitizing sand bars is best used for calculating sand bar area, but should be used at lower flow rates in the interest of accuracy. In order to incorporate depth of the sand bar into the results, many field measurements are required. Given the significant variability encountered in thickness of sediment in sand bars and draped sediment along the channel, as many measurements as possible would be prudent. However, there is also a case of "diminishing returns" in this type of work, where errors may be reduced but only at the expense of time-consuming and costly measurements.

This type of sediment budgeting procedure can be useful for accounting for the sediment flux of many coastal plain rivers. People around the world who are affected by rivers can benefit from further study of sediment flux in rivers. Beaches and coastal waterways can be managed, not specifically at the end point in the delta, but further up the river that feeds the sediment into the delta. Engineering projects such as roads and bridges that have an impact on rivers can plan for the sediment flux that flows in the river rather than simply building around it. Sediment within rivers has been a part of fluvial systems that has been understudied within the context of the drainage basin. These methods of sediment budgeting, in addition to added sediment gaging stations for a larger databank to work with, can help us learn more about sediment transport within a fluvial system and in turn about future challenges our rivers face.

APPENDIX A

TRIBUTARY, NRI, AND LAKE SURVEY DATA

Middle and Lower Trinity	Area (km^2)	Upstream input	Minimum local input from tributary data	NRI local input	Maximum local input from lake survey data
Oakwood	33,237	1,500,000	404,843	558,404	879,486
Crockett	36,029	1,900,000			

Estimation of sediment input (tons $year^{-1}$).

Middle and Lower Trinity	Downstream output	Maximum Storage From tributary data	Maximum Storage from NRI data	Maximum Storage from lake survey data
Oakwood				
Crockett	1,900,000	4,843	158,404	479,486

Estimation of sediment storage (tons $year^{-1}$).

Middle and Lower Trinity	Area (km^2)	Upstream input	Specific Yield
Oakwood	33,237	1,500,000	45
Crockett	36,029	1,900,000	53

Estimation of sediment storage (tons km^2 $year^{-1}$).

APPENDIX B

SEDIMENT YIELD DATA

lower bound of % time increment	Time in increment (delta %)	Median of time increment (%)	**Mean daily Q (cfs)**	Instantaneous QS (tons/day)	Mean sediment Q for time increment
0.02	0.02	0.01	**109000.00**	249777.2	50.0
0.1	0.08	0.06	**97283.33**	209076.3	167.3
0.2	0.1	0.15	**72833.33**	132948.8	132.9
0.5	0.3	0.35	**56241.30**	88731.0	266.2
1	0.5	0.75	**44253.25**	60986.9	304.9
2	1	1.5	**36824.18**	45751.2	457.5
3	1	2.5	**31141.56**	35200.4	352.0
5	2	4	**26594.79**	27500.3	550.0
9	4	7	**21719.25**	20034.2	801.4
15	6	12	**17154.07**	13851.2	831.1
25	10	20	**11093.17**	7004.6	700.5
35	10	30	**6212.32**	2828.4	282.8
45	10	40	**3673.06**	1243.3	124.3
55	10	50	**2363.29**	623.8	62.4
65	10	60	**1685.59**	367.7	36.8
75	10	70	**1296.85**	244.0	24.4
85	10	80	**1000.86**	162.7	16.3
95	10	90	**757.53**	105.2	10.5
99	4	97	**533.23**	60.8	2.4
99.8	0.8	99.4	**379.16**	35.6	0.3
	99.8				

5173.9 Mean tons/day
1888491 Mean tons/year

Sediment yield data at Crockett gaging station.

lower bound of % time increment	Time in increment (delta %)	Median of time increment (%)	**Mean daily Q (cfs)**	Instantaneous QS (tons/day)	Mean sediment Q for time increment	
0.02	0.02	0.01	**138166.67**	408.6	0.1	Oakwood rating 1
0.1	0.08	0.06	**99991.67**	622.4	0.5	
0.2	0.1	0.15	**80003.33**	832.0	0.8	
0.5	0.3	0.35	**62418.89**	1149.2	3.4	
1	0.5	0.75	**49470.67**	1555.3	7.8	
2	1	1.5	**37938.54**	2196.9	22.0	
3	1	2.5	**29633.33**	3030.1	30.3	
5	2	4	**23834.44**	4022.9	80.5	
9	4	7	**18110.73**	5751.1	230.0	
15	6	12	**13428.86**	30394.6	1823.7	Oakwood rating 2
25	10	20	**8278.12**	12418.1	1241.8	
35	10	30	**4384.90**	3832.2	383.2	
45	10	40	**2440.26**	1295.8	129.6	
55	10	50	**1544.79**	556.1	55.6	
65	10	60	**1064.98**	279.4	27.9	
75	10	70	**786.55**	159.5	16.0	
85	10	80	**554.36**	83.5	8.3	
95	10	90	**309.40**	28.4	2.8	
99	4	97	**131.81**	5.9	0.2	
99.8	0.8	99.4	**66.17**	1.6	0.0	
	99.8					
					4064.6	Mean tons/day
					1483591	Mean tons/year

Sediment yield at Oakwood1 gaging station.

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ABSTRACT

METHODS FOR SEDIMENT BUDGETING ALONG THE MIDDLE TRINITY RIVER

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Professor of Environmental Science and Chair of the Department

This thesis examines the procedures and relative merits of some of the methods available for sediment budgeting focusing on the middle Trinity River, Texas. These methods included analysis of historical sediment and flow gaging station data, GIS digitization of sand bars, and field measurement of sand bar storage. The gaging station data indicated the middle Trinity River acts as a sediment source for the lower reaches. To understand where this surplus of sediment is coming from, it was necessary to consider tributary loading data, GIS analysis of Natural Resource Inventory (NRI) erosion rates, and lake survey data. This information showed that sediment storage along the Trinity River is extensive. We infer that sediment in the middle Trinity River is most likely being sourced from the reworking of sediment as the river moves across the floodplain in addition to river channel itself.