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Dam-to-delta sediment inputs and storage in the lower trinity river, Texas

Jonathan D. Phillips[a,*], Michael C. Slattery[b], Zachary A. Musselman[a]

[a] Tobacco Road Research Team, Department of Geography, University of Kentucky, Lexington, KY 40506-0027, USA
[b] Department of Geological Sciences, Texas Christian University, Fort Worth, TX, USA

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Abstract

Livingston Dam on the Trinity River in SE Texas, USA disrupts the transport of sediment to the lower Trinity River and the Trinity Bay/Galveston Bay estuary. However, a sediment budget of the lower basin shows that the effects of this disruption are undetectable in the lower river. Sediment trapped in Lake Livingston is partly offset by channel erosion downstream of the dam and by inputs from the lower basin. Most importantly, however, the lower coastal plain reaches of the Trinity are characterized by extensive alluvial storage and are a bottleneck that buffers the bay from effects of upstream changes in sediment flux. Storage is so extensive that the upper Trinity basin and the lowermost river reaches were essentially decoupled (in the sense that very little upper-basin sediment reached the lower river) long before the dam was constructed. Whereas sediment storage in Lake Livingston is extensive, alluvial storage on the Trinity flood plain is even more extensive. Dam-related sediment starvation effects are noted for about 52 km downstream, and the sediment budget suggests that a majority of the sediment in this reach is likely derived from channel scour and bank erosion. The capacious alluvial storage in the lower Trinity not only limits flux to the bay, but the large amount of remobilizable alluvium also allows the system to adjust to localized sediment shortages, as illustrated in the dam-to-Romayor reach. Internal adjustments within the lower Trinity River valley thus buffer the bay from changes in sediment supply upstream.

Keywords: Sediment budget; Trinity River; Alluvial storage; Dam effects; Buffering

1. Introduction

The lower Trinity River, Texas is a dynamic, low-gradient coastal plain river influenced in the recent geological past by rising Holocene sea levels and Quaternary climate change and more recently by a major impoundment and water withdrawals. In recent decades, the lower Trinity has experienced erosion and subsidence of its delta, rapid channel shifting and bank erosion, channel scour (which has imperilled bridge crossings), and damaging floods. This combination of geological, climatic, and anthropic forcings, along with the resource management issues associated with recent events, motivate our efforts to understand the recent geomorphic evolution and dynamics of the lower Trinity River system. The purpose of this study is to determine the fluvial sediment budget for the

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* Corresponding author. Tel.: +1-859-257-6950; fax: +1-859-323-1969.
E-mail address: jpd@uky.edu (J.D. Phillips).

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Trinity River from Livingston Dam and Lake Livingston to the Trinity River delta and Trinity Bay (Fig. 1).

Two critical issues in this study are the downstream geomorphic effects of dams and the extent to which upper-basin sediment is delivered to lower river reaches in drainage basins such as the Trinity that cross extensive coastal plains. The contemporary sediment regime of the river and effects of Lake Livingston are embedded within the legacies and the continuing influences of climate fluctuations and sea level change.

Dams typically have significant geomorphic effects downstream, but impacts vary according to size of the river and dam, hydrologic regime, environmental setting, history, and channel morphology, as well as with the purpose and operation of the impoundment (Williams and Wolman, 1984; Friedman et al., 1998; Brandt, 2000; Phillips, 2001, 2003; Graf, 2001). In some cases, dams dramatically reduce sediment transport for a considerable distance downstream, whereas in other cases impact on sediment regimes is not apparent except in the reach immediately downstream of the dam (Brandt, 2000). Phillips (1992a,b, 1995) has documented this pattern in large rivers of the North Carolina coastal plain, and more recently on a small east Texas stream and the Sabine River, Texas/Louisiana (Phillips, 2001, 2003; Phillips and Marion, 2001). Extracting any generalizations is difficult even within Texas, as the downstream effects of impoundments appear to differ qualitatively (Solis et al., 1994; Phillips, 2001).

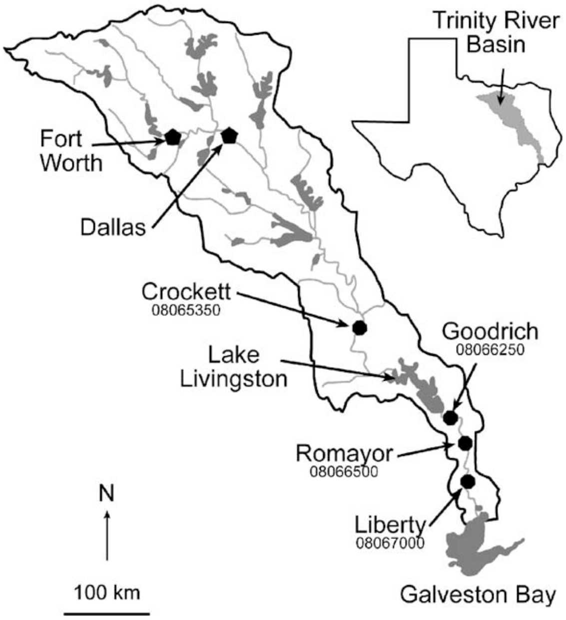

Fig. 1. Study area map showing locations referred to in the text.

Some river systems, particularly where coastal plains are extensive, are characterized by upper- and lower-basin decoupling, at least during periods such as the Holocene which has been characterized by rising sea level. That is, relatively little upper-basin sediment is delivered to the river mouth, instead being stored as alluvium on flood plains or in channels. Upper-basin sediment delivered to the lower river is sometimes overwhelmed by lower-basin sources. This pattern has been documented in some rivers of the U.S. south Atlantic Coastal Plain, including systems with and without major dams and reservoirs (Phillips, 1991, 1992a,b, 1993, 1995; Slattery et al., 2002). Upper- and lower-basin decoupling also appears to be the case in some east Texas streams, including Loco Bayou (in the Angelina River system) and the Sabine River (Phillips and Marion, 2001; Phillips, 2003). The decoupling phenomenon is not confined to the southern US and has been shown in drainage basins in the Great Lakes region and in Australia as well (Beach, 1994; Brizga and Finlayson, 1994; Olive et al., 1994; Fryirs and Brierly, 1999). If sediment delivery from the upper basin is indeed small compared to lower-basin sediment sources, then geomorphic changes in the lower river are likely to be linked to controls within the lower basin (as opposed to changes in sediment delivery from the upper basin, including those associated with sediment trapping behind dams).

2. Background

The Trinity River drainage basin has an area of 46,100 km^2, with the headwaters in north Texas, west of Fort Worth. It drains to the Trinity Bay, part of the Galveston Bay system on the Gulf of Mexico (Fig. 1). Most of the basin (and all of the lower basin) has a humid subtropical climate and a generally thick, continuous soil and regolith cover. Soils on stable upland sites are mainly Ultisols and Alfisols. Most of the drainage area (42,950 km^2; 95%) lies upstream of

Livingston Dam, which was completed in 1968 to form Lake Livingston. The lake has a conservation pool capacity of >2.2 billion m^3; its primary purpose is water supply for Houston. The dam has no flood control function and Livingston is basically a flow-through reservoir.

White and Calnan (1991) and Solis et al. (1994) have examined sediment records for the Trinity River gage at Romayor, 51 km downstream of Lake Livingston. This evidence suggests that the dam has significantly reduced downstream sediment inputs. Changes in historical aerial photographs show that the coastal zone near the mouth of the Trinity is experiencing erosion along barrier beaches and subsidence and wetland loss in its estuaries. Along Galveston Island 57% of the shoreline has experienced erosion rates averaging 0.6 m $year^{-1}$ or more in recent years, while on Bolivar Peninsula the figure is 86%. In the Galveston Bay estuarine system, which includes the Trinity Bay and Trinity River delta, shoreline retreat of 1.5 to >3 m $year^{-1}$ is common in recent years, and conversion of marshes to open water at a rate of 47 ha $year^{-1}$ has been documented for the Trinity Delta (Morton and Paine, 1990; White and Calnan, 1991; Morton, 1993; GLO, 2002). The erosion and land loss has, in many cases, accelerated within the past 50 years. White et al. (2002) note that the Trinity River Delta was prograding through most of the 20th century, with a transition to degradation beginning between 1956 and 1974. Beach erosion in Texas shows an apparent increase beginning in the 1960s (Morton, 1977, Morton and Paine, 1990; Davis, 1997). The increase in erosion and land loss roughly coincides with the impoundment of the Trinity and other Texas rivers and suggests the possibility that, in addition to the other factors that influence coastal geomorphology, human modifications of both coastal systems and the fluvial systems draining to them may be contributing to erosion and coastal land loss.

Recent lateral and vertical channel erosion has also occurred in the lower Trinity. The flood plain contains numerous oxbow lakes, meander scars, and other evidence of Holocene and historical channel change; and abundant evidence of Pleistocene channel migration is preserved on upper parts of the flood plain and the lower alluvial terraces. The contemporary river has ample evidence of bank erosion and point bar accretion. Thus, the lower river is an actively migrating channel and has been throughout the Quaternary. Additionally, studies of planimetric channel changes (Wellmeyer et al., 2003) suggest that claims by local residents that bank erosion and channel shifting has increased in recent years may be correct and possibly linked to fluctuations in precipitation. Problems associated with channel scour are evident immediately downstream of the dam (where boat ramps and other features have been damaged or destroyed) and at bridge crossings near Goodrich and Romayor, necessitating bridge repairs and replacements.

Channel erosion, as well as erosion and subsidence in the delta and bay, are possibly linked to changes in the sediment budget, particularly those that reduce sediment inputs from tributaries, upland erosion, or the upper basin (upstream of Livingston Dam). This would not only reduce sediment input but also potentially increase the erosive activity of flow if sediment supply is less than transport capacity. Reduced river sediment loads or delivery to the lower river could starve the delta and bay area of sediment, reducing its ability to keep pace with sea level rise. This change could also trigger a remobilization of stored alluvium via bank erosion.

Information is inadequate to determine whether the Trinity River has been characterized by stable sediment yields over Quaternary time scales. The Colorado River, Texas has apparently experienced a major decline in sediment yields, based on a comparison of dated Quaternary deltaic accumulations offshore and contemporary and historical sediment yields (Blum and Price, 1994). Estimates of long-term sediment budgets and yields for coastal plain rivers such as the Trinity are difficult because of the migration of depocenters as sea level varies. Fluvial and deltaic deposits associated with the Trinity River are found well offshore of the current coastline and evidence exists that sea level rise may have influenced aggradation up to 130 km upstream of the highstand shoreline (Thomas and Anderson, 1994). Thus the “mouth” of the river may have varied in location by as much as 200 km in the upstream–downstream direction, considerably complicating efforts to define an accumulation basin. At present, the distance from the point near Liberty, where the channel bed is below sea level, to the river mouth at Trinity Bay is 60 km.

The alluvial morphology and stratigraphy of the lower Trinity (and the nearby and similar Sabine

River) and the deposits and paleochannels now submerged in Trinity and Galveston Bays and the Gulf of Mexico preserve evidence of climate, sea level, and upstream sediment delivery changes (Anderson et al., 1992; Thomas and Anderson, 1994; Blum et al., 1995; Anderson and Rodriguez, 2000; Rodriguez and Anderson, 2000; Rodriguez et al., 2001; Phillips, 2003; Phillips and Musselman, 2003). Therefore, contemporary modifications to flow and sediment regimes are superimposed on long-term changes controlled primarily by climate and sea level change.

3. Methods

A sediment budget is an accounting of the production or input of sediment to a geomorphic system, the loss or output, and additions to or losses of storage. In the lower Trinity, our budget attempts to account for tributary inputs and upland erosion within the lower Trinity Basin (the drainage area of the portion of the river downstream of Lake Livingston), inputs from upstream of the lake, and sediment delivery to the fluvial/estuarine transition zone downstream of Liberty. We do not attempt to account for colluvial storage or other sediment dynamics between the original source and delivery to the fluvial system. 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.

3.1. Sediment supply to the lower trinity

Estimates of sediment delivery to streams are based on two sources. First, daily suspended sediment samples were collected for the 1964–1989 period at a gaging station on Long King Creek (see next section for sampling methods and data conversions). The Long King Creek gaging station at Livingston, TX has an upstream drainage area of 365 km^2, representing about 16% of the drainage area for the river downstream of the lake. Dividing the mean annual sediment yield by this area gives a figure for sediment delivery per unit area.

Independent estimates of sediment delivery to streams in the lower Trinity basin are available from reservoir surveys conducted by the Texas Water Development Board (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). Thus, we assume a density of 1 Mg m^{-3}, a conservative estimate that follows the practice of Smith et al. (2002). Data were averaged for 27 lakes in east and central Texas, in the same land resource areas as those encompassing the Trinity drainage basin.

3.2. Sediment transport in the lower trinity

The TWDB collected daily suspended sediment samples at three stations on the Trinity River (Liberty and Romayor downstream and Crockett upstream of Lake Livingston) and Long King Creek over the 1964–1989 period. All sampling locations are U.S. Geological Survey (USGS) gaging stations, and the measured concentrations were converted to daily transport values based on the mean daily flows recorded at the gaging stations. The samples were taken with the "Texas Sampler", a point-sampler that yields results lower than, but systematically related to, yields based on depth-integrated sampling using standard USGS methods (Welborn, 1967; Andrews, 1982). Values at the Romayor station were compared to same-day samples collected by the USGS, indicating that a multiplier of 2.37 should be used to convert TWDB values to equivalent depth-integrated values. Similar results were obtained in comparing the Texas sampler to USGS depth-integrated samples by Welborn (1967) and Andrews (1982).

The suspended sediment measurements underestimate transport by not accounting for bed load. It is conventional in many studies to add 10% to account for bed load. At the Romayor station on the Trinity River, on 12 occasions between 1972 and 1975 the U.S. Geological Survey measured suspended and bed load on the same day. Bed load represented 1.4% to 21.4% of total sediment load, with a mean of 9.7%. Thus, sediment transport estimates based on suspended measurements alone were increased by 10%.

Table 1
Sediment delivery and yields in the lower Trinity River Basin

Station	Drainage area (km^2)	Yield (t year^{-1})	Specific yield (t km^{-2} year^{-1})
Long King Creek	365	170,637	467
Trinity at Crockett	36,029	5,112,515	142
Trinity at Romayor	44,512	3,378,461	76
Trinity at Liberty	45,242	69,673	1.6

Sediment data from the Texas Water Development Board, adjusted as described in the text.

3.3. Alluvial storage

Measuring rates of alluvial storage over large areas is difficult, particularly over periods of decades or longer for constructing an average annual sediment budget. We infer alluvial storage magnitudes based on the difference between sediment delivered to the stream and sediment yield. We also estimate the total quantity of stored alluvium based on the width of the flood plain measured from digital orthophotoquads with a 2.5 m resolution, combined with field measurements of the elevation of the flood plain above the channel at 12 cross sections between Livingston Dam and the delta. Assuming that this represents the depth or thickness of potentially mobile alluvium, this allows an estimate of flood plain volume that we convert to mass using a bulk density of 1.4 g cm^{-3}, based on data from soil surveys of Polk, San Jacinto, and Liberty Counties in the lower Trinity region.

In addition, dendrogeomorphic estimates of alluvial storage were made at several sites. These are not extensive enough to produce reliable quantitative storage estimates, but do provide independent evidence to examine implications of other estimates. Flood plain surface sedimentation rates were measured using 14 trees at three sites based on the principle that upon germination tree root crowns and basal flares are approximately flush with the ground surface. All trees were above, but within 50 m of, the bank top. Substantial amounts of sedimentation may bury these features. By measuring the distance from the present surface to the root crown, the depth of burial may be estimated. Ring count determination of tree ages (using an increment borer to extract cores) allows the time frame of accretion to be determined and a minimum mean rate to be estimated. The rate is a minimum in that it assumes sedimentation began immediately after tree establishment. In some cases, buried tree bases send out adventitious roots; these may allow some additional discrimination of sedimentation rates and timing. Dendrogeomorphic methods for measuring alluvial sedimentation are described in more detail and illustrated by Hupp and Bazemore (1993), Martens (1993), and Hupp and Osterkamp (1996). These techniques have previously been used in east Texas (Phillips, 2001; Phillips and Marion, 2001).

Dendrogeomorphic measurements were made at the Goodrich, Moss Hill, and Liberty sites. Additionally, field assessments of vegetation burial (excavations to confirm burial but without ring counts) were

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/surveytech.htm)

Lake	Drainage area	Storage loss	Years	Yield
	km^2	m^3		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.	471	5,051,183	39	275
Mean (all)	7,308	11,412,349	31	275
Mean (CP)	2,297	9,485,087	35	375

made at the mouth of Menard Creek, Romayor, and Port of Liberty (two sites).

4. Results

4.1. Sediment production and delivery

The Trinity River has apparently experienced some recent changes in sediment delivery to the lower reaches of the river as a consequence of Lake Livingston and Livingston Dam. Channel scour and alluvial remobilization immediately downstream of the dam are apparent. Suspended sediment monitoring shows a reduction in sediment loads at Romayor, approximately 50 km downstream (Solis et al., 1994), although no previous studies have examined trends in sediment yield further downstream.

The gaging station on Long King Creek at Livingston has a drainage area of 365 km^2 and a mean annual sediment yield of 467 t km^{-2} year^{-1}. As shown in Table 1, this is considerably higher than sediment yield per unit area for any of the stations on the lower Trinity River, including the Crockett station upstream of Lake Livingston. At Liberty, where the gage datum is 0.7 m below sea level, the specific sediment yield is <1.6 t km^2 year^{-1}. The inverse relationship between drainage area and sediment yield per unit area evident in Table 1 is consistent with many other studies in humid perennial streams where the major source of sediment is upland erosion and tributary inputs within the basin (this literature is reviewed by Meade, 1982; Walling, 1983; Sutherland and Bryan, 1991; Ferro and Minacapilla, 1995).

Field reconaissance shows that Long King Creek and its tributaries have significant flood plain development and alluvial storage both upstream and downstream of the gaging station, suggesting significant alluvial storage buffering of basin sediment production and delivery to the river.

The lake surveys suggest sediment yields of 6 to 1002 t km^2 year^{-1}, with a mean of 275 (Table 2). These data include three cases where measured storage capacities increased as a result of dredging, flushing, or increasing dam heights. Of the lakes shown in Table 2, the coastal plain lakes are in settings similar to those in the lower Trinity Basin. These lakes have specific sediment yields ranging from 6 to 841 t km^{-2} year^{-1}, with a mean of 375. The lakes upstream of Livingston Dam, or in similar environmental settings, have a mean annual sediment yield of 265 t km^{-2} 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, conservative 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. The estimates are conservative in the sense that the lakes are likely not all perfect sediment traps. The lake storage loss data will not accurately reflect fluvial sediment input if there are other major sediment sources such as aeolian input or lakeshore

Table 3
Alluvial storage by reach[a]

Reach	Upstream input[b]	Local input	Downstream output[b]	Minimum storage[c]	Maximum storage[d]
Headwaters to Crockett	0	9,907,975	5,112,515	4,795,460	
Crockett to Romayor	5,112,515	3,393,200	3,378,461	1,734,054	5,127,254
Romayor to Liberty	3,378,461	292,000	69,673	3,308,698	3,600,698
Liberty to Trinity Bay	69,673	343,200	73,760 (1)	339,113 (2)	412,873 (2)

(1) An unrealistically high estimate based on the assumption of the 1.6 t km^{-2} year^{-2} yield at Liberty, applied at the basin mouth.

(2) Minimum storage based on adding upstream and local input and subtracting downstream output. Maximum storage assuming no sediment delivered to the reach is transported to Trinity Bay.

[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.

Table 4
Dendrogeomorphic estimates of recent flood plain accretion rates[a]

Site	No. of trees	Measurements[b]	Age range (years)	Mean accretion rate	Minimum accretion rate	Maximum accretion rate
Goodrich	7	10	1–27	18.5	0	41.0
Moss Hill	5	6	1–16	45.4, 18.5 (1)	3.6	180,41.2 (1)
Liberty	2	3	2–21	39.9	28.1	56.7

(1) First number includes 180 mm of deposition in 1 year as measured by adventitious root. The second number excludes this measurement.

[a] In mm year^{-1}.

[b] The number of measurements exceeds the number of trees because in some cases adventitious roots were examined.

erosion and mass wasting. Major aeolian inputs are unlikely in the well-vegetated humid areas of east Texas. Lakeshore erosion occurs but is minor in the lakes visited in the field (Lake Livingston and the following included in Table 2: Nacogdoches, Conroe, Somerville).

Based on the lake and Long King Creek data, sediment loadings within the lower Trinity basin are estimated at 400 t km^{-2} year^{-1}. Loadings for the Trinity basin upstream of Lake Livingston are estimated as 265 t km^{-2} year^{-1}.

4.2. Alluvial storage

Comparison of average annual sediment yields in Table 1 shows the apparent effects of alluvial storage. Yields at Crockett are >1.7 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.

The amount of average annual alluvial storage can be constrained as shown in Table 3. 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 265 for the upper basin and 400 t km^{-2} year^{-1} for the lower basin) is transported to the Trinity River. Thus, the estimate of maximum storage for reaches between Livingston Dam and Liberty is based on upstream input plus sediment produced in the drainage area between the upstream

Fig. 2. Tree on flood plain at Port of Liberty 2 site, with base buried by recent deposition. Note the branches close to ground surface.

Fig. 3. Typical appearance of flood plain surface just downstream of Liberty, lower Trinity River. Note the buried bases and "utility pole" appearance of lower tree trunks, indicating recent sedimentation.

and downstream ends of the reach, minus downstream output. Estimates for the upper basin (headwaters to Crockett reach) are for alluvial storage within the entire basin, as opposed to the river itself. Estimates for the unmeasured coastal reach of the river, from Liberty to Trinity Bay, are based on extrapolations of per unit area sediment yield at Liberty to the river mouth, which would produce an unrealistically high estimate. The maximum storage for this reach is based on the assumption that no sediment is exported to Trinity Bay. Thus, the minimum and maximum storage estimates for the lowermost reach of the river (being unrealistically low and high, respectively) should constrain or bracket the actual value.

Several trends are apparent from Table 3. First, alluvial sediment storage is extensive. Storage is particularly apparent in the lowermost reaches. Second, more alluvial sediment is stored between Romayor and Liberty—that is, in the lower Coastal Plain portion of the river above tidal influences—than in Lake Livingston. Third, in the lowermost river, alluvial storage dwarfs sediment yield.

The Trinity valley from Livingston Dam to the head of Trinity Bay extends 174 km. The average width of the flood plain is ~ 5 km. Channel surveys at 12 locations indicate a mean bank height of ~7 m. Taking the latter as an effective thickness of potential activation of alluvium (a reasonable assumption, as the Trinity is near bedrock at many locations below Lake Livingston) yields a total volume of potentially remobilizable alluvium of 6.1×10^9 m^3. At a typical bulk density of 1.4 t m^{-3}, 8.52×10^9 t are available. At recent rates of sediment yield at Liberty, this volume is equivalent to >87,000 years of sediment discharge.

From Romayor downstream, the mean annual alluvial storage is 5.4 to 9.1 million t year^{-1}. The total amount of alluvium estimated above represents about 1000 years of net input at this rate (666 to 1131 years), recalling that storage rates from the dam to Romayor are not accounted for.

These estimates suggest active flood plain sedimentation in the lower Trinity. This is confirmed by the dendrogeomorphic evidence. As shown in Table 4, significant accretion is occurring at all sites in recent

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

Reach	Total input (t year^{-1})	Percent yield	Percent alluvial storage
Headwaters to Crockett	9,907,975	46.9	53.1
Crockett–Romayor	8,505,715	39.7	60.3
Romayor–Liberty	3,670,461	1.9	98.1
Liberty–Bay	412,873	<2	>98

Table 6
Sediment yield and storage per unit drainage area (t km^{-2} year^{-1})

Station	Yield	Alluvial storage
Crockett	142	133
Romayor	76	147 to 223
Liberty	1.6	217 to 299
Trinity Bay	< 1.6	>221 to < 302

years. Typical accretion rates of 18 to 40 mm year^{-1} are consistent with vertical accretion rates in alluvial flood plains elsewhere in the US Atlantic and Gulf coastal plains, which range from < 1 to 61 mm year^{-1} over periods of 1 to 25 years (Phillips, 2001: Table 3). Obvious burial of vegetation indicating recent sedimentation was also noted at the mouth of Menard Creek, Romayor, and Port of Liberty 2 sites (see Figs. 2 and 3).

4.3. Sediment budget

Between Romayor and Liberty, a dramatic increase in alluvial storage occurs, and a corresponding decrease in river sediment transport (Tables 5 and 6).

Fig. 4. Digital orthophotoquad of the Trinity River near Romayor, TX (original in color). Point A is the highway 787 bridge, location of the Romayor gaging station. Point B denotes one of the meander scars evident in the Pleistocene Deweyville deposits. These features are not associated with the modern Trinity River. At point C, there are several oxbows and other depressions, which characterize the Trinity River below this point. Note the paucity of such features upstream.

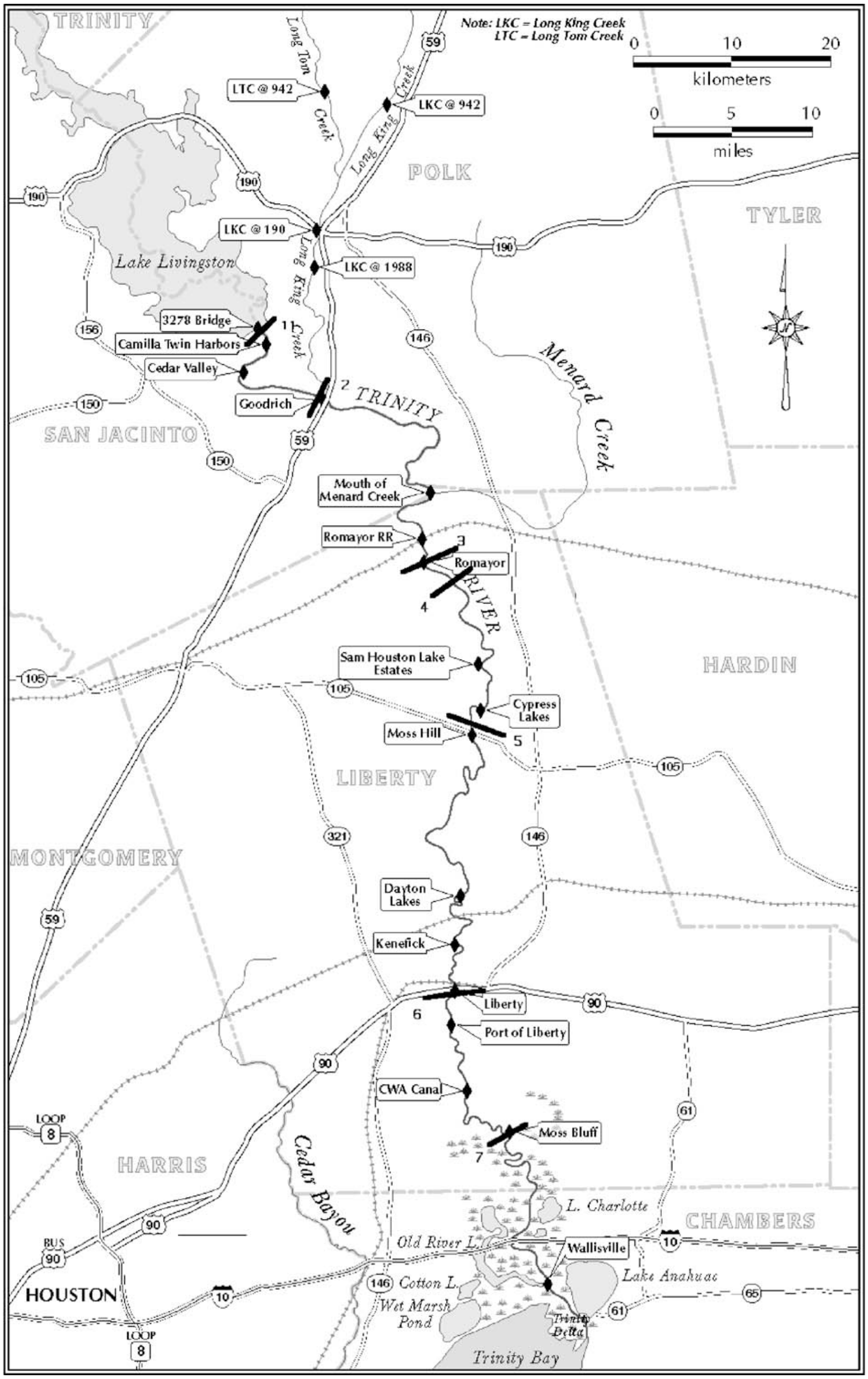

Fig. 5. Lower Trinity River, showing approximate location of the topographic cross sections (numbered bars). Field sites used in this and other related studies are also indicated.

Though the reach boundaries are defined by the sediment-monitoring stations, a profound change in flood plain morphology indeed occurs a short distance downstream from Romayor. The flood plain becomes wider, lower in elevation, and characterized by a greater size and number of oxbows and other depres-

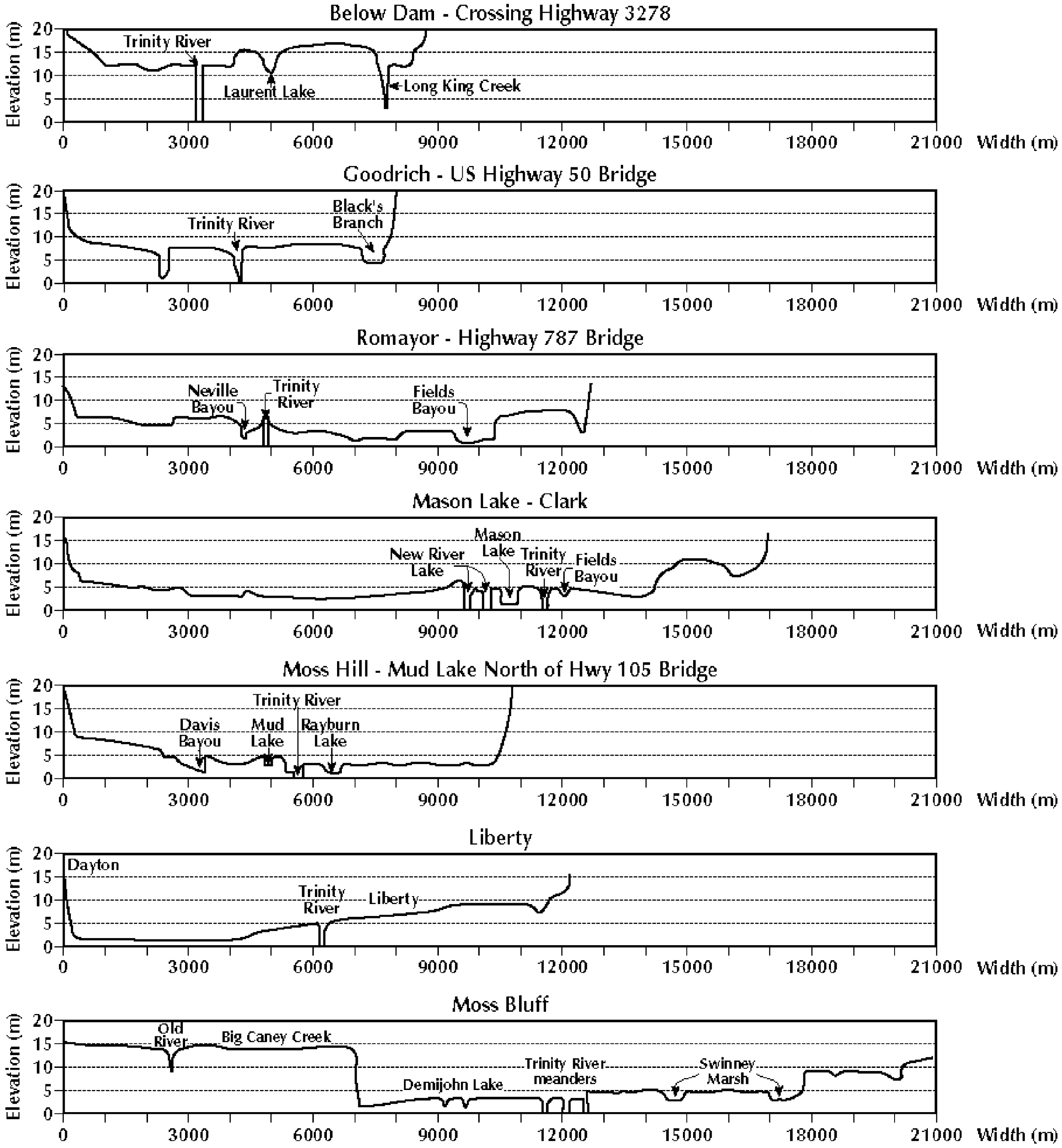

Fig. 6. Flood plain cross sections derived from digital elevation models. Numbers correspond to sites in Fig. 5.

sions (Fig. 4). This is evident from a number of flood plain cross sections derived from digital elevation models (Figs. 5 and 6).

The greater frequency of overbank flooding in the lowermost reaches can be illustrated by examining the recurrence interval of flood-stage discharges at Romayor and Liberty. The 2364 $m^3\ s^{-1}$ discharge associated with the flood stage at Romayor has an annual exceedence probability of 29%. By contrast, the flood stage discharge of 989 $m^3\ s^{-1}$ at Liberty is exceeded in 60% of all years.

4.4. Sediment sources

Because much of the upstream sediment load is captured in Lake Livingston, questions arise as to the source of sediments in the lower Trinity. Of the total drainage area at Romayor, 717 km^2 are downstream of the lake. At 400 t km^{-2} $year^{-1}$, this would yield 286,800 t $year^{-1}$, or only about 8.5% of the sediment yield at Romayor. This implies that much of the sediment transported at Romayor comes from upstream of the dam—e.g., is transported through the lake—or is derived from channel erosion downstream of the dam.

Trap efficiency of reservoirs is often estimated from the capacity/inflow ratio via a relationship developed by Brune (1953) and Verstraeten and Poesen (2000):

$$E = 100\left({}_{0.97}0.19^{\log C/I}\right) \qquad (1)$$

where E is trap efficiency in %, C is reservoir capacity, and I is inflow. The C/I ratio for Lake Livingston is 0.316, yielding a trap efficiency of 81%. If sediment yield per unit area at Crockett is extrapolated to the entire 42,950 km^2 upstream of the dam, sediment inputs of about 6 million t $year^{-1}$ would result. If 19% of this is transported through the lake, it could account for 1.14 million t $year^{-1}$, about 34% of the yield at Romayor.

Unless trap efficiency of Lake Livingston is significantly overestimated or sediment input between Livingston Dam and Romayor is markedly underestimated, this implies that more than half the sediment transport at Romayor is derived from channel erosion. We believe that, if anything, trap efficiency of the lake is underestimated by the capacity–inflow ratio, based on observations of essentially clear water immediately downstream of the dam, even at high flows.

Channel scour from the dam to Romayor is indeed evident in the field. Figs. 7–9 show field evidence of channel scour between the dam and Romayor. Although such scour is clearly occurring at a significant

Fig. 7. Trinity River channel just downstream of Livingston Dam. The exposed tree roots are indicative of recent channel scour and bank erosion. The box highlights light-colored stains on the tree, derived from scour of gray clay bed sediments during high flows.

Fig. 8. Railroad bridge near Goodrich, TX between Livingston Dam and the Romayor gaging station. The box in mid-photo highlights a concrete pad that was flush with the river bed when the bridge was constructed in 1917. At the time of the photograph (May 2002), the pad was about 2 m above the water surface and 5 m above the channel bottom.

pace, the amount, rates, and timing are not well understood and deserve further investigation. Interestingly, results from a study on channel change conducted on the Trinity below Lake Livingston suggest contributions from channel erosion may exceed 50% (Wellmeyer et al., 2003). In this report, the authors use historic aerial photographs from 1938 to 1995, digitized and imported into a GIS, to quantify long-term channel bank stability. Mean annual channel erosion was computed at 30.2 ha $year^{-1}$. Using the average channel depth of 7 m and a mean bulk density of 1.4 Mg m^{-3} yields a possible 2.96×10^6 Mg of sediment per year, which is equivalent to 87.6% of the annual sediment load measured at Romayor.

Data from the Romayor station show a clear decline in sediment transport following completion

Fig. 9. Exposed bedrock in the Trinity River channel just downstream of the Romayor gaging station.

of Livingston Dam (Fig. 10). Sediment loads at Liberty, however, show no evidence of a change in sediment regime (Fig. 10). The very low sediment yields and concentrations at Liberty compared with those at Romayor suggest extensive alluvial storage between Romayor and Liberty, as noted earlier, and that little sediment reaches the lower river at Liberty, with or without Lake Livingston.

Comparing sediment loads for Romayor and Crockett for all post-dam years (Fig. 11) shows that in general the downstream station has lower yields, presumed to be primarily the result of sediment trapping in Lake Livingston. These effects are sometimes apparently more than compensated for by other sediment sources, and in most cases any deficit is < 20,000 t. By contrast, subtracting sediment loads at Romayor from those at Liberty (10-day means) always shows a loss of sediment and these losses are often greater than the Crockett-to-Romayor deficits. This suggests that sediment storage in the lower Trinity is greater than storage in Lake Livingston and suggests that alluvial storage in

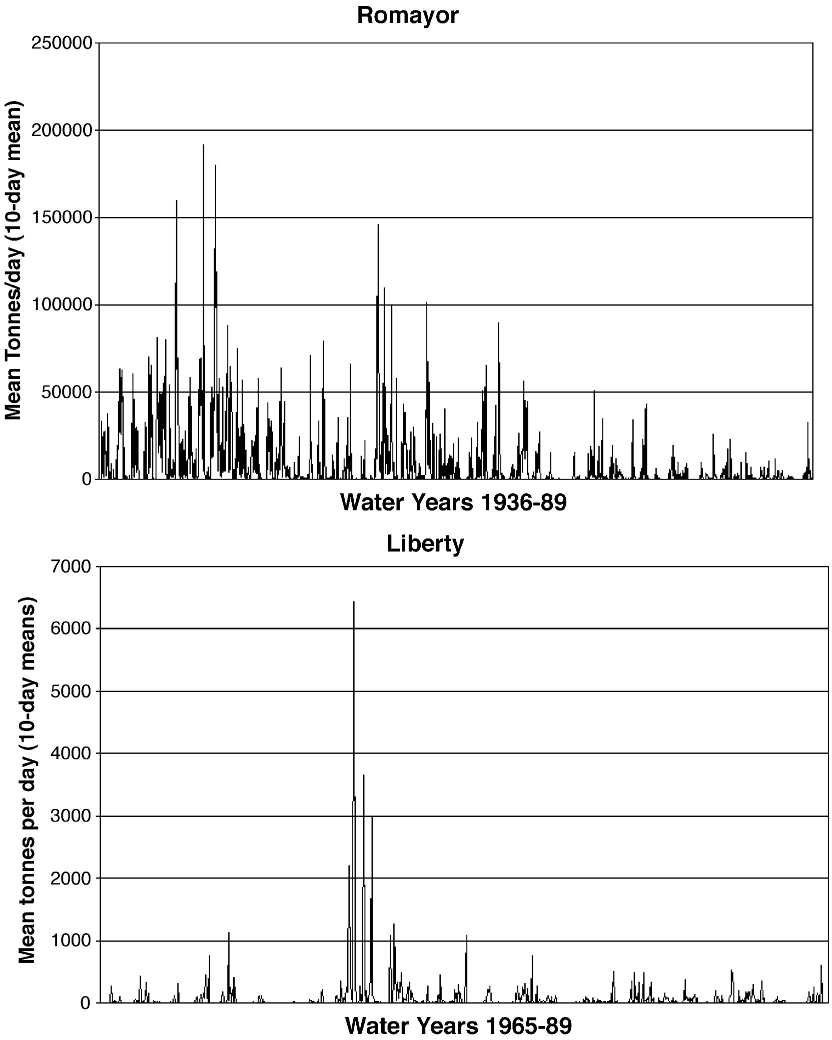

Fig. 10. Sediment loads for lower Trinity River gaging stations at Romayor and Liberty. Values are means for 10-day periods. Note the difference in scale of y-axis.

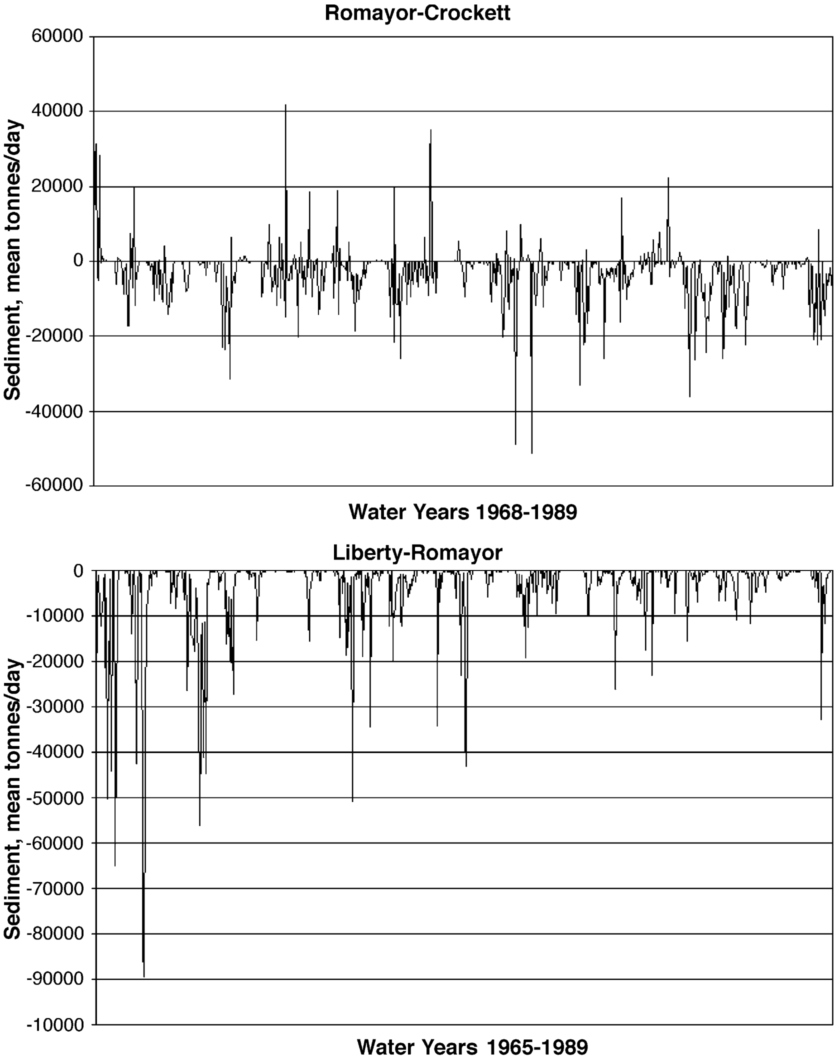

Fig. 11. Comparison of sediment loads (daily means for 10-day periods) from Crockett to Romayor and Romayor to Liberty, obtained by subtracting Crockett from Romayor and Romayor from Liberty values, respectively.

the lower river is a bottleneck for sediment delivery to the coast, independently of the effects of upstream impoundment.

5. Discussion

The sediment fluxes and storage in the lower Trinity River reflect several important phenomena. First, the lowermost river reaches are characterized by a high rate of alluvial sediment storage and are effectively a bottleneck for sediment delivery to the river mouth. This sediment storage essentially buffers the Trinity delta from changes in sediment supply and transport upstream. No evidence was found of any decline in sediment delivery to Liberty and points downstream following the construction of Livingston Dam. Thus, any decline in deltaic sedimentation or any coastal land loss is attributable to factors other than reduced inputs of river sediment.

Second, the lower Trinity River is characterized by at least two distinct sediment flux/storage zones, not including the lowermost estuarine and deltaic areas. Between Livingston Dam and (roughly) Romayor, the Trinity is characterized by a combination of sediment storage and aggradation on flood plains, along with degradation and scour of channels. This may initially appear an unlikely combination, but during high-flow overbank events bed and bank shear strength may be exceeded by shear stress in the channel, even as stream power on the flood plain is low enough to allow deposition. In this reach, sediment supplied from uplands, tributaries, and passed through Lake Livingston is apparently less than transport capacity. Downstream, wider, lower flood plains and increased frequency of overbank flow promote deposition and sediment storage. Sediment supply from upstream and from the local drainage area greatly exceeds transport capacity.

In the case of the Trinity River and Lake Livingston, the role of reservoirs as sediment traps may be overestimated. The estimated trap efficiency of the lake is 81%, but alluvial storage accounts for more than half of the sediment delivered to the fluvial system upstream of the lake, and the "trap efficiency" of the alluvial valley in the lower reaches exceeds that of Lake Livingston. Channel scour downstream of Livingston Dam is no doubt at least partly a consequence of "hungry water" with unfilled transport capacity released from the dam. However, the Trinity channel is active, with shifting banks, throughout its lower reaches, including the transport-limited reaches between Romayor and Liberty.

The river is at or near bedrock from the dam to Romayor, indicating that additional downcutting will be quite slow. This indicates that lateral channel migration may be expected to increase.

6. Conclusions

The sediment budget of the lower Trinity River shows no evidence that Lake Livingston and Livingston Dam have reduced sediment delivery to Trinity Bay. The lower river is an effective sediment bottleneck. Storage is so extensive that the upper Trinity basin and the lowermost river reaches were essentially decoupled (in the sense that very little upper-basin sediment reached the lower river) even before the dam was constructed. Whereas sediment storage in Lake Livingston is extensive, alluvial storage on the Trinity flood plain is more extensive.

Dam-related sediment starvation effects are evident for ~ 52 km downstream, and the sediment budget suggests that a majority of the sediment in this reach is likely derived from channel scour and bank erosion.

The extensive alluvial storage in the lower Trinity essentially buffers Trinity Bay from the effects of fluctuations in fluvial sediment dynamics. Not only does the sink in the lower river limit flux to the bay, but the large amount of remobilizable alluvium also allows the system to adjust to localized sediment shortages, as illustrated in the dam-to-Romayor reach. Internal adjustments within the lower Trinity River valley thus buffer the bay from changes in sediment supply upstream.

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References

Anderson, J.B., Rodriguez, A.B., 2000. Contrasting styles of sediment delivery to the east Texas shelf and slope during the last glacial-eustatic cycle: implications for shelf-upper slope reservoir formation. Transactions-Gulf Coast Association of Geological Societies 50, 343–347.

Anderson, J.B., Thomas, M.A., Siringan, F.P., Smyth, W.C., 1992. Quaternary evolution of the east Texas coast and continental shelf. In: Fletcher, C.H., Wehmiller, J.F. (Eds.), Quaternary Coastlines of the United States: Marine and Lacustrine Systems. SEPM (Society for Sedimentary Geology), Tulsa, OK, pp. 253–263.

Andrews, F.L., 1982. Monthly and Annual Suspended Sediment Loads in the Brazos River at Richmond, Texas, 1966–1986 Water Years. U.S. Geological Survey, Department of the Interior, Washington, D.C. Water Resource Investigation Report, 88–4216.

Beach, T., 1994. The fate of eroded soil: Sediment sinks and sediment budgets of agrarian landscapes in southern Minnesota, 1851–1988. Annals of the Association of American Geographers 84, 5–28.

Blum, M.D., Price, D.M., 1994. Glacio-eustatic and climatic controls on Quaternary alluvial plain deposition, Texas coastal plain. Transactions-Gulf Coast Association of Geological Societies 44, 85–92.

Blum, M.D., Morton, R.A., Durbin, J.M., 1995. Deweyville terraces and deposits of the Texas Gulf coastal plain. Transactions-Gulf Coast Association of Geological Societies 45, 53–60.

Brandt, S.A., 2000. Classification of geomorphological effects downstream of dams. Catena 40, 375–401.

Brizga, S.O., Finlayson, B.L., 1994. Interactions between upland catchment and lowland rivers: an applied Australian case study. Geomorphology 9, 189–201.

Brune, G.M., 1953. Trap efficiency of reservoirs. Transactions-American Geophysical Union 34, 407–418.

Davis, R.A., 1997. Regional coastal morphodynamics along the U.S. Gulf of Mexico. Journal of Coastal Research 13, 595–604.

Ferro, V., Minacapilla, M., 1995. Sediment delivery processes at basin scale. Hydrological Sciences Journal 40, 703–717.

Friedman, J.M., Osterkamp, W.R., Scott, M.L., Auble, G.T., 1998. Downstream effects of dams on channel geometry and bottomland vegetation: regional patterns in the Great Plains. Wetlands 18, 619–633.

Fryirs, K., Brierly, G.J., 1999. Slope-channel decoupling in Wolumla catchment New South Wales Australia: the changing nature of sediment sources following European settlement. Catena 35, 41–63.

GLO (Texas General Land Office), 2002. Shoreline Erosion Rates. http://www.glo.state.tx.us/coastal/erosion/erosionrates.html, accessed 12/17/02.

Graf, W.L., 2001. Damage control: restoring the physical integrity of America's rivers. Annals of the Association of American Geographers 91, 1–27.

Hupp, C.R., Bazemore, D.E., 1993. Temporal and spatial patterns of wetland sedimentation, west Tennessee. Journal of Hydrology 141, 179–196.

Hupp, C.R., Osterkamp, W.R., 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14, 277–295.

Martens, D.M., 1993. Hydrologic influences from tree-ring studies on the Hawkesbury River, Sydney, Australia. Geomorphology 8, 147–164.

Meade, R.H., 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. Journal of Geology 90, 235–252.

Morton, R.A., 1977. Historical shoreline changes and their causes. Transactions-Gulf Coast Association of Geological Societies 27, 353–363.

Morton, R.A., 1993. Shoreline Movement Along Developed Beaches of the Texas Gulf Coast: A Users' Guide to Analyzing and Predicting Shoreline Changes. Bureau of Economic Geology, University of Texas at Austin, Open-File Report 93-1. 79 pp.

Morton, R.A., Paine, J.G., 1990. Coastal land loss in Texas—an overview. Transactions-Gulf Coast Association of Geological Societies 40, 625–634.

Olive, L.J., Olley, J.M., Murray, A.S., Wallbrink, P.J., 1994. Spatial variability in suspended sediment transport in the Murrumbidgee River, New South Wales, AustraliaVariability in Stream Erosion and Sediment Transport, vol. 224. International Association of Hydrological Sciences Publication, Wallingford, U.K., pp. 241–249.

Phillips, J.D., 1991. Fluvial sediment delivery to a coastal plain estuary in the Atlantic drainage of the United States. Marine Geology 98, 121–134.

Phillips, J.D., 1992. The source of alluvium in large rivers of the lower Coastal Plain of North Carolina. Catena 19, 59–75.

Phillips, J.D., 1992. Delivery of upper-basin sediment to the lower Neuse River, North Carolina. Earth Surface processes and Landforms 17, 699–709.

Phillips, J.D., 1993. Pre- and post-colonial sediment sources and storage in the lower Neuse River basin, North Carolina. Physical Geography 14, 272–284.

Phillips, J.D., 1995. Decoupling of sediment sources in large river basinsEffects of Scale on Interpretation and Management of Sediment and Water Quality, vol. 226. International Association of Hydrological Sciences Pub., Wallingford, U.K., pp. 11–16.

Phillips, J.D., 2001. Sedimentation in bottomland hardwoods downstream of an east Texas dam. Environmental Geology 40, 860–868.

Phillips, J.D., 2003. Toledo Bend Reservoir and geomorphic response in the lower Sabine River. River Research and Applications 19, 137–159.

Phillips, J.D., Marion, D.F., 2001. Residence times of alluvium in an east Texas stream as indicated by sediment color. Catena 45, 49–71.

Phillips, J.D., Musselman, Z.A., 2003. The effect of dams on fluvial sediment delivery to the Texas coast. Proceedings of Coastal Sediments. American Society of Civil Engineers, New York, pp. 1–14.

Rodriguez, A.B., Anderson, J.B., 2000. Mapping bay-head deltas within incised valleys as an aid for predicting the occurrence of barrier shoreline sands: an example from the Trinity/Sabine incised valley. Transactions-Gulf Coast Association of Geological Societies 50, 755–758.

Rodriguez, A.B., Fassell, M.L., Anderson, J.B., 2001. Variations in shoreface progradation and ravinement along the Texas coast, Gulf of Mexico. Sedimentology 48, 837–853.

Slattery, M.C., Gares, P.A., Phillips, J.D., 2002. Slope-channel linkage and sediment delivery on North Carolina coastal plain cropland. Earth Surface Processes and Landforms 27, 1377–1387.

Smith, S.V., Renwick, W.H., Bartley, J.D., Buddemeier, R.W., 2002. Distribution and significance of small, artificial water bodies across the United States landscape. Science of the Total Environment 299, 2–36.

Solis, R.S., Longley, W.L., Malstaff, G., 1994. Influence of inflow on sediment deposition in delta and bay systems. In: Longley, W.L. (Ed.), Freshwater Inflows to Texas Bays and Estuaries. Texas Water Development Board, Austin, pp. 56–70.

Sutherland, R.A., Bryan, R.B., 1991. Sediment budgeting: a case study in the Katiorin drainage basin, Kenya. Earth Surface Processes and Landforms 16, 383–398.

Thomas, M.A., Anderson, J.B., 1994. Sea-level controls on the facies architecture of the Trinity/Sabine incised-valley system, Texas continental shelf. In: Dalrymple, R.W., Boyd, R., Zaitline, B.Z. (Eds.), Incised-Valley Systems: Origin and Sedimentary

Sequences. SEPM (Society for Sedimentary Geology), Tulsa, OK, pp. 63–82.

Verstraeten, G., Poesen, J., 2000. Estimating trap efficiency of small reservoirs and ponds: methods and implications for the assessment of sediment yield. Progress in Physical Geography 24, 219–251.

Walling, D.E., 1983. The sediment delivery problem. Journal of Hydrology 65, 209–237.

Welborn, C.T., 1967. Comparative Results of Sediment Sampling with the Texas Sampler and the Depth-Integrating Samplers and Specific Weight of Fluvial Sediment Deposits in Texas Texas Water Development Board, Austin.

Wellmeyer, J.L., Slattery, M.C., Phillips, J.D., 2003. Quantifying downstream impacts of impoundment on flow regime and channel activity, Lower Trinity River, Texas. Report to the Texas Water Development Board, Austin, TX, 1–67.

White, W.A., Calnan, T.C., 1991. Submergence of vegetated wetlands in fluvial-deltaic area, Texas Gulf coast. Coastal Depositional Systems of the Gulf of Mexico. 12th Annual Research Conference. Society of Economic Paleontologists and Mineralogists, Gulf Coast Section, Tulsa, OK, pp. 278–279.

White, W.A., Morton, R.A., Holmes, C.W., 2002. A comparison of factors controlling sedimentation rates and wetland loss in fluvial-deltaic systems, Texas Gulf coast. Geomorphology 44, 47–66.

Williams, H.F.L., 1991. Character and growth of deltaic deposits in Lewisville Lake, Texas. Texas Journal of Science 43, 377–389.

Williams, G.P., Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers. U.S. Geological Survey Professional Paper 1286, 1–61 (Washington, D.C.).