Sediment budgeting in the upper and middle basins of the Brazos and Trinity Rivers, TX: An assessment of methods and directions for future work

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1. Introduction

A sediment budget can be 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, p. 3). Sediment budgets generally focus on sediment production or input to a geomorphic system, transfer mechanisms within that system, the loss or output, and additions to or losses of storage. It represent 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, however, a substantial oversimplification because production, transport, and storage units occur repeatedly across basins, particularly large, multi-land use systems. For instance, sediment production from rills and gullies in headwater areas may settle into mid-basin storage in fans 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 basin. Furthermore, sediment transport is highly episodic: large amounts of material may be mobilized during flood events, but equally large volumes may be deposited in storage locations, eventually to be re-mobilized in later events.

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, other things being equal, easier to work with. But the huge quantities of area, sediment, water, and other mass represented or transported and stored by large rivers, such as those crossing the coastal plain of Texas, demands that we engage them. This is a major challenge, both logistically and conceptually.

Sediment delivered to streams has several potential downstream impacts. High loads of suspended sediment, the silts and clays that are carried in the flow, degrade water quality in streams, reservoirs and estuaries. This is a result of both the sediment itself and the nutrients that the sediment carries. High suspended sediment concentrations reduces stream clarity, inhibits respiration and feeding of stream biota, and diminishes light needed for plant photosynthesis. Large sediment loads also exert important controls on channel morphology that affect habitat quantity and quality for aquatic and riparian species. Sediment transport and storage characteristics 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 amount of sediment stored within channels is also critical in determining environmental (i.e., in-stream) flows. This report documents various approaches to sediment budgeting in the upper and middle Brazos and Trinity River basins in Texas (Figure 1). The goal is not to construct the fluvial sediment budgets for these basins *per sé*; rather, the focus is on the methods used to construct individual components of a sediment budget and the types of data that can be generated using fairly rapid and straightforward estimation techniques. The time frame and scope of this project necessitated using a rapid sediment budget approach using existing information and limited field surveys. Recommendations on ways to refine aspects of the sediment budget in future work are also made.

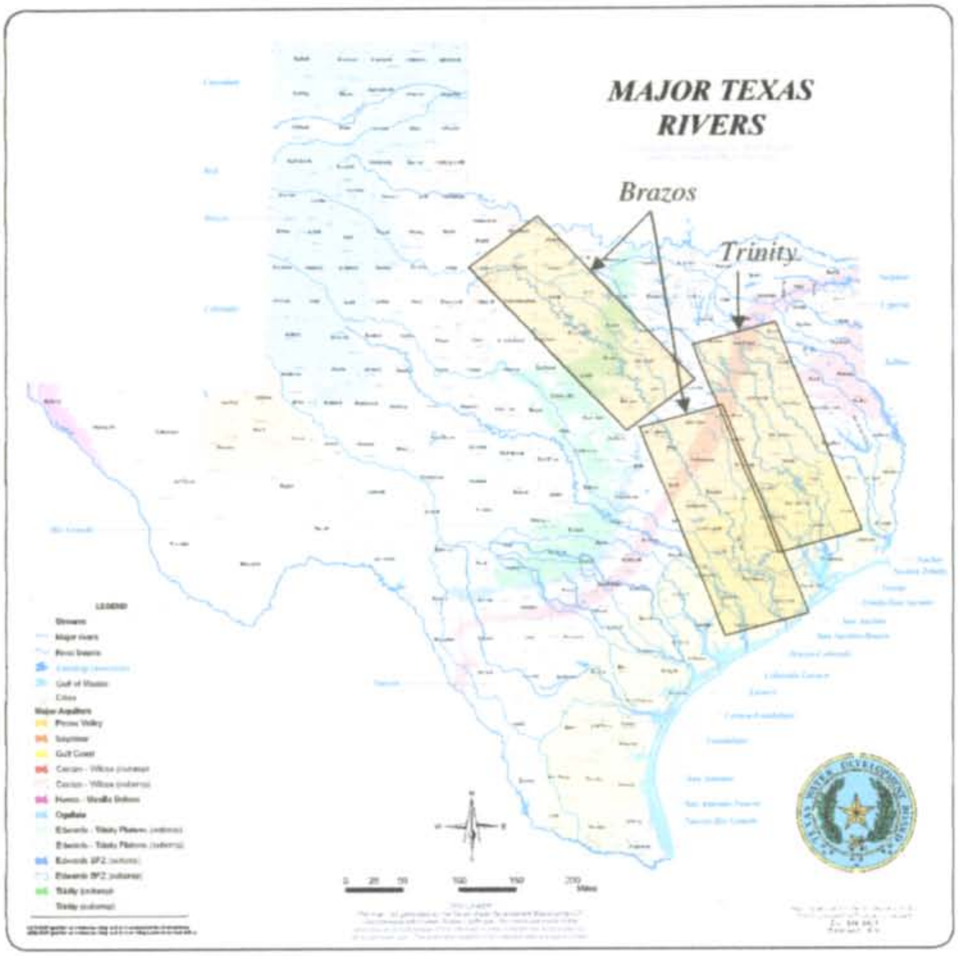

Figure 1. Sections of the Brazos and Trinity River basins studied in this paper (map source: Texas Water Development Board).

2. Methods

2.1 Sediment supply to mainstem reaches

Estimates of sediment production and delivery to mainstem reaches are based on three sources. First, daily suspended sediment samples have been collected at gaging stations along several tributaries in the Brazos and Trinity basins by the United States Geological Survey (USGS) and Texas Water Development Board (TWDB). 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.

Independent estimates of sediment delivery to streams in the two basins were made from reservoir surveys conducted by the TWDB. The surveys document changes in reservoir capacity, which are 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 range 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). We assumed a conservative density of 1 Mg m^{-3}. Data were averaged for 27 lakes in east and central Texas, in the same land resource areas as those encompassing the study basins.

Annual sediment production rates in sub-basins of the Trinity watershed were also calculated 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 a field associated with an NRI sample site that is under cropland, pastureland, or land enrolled in the Conservation Reserve Program. In this study, we 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. We then imported the USLE soil loss (land use/cover by county) estimates into the GIS dataset to get soil loss by 12-digit HCU (see Figure 2).

The erosion/production rates produced by these three approaches are essentially surrogates for all sediment processes occurring within the basins, such as rainsplash, sheet and rill erosion, cutbank erosion by fluvial processes, and mass failure of unstable banks, etc. We do not differentiate between these processes at this scale.

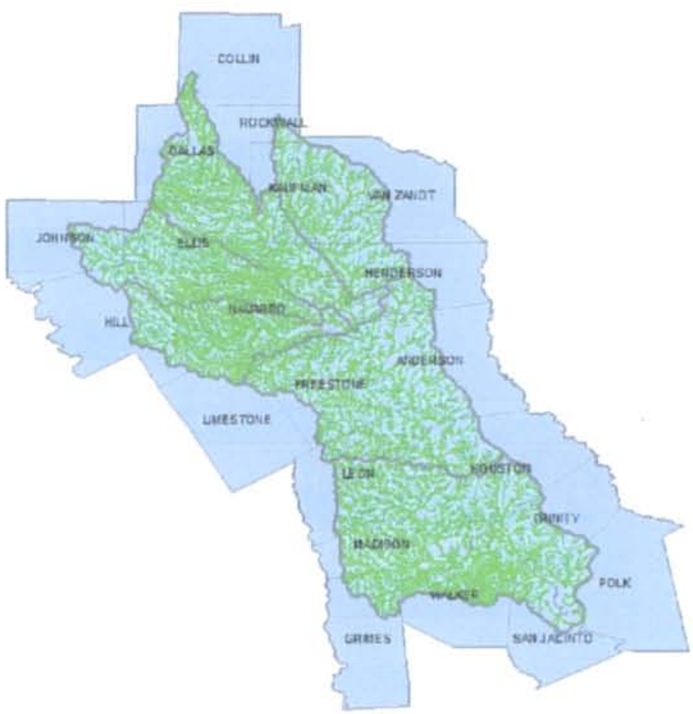

Figure 2. The 12-digit HCU's (Hydrologic Cataloging Unit's) in the middle Trinity used to estimate sediment production using the NRI.

2.2 Mainstem erosion and sediment transport

Mainstem bank erosion rates were computed along a 75-km length of the lower Trinity River between Romayor and Liberty. This work was carried out as part of an earlier study on channel planform change and published in the journal *Geomorphology* (see Wellmeyer *et al.*, 2005). However, we include a summary of the methods and results here because it is an extremely useful (and recommended) approach to estimating channel bank contributions to any future sediment budgeting work in these basins.

Channel change (and derived erosion rates) were obtained by comparing historic aerial photographs over five time periods from 1938 to 1995. Each image was digitized, geo-referenced, spatially corrected, and imported into the Arcview GIS. For each of the periods, a vector outline of the bankfull channel location was manually digitized at three locations (see Figure 3). Rates of channel creation (or floodplain erosion) occurring during individual photographic intervals were measured by raster overlay (Figure 4). Layers of two consecutive years of channel occupancy were overlain resulting in three classes of cells; those occupied during both time periods, those occupied only in the first photograph, and those occupied only in the second photograph.

Created channel area is computed from cells occupied only during the more recent photograph. Rates of each process are then computed by dividing the total area of process by the time elapsed between photographs from which the channel occupancy maps were derived (Figure 4). By comparing the relative areas of channel creation, a net change in channel area for a specific time period could be calculated. Annual volumetric sediment production from streambank erosion in sample reaches was then calculated by multiplying the area of eroding bank per unit stream length by an average annual depth of bank erosion measured at several sites.

For mainstem sediment transport, suspended sediment samples collected by the USGS and TWDB at stations on the Brazos River and Trinity River were used. Data collected in a recent study on the lower Trinity by Slattery *et al.* (2007) were also used. The measured concentrations were converted to daily transport values based on the mean daily flows recorded at the gaging stations. As with tributary data, flow duration curves and sediment rating curves were constructed for each station in order to determine annual sediment yield at various points along the mainstem reaches.

It is important to note that suspended sediment measurements underestimate transport by not accounting for bed load. It is conventional in many studies to add 10 percent to account for bed load. At the Romayor station on the Trinity River, on 12 occasions between 1972 and 1975, the USGS measured suspended and bed load on the same day. Bed load represented 1.4 percent to 21.4 percent of total sediment load, with a mean of 9.7 percent. Recent work on the Trinity suggests that bed load transport is considerably less than this 10 percent figure (Slattery *et al.*, 2007), though variability among samples was high. Thus, sediment transport estimates based on suspended measurements alone were increased by 10 percent.

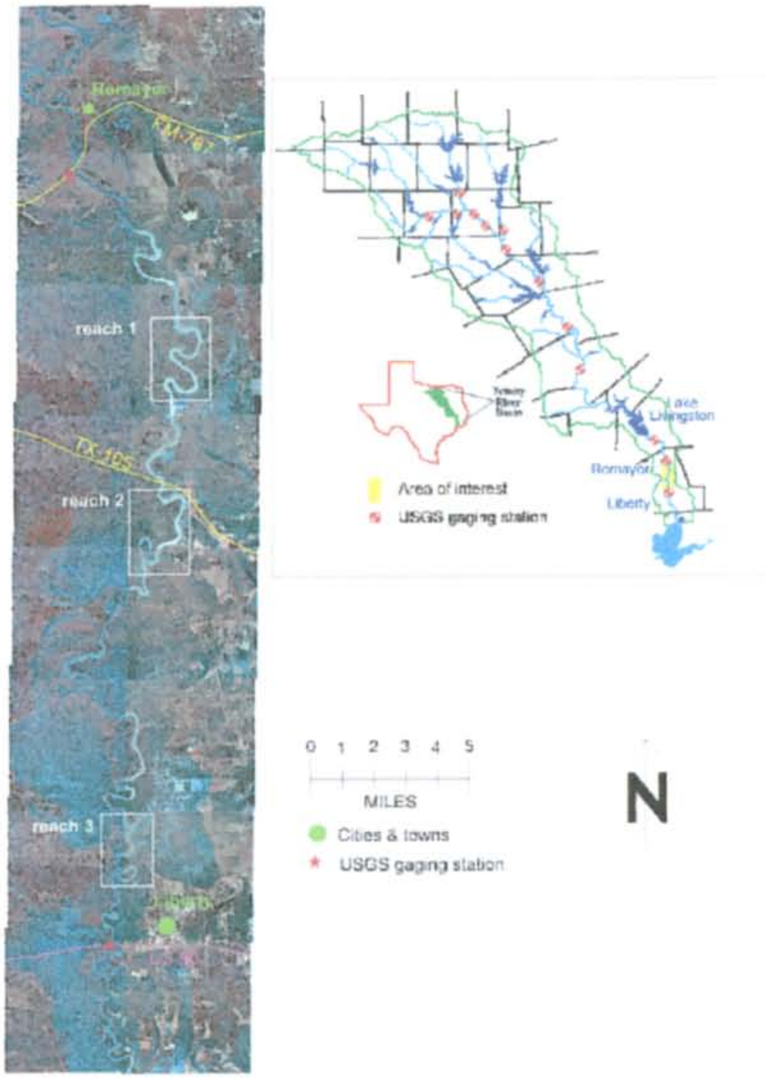

Figure 3. Locations of channel erosion estimates using the GIS approach described in the text.

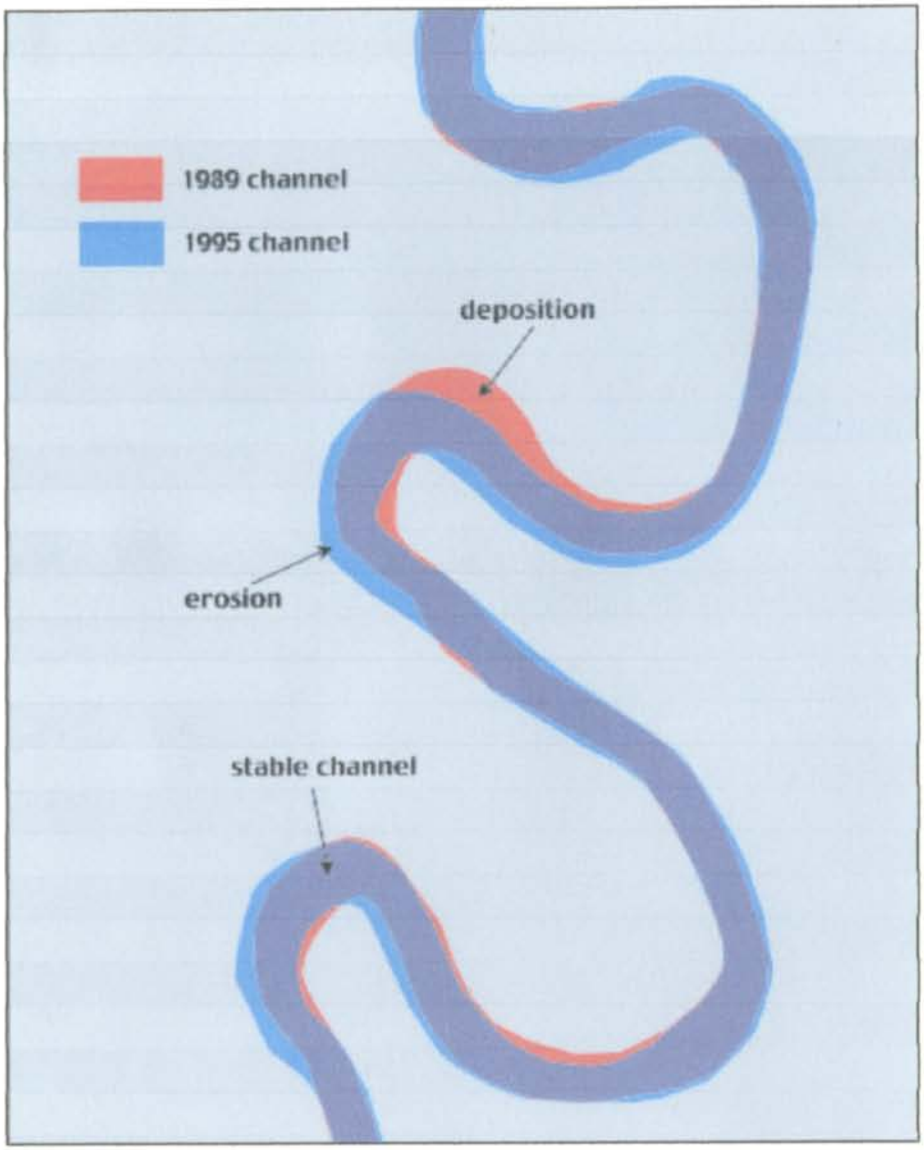

Figure 4. Example of channel overlays for 1989 and 1995.

2.3 Alluvial 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 difficult, particularly over periods of decades or longer for constructing an average annual sediment budget. Two methods were used to estimate alluvial storage magnitudes. First, storage was inferred simply on the difference between sediment delivered to the stream and 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 (estimated using the three approaches outlined in section 2.1 above) is transported to the main channel. For example, the estimate of maximum storage for the reach on the Trinity between Oakwood and Crockett is based on upstream input (i.e., yield at Oakwood). plus sediment produced in the drainage area between the upstream and downstream ends of the reach, minus downstream output (i.e., at Crockett).

Storage of sediment on the mainstem of the Brazos was also investigated via volumetric surveys using a Leica Total Station digital surveying system. We mapped channel bars at low flows along representative sections and produced three dimensional terrain models of the sand bars using the *Surfer 8* computer graphics program. The digital terrain models were then used to calculate volumes of sediment stored within the channel at various flow levels. Extrapolating the data to a larger scale, though not devoid of problems, does allow an estimate to be made of the amount of sediment accumulating and being stored in channel depositional structures rather than transported through the system.

3. Results and Discussion

3.1 Sediment production and delivery

The sediment rating curves for stations along the Brazos and Trinity rivers are shown in Figures 5 and 6 (the flow duration curves used to construct the sediment-discharge relationships are given in Appendix I). The computed sediment yields at each station are given in Table 1.

The gaging stations on Long King Creek at Livingston (Trinity) and Mill Creek near Bellville (Brazos) have mean annual sediment yields of 467 t km^{-2} $year^{-1}$ and 583 t km^{-2} $year^{-1}$, respectively. As shown in Table 1, these are considerably higher than sediment yield per unit area for any other tributary stations on either the Brazos or Trinity (mean of other tributaries = 17.5 t km^{-2} $year^{-1}$). However, we emphasize that the historic sediment record on the Brazos and Trinity (with the exception of Long King Creek) 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 here must be seen as *broad estimates of sediment transport* rather than precise calculations. Augmenting the historic record with either manual measurements or the use of turbidity probes (as we have done on the lower Trinity in previous work; see Slattery *et al*., 2007) is possible, though doing so increases the time (and cost) required to construct the sediment budget. Notwithstanding, based on the tributary data, sediment loadings within the Brazos and Trinity basins are estimated at 145 t km^{-2} $year^{-1}$ (σ = 238 t km^{-2} $year^{-1}$).

The lake surveys indicate sediment yields of 6 to 1002 t km^{-2} $year^{-1}$, with a mean of 275 (σ = 331 t km^{-2} $year^{-1}$, Table 2). These data include three cases where measured storage capacities increased as a result of dredging, flushing, or increasing dam heights. The lakes have a mean annual sediment yield of 315 t km^{-2} $year^{-1}$ (σ = 330 t km^{-2} $year^{-1}$) when the three lakes with increases in capacity are excluded.

If reductions in reservoir capacity are indeed due to fluvial sedimentation, these data represent a reasonable estimate of sediment delivery to the fluvial system as lake sediments include bed load as well as suspended loads, and reflect sediment actually delivered to the fluvial system. Based on the lake data then, sediment loadings within the Brazos and Trinity basins are estimated at 315 t km^{-2} $year^{-1}$.

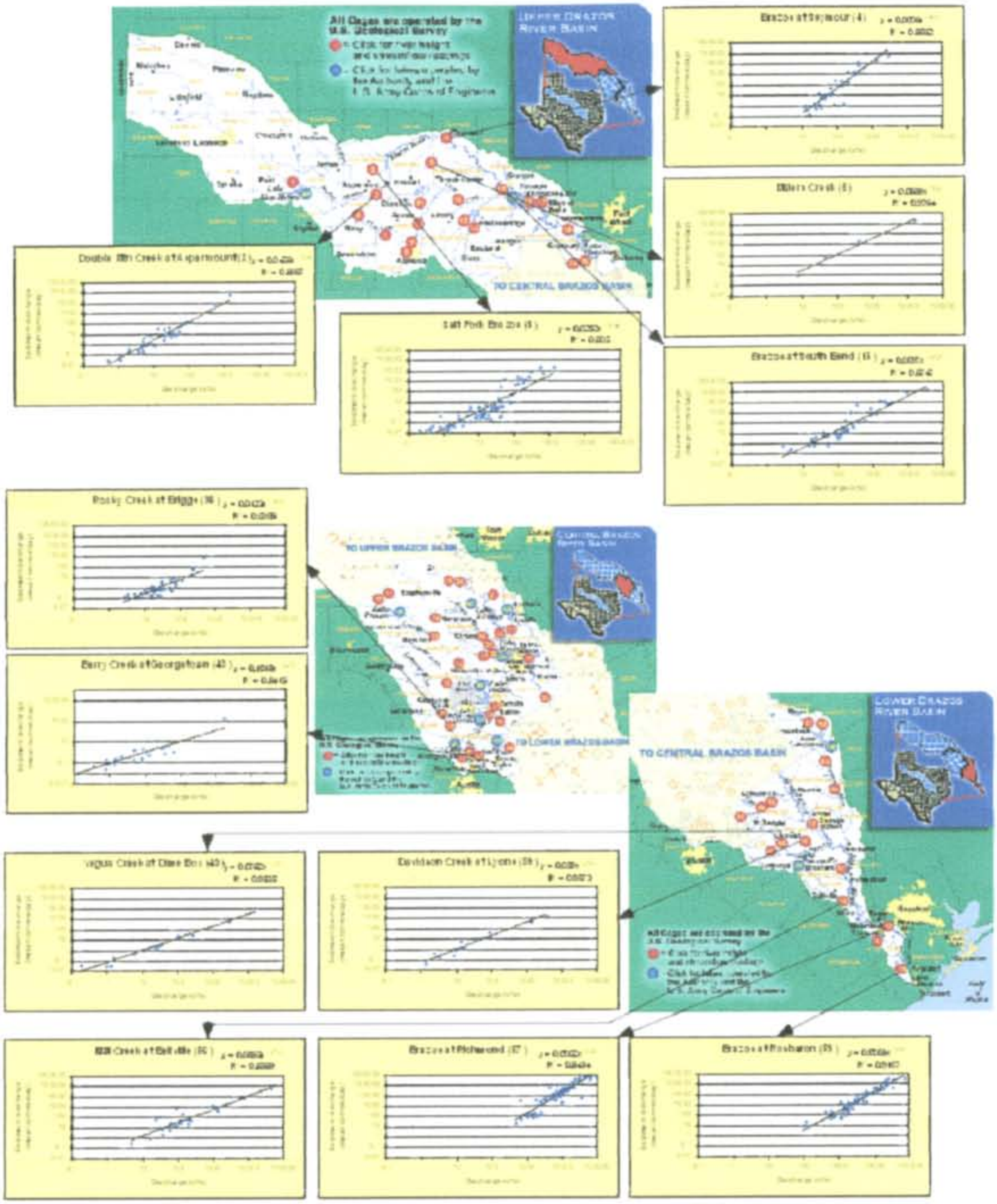

Figure 5. Sediment rating curves for 12 stations along the Brazos River and its tributaries.

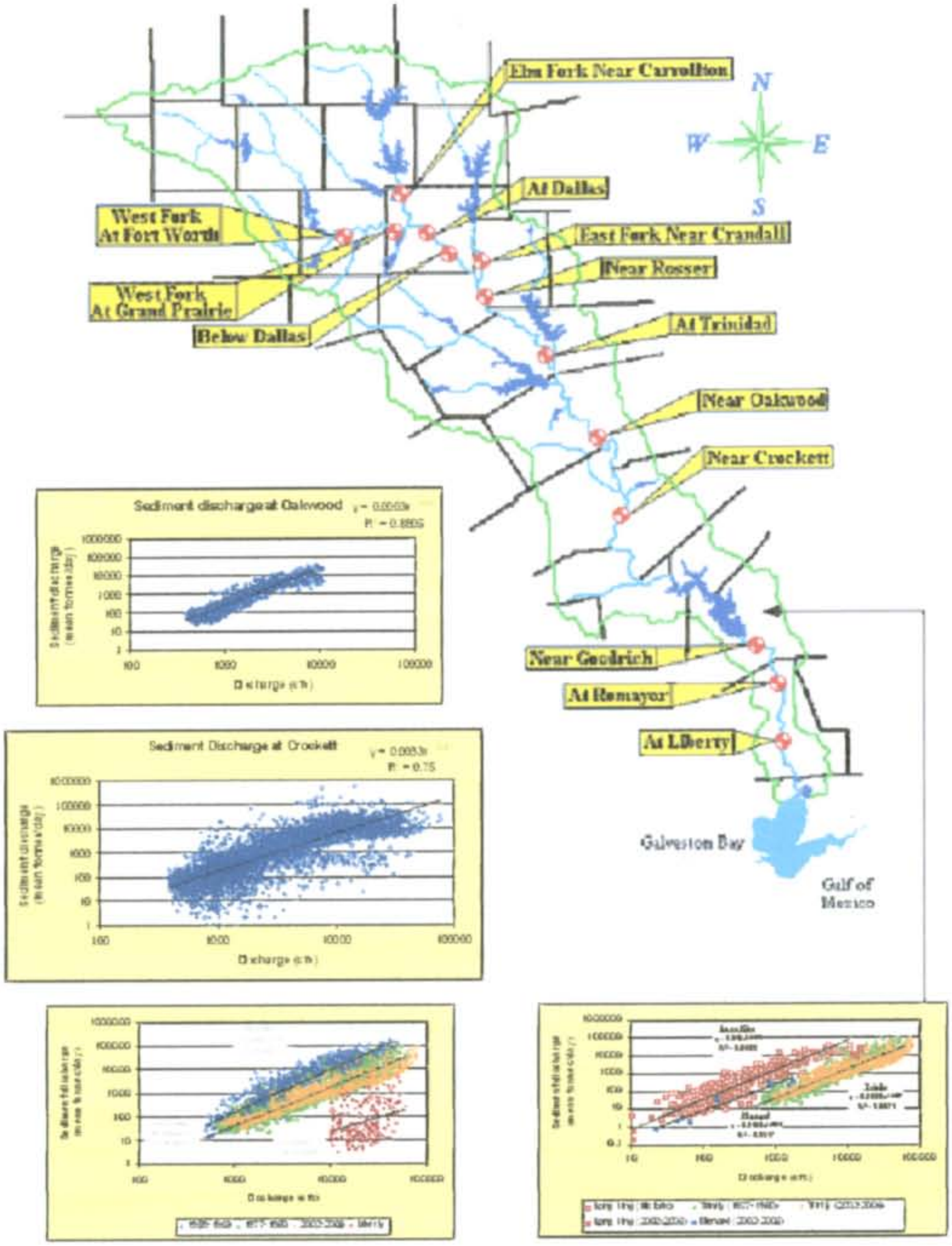

Figure 6. Sediment rating curves for 6 stations along the Trinity River and its tributaries.

Table 1. Sediment delivery and yields for tributaries in the Brazos and Trinity River Basins. Sediment data analyzed from the USGS, TWDB, and Slattery *et al.* (2007).

	Area (km^2)	Sediment Yield (t/year)	Specific Sediment Yield ($t/km^2/year$)
Upper Brazos			
USGS 08082700 Millers Ck nr Munday, TX	269	8,140	30
Middle Brazos			
USGS 08103900 S Fk Rocky Ck nr Briggs, TX	86	160	2
USGS 08105100 Berry Ck nr Georgetown, TX	215	874	4
Lower Brazos			
USGS 08109800 E Yegua Ck nr Dime Box, TX	632	4,074	6
USGS 08110100 Davidson Ck nr Lyons, TX	505	9,435	19
USGS 08111700 Mill Ck nr Bellville, TX	974	567,756	583
Middle and Lower Trinity			
USGS 08066200 Long King Ck at Livingston, TX	365	170,500	467
USGS 08066300 Menard Ck nr Rye, TX	394	17,070	43

Table 2. 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 (km^2)	Storage loss (m^3)	Years	Yield $t/km^2/yr$
Choke Canyon	14,219	(5,107,924)	11	(33)
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
Medina	1,642	(10,398,410)	83	(76)
Granger	1,891	13,852,205	15	488
Aquilla	660	7,941,273	12	1,002
Somerville	2,608	62,338,623	28	854
Pat Cleburne	259	(209,695)	40	(20)
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 Cr.	47	1 5,051,183	39	275
Mean (all)	7,308	11,412,349	31	275
Mean (CP)	2,297	9,485,087	35	375

The USLE-based estimates of 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} $year^{-1}$ (Figures 7 and 8). 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} $year^{-1}$.

Sediment production rates based on the modeling, lake surveys, and field measurements of sediment transport in channels, give broadly consistent and comparable results, ranging between 145 and 315 t km^{-2} $year^{-1}$. However, production estimates using the three independent methods all have unique 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 as well as the lack of spatial resolution to the data at this scale. 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 basin and the data is clearly sparse.

USLE SOIL LOSS ESTIMATE

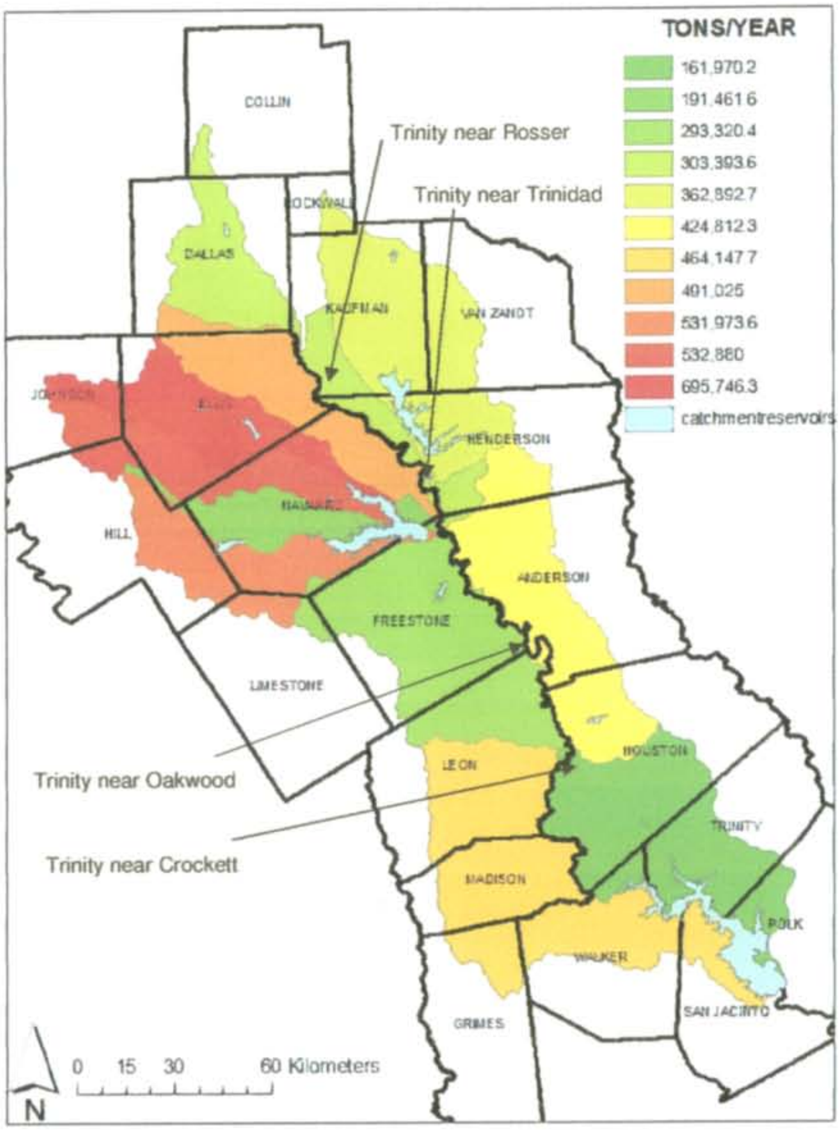

Figure 7. Computed annual sediment production in sub-basins of the Trinity River using NRI erosion rates incorporated into a GIS.

USLE SOIL LOSS IN TONS/HECTARE/YEAR

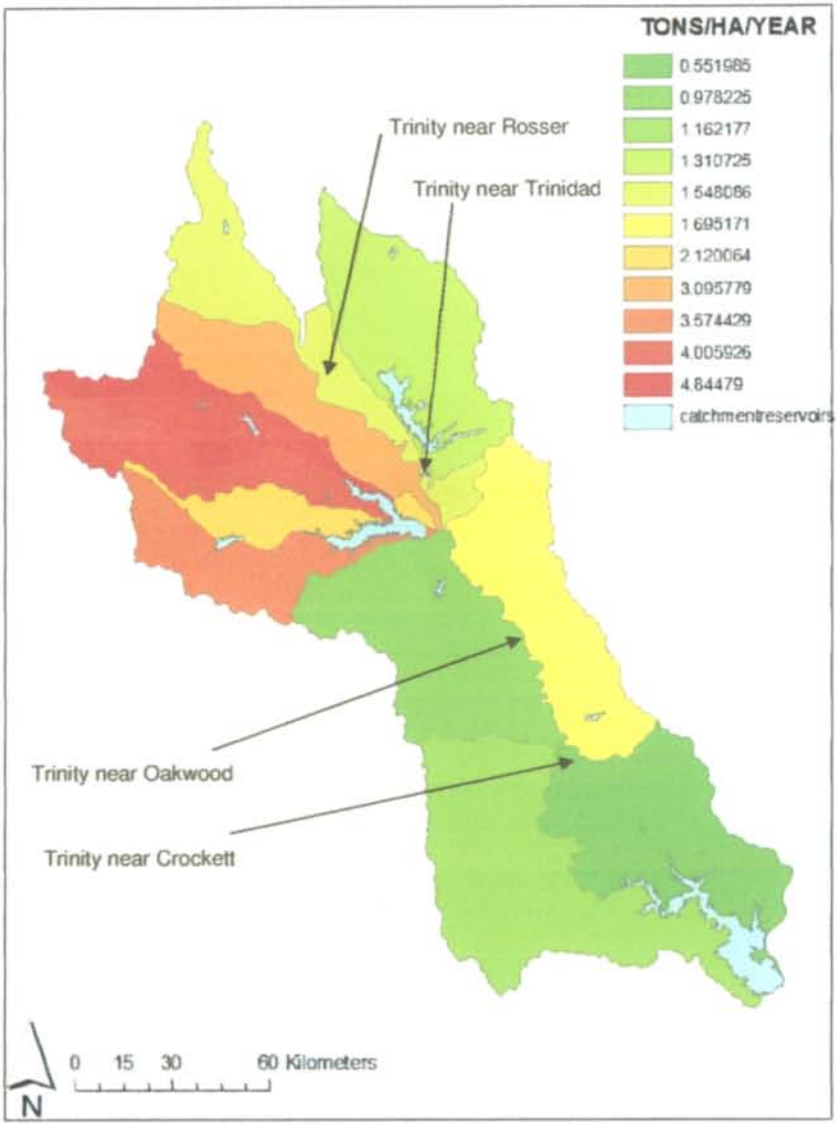

Figure 8. Computed annual sediment production per unit area in sub-basins of the Trinity River using NRI erosion rates incorporated into a GIS.

3.2 Alluvial storage

Comparison of average annual sediment yields along the main reaches of the Brazos and Trinity (Table 3) shows the apparent effects of alluvial storage. On the Trinity, yields at Oakwood are > 1.5 million t $year^{-1}$ greater than at Crockett and > 3.2 million t $year^{-1}$ greater than at Romayor, with Lake Livingston presumably accounting for much of the intervening storage. Sediment yields at Romayor are almost 50 times those at Liberty.

On the Brazos, sediment yields in the upper basin suggest a more complex picture of sediment delivery and storage. Yields at Seymour (1,220 t km^{-2} $year^{-1}$) 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 Texas. The sediments of the Brazos River have a distinctive red color and are characterized by fine grain sizes (Curtis *et al.*, 1973). 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. 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, which 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, there is also no clear reason as to why sediment yield would fall so rapidly (> 30 fold) between Seymour and South Bend over a distance of just 95 river miles. Sediment yields at Richmond and Rosharon, however, seem consistent and reasonable.

Table 3. Sediment delivery and yields in the Brazos and Trinity River Basins.

	Area (km^2)	Sediment (t/year)	Sediment (t/km^2/year)
Upper Brazos			
USGS 08082500 Brazos Rv at Seymour, TX	15,467	18,865,039	1,220
USGS 08088000 Brazos Rv nr South Bend, TX	33,947	559,286	16
Lower Brazos			
USGS 08114000 Brazos Rv at Richmond, TX	92,051	13,259,479	144
USGS 08116650 Brazos Rv nr Rosharon, TX	92,652	7,464,018	81
Middle and Lower Trinity			
USGS 08065000 Trinity Rv nr Oakwood, TX	33,237	6,623,012	199
USGS 08065350 Trinity Rv nr Crockett, TX	36,029	5,112,515	142
USGS 08066500 Trinity Rv at Romayor, TX	44,512	3,378,461	76
USGS 08067000 Trinity Rv at Liberty, TX	45,242	69,673	1.6

The amount of average annual alluvial storage can be constrained as shown in Table 4. The minimum storage is simply the upstream input as measured at the gaging stations minus the downstream output. Maximum storage assumes that all sediment delivery to channels (estimated at 145 using tributary loadings and 315 t km^{-2} $year^{-1}$ using lake loadings) is transported to the Brazos and Trinity Rivers. Using both the tributary and lake loading estimates gives us a minimum and maximum local input and thus a lower and upper estimate for maximum storage. The estimate of maximum storage for reaches is based on upstream input plus sediment produced in the drainage area between the upstream and downstream ends of the reach, minus downstream output.

Table 4. Alluvial storage by reach[a]

Middle and Lower Trinity	Area (km^2)	Upstream input	Minimum local input	Maximum local input	Downstream output[b]	Minimum storage[c]	Maximum storage[d]	Maximum storage[d]
Oakwood to Crockett	33,237	6,623,012	404,843	879,486	5,112,515	1,510,497	1,915,340	2,389,983
Crockett to Romayor	36,029	5,112,515	1,229,964	2,671,991	3,378,461	1,734,054	2,964,018	4,406,045
Romayor to Liberty	44,512	3,378,461	105,850	229,950	69,673	3,308,788	3,414,638	3,538,738
Liberty to Trinity Bay	45,242	69,673						
Brazos								
Seymour to Richmond	15,467	18,865,039	11,104,680	24,123,960	13,259,479	5,605,560	16,710,240	29,729,520
Richmond to Rosharon	92,051	13,259,479	87,145	189,315	7,464,018	5,795,461	5,882,606	5,984,776
Rosharon to Galveston Bay	92,652	7,464,018						

[a] All numbers in t $year^{-1}$.

[b] Upstream input and downstream output, respectively, refer to sediment yields at the upper and lower ends of the reach.

[c] Minimum storage is simply input–output.

[d] Maximum storage accounts for sediment delivery from the drainage area downstream of the upper and upstream of the lower end of the reach.

Several trends are apparent from Table 4. First, alluvial sediment storage in both basins is extensive. Storage is particularly apparent in the lowermost reaches of the Trinity. We have reported on an effective sediment bottleneck downstream of the Romayor gaging station (Phillips *et al.*, 2004) where alluvial storage dwarfs sediment yield. From Romayor downstream, the mean annual alluvial storage is 3.3 to 3.6 million t $year^{-1}$, or about 98 percent of the total input into the reach (Table 5). In the Brazos, there is no such sediment bottleneck, and storage in the lower basin approximates 45 percent of the total input to the system.

Table 5. Sediment yield and storage as percentage of total input to the fluvial system.

Middle and Lower Trinity	Area (km^2)	Total input	Downstream output	Percent Yield	Percent storage
Oakwood - Crockett	33,237	7,265,177	5,112,515	70.4	29.6
Crockett - Romayor	36,029	7,063,492	3,378,461	47.8	52.2
Romayor - Liberty	44,512	3,546,361	69,673	2.0	98.0
Liberty - Trinity Bay	45,242	69,673			
Brazos					
Seymour - Richmond	15,467	36,183,018	13,259,479	36.6	63.4
Richmond - Rosharon	92,051	13,397,709	7,464,018	55.7	44.3
Rosharon - Galveston Bay	92,652	7,464,018			

In-stream channel storage was estimated at two locations along a reach of the Middle Brazos (Figure 9). This area is considered an important section of the reach because the channel here is shallow and wide, and at low flow levels large expanses of sandbars are exposed, making the channel unnavigable in many areas. The issue is that it is an important recreational area from which many paddlers embark on their downstream journey toward Lake Whitney.

At a reference gauge height of 2.8 feet (= discharge of approximately 7.2 cfs), the volume of sediment exposed in the channel bars at the bridge site at FM 200 and the confluence of the Brazos and Paluxy Rivers is more than 7.6 million cubic feet. Total volume of sediment includes that which is unsurveyed below the water line, but at discharge representing extremely low flows, the calculation of the exposed sediment amount provides a reasonable representation of the stored alluvium that stream power is working with at the onset of a storm event. Using an average bulk density of 1.6 Mg m^{-3} for medium-grained sand, we calculate a total of 347,000 tons of sediment in storage in these mid-channel bars.

3.3 Mainstem erosion

Given the relatively low sediment yields from tributaries to the Brazos and Trinity Rivers, questions arise as to the source of sediments. For example, of the total drainage area at Romayor on the lower Trinity, 717 km^2 are downstream of Lake Livingston. Maximum local input from tributaries and other sources in this reach is estimated at 229,950 tons $year^{-1}$, approximately 8 percent of the sediment yield at the Romayor station. This implies that much of the sediment transported in the lower reaches of the Trinity either comes from upstream of the dam (which we know is not the case, given the clarity of the water downstream of the dam) or is derived from channel erosion between the dam and Trinity Bay.

Channel erosion is indeed evident in the field (Figure 10) and appears to be occurring at a significant pace. Channel scour and bank erosion has chronically threatened at least two bridge crossings in recent years in the lower Trinity, and bank erosion and channel migration have proved to be a recurring threat to property owners. Interestingly, the results from the channel change study support the notion 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 yr^{-1}, with mean annual channel erosion calculated at 30.2 ha $year^{-1}$ (Figure 11). Using an average channel depth of 7 m and a mean bulk density of 1.4 Mg m^{-3} yields a possible 2.96 x 10^6 Mg of sediment per year, which is equivalent to 87.6% of the annual sediment load measured at Romayor.

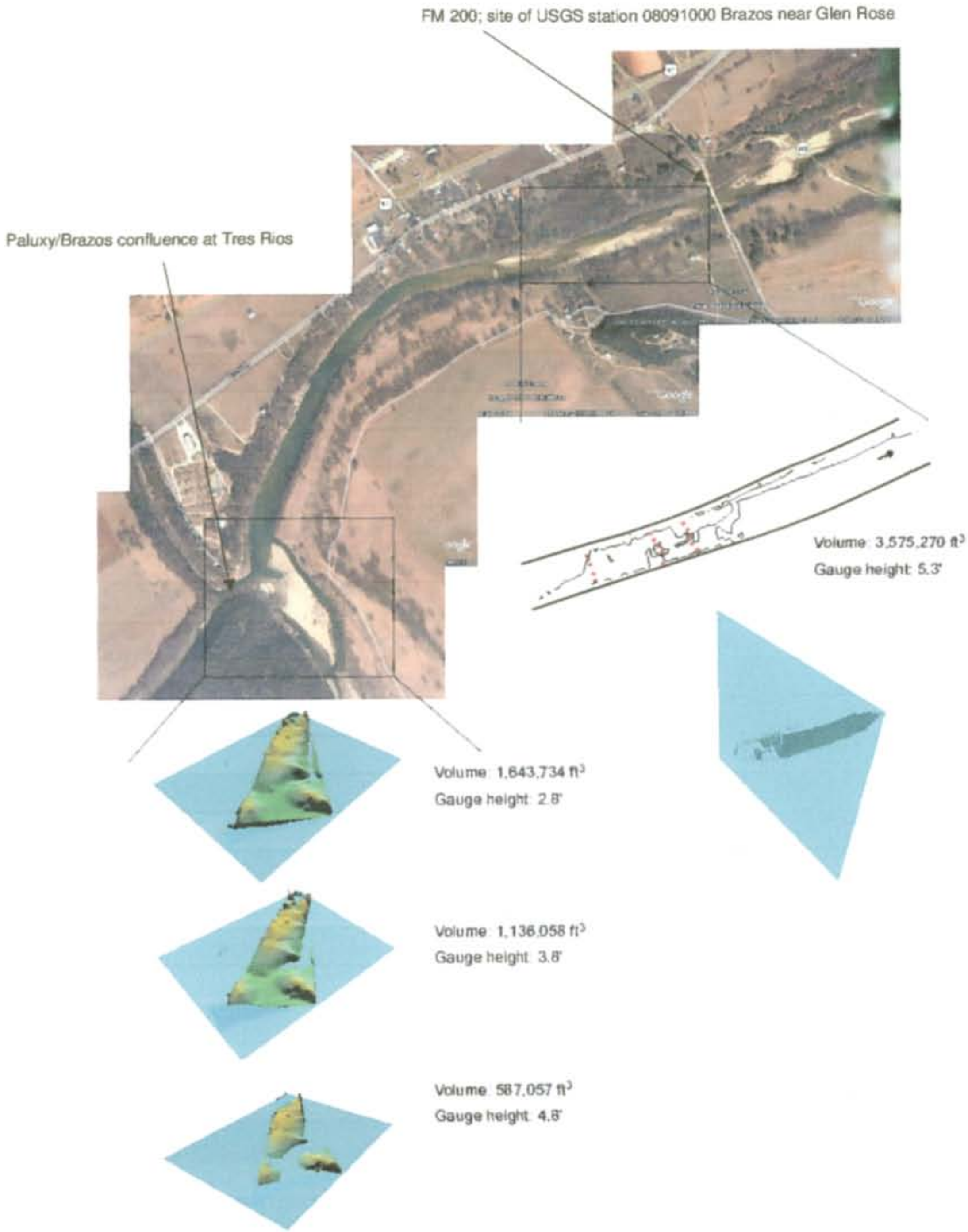

Figure 9. Sediment storage in mid-channel bars in the Brazos River between lake Granbury and Lake Whitney. At the confluence of the Paluxy and Brazos Rivers (left) we show progressive submergence of the bar system at 1 foot stage intervals.

Figure 10. Channel bank erosion upstream of the gaging station at Romayor.

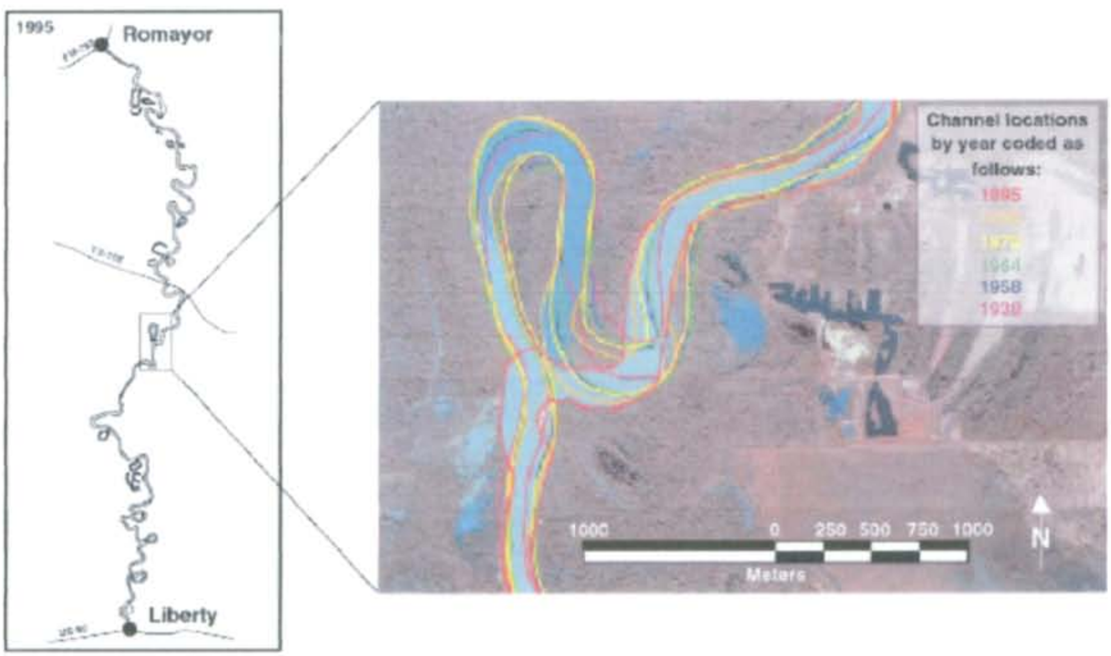

Figure 11. 1995 DOQQ showing a section of the Trinity River downstream of Romayor. Channel locations are mapped by individual photographic year and later overlain to permit computation of spatial change.

4. Conclusions and recommendations

The sediment budget estimates reported in this work are all potentially subject to numerous refinements. Certainly, more detailed field investigations could be conducted to address apparent deficiencies in process rate estimates: better information on tributary erosion rates, upland erosion, and mainstem incision rates would all assist in refining a sediment budget. We acknowledge that sediment storage at field edges, in upland depressions and tributary valleys, and in other locations is no doubt significant, but data and field evidence are not yet sufficient to address these processes. More detailed information is also needed on in-stream sediment yields.

This sediment budget work has been undertaken within a short time period and necessitated using a rapid sediment budget approach using existing information and limited field surveys. The goal of the work was to assess a number of methods that could be used to construct individual components of a sediment budget and the "usefulness" of the data generated. The intention is that, over time and with additional funding, further studies might be undertaken to improve the accuracy and precision of the processes and budget estimates.

Potential studies that could be undertaken to refine aspects of the sediment budget are organized below into two broad areas of inquiry.

4.1 Determination of sediment sources and process rates

- There are few direct measurements of sediment transport in regional catchments, and it is generally unrealistic to initiate sampling programs of river sediment loads and expect meaningful results within three to five years. In addition, direct measurements of sediment transport are time consuming and costly. Nevertheless, there is a clear need to improve the resolution of in-stream sediment yield data in Texas rivers. Such data provide the only reliable estimates of land-to-ocean sediment flux in large basins. We recommend deploying turbidity probes at key locations along mainstem reaches. On the Brazos, for example, we would identify Seymour, South Bend, Waco, and Rosharon as key sites. High-resolution data from these four stations would give a much clearer picture of sediment delivery through the system. Specifically, the difference in annual yield data between Seymour and South Bend cannot be explained in physical terms and appears to be in error. This must be clarified, particularly if in-stream flows are to be accurately assessed. The turbidity data would have to be calibrated with on-site, depth-integrated sampling (as we have done at the Romayor gaging station on the Trinity in other work). This is labor intensive, but could realistically be done over a period of three years so long as the sampling is carried out by personnel at institutions proximal to the sampling sites. The estimated cost to conduct this work at four gaging sites in five major river basins over three years is $225,000.
- Identifying the source area(s) of a stream's suspended load is a complex and difficult task. However, in order to develop a more complete understanding of sediment delivery processes and sediment movement in fluvial environments, better ***quantification*** of sediment source contributions is needed. Because these rivers clearly carry sediment generated from erosion of the stream banks themselves, this needs to be considered before examining river sediment loads. The Trinity River in particular has undergone major channel widening and bed degradation throughout its lower reach in historic times. The aerial mapping of channel erosion using the GIS-overlay approach proved extremely useful, generating high-quality data over large areas in a relatively short period of time. Such data can be extrapolated to over entire basins so long as good aerial coverage exists. We recommend continuing with this approach to quantify channel contributions to the fluvial sediment budgets of Texas streams. Some field

sampling of bank erosion would be required, but this would be primarily to determine representative bank heights to compute volumetric erosion from the aerial maps. We estimate the cost at $150,000 (one graduate student per basin at $30,000 per assistantship – five basins over a two-year period).

- The GIS-based approach provided the most practical framework for assessing rates of sediment production across large, complex (i.e. multiple land cover/use) basins such as the Trinity and Brazos. The NRI data incorporated into Arcview, and extrapolated across sub-basins and HUC's using appropriate expansion factors, gave results consistent with field-based measurements. Thus, we recommend continuing with this approach in lieu of extensive field sampling for the major basins across Texas. As with channel digitization, we estimate the cost at $150,000 (one graduate student per basin at $30,000 per assistantship – five basins over a two-year period).

4.2 Improvements in the resolution of process and sediment storage estimates

- Sediment storage remains the most problematic component of the sediment budget to quantify, particularly at this scale. Surveys using the total station were easy to conduct and yielded accurate volumetric data of storage in channel bars (we experimented with RTK (real-time GPS surveying) but the density of the riparian canopy blocked access to the satellites and proved difficult to complete). Generating the three-dimensional models of bar complexes was also straightforward. This type of data will be important for in-stream flow requirements, particularly for recreational flows; it allows you to "flood" the bars with progressive increases in flow to determine the proportion of the channel that become navigable with increasing flow. But conducting such surveys over long stretches of river reach will be time-consuming. One approach we recommend would be to combine (1) in-stream surveys of bars at low flow at several sites along mainstem reaches, and (2) aerial mapping of channel bar surfaces. A generalized predictive relationship could potentially be developed between computed volumes from surveyed bars and digitized bars from photographs, allowing researches to simply map bars from photographs and predict stored volumes. We estimate the cost of such work at $180,000 (six graduate assistants at $30,000 working in various basins throughout Texas).
- Reservoir sedimentation data provide an excellent tool for summarizing trends in sediment transport (specifically in relation to upland erosion rates) over long periods of time. One area that has been overlooked is the role of small impoundments (e.g., stock tanks and NRCS floodwater retarding structures) in sequestering sediment and their connectivity along the sediment conveyance route. We recommend investigating the effect that NRCS structures and smaller reservoirs are having on the delivery of sediment to the larger (downstream) water supply reservoirs and mainstream reaches. This would be field-intensive, but in a well-managed project and with landowner cooperation, two people working together could do 3 to 4 ponds a day if they are close to each other. The recommended approach would be to have a stratified sampling system where groups of ponds were sampled in various parts of the state. The best method would be to conduct detailed sampling of a few ponds to build up a correlation between total sediment thickness and maximum sediment thickness, and then just measure maximum thickness in more ponds. We estimate the cost of such work at $120,000 (three graduate students at $30,000 plus expenses for field assistants).

Construction of sediment budgets requires us to conceptualize the sources, transport pathways, and sinks of sediment in a basin. This means identifying where sediment is derived from, where it is stored within the basin, and how much is delivered downstream to rivers and the sea. Quantifying sources, stores, and delivery in large, complex basins like the Brazos and Trinity will be a major challenge. There are few direct measurements of sediment transport in basins this size, and it can be argued that it would be unrealistic to initiate sampling programs now and expect statistically meaningful results within five to ten years. However, we do suggest that some targeted sampling be done in critical areas in order to better quantify mainstem sediment flux. The most practical framework to assess the spatial patterns of sediment production on a basin-wide scale is the spatial modeling framework afforded by the integrated NRI/USLE-based approach.

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APPENDIX I: Flow duration curves for the Brazos and its tributaries.