QUANTIFYING INSTREAM SEDIMENT TRANSPORT IN SEVERAL REACHES OF THE UPPER BRAZOS RIVER BASIN, TEXAS

by

LISA LEEANN BLACK

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Midwestern State University
Wichita Falls, Texas

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INTRODUCTION

Rivers are considered the major source for ocean sediment, with coastal marine environments as the main sink for sediments carried by river waters. Deposition within these environments is often used as an indicator of erosion rates and sediment transport dynamics upstream. The assumption here is that changes in erosion and sediment transport within different drainage basins will be reflected in sediment delivery to the coast (Phillips *et al*., 2004). This may be and often is the case in steep-sloped or mountainous regions, but is not always a reliable assumption in coastal plain rivers. Overall sediment flux to the ocean from coastal plain rivers is often over-estimated due to poor or insufficient data in critical areas. It has also long been recognized that coastal plain rivers may deliver only a fraction of their sediment load to the coast, and that sediment gaging stations typically overestimate that load (Phillips *et al*., 2004). Even with these apparent difficulties, sediment gaging stations are still used to evaluate reservoir and dam impacts, as well as land modification by humans and their impact on sediment delivery.

Previous work on Texas coastal plain rivers, specifically the Brazos and Trinity rivers, has shown that there is a clear need to improve the record and resolution of in-stream sediment yield data in Texas Rivers. Improved data would provide the only reliable estimates of land-to-ocean sediment flux in large basins. Obtaining improved data can be accomplished in many ways, but should begin by understanding sediment transport dynamics within sub-basins of large rivers.

Sediment transport dynamics exert important controls on channel morphology and texture that affect habitat quantity and quality for aquatic and riparian species. Aquatic habitat

attributes such as spawning gravel availability and the amount of fine sediment in the channel bed are determined by size distribution and rate of sediment input and by the capacity of stream channels to store and transport sediment. Sediment transport and storage characteristics further control the average time required for sediment of various sizes to be routed through the channel network, influencing the sensitivity of channels to disturbances.

The Brazos River is the longest river in Texas, the one with the greatest discharge, and it is a powerful agent in sediment transport. The Brazos has the highest sediment load of any Texas river but appears to be one of the least studied when it comes to sediment transport. Most work to date has focused on the Lower Brazos River and its delta, with research and understanding of the river decreasing as you move toward the headwaters. The historic sediment record on the Brazos is very incomplete, and does not cover the full range of flow conditions. Because of this, any specific sediment yield data must be seen as broad estimates of sediment transport rather than precise calculations.

The purpose of this study is to develop a more detailed understanding of sediment transport within several reaches in the Upper Brazos River basin. This research is important because future geomorphic assessments of in-stream flow scenarios for river segments will be based on sediment budgets and related sediment studies.

LITERATURE REVIEW

The transport of sediment in most rivers is affected by multiple interdependent factors that include land-use changes in the basin, natural erosion processes along the main stem and tributaries, basin hydrology (particularly extreme events), water-resource development, and human activities in the main channel. River morphology and sediment transport change continually as a river adjusts in response in these and other factors (Dunn and Raines, 2001). A sediment budget is one method that can be used to understand the effects of these factors on sediment. A sediment budget is defined as "…an accounting of the sources and deposition of sediment as it travels from its point of origin to its eventual exit from the drainage basin" (Reid and Dunne 1996). Sediment budgets typically focus on and attempt to define the input of sediment to a geomorphic system, transfer mechanisms within that system, output, and additions to or losses of storage. It represents a mass balance most simply conceptualized as

$$I - \Delta S = O$$

where the output of sediment discharging from the watershed (O) is a result of the sediment input generated within the watershed (I) and changes in the sediment stored within the watershed (ΔS). Quantitatively, this becomes a statement of the rates of sediment production, transport, and discharge, focusing attention on four key elements: spatial patterns of production, storage, transfer, and rates of movement through storage (Dietrich *et al.* 1982).

Typically, sediment production and transfer are perceived to be dominant in upslope and headwater areas, storage and transfer predominate in the mid-basin reaches, and storage (deposition) dominates the lower reaches. This pattern is grossly oversimplified because

production, transport, and storage units occur repeatedly across large, multiple land use watersheds. For instance, sediment production from rills and gullies in the upper basin and headwaters may settle into mid-basin storage in fans, bars and other features without ever reaching the channel, while incision of the lower reaches may make the main channel the dominant source of sediment in the watershed. Consideration should also be given to the fact that sediment transport is highly episodic, large volumes of sediment may be mobilized during flood events, but equally large amounts may deposited in storage locations, to eventually be remobilized in later events. Therefore, extensive field monitoring, or field reconnaissance, is required to identify and quantify sediment transport and delivery processes within a given watershed.

Sediment budgets may be constructed to varying levels of detail, ranging from those that incorporate extensive field measurement of sediment supply, transport, and storage processes, frequently coupled with sediment routing modeling, to "rapid" (and often crude) sediment budgets that describe geomorphic processes using the best available information (Reid and Dunne, 1996). Generally speaking, sediment budgets are easier to construct in small basins. They are more responsive and also, all other things being equal, easier to work with. But the huge quantities of sediment and water transported and stored by large rivers, such as those crossing the coastal plain of Texas, require attention. The very size and nature of these river systems make determining a sediment budget a major challenge, both logistically and conceptually. When given such a challenge it is at times best to start with the basic components of the budget and examine each individually, later combining the parts to create a more accurate and comprehensive sediment budget. Such is the case in the Upper Brazos River Basin. While the focus of this research is the component of sediment transport and not the completion

of a sediment budget, sediment delivery and storage are examined briefly because they both directly relate to and reflect on sediment transport.

Sediment Delivery

The study of river systems and their associated processes has greatly advanced over the years, but with these advancements significant research needs have been uncovered. Understanding erosion rates and soil loss within a drainage basin system and its connection to sediment yield at the basin outlet, as well as an improved knowledge of the associated processes of sediment delivery, all represent areas where research and clarification is needed. Typically, only a small fraction of sediment eroded from a drainage basin will make it to the basin outlet in the form of sediment yield. Increasing basin size tends to directly affect the relative magnitude of this loss. Studies of sediment transported downstream past a series of gaging stations located on a major river have in some cases exhibited such a decline. The term *sediment delivery* typically encompasses all of the various processes involved between on-site erosion and downstream sediment yield as well as the concept of a sediment delivery ratio (SDR). The sediment delivery ratio is defined as the ratio of sediment delivered at the catchment outlet (t km^{-2} yr^{-1}) to gross erosion within the basin (t km^{-2} yr^{-1}); it has been introduced to quantify the differences between erosion and yield. The magnitude of the sediment delivery ratio for a particular basin can and will be influenced by numerous environmental and physical factors including the location, extent, and nature of sediment sources, vegetation cover, relief and slope, drainage pattern, channel characteristics, soil type and texture, and land use.

Numerous studies have attempted to produce an empirical prediction equation for the SDR. This was brought on by the simple idea that a reliable assessment of the sediment delivery ratio would create a ready means for estimating sediment yield of a basin from estimates of soil loss determined from various techniques. The failed attempt to define an applicable equation is most likely because of the complex nature of sediment delivery and its related processes. There is no single best method to predict sediment delivery; in fact, there are numerous acceptable methods and those used are dependent on the researcher. Typically, more than one method is used when undertaking studies of sediment delivery within a basin.

Previous work done within the Brazos has estimated sediment production and delivery to mainstream reaches in two ways. Daily suspended sediment samples have been collected at gaging stations along several tributaries in the Brazos River Basin by the United States Geological Survey (USGS). Flow duration curves and sediment rating curves were constructed for these stations in order to determine annual sediment yield at each location. Dividing the mean annual sediment yield by the upstream contributing area gives a figure for specific yield, or sediment delivery per unit area.

Sediment delivery data from the stations on the Brazos is consistent with a coastal plain river, with the exception of those associated with Seymour (Brazos), South Bend (Brazos) and Mill creek (tributary to the Brazos near Bellville). Seymour posted an extremely high sediment yield, while the next downstream gage (South Bend) showed a considerable decrease. In fact, sediment yields at Seymour (1,220 t km^{-2} yr^{-1}) are the highest in the basin. At first glance, this seems reasonable, given that the average annual suspended-sediment yield of the Brazos is generally considered the highest of all rivers in the state of Texas. Most of the sediments in the Brazos are derived primarily from Triassic red beds located in the upper reaches of the drainage

basin in northwestern Texas and northeastern New Mexico. Thus, high yields at the Seymour station would be consistent with this source-delivery linkage.

However, closer examination of the historic sediment record shows suspended sediment concentrations of between 7,000 and 14,500 mg l^{-1} in some cases, measurements that are extraordinary by any standard. After consulting with scientists from the USGS, they concurred that the values at Seymour seem unrealistically high, but they could find no error in the calculation of the sediment loading. However, to date there is no identifiable reason as to why sediment yield would fall so drastically (> 30 fold) between Seymour and South Bend over a distance of just 95 river miles.

The gaging station on Mill Creek near Bellville (tributary in the Lower Brazos basin) has a mean annual sediment yield of 583 t km^{-2} $year^{-1}$, considerably higher than sediment yield per unit area for any other tributary stations on the Brazos (mean of other tributaries =17.5 t km^{-2} $year^{-1}$) (Slattery, 2007). However, it should be noted that the historic sediment record on the Brazos is very incomplete, with sample size on the tributaries ranging from n = 4 (Millers Creek) to n = 47 (Rocky Creek). Moreover, the historic record on these streams does not cover the full range of flow conditions, and so the specific sediment yield data reported must be seen as broad estimates of sediment transport rather than precise calculations. Augmentation of 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 *et al*., 2007) is needed to produce more reliable sediment yield estimates.

Independent estimates of sediment delivery to streams in the Brazos River basin have also made from reservoir surveys conducted by the Texas Water Development Board (Phillips *et al*., 2004). The surveys document changes in reservoir capacity, assumed to be the result of sedimentation. Dividing the capacity change by the number of years between surveys gives a

volume of sediment accumulation per year. This is further adjusted for drainage areas to produce a virtual rate in m^3 km^{-2} $year^{-1}$. Bulk density of newly deposited lake sediments in Texas ranges from 0.5 to 0.9 Mg m^{-3}, and those of older, more compacted lake sediments are typically 1.1 to 1.3 (Welborn, 1967; Williams, 1991). A conservative density of 1 Mg m^{-3} was used in the previously mentioned study. Data were averaged for 27 lakes in east and central Texas in the same land resource areas as those encompassing the study basins (see Table 1).

TABLE 1: Upland-to-stream sediment yields estimated from lake capacity surveys conducted by the Texas Water Development Board (http://www.twdb.state.tx.us/assistance/lakesurveys/compsurveys.asp)

Lake	**Drainage area (km2)**	**Storage loss (m^3)**	**Years**	**Yield ($t/km^{-2}/yr$)**
Limestone	1,748	11,905,742	14	486
Granbury	66,742	19,263,570	27	11
Possum Kingdom	61,114	17,297,371	20	14
Arlington	370	1,412,358	14	272
Belton	9,145	9,231,514	28	36
Waco	4,279	5,390,395	25	50
Cedar Creek	2,608	51,831,670	29	685
Stillhouse Hollow	3,401	11,887,240	27	129
Georgetown	640	86,345	15	9
Granger	1,891	13,852,205	15	488
Aquilla	660	7,941,273	12	1,002
Somerville	2,608	62,338,623	28	854
Brownwood	4,053	22,814,816	64	88
Squaw Creek	166	20,970	20	6
Coastal Plain				
Wright Patman	8,917	42,432,400	41	116
Tawakoni	1,958	5,928,210	37	82
Conroe	1,153	17,308,472	26	578
Houston	7,325	1,227,333	29	6
Nacogdoches	228	3,447,633	18	841
Benbrook	1,111	3,209,567	53	55
Gladewater	42	1, 601,527	50	763
Murvaul	298	7,555,730	41	618
Tyler	277	813,296	30	98
Striker Creek	47	15,051,183	39	275

The lake surveys indicate sediment yields of 6 to 1002 t km^{-2} yr^{-1}, with a mean annual sediment yield of 315 t km^{-2} yr^{-1}. Lakes where measured storage capacities increased as a result

of dredging, flushing, or increasing dam heights were not included in these estimates. If reductions in reservoir capacity are indeed due to fluvial sedimentation, these data represent a reasonable estimate of sediment delivery to the fluvial system, and therefore a basis for comparison with other sediment delivery estimation techniques. This is because lake sediments typically reflect sediment actually delivered to the fluvial system.

However, sediment production estimates using any of the previously mentioned methods all have uncertainties and assumptions. First, none of the methods quantify the influence of individual production processes, such as sheet and rill erosion. Moreover, standard deviations about the mean estimates are all large, emphasizing the substantial spatial variability inherent in sediment delivery at this scale. Also, the degree to which estimates of tributary erosion reflect average rates throughout each sub-basin remains uncertain without statistically significant sample sizes and repeated measurement of sediment transport over multiple years. Historic measurements of tributary erosion rates were limited to a small number of sample sites within each of the Brazos River basins and the data is clearly sparse. Thus again highlighting the need for further, more detailed study.

Storage

Sediment storage provides the link between hillslope erosion processes that deliver sediment to stream channels (the input component of the sediment budget) and sediment transport processes that export sediment (the output component). However, measuring rates of alluvial storage over large areas is often quite difficult, particularly over periods of decades or longer for constructing an average annual sediment budget. A majority of the previous work done on storage in the Brazos River has focused on understanding this process in the Middle

and Lower Brazos River Basins. Storage within these basins has previously been inferred based simply on the difference between sediment delivered to the stream and in-stream sediment yield. The minimum storage along a reach is the upstream input as measured at the gaging stations minus the downstream output. Maximum storage assumes that all sediment delivery to channels is transported to the main channel. For example, if an estimate of maximum storage were to be done on a reach of the Brazos in the Upper Basin, namely the reach of the Brazos between Seymour and South Bend, it would be based on upstream input (i.e., yield at Seymour), plus sediment produced in the drainage area between the upstream and downstream ends of the reach, minus downstream output (i.e., at South Bend).

Storage of sediment on the main stem of the Brazos has also been investigated via volumetric surveys using digital surveying (Smith, 2007). Channel bars within the Middle Basin were mapped at low flows along representative sections. Three dimensional terrain models of the sand bars were produced that were then used to calculate volumes of sediment stored within the channel at various flow levels. Extrapolating the data to a larger scale allows for an estimate to be made of the amount of sediment accumulating and being stored in channel depositional structures rather than transported through the system. Based on the above studies, alluvial storage in the Brazos River is considered to be quite extensive.

Sediment Transport

The maximum concentration of sediment (mass of sediment per unit volume of water per unit area of bed) that can be moved downstream is determined by the transport capacity of the river. This capacity is limited by the ability of that river to disperse sediment either through

turbulence or traction. The maximum size of sediment that can be moved by a given flow condition is referred to as competence.

For a river to begin transporting sediment, the bed shear stress exerted by the river must exceed the critical shear stress of the bed. The critical sheer stress is the sheer stress at which movement, or entrainment, of streambed sediment begins. The critical sheer stress equation, given below, can be used to estimate the critical sheer stress for entrainment of sediment d_{50} on a variety of alluvial surfaces.

$$\tau_c = \tau^*_c (\gamma_s - \gamma) d_{50}$$

τc is critical sheer stress in Newton's per m^2, τ^*_c is dimensionless critical sheer stress or shields parameter, γ_s is the specific weight of the sediment (assumed to be 2.65 times the specific weight of water, γ is the specific weight of water, and d_{50} is the median particle size in meters.

Once this occurs, the method of sediment transport depends on the characteristics of the sediment and the water. The settling velocity is the minimum velocity a body of moving water must have in order to transport sediments, and (for a dilute suspension) is given by Stokes' Law:

$$w = \frac{2(\rho_p - \rho_f) g r^2}{9\mu}$$

where *w* is the settling velocity, *ρ* is density (the subscripts *p* and *f* indicate particle and fluid, respectively), *g* is the acceleration due to gravity, *r* is the radius of the particle and *μ* is the dynamic viscosity of the fluid. It is important to note that this equation is only valid for particle

Reynold's numbers that are greater than 1. If the velocity of the flow is greater than the settling velocity, sediment will be transported downstream in one of several ways.

The sediment load of a river can be divided based on the mode of transport or by the source. When divided by source, the total sediment load is split between wash load and bed load material. Sediment that has been introduced into the river from upland sources is considered wash load, this sediment is generally supplied by bank erosion, mass wasting, and mass transport of sediment from adjacent watersheds into the stream during rainstorms. The sediment that comprises the wash load is characteristically fine grained and the river is generally always able to entrain it and keep it in suspension. The wash load is normally comprised of clay, silt and at times fine grained sands. The exception to this is when dealing with steep headwater streams; in these cases wash load can include coarse sand and pebbles. Bed load material is sediment derived from the riverbed and is typically composed of sands and gravels. The concentration of the bed load is directly related to the rivers transport capacity.

When divided by mode of transport the total sediment load is split between suspended load, bed load, and dissolved load. The suspended load consists of sediment particles that are mechanically transported by suspension within the river. This is in contrast to bed load which consists of particles that are moved along the bed of the river, and dissolved load, which consists of material that has been dissolved in the water of the river. In most rivers, the suspended load is composed primarily of silt and clay size particles. Sand-size particles can be part of the suspended load if the flow velocity and turbulence are great enough to hold them in suspension. The suspended load is dispersed in the flow by turbulence and is commonly carried great distances without touching the bed. The composition of the suspended load can consist of particles that are intermittently lifted into suspension from the river bed and of wash

load. This is because water density is proportional to the amount of suspended load being carried. Muddy water high in suspended sediment will increase the particle buoyancy and reduce the critical shear stress required to move the bed load of the stream, thus allowing larger and heavier particles to be entrained. The bed load is generally composed of the coarser sediment, moving in almost continuous contact with the bed of the river by rolling, sliding, or by saltation. As you move downstream the bed load typically becomes finer, this is due to sorting and abrasion. Because of this the suspended load increasingly dominates the bed load.

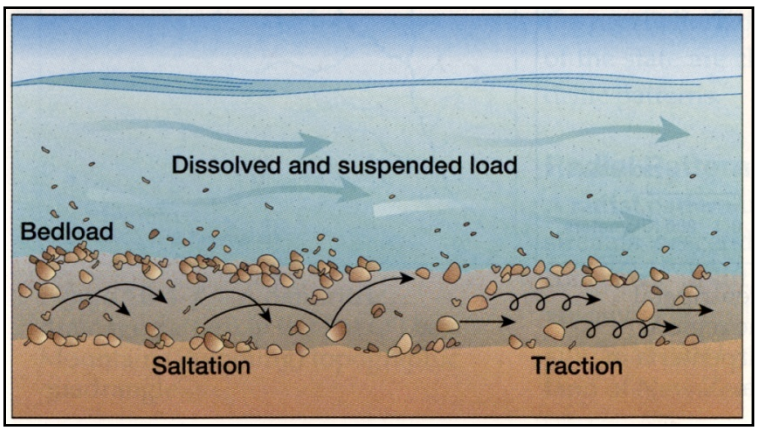


Figure 1: Diagram displaying various modes of sediment transport

The ratio of suspended load to bed load in a river depends on the ratio of the shear velocity (property water that reflects the degree of turbulence) and the settling velocity. Generally speaking, bed-load transport dominates when the shear velocity is significantly less than half the fall velocity and suspended load transport dominates when the shear velocity is two or three times greater than the fall velocity.

Differences between the source/supply of the sediment and the mode of transport of the suspended and bed loads are shown in the different methods used to determine them.

Suspended load is often related more to the sediment supply than transport capacity and therefore it is typically measured directly. Bed load is generally controlled by the transport capacity and may, in theory, be more readily determined by a theoretical or empirical approach.

OBJECTIVES

The purpose of this study is to develop a more detailed understanding of sediment transport within several reaches in the Upper Brazos River basin. Specifically this study will:

(1) Use historical suspended sediment data to reconstruct sediment rating curves and test the accuracy as well as the validity of these curves with contemporary hand held suspended sediment data.

(2) Determine annual sediment yield along main channel reaches using historical and contemporary suspended sediment data.

(3) Construct turbidity vs. suspended sediment concentration rating curve for future use within the basin.

(4) Examine suspended sediment concentration and turbidity dynamics during the spring flush.

SITE DESCRIPTION AND METHODS

This thesis involved an extensive field sampling protocol, coupled with analysis of historic discharge and sediment data in the Upper Brazos River basin, which compromises approximately 59% of the total basin area. The Brazos River drainage basin extends from New Mexico to the Gulf of Mexico and comprises 44,620 mi², 42,000 mi² of which are in Texas; 24,886 mi² constitutes the upper basin. The Brazos River arises at the confluence of its Salt Fork and Double Mountain Fork near the eastern boundary of Stonewall County and flows across the state of Texas to its mouth on the Gulf of Mexico, two miles south of Freeport in Brazoria County. The two forks emerge from the Caprock approximately 150 miles above the confluence forming the 1,050 mile drainage basin.

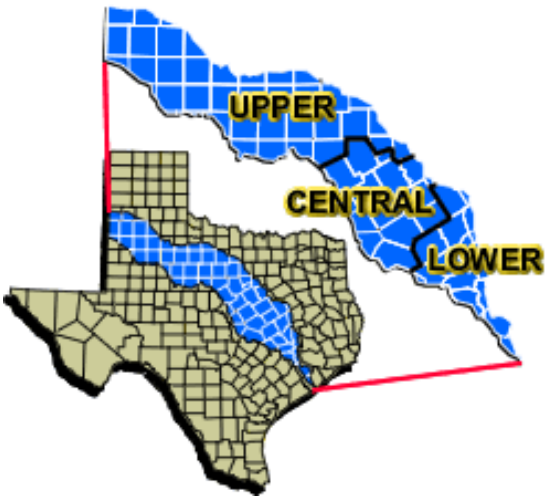


FIGURE 2: Brazos River Basin and its subdivisions (Source: www.brazos.org)

The Upper Basin lies within the physiographic region know as the Great Plains, with climate ranging from desert-like conditions in the northern portions of the basin to a humid-

subtropical climate to the south. The basin as a whole experiences hot summers, relatively mild winters, and is characterized by a wide annual temperature range. Precipitation varies considerably, ranging from less than 20" in the North to more than 50" as you move southeast. Land use within the basin is divided between range land, forest, agriculture, pasture, and urban development (see Figure3).

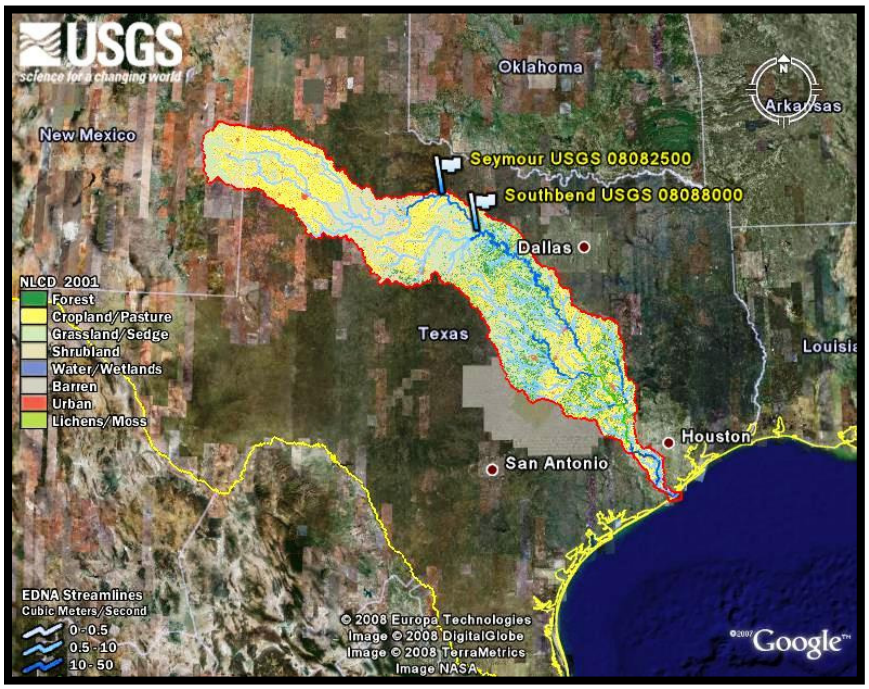


FIGURE 3: Land use map

The sediments of the Brazos River have a distinctive red color and are characterized by fine grain sizes (Curtis *et al.,* 1973); most of the sediment load is of clay-size. These sediments are derived primarily from Triassic red beds located in the upper reaches of the drainage basin in northwestern Texas and northeastern New Mexico.

Data Acquisition Locations

This study focuses on sediment transport along several reaches of river within the upper basin, specifically along the Salt Fork, Double Mountain Fork, Millers Creek (a tributary), and a segment of the main channel of the Brazos River. The main emphasis was placed on the reach of the Brazos located between Seymour, Texas and South bend, Texas.

The methodology utilized in this study consisted of both historic sediment data and contemporary measurements by the author at two sites on the Brazos River. These two sites are the Brazos River at South bend, Texas and the Brazos River at Seymour, Texas. These two sites were chosen based on (i) a discrepancy in sediment yields calculated from historical USGS records, although no observable error could be found in the sediment calculations, and (ii) the fact that both are major gaging stations upstream of Possum Kingdom Lake. Due to the time frame of this study, contemporary samples were not taken along tributaries. Here, sediment calculations were based on historical data gathered by the USGS intermittently over the last forty years.

The Brazos River was sampled in two different places in the upper basin. First, samples were taken from the bridge on U.S. Highway 183 just south of Seymour. This location is the site of USGS gaging station 08082500, the first gaging station on the main channel of the Brazos River. South bend was the second site used to sample the Brazos River. Samples were taken from a bridge on State Highway 67, which is approximately six miles south of Graham and 95 river miles south of the Seymour site. South bend is the site of USGS gaging station 0808800. At each site, bed load and suspended sediment samples were taken during various flow conditions.

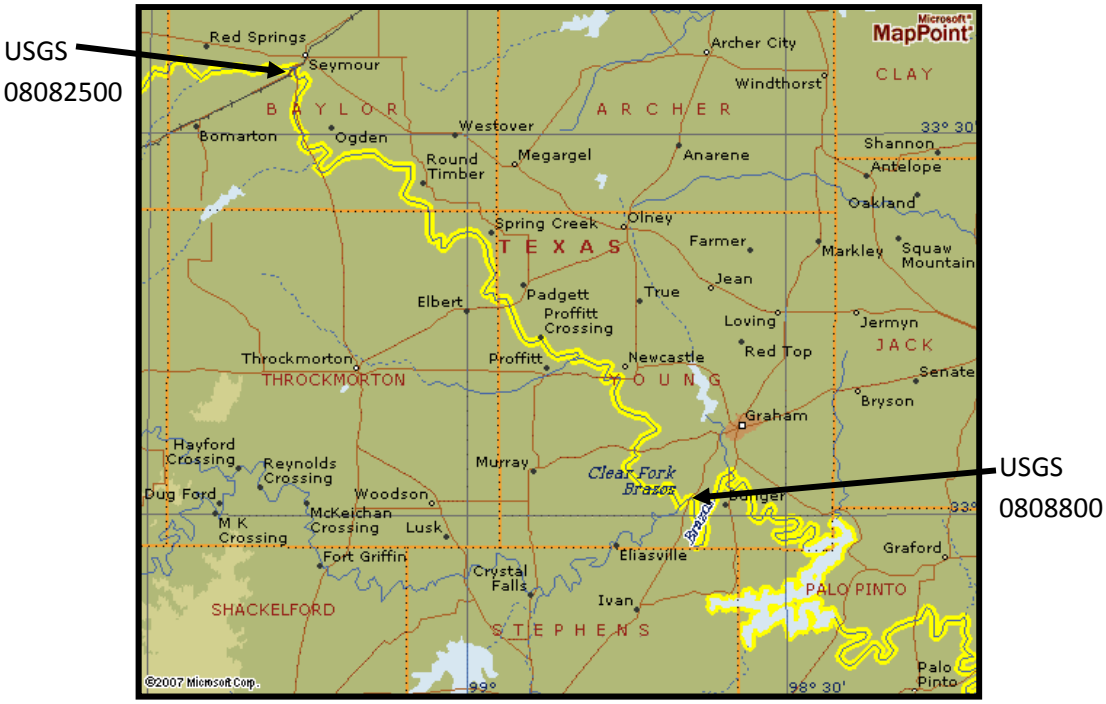


FIGURE 4: Sampling sites

A YSI 600 OMS turbidity probe was installed in the Brazos River on the south side of the bridge at South Bend. The turbidity probe was programmed to take measurements every six hours. The data is stored in the probe and downloaded every three months for analysis. This is an extremely effective way to obtain large amounts of sediment data, without potentially dangerous, time consuming, and costly field measurements. The turbidity probe transmits a signal and measures the amount of light reflected back to the receiver. The measure of light reflected back is a function of the clarity of the water and thus the amount of suspended sediment contained in the water. The turbidity probe was placed at a USGS gaging station to allow for correlation between the suspended sediment samples and six hour discharge data.

FIGURE 5: Downstream and upstream views of the Brazos River at Seymour

Suspended Sediment Data

Sampling of the fine grained suspended sediments was accomplished using a US D-74 depth-integrating sampler that was lowered over the side of the bridge using a hydrological crane. After the tail of the torpedo-style sampler touched the water surface and stabilized with the water current, the time was noted and the sampler was lowered into the water. The depth integration consisted of allowing the sampler to descend to as close to the river bottom as possible, and then ascend back to the water surface. Ideally, this is accomplished as one fluid motion, the ascent and descent being of equal time and the sample vial filling completely as you break the water surface. The length of the process was dependent on the level of the water flowing through the river at the time of sampling. The sample in the collection bottle was removed from the sampler, labeled, and sealed for further analysis back in the lab. Lab analysis of the suspended sediment samples consisted of separating the silts and clays from the water column. This was accomplished by filtering the water sample through a 0.45µg Millipore membrane using a vacuum pump for suction. After the entire sample was collected on the filter

paper it was dried in an oven for approximately 4-5 hours to drive off any remaining molecules of water. The filter was then weighed and the final weight of the filter and sediment was compared to the original filter weight, the difference being milligrams of sediment per liter of water.

Bed load Data

Bed load samples were obtained using the Helley-Smith pressure-difference bed load sampler. The method of obtaining bed load samples is similar to that of suspended sediment sampling in that the apparatus is again lowered over the side of the bridge using a hydrological crane. The sampler was lowered through the water and allowed to rest on the river bottom. Once arriving at the bottom, the time was noted and the sampler was allowed to rest on the channel bottom for 5-10 minutes, before the sampler was then retrieved. During high or extreme flow conditions the sampler was submerged for about 5 minutes; with lower and more tranquil conditions, the sampler was allowed to rest on the bottom for 10 minutes. The samples which consisted of sand, gravel and larger particles were left in the sample bags, labeled, and stored for later analysis. The samples were allowed to dry in the collection bags to avoid losing sediment by attempting a wet transfer. Once in the lab the air dried bed load samples were transferred to beakers and weighed for total mass. The weight of the sediment was determined by comparing the weight of the beaker and sediment from the original weight of the beaker. To calculate bed load flux, the width of the opening on the bed load sampler was multiplied by the width of the channel and then by the sampling interval. This calculation gives bed load in t day^{-1}. This calculation makes an assumption that bed load

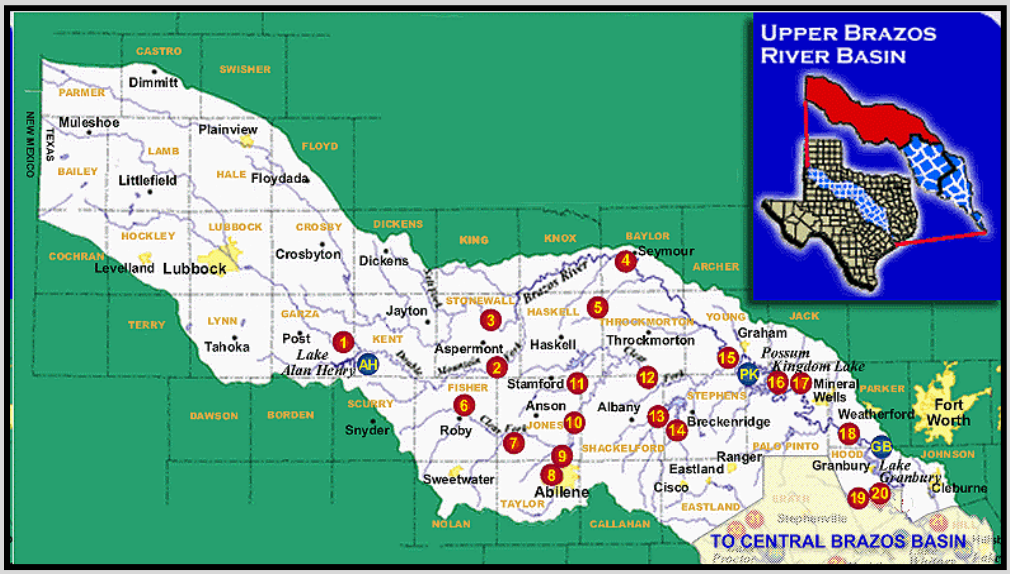
transport is uniform across the entire width of the channel, an aspect that is not necessarily true.

RESULTS AND DISCUSSION

Flow Duration Curves

The flow duration curve shows the percentage of time the flow in a stream will equal or exceed a given value. These curves are widely used for quantifying the temporal variability in a discharge record. They also characterize the basins ability to provide flows of various magnitudes. The shape of the curve in the upper and lower regions is extremely important when evaluating stream and basin characteristics. The shape of the curve in the high flow area indicates the type of flood regime the basin is likely to experience, while the shape of the low flow area characterizes the ability of the basin to sustain flows during dry months. Very steep curves (i.e., high flow for short periods) are indicative of rain-caused floods within small watersheds. An intermittent stream would exhibit periods of no flow, while a very flat curve indicates moderate flows are sustained throughout the year.

Flow duration curves were constructed for six gaging stations within the upper basin. These curves were constructed using mean daily discharge values collected by the USGS for the last 25 years (see figure 7).



1 = Double Mountain Fork of the Brazos River at Justiceburg, TX
2 = Double Mountain Fork of the Brazos River near Aspermont, TX
3 = Salt Fork of the Brazos River near Aspermont, TX
4 = Brazos River at Seymour, TX
5 = Millers Creek near Munday, TX
15 = Brazos River at South Bend, TX

FIGURE 6: Map of the Upper Brazos River Basin showing the position of the 6 USGS gaging stations used. Map source: www.brazos.org

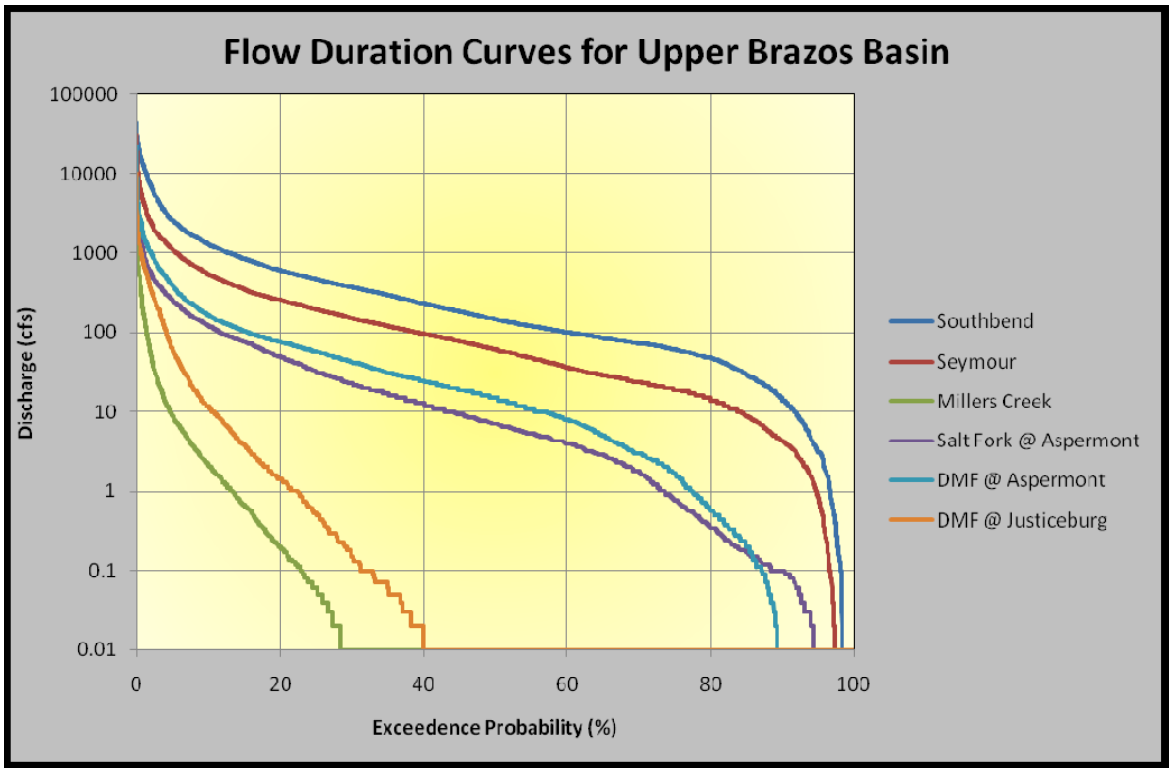


FIGURE 7: Flow Duration Curves constructed for six gaging stations along the Brazos River and its tributaries.

The flow duration curves for the Brazos indicate that both Seymour and South Bend experience similar high and low flow regimes, with the magnitude of the flow being the only difference. South Bend has an overall higher discharge and flow regime than Seymour, not surprising given the significantly larger contributing area at South Bend. Median discharge (Q0.5) at South Bend is 120 cfs, whereas Q0.5 at Seymour is 80 cfs. High magnitude flows at both these stations on the main stem are comparable, with Q0.05 at South Bend 5,000 cfs and 2,500 cfs at Seymour, respectively. The overall shape of these two curves is typical of sub-humid basins with significant flow regulation. The Double Mountain Fork at Justiceburg and Millers Creek have very steep curves that reach high discharge values. The curves indicate that these streams are intermittent in nature, remaining dry more than 50% of the time. The

extremely high flows are due to heavy rainfall. In dry basin areas, rainfall of this magnitude will produce flash floods, causing the typically dry streambeds to resemble mighty rivers. Because intermittent streams remain dry for long periods of time, sediment is often more easily erodible, therefore when events such as a flash flood occur vast amounts of sediment can be transported downstream in short time frames.

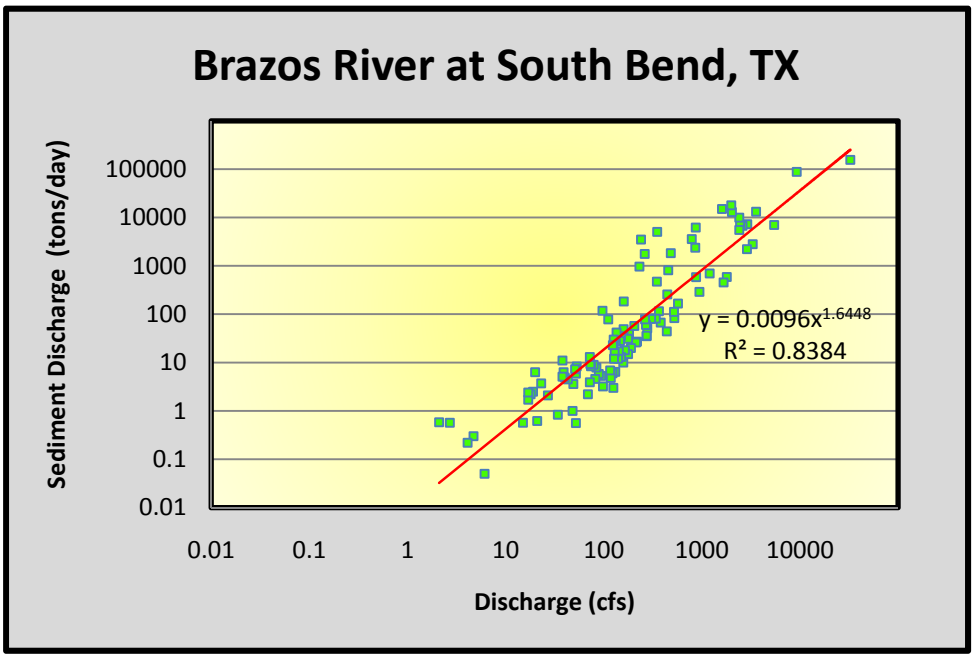
Sediment Rating Curves

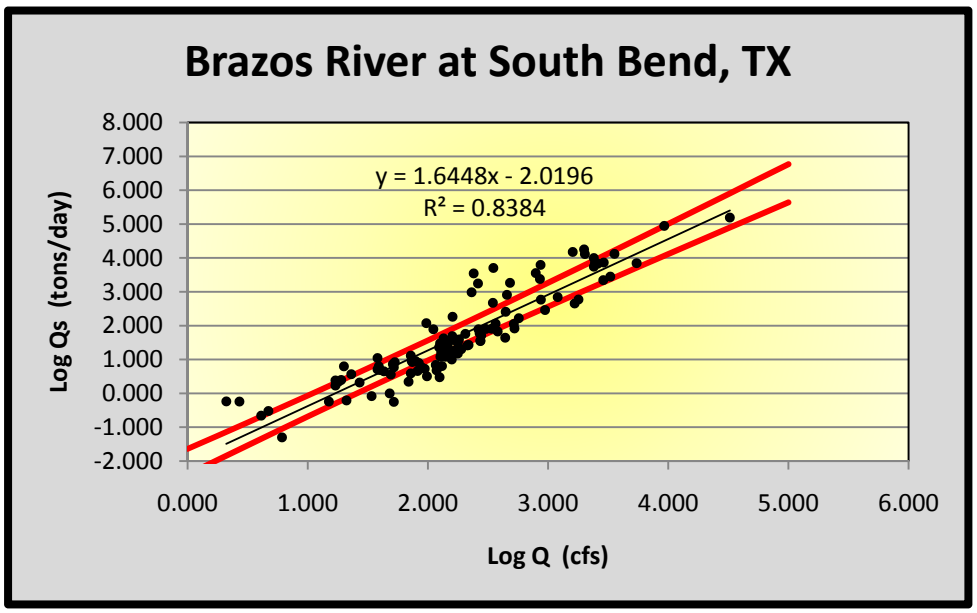
Daily suspended sediment samples have been collected by the United States Geological Survey (USGS) at gaging stations along the main stem of Brazos River and its tributaries for over forty years. This data was used to create sediment rating curves for six gages within the upper basin. Sediment rating curves plot suspended sediment concentrations against discharge allowing for a predictive empirical relationship to be derived between the two. These curves are widely used to estimate the sediment load carried within a stream at specific discharges. For each gaging station a sediment rating curve was produced and 95% confidence intervals were fitted to the data. The sediment rating curves for the six stations are shown in figures 8a and 8b through 13a and 13b. Although the best fit regression line for all of the gaging stations indicates a good relationship between stream discharge and suspended sediment discharge, there exists a fair amount of scatter around the lines. This scatter is most likely due to a hysteresis effect in the concentration of suspended sediment relative to discharge. In most river systems as stream discharge rises, sediments stored within the stream channel and those mobilized in areas proximal to the main reach are transported through the system first. Because of this flushing, samples collected while the stream is rising typically have greater concentrations than those taken at a similar discharge as the stream is in recession. But this is

not the case at South Bend; in fact it is the opposite. Graphs plotting sediment discharge versus discharge for specific storm events show that in most cases higher concentrations occur as stream discharge is falling (see section on Temporal Variability in Sediment Transport). The rating curves display a high degree of predictability, with R^2 values greater than 0.8, with the exception of the Salt Fork which displays an R^2 of 0.787.

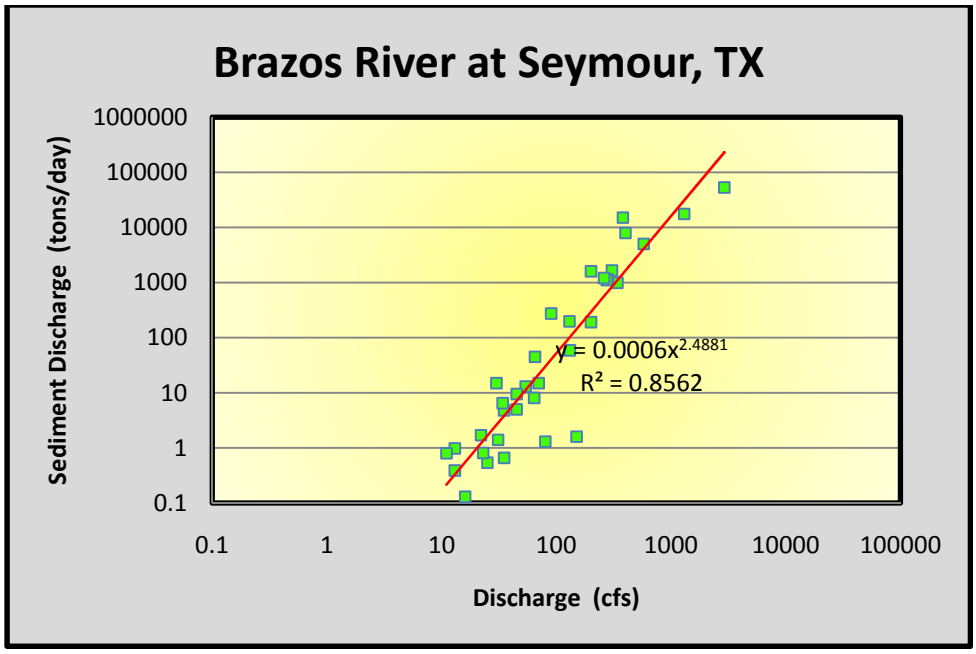
The rating curve for the Brazos River at Seymour has a much steeper slope when compared to the other stations. A steeper slope indicates a much more dramatic response in suspended sediment transport as stream discharge rises. But as previously stated, the historic data at Seymour contained sediment concentrations of extraordinary values and the extreme nature of these values resulted in the slope of 2.4881. This anomaly was investigated further through the use of hand sample data.

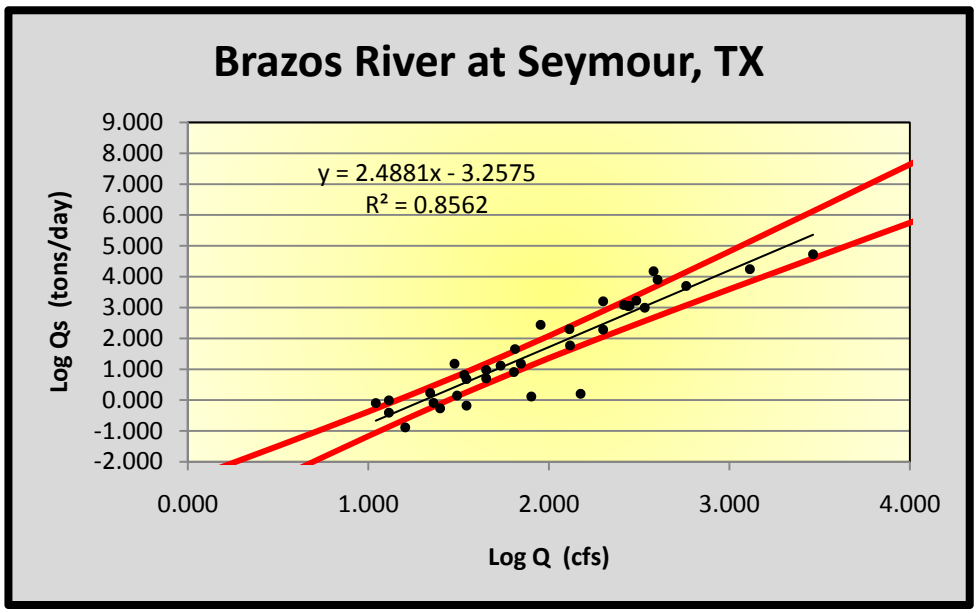
In order to assess the reliability of the historical data, confidence intervals for each sediment rating curve were constructed at a confidence level of 95%. This means that if the same data is sampled on numerous occasions and interval estimates are made on each occasion, the resulting intervals would bracket the true data parameter approximately 95% of the time. A narrow confidence interval such as is seen on these graphs typically implies high precision. When looking at the confidence intervals it is important to note how many data points are within the bands, as well as the number located outside of the bands. Many of the higher concentration values lay outside of the banded interval; this is most likely related to the hysteresis effect in sediment concentrations mentioned previously. Those data points found within the bands represent a more reliable relationship between sediment concentration and discharge.



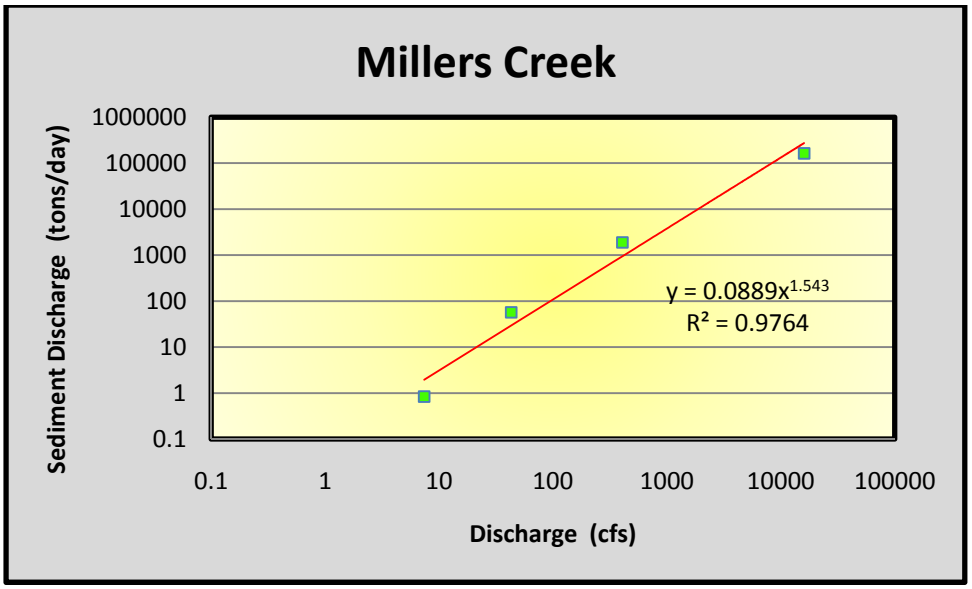


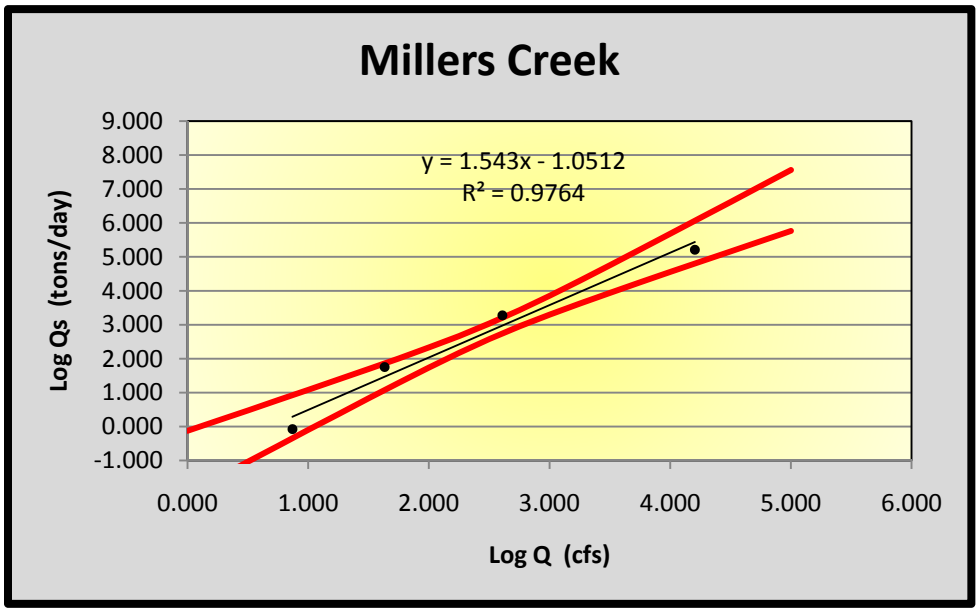
FIGURES 8a and 8b: Sediment rating curve and confidence interval graph for the Brazos River at South Bend, TX.



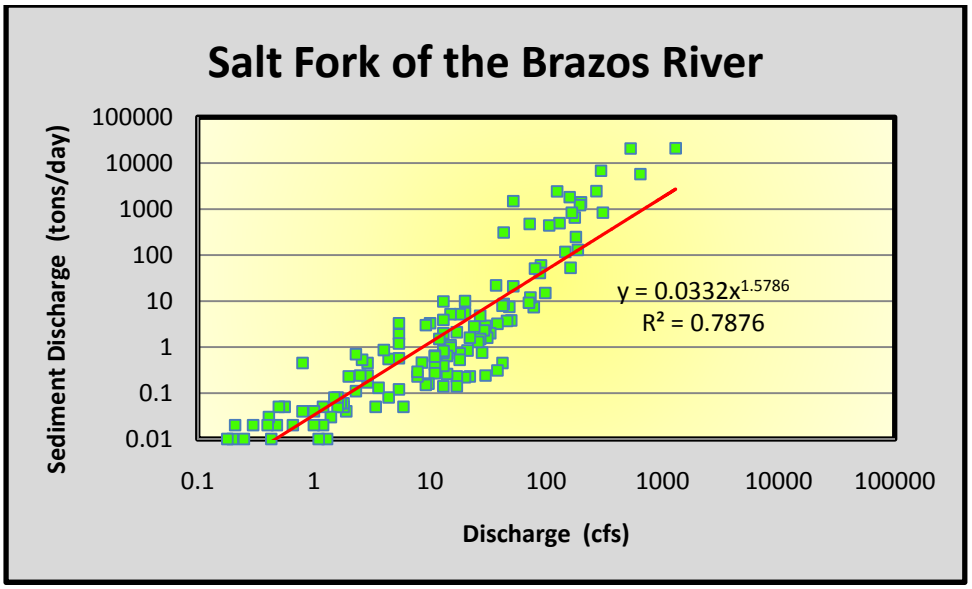


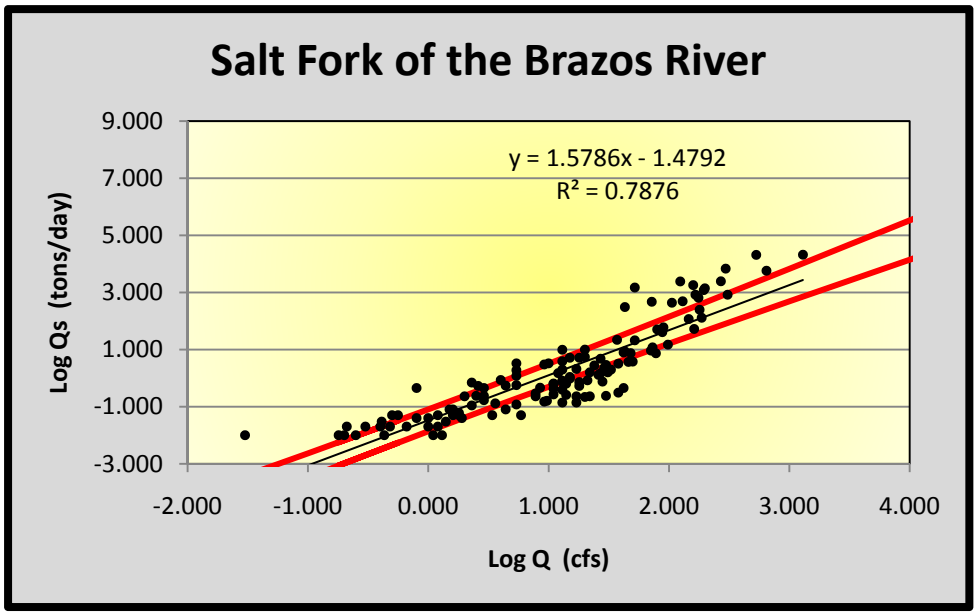
FIGURES 9a and 9b: Sediment rating curve and confidence interval graph for the Brazos River at Seymour, TX.



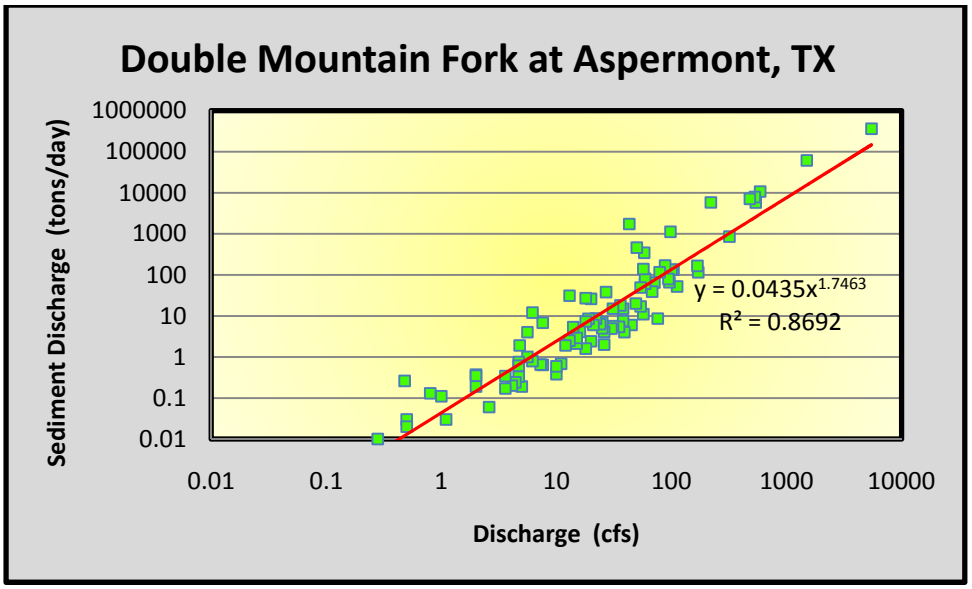


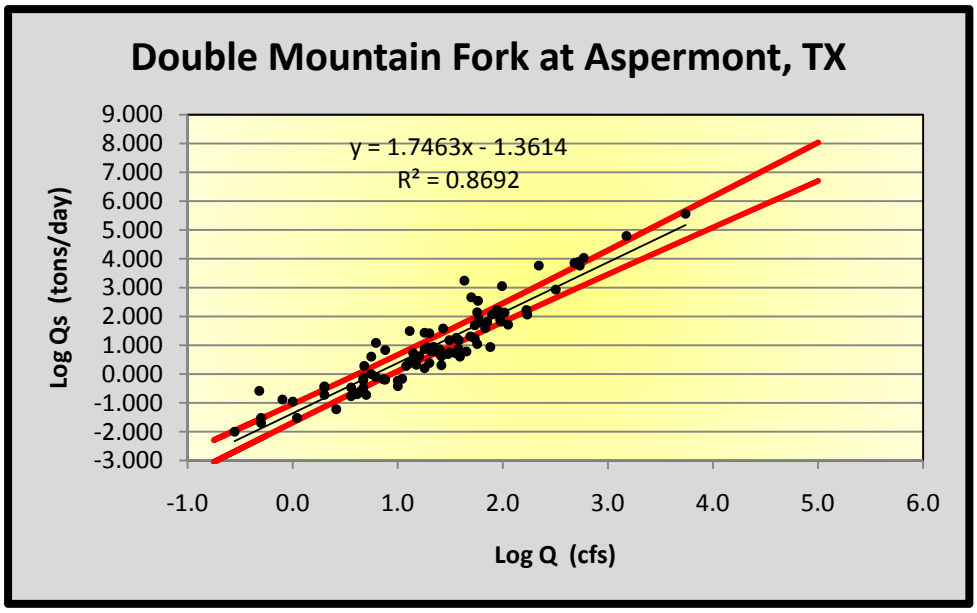
FIGURES 10a and 10b: Sediment rating curve and confidence interval graph for Millers Creek



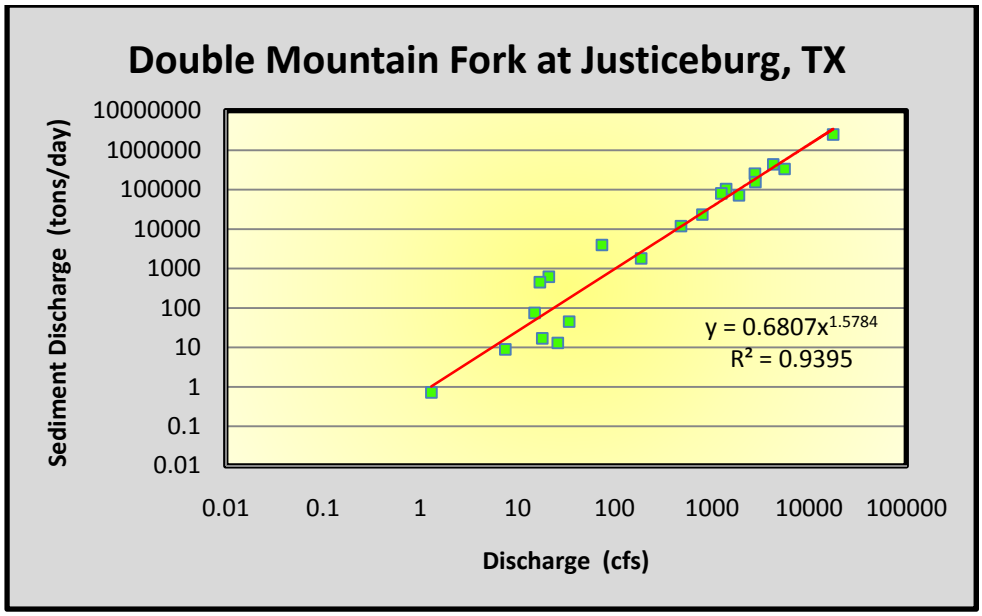


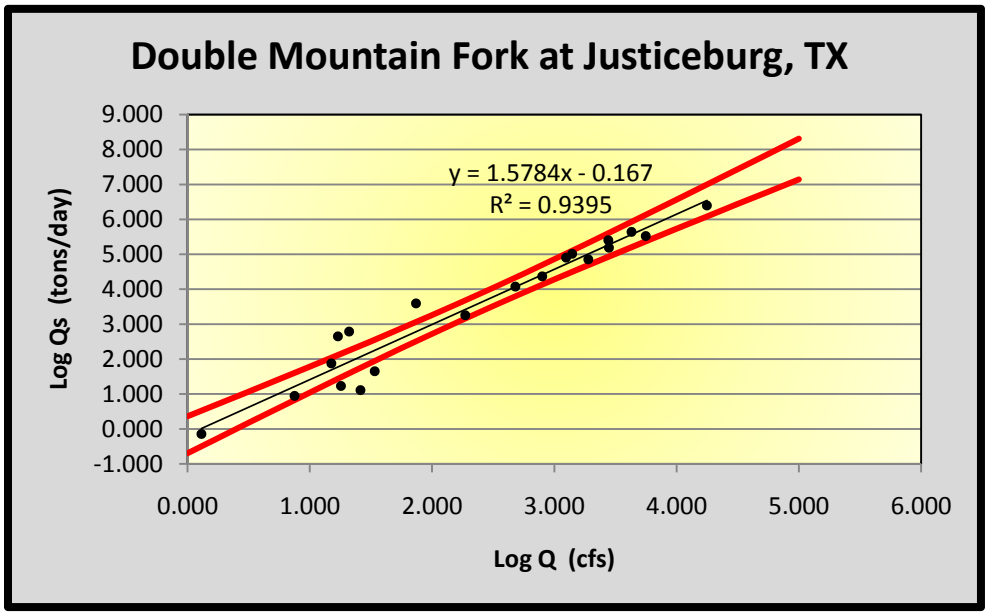
FIGURES 11a and 11b: Sediment rating curve and confidence interval graph for the Salt Fork of the Brazos River.





FIGURES 12a and 12b: Sediment rating curve and confidence interval graph for the Double Mountain Fork of the Brazos River at Aspermont, TX.





FIGURES 13a and 13b: Sediment rating curve and confidence interval graph for the Double Mountain Fork of the Brazos River at Justiceburg, TX.

Contemporary hand samples of suspended sediment were taken at the Seymour and South Bend locations during various discharge levels from August 2007 through June 2008. Once sediment concentrations were determined, sediment rating curves were constructed using the contemporary data. These new curves were then overlain on the historical curves (figure 14 and 15). When comparing the two curves, the differences become quite apparent. At Seymour, the slope of the contemporary line is much lower and the data points are much closer together and lack significant scatter relative to the USGS record. At South Bend the slope becomes slightly higher than that of the historic data. This becomes significant when sediment yield is determined.

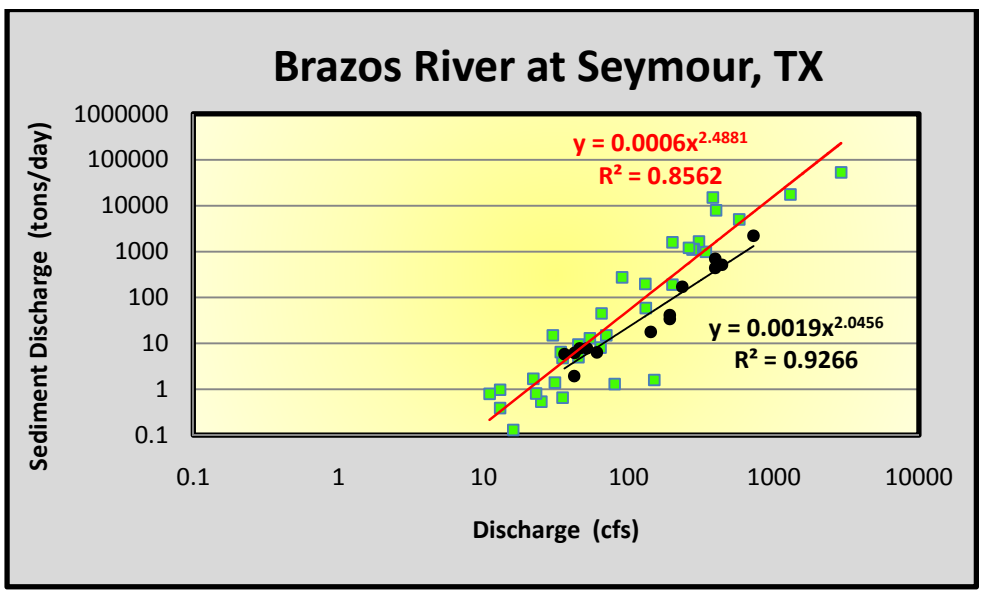


FIGURE 14: Historical sediment rating curve overlain by contemporary sediment rating curve for the Brazos River at Seymour, TX.

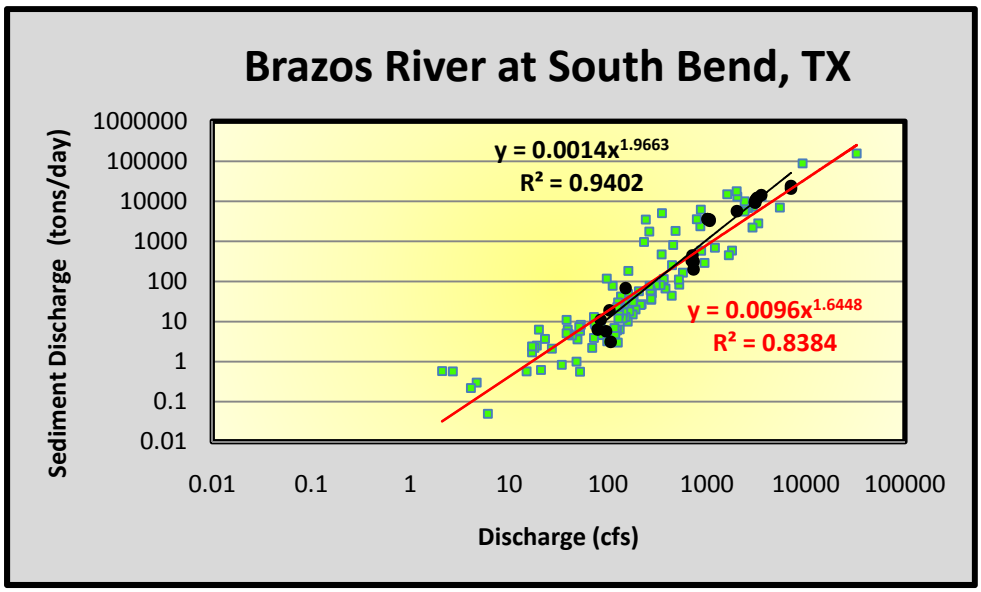


FIGURE 15: Historical sediment rating curve overlain by contemporary sediment rating curve for the Brazos River at South Bend, TX.

Sediment yield

Sediment yield is the amount of material eroded from the land surface by runoff and then delivered to a river system and measured at a specific location. The flow duration curves and sediment rating curves were used to determine sediment yield at each of the six gaging stations. Specific yield, or sediment delivery per unit area, was determined by dividing the mean annual sediment yield by the upstream contributing area. Specific yield for the six gaging stations was calculated using the historical data and then the contemporary data (table 2 and 3).

When determining the specific sediment yield using the historic data, Seymour posted an extremely high sediment yield, while the next downstream gage (South Bend) showed a considerable decrease. In fact, sediment yields at Seymour (1,708 t km^{-2} yr^{-1}) are the highest in the basin. At first glance, this seems reasonable, given that the average annual suspended-

sediment yield of the Brazos is generally considered the highest of all rivers in the state of Texas. Most of the sediments in the Brazos are derived primarily from the upper reaches of the drainage basin in northwestern Texas and northeastern New Mexico. Thus, high yields at the Seymour station would be consistent with this source-delivery linkage.

Closer examination of the historic sediment record, however, shows suspended sediment concentrations of between 7,000 and 14,500 mg l^{-1} in some cases, measurements that are extraordinary by any standard. After consulting with scientists from the USGS, they concurred that the values at Seymour seem unrealistically high, but they could find no error in the calculation of the sediment loading at Seymour. In addition, annual sediment yields at South Bend are only 20 t km^{-2} yr^{-1} and we could find no plausible reason for such a drastic fall in sediment flux between the two stations. There is, for example, no evidence of extensive alluvial storage within the reach beyond the expected channel bars and channel bank deposits.

Gage	Area (km^2)	Sediment (t/yr) Historical data	Sediment ($t/km^2/yr$) Historical data
#1 Double Mountain Fork at Justiceburg	632	444,506	703
#2 Double Mountain Fork at Aspermont	4,827	504,439	104
#3 Salt Fork at Aspermont	6,464	44,430	7
#4 Brazos River at Seymour	15,467	26,421,444	1,708
#5 Millers Creek	269	12,868	47
#15 Brazos River at South Bend	33,947	695,264	20

TABLE 2: Specific sediment yield using historical data.

Specific sediment yield was recalculated using the contemporary data. Because samples were only collected at Seymour and South Bend, those were the only station values to change.

The contemporary samples at Seymour produced a rating curve with a much lower slope, and specific sediment yield dropped from 1,708 t km^{-2} yr^{-1} to a more reasonable 70 t km^{-2} yr^{-1}. The yield at South Bend, which was considered low at 20 t km^{-2} yr^{-1}, was raised to 62 t km^{-2} yr^{-1}, an amount which seems more consistent with that of the basin as a whole.

Gage	Area (km^2)	Sediment (t/yr) contemporary data	Sediment ($t/km^2/yr$) contemporary data
#1 Double Mountain Fork at Justiceburg	632	~	~
#2 Double Mountain Fork at Aspermont	4,827	~	~
#3 Salt Fork at Aspermont	6,464	~	~
#4 Brazos River at Seymour	15,467	1,076,000	70
#5 Millers Creek	269	~	~
#15 Brazos River at South Bend	33,947	2,128,483	62

TABLE 3: Specific sediment yield using contemporary data.

Similar work done in the Middle Trinity River Basin produced mean annual sediment yields for gages located on the main stem near Oakwood, TX and Crockett, TX of 45 t km^{-2} $year^{-1}$ and 53 t km^{-2} $year^{-1}$, respectively (Garnett, 2008). These values are consistent with those calculated for the Upper Brazos River, even though these stations are located in the middle basin of the Trinity River. Although not directly comparable, these values at least give a fairly consistent regional picture of sediment transport in Texas rivers. The Trinity River Basin is adjacent to the Brazos River Basin (see figure 16), and both display similar attributes within their basin boundaries. Therefore consistent sediment data is to be expected. The similarity between specific sediment yield data reported in this study and others should, therefore, be seen as broad estimates of sediment transport to the main channels rather than precise calculations.

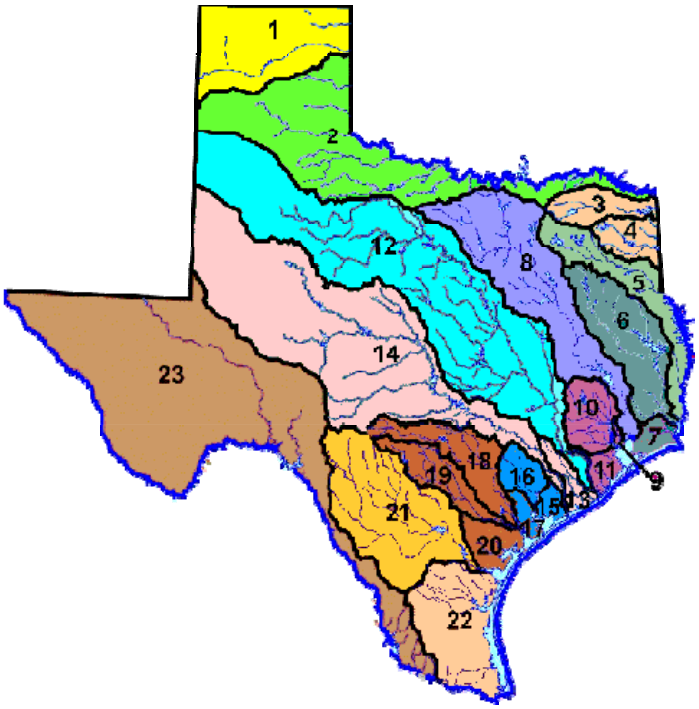


Figure 16: Map showing the major river basins in the state of Texas. Brazos River Basin (12), Trinity River Basin (8). Map taken from www.tceq.tx.us

The contemporary hand sample data warrants further discussion. The number of contemporary samples collected is comparatively smaller than that of the historic record. Arguably, this relatively small number could result in unintentional manipulation of the curves or bias, thus giving an outcome that is more expected and explainable.

However, several things should be taken into consideration. First the contemporary hand samples were taken over a period of one year at the same location, by the same person, with the same equipment, and following the same sampling protocol each time. The historic record spans over forty years, during that time frame equipment and sampling protocol has changed and improved, and the samples were taken by numerous people, introducing operator bias and potential sample inconsistency. Second, the difference between the number of

contemporary samples and that of the historic record is not that large, especially at Seymour. The historic rating curve constructed for Seymour consisted of thirty-five samples, while the contemporary curve was created using fourteen. At South Bend the difference is greater, one hundred twenty historic samples versus twenty- two contemporary samples, but still reasonably comparable. The most important item to consider is that the historic record at Seymour contains sediment concentrations that are extreme by any standard. It stands to reason that sediment yields calculated using these concentrations would be extreme and most likely in error. The historic record at South Bend did not contain any obvious suspect values, and we therefore determined that the rating curves and sediment yield calculated with the historic data are fairly reliable. The contemporary data for South Bend was fairly consistent with the historic record, a fact shown by similar slopes on the rating curves. All things considered, the contemporary curves provide a more realistic picture of sediment transport in the Brazos River.

Sediment Transport Dynamics

In order to better understand sediment transport dynamics in the long term and in greater detail, a YSI 600 OMS turbidity probe was installed in the Brazos River at South Bend. The probe was placed in the river from October to February (low flow), and from March to June (spring flush). The turbidity probe was placed at a USGS gaging station to allow for correlation between contemporary suspended sediment samples and discharge data. Turbidity readings from the probe were plotted against contemporary sediment concentrations taken at the same. This allows for the development of a turbidity-suspended sediment concentration curve (see figure 17).

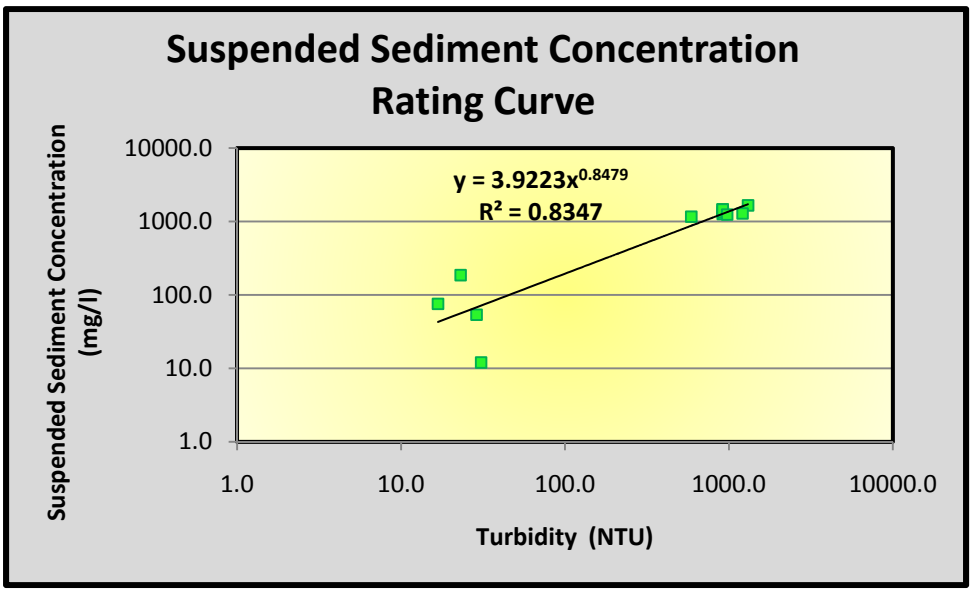


Figure 17: Suspended sediment rating curve developed from turbidity data and contemporary hand samples.

The cluster of data at base of the slope represent data collected from October through February (almost constant low flow), while the points at higher discharges represent data collected from March through June (high flow). The correlation of hand samples and turbidity data allows for the development of a predictive equation for suspended sediment concentration. This equation can then be used to determine sediment concentration for all turbidity data. Once this was accomplished, sediment rating curves were constructed for the two time frames.

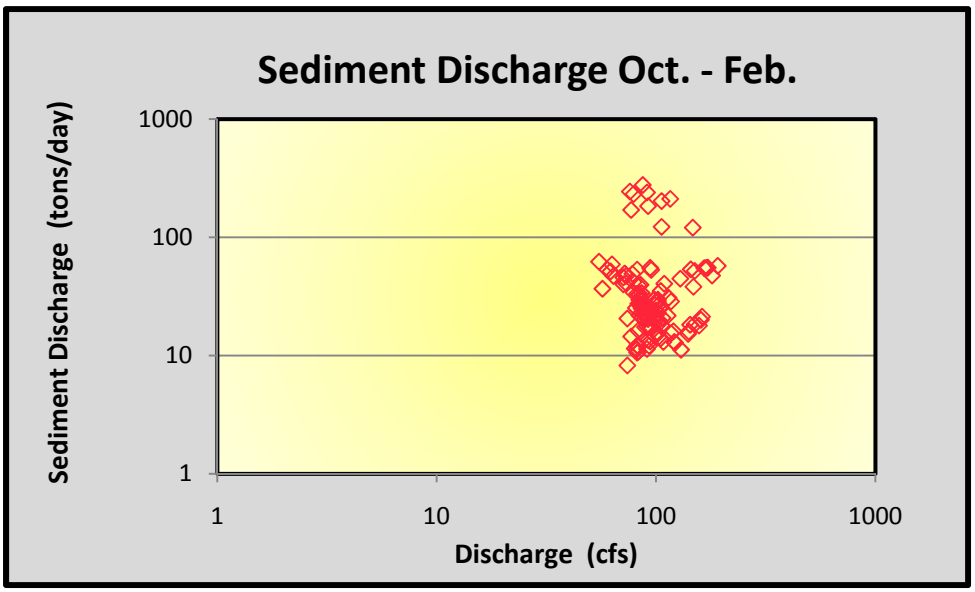


Figure18: Sediment rating curve for the Brazos River at South Bend using turbidity probe data from October 2007 through February 2008.

Turbidity values were collected every six hours for the time period of October 2007 through February 2008. During this period discharge levels remained low, with the highest discharge only reaching around 170 cfs. While getting a large number of readings for low discharge could give a good idea of sediment concentrations at that level, it does not reveal much about the overall behavior of the river at all discharge levels. The greatest problem with the constant low flow was the buildup of sediment on the probe pod. With no high velocity discharge to clean off the buildup, the pod that reads the turbidity of the water often became clogged with sediment, giving faulty readings and unreliable data. Figure 18 displays the rating curve that was created using the available data.

After this problem was discovered the probe was removed for cleaning and recalibration, it was then re-installed in March 2008, and set to take readings every four hours. During these months heavy and frequent rainfalls are common, providing what is typically called

a spring flush of sediment. Essentially the river has experienced low discharge over the drier winter months, so when spring arrives with large storm events all of the sediment that has eroded over winter is washed downstream. The probe remained in the river until June 2008, capturing turbidity readings through several high discharge events. Figure 19 shows the rating curve created with the more reliable data captured during this time frame. There was significant variation within discharge levels (50 cfs – 4,500 cfs); this allows for a more complete picture of sediment transport dynamics at all levels within the river system. Once again the curve shows a high degree of predictability with R^2 = .7.

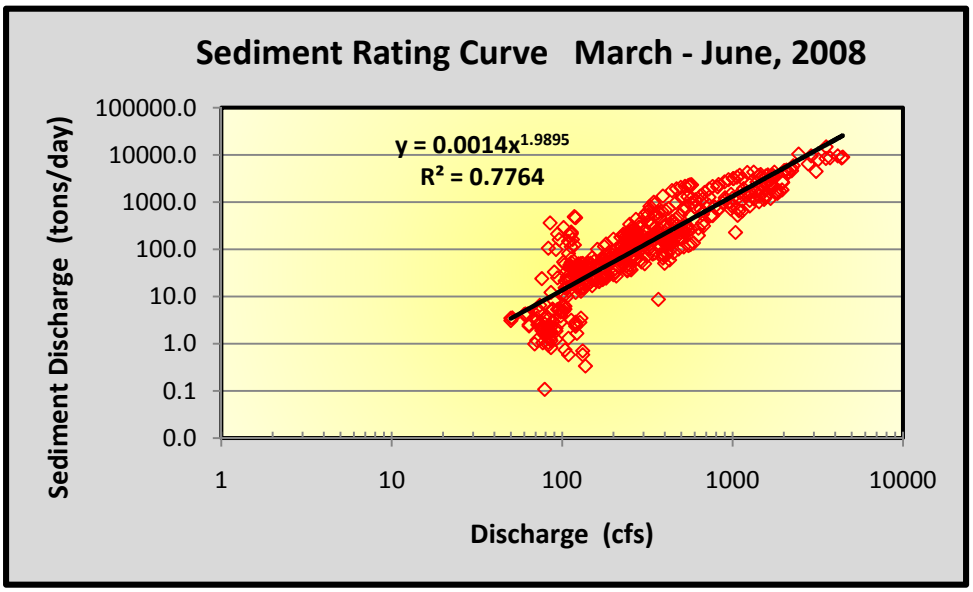


Figure 19: Sediment rating curve constructed with turbidity data from March through June 2008.

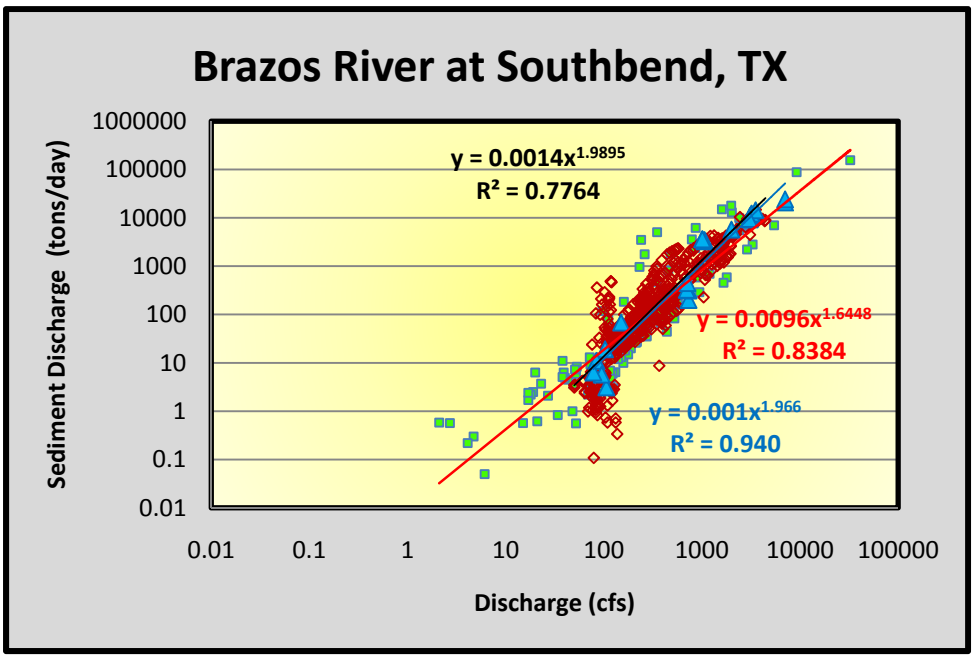


FIGURE 20: Sediment rating curve comparing historic (green), contemporary (blue) and turbidity probe data (red)

Figure 20 shows the historic suspended sediment data compared to the contemporary hand samples and turbidity data. When the data sets are overlain all three display a similar slope. The similarity in the slopes confirms that the contemporary data is reliable and gives a better overall picture of sediment transport.

Temporal Variability in Sediment Transport

This study also examined the temporal variability of sediment during several storm events, occurring from March through June, 2008. Negative hysteresis was common between all events except one. The driving force behind the negative hysteresis is heavy rainfall within the upper basin reaches and to a lesser degree rainfall in immediate upstream areas. Figure 20 shows the individual storm events and their relative discharges.

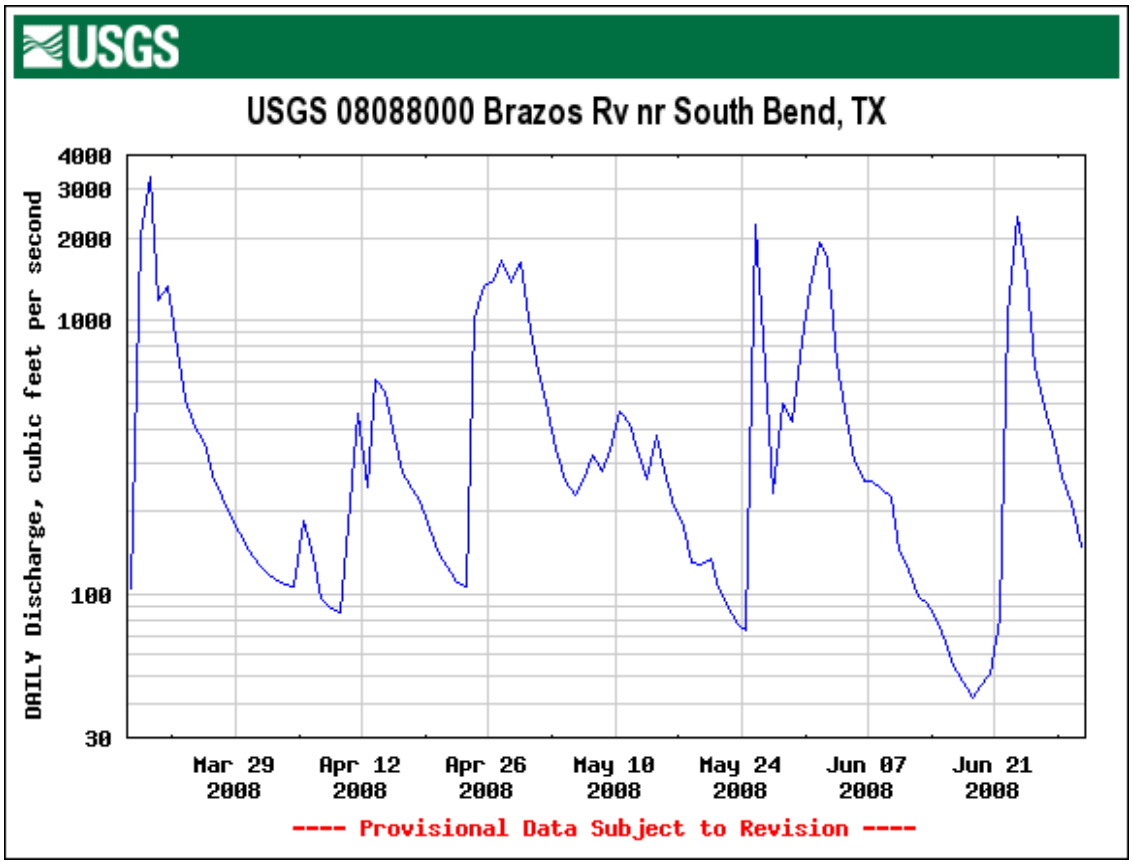


Figure 21: Storm events and peak discharges occurring from March to June 2008.

Using the sediment discharge data from the turbidity probe, suspended sediment concentration levels were tracked for each storm event. Graphs plotting the sediment concentration/discharge change were created, and are shown in figure 22 A-F.

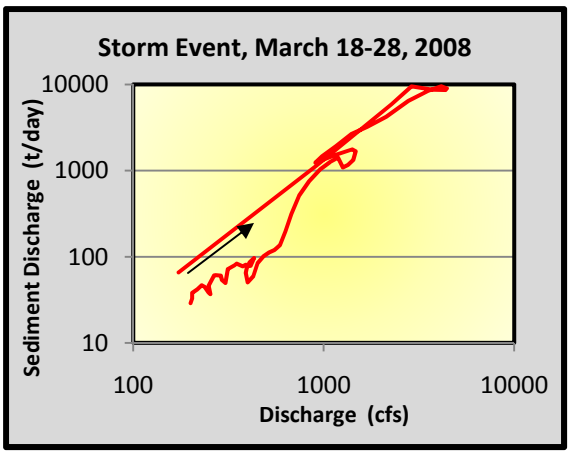


FIGURE A

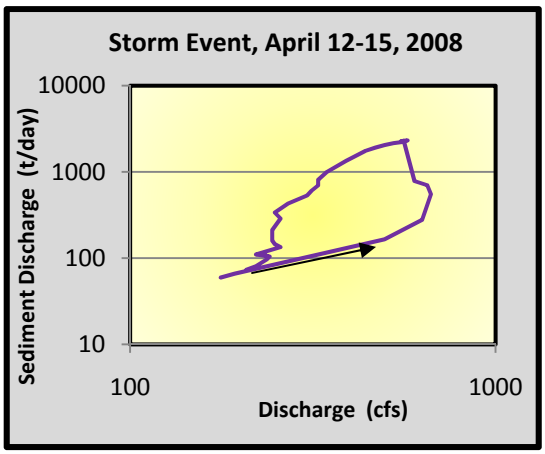


FIGURE B

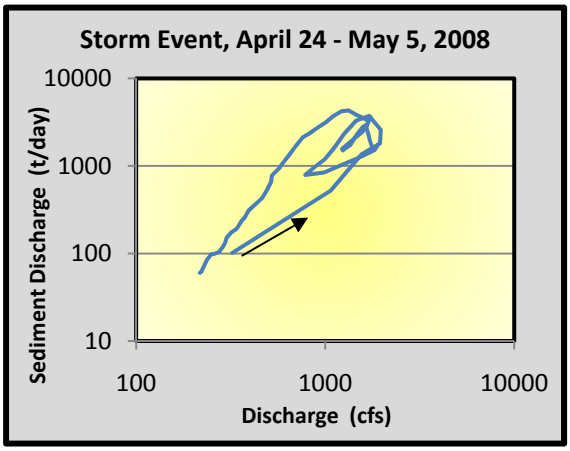


FIGURE C

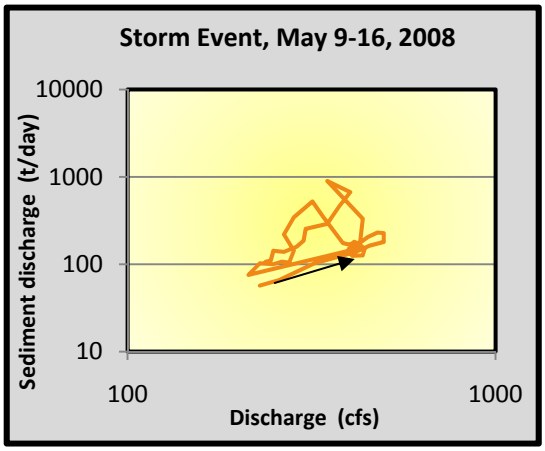


FIGURE D

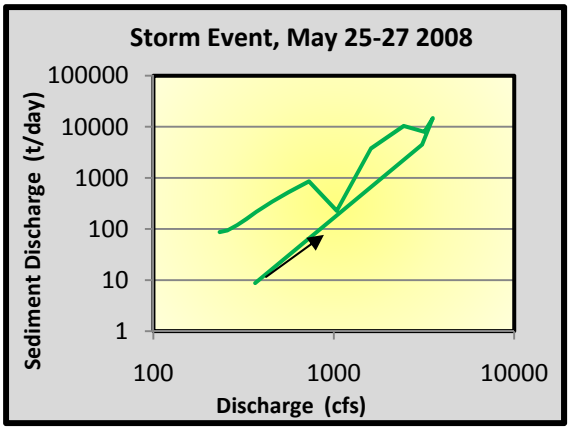


FIGURE E

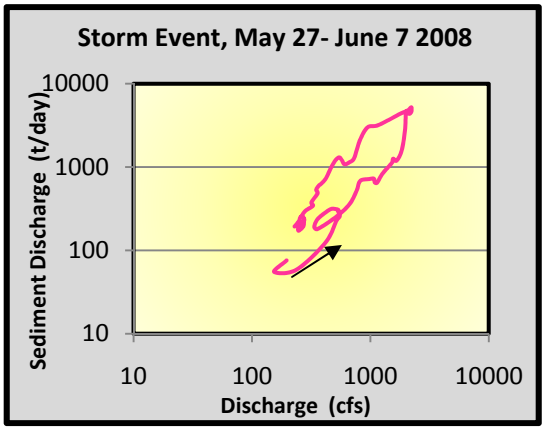


FIGURE F

FIGURE 22 A – F: Graphs Plot suspended sediment discharge versus discharge for specific storm events. Arrows indicate the beginning of the storm.

Figure 22 A is the only plot to display positive hysteresis with the sediment concentration opening in a clockwise direction. The rise in sediment discharge and subsequent fall in concentration levels as discharge drops represents the initial flushing event. Prior to this first major storm event the river has experienced low flow and drier winter months. Sediment has accumulated within the channel itself due to settling, and sediments located adjacent to the river are more easily erodible due to exposure to organisms and the elements. This essentially primes the sediment for entrainment as discharge increases. The magnitude of sediment transported within the water column will decrease over this initial storm event due to flushing.

All of the other sediment hysteresis plots display a negative hysteresis, opening in a counterclockwise loop. Essentially with these storm events the higher sediment concentrations are seen after peak discharge has occurred and the discharge level is dropping. The reason for ths occurrence could be one of three things: (i) limited sediment exhaustion, (ii) delayed triggering of sediment supplies, (iii) or a distant source of sediment. The most likely scenario in this reach of the Brazos is that most of the sediment supplied to the river is from distant upstream reaches rather than immediately up river and proximal to the gaging station.

The storms events measured within this time frame were not simply isolated thunderstorms, but rather large complex systems dropping large amounts of rainfall. The Brazos River at South Bend displays a flashy response to these storm events, with a rather quick and steep rise in discharge and a gentler decline. The immediate response or rise in discharge is associated with rainfall within the adjacent area, while the slower decline is due to the influx of storm water from upper basin reaches. This influx from the upper basin slows the overall discharge decline rate, and brings with it sediment laden waters. The sediments located in the

upper basin are easily erodible and heavy rainfall washes large amounts into the river. This influx of sediment causes the rise in sediment concentrations as the discharge rate drops.

Bed Load Transport

Figure 23 and 24 show the suspended and bed load rating curves for the Brazos River at South Bend and Seymour, TX. Both graphs show similarity in the slope when comparing the suspended load and bed load curves, suggesting a seemingly consistent increase in sediment discharge as flow increases. However, at both stations suspended sediment discharge is at least an order of magnitude greater than bed load discharge. This difference is even greater at the higher-end flows. It should be noted that at both stations there are fewer bed load samples than suspended load samples and more data is needed to confirm the relationship between suspended load and bed load.

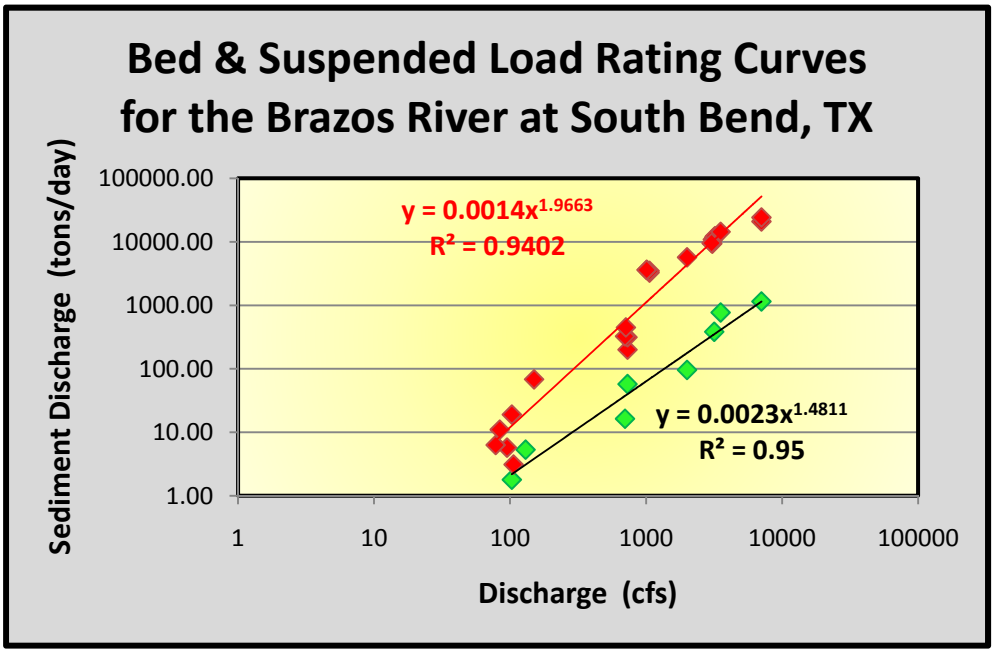


Figure 23: Bed load (green) and suspended load (red) rating curves for the Brazos River at South Bend, TX, created using contemporary hand sample data.

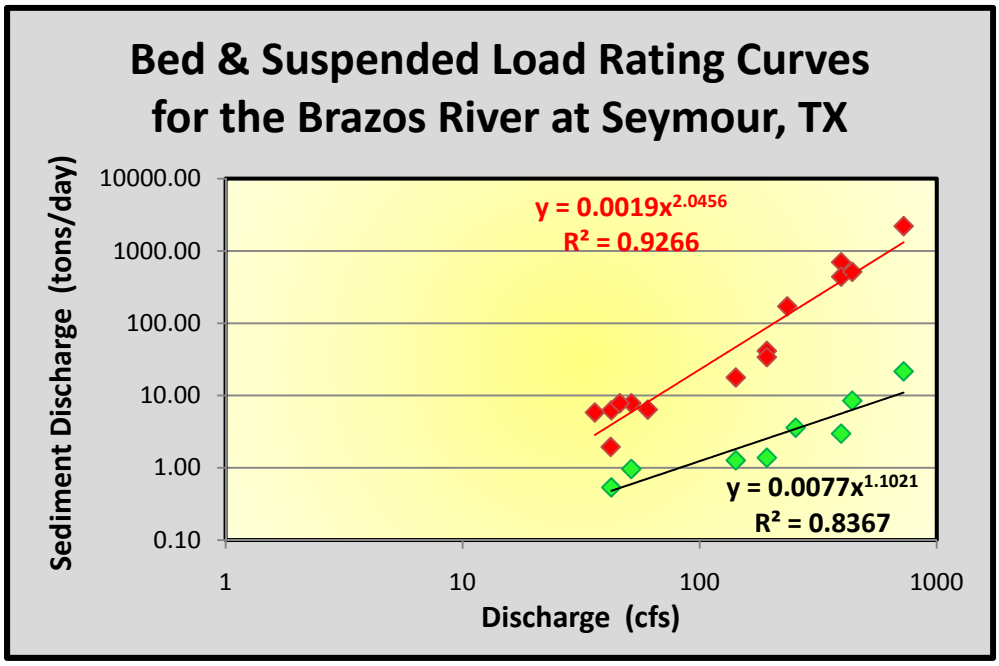


Figure 24: Bed load (green) and suspended load (red) rating curves for the Brazos River at Seymour, TX, created using contemporary hand sample data.

Obtaining bed load samples is often difficult, and there is considerable inherent variability in bed load transport even at low discharge rates or unchanging conditions. Nonetheless, the data consistently show that the Brazos River at Seymour and South Bend transports more sediment in the suspended column than along the channel bed. This is most likely related to the sediment source areas located within the upper basin. These source areas readily produce fines such as clay and silt. These particles are often difficult to entrain within the water column but once captured they remain in suspension until flows drop significantly. This means that flows that would not transport heavier particles can still transport significant amounts of suspended sediments, thus producing the higher curves. Sandy areas are also common within the upper basin. Sand-sized particles are most typically stored in bar forms

within the river channel, and will move in small amounts through the river system at low flows. Higher discharges contain more power and are therefore more capable to transport bed load.

Truly reliable bed load data is difficult to acquire in any form and there is often significant scatter and inconsistency within the bed load rating curves created from such data. Inconsistency and scatter are apparent within the graphs above. Bed load samples taken at similar discharges at South Bend have vastly different sediment discharges, while at Seymour similar sediment discharges are found at varying flow conditions.

There are two major reasons why bed load data acquisition is difficult. First, it is assumed that bed load transport is uniform across the riverbed. Bed load samples are taken at one point on the riverbed, directly off the riverbed, and are subject to numerous disturbances. In suspended sediment sample acquisition, depth integration allows for greater control in measuring the amount of sediment transported throughout the water column. The way bed load samples are acquired does not account for variation across the channel. The riverbed is a dynamic environment and is continually changing, while the water column is fairly constant varying only in discharge level and sediment concentration. The channel bed can change significantly from one flow event to another, and bed forms are created and destroyed daily. If samples are taken at one point along the river bed, they will be influenced by these changing parameters. If the sampler were mover slightly left or right the sample collected could change drastically. The crux of the problem is that the mouth of the Helley – Smith sampler is approximately 7 cm in diameter, and the bed load was extrapolated from this small area to the entire channel width, which in this case was 140-170 feet. Obviously there is a lot of room for error, but this is the only way to estimate the overall bed load transport.

The other problem lies within the equipment itself. The sampler itself is bulky, extremely heavy, and often difficult to maneuver in high flow events. Because of the size of the sampler it is often entrained within the flow in high discharge events, pulling the sampler under the bridge, making retrieval difficult. This makes it next to impossible to control the position of the sampler, thus limiting the amount of sediment entering the mouth. Because of the length of time the sampler must remain on the riverbed, debris is a major obstacle as well. High discharges often carrier large debris which could catch on the line and pull the whole rig into the river. Debris was a major issue when sampling on the Brazos during high flows, effectively limiting the number of high discharge samples taken due to safety concerns.

CONCLUSIONS

This thesis has examined the sediment transport dynamics of the Brazos River within the upper basin. The following conclusions have been reached:

1) The flow duration curves for the Brazos indicate that both Seymour and South Bend experience similar high and low flow regimes, with the magnitude of the flow being the only difference. South Bend has an overall higher discharge and flow regime than Seymour, not surprising given the significantly larger contributing area at South Bend. Median discharge (Q0.5) at South Bend is 120 cfs, whereas Q0.5 at Seymour is 80 cfs. High magnitude flows at both these stations on the main stem are comparable with Q0.05 at South Bend 5,000 cfs and 2,500 cfs at Seymour, respectively.
2) The contemporary samples at Seymour produced a rating curve with a much lower slope, and specific sediment yield dropped from 1,708 t km^{-2} yr^{-1} to a more reasonable 70 t km^{-2} yr^{-1}. The yield at South Bend, which was considered low at 20 t km^{-2} yr^{-1}, was raised to 62 t km^{-2} yr^{-1}, an amount which seems more consistent with that of the basin as a whole.
3) Heavy rainfall within the upper basin region of the Brazos River typically produces negative hysteresis within the sediment discharge. The sediment concentrations are greater as discharge is dropping, this occurs in this reach of the Brazos because most of the sediment supplied to the river is from distant upstream reaches rather than immediately up river and proximal to the gaging station.
4) Turbidity data collected from March to June 2008 produced a modern sediment rating curve. This data was compared to the historical suspended sediment record

and the contemporary data When the data sets are overlain all three display a similar slope. The similarity in the slopes confirms that the contemporary data is reliable and gives a better overall picture of sediment transport within the upper basin

5) At both Seymour and South Bend suspended sediment discharge is at least an order of magnitude greater than bed load discharge. The low bed load values suggest that bed load contributes less to the overall sediment load of the Brazos River.

Because bed load data is often difficult to obtain, for numerous reasons, there was a significant lack in the quantity and resolution of samples. Future studies within the basin should focus on clarifying the more wholly quantifying this component. Contemporary sampling should be continued at both South Bend and Seymour. Continued sampling would further improve the understanding of sediment transport dynamics within this region. A final issue that should be addressed is that of sediment sourcing and residence time. Essentially where is the sediment coming from, and how long is it staying. GIS and Remote sensing technology could prove valuable in assessing these attributes.

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VITA

Personal Background

Lisa Leeann Black
Born June 12, 1979 in Homestead, Florida
Daughter of Ray and Debbie Black
Married James William Knightstep, March 31, 2007
One child

Education

M.S. in Geology, August 2008, Texas Christian University, Fort Worth, TX
B.S. in Geology, May 2006, Midwestern State University, Wichita Falls, TX

Experience

Geologist, Quatro Oil and Gas, Wichita Falls, TX, May 2006-Present
Teaching Assistantship, Texas Christian University, Fort Worth, TX, August 2006-May 2008
Teaching Assistant, Midwestern State University, Wichita Falls, TX, August 2004-May 2006

ABSTRACT

QUANTIFYING INSTREAM SEDIMENT TRANSPORT IN SEVERAL REACHES
OF THE UPPER BRAZOS RIVER BASIN, TEXAS

By Lisa Leeann Black, M.S. 2008
Department of Geology
Texas Christian University

Thesis Advisor, Michael C. Slattery
Department Chair and Professor of Department of Environmental Science

The focus of this research was the clarification of discrepancies found within the historic suspended sediment record for the Upper Brazos River, specifically at South Bend and Seymour, TX, as well as quantifying sediment transport dynamics within the upper basin. Flow duration curves constructed for the Brazos River indicate that both Seymour and South Bend experience similar high and low flow regimes, with the magnitude of the flow being the only difference. Contemporary samples at Seymour and South Bend produced specific sediment yields of 70 t km^{-2} yr^{-1} and 62 t km^{-2} yr^{-1} respectively. Heavy rainfall within the upper basin region of the Brazos River typically produces negative hysteresis within the sediment discharge. These concentrations are greater as discharge is dropping, this occurs in this reach of the Brazos because most of the sediment supplied to the river is from distant upstream reaches rather than immediately up river and proximal to the gaging station.