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# *Geomorphic Impacts of Lake Livingston on the Lower Trinity River, Texas*

**Report to the Texas Water Development Board, Austin**
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# SECTION 1: SUMMARY AND INTRODUCTION

## SUMMARY

This study seeks to document the effects of the Lake Livingston dam on downstream sediment regimes, in particular the delivery of sediment to the lower Trinity River and the Trinity Bay estuary.

The study addresses the following problems:

1) What are the geomorphological and sedimentological impacts of Lake Livingston on the Trinity river system downstream of the dam?

2) How has this affected the transport of sediments into the upper Trinity River Delta?

3)If there has been a significant reduction in sediment delivery, are there any economically feasible available sources of sediment to increase the total sediment load to the delta?

Results indicate no detectable reduction in sediment delivery to the lowermost reaches of the Trinity River, and to Trinity Bay. Flow regimes downstream of Livingston Dam have not been greatly modified, and there is no flow-related decline in sediment transport capacity. There is also no shortage of available sediment in the lower Trinity. Sand is abundant, and there is no evidence of depletion of sandy bars since the dam was constructed. Floodplain accretion is occurring, also indicating that the river is not sediment-supply-limited.

The sediment budget of the lower Trinity River shows that while sediment trapping in Lake Livingston is quite extensive, sediment storage in the Trinity valley downstream of Romayor is even more extensive. The lowermost river valley is, in effect, a sediment bottleneck which buffers the Trinity delta and bay from effects of upstream changes in sediment supply (such as Lake Livingston). Sediment loads at Romayor show evidence of a post-dam decline, but sediment yields further downstream at Liberty show no such evidence.

There is evidence of dam-induced channel change in the reach 50 to 60 km downstream of the dam. Scour by water released from the dam with low sediment loads ("hungry water" ) has resulted in incision (downcutting) and channel widening (bank erosion).

Results also show three zones of distinct morphology and geomorphological response between Livingston Dam and Trinity Bay. The first extends to just downstream of Romayor and is characterized by dam-related incision and channel enlargement, a post-dam sediment yield reduction, and a net remobilization of previously stored alluvium. The second, extending to downstream of Liberty, is characterized by extensive sediment storage and net storage of alluvium. Channels are active and lateral migration is common, but no channel incision or enlargement (except by floods) is observed. The third reach, to be further analyzed in future studies, includes river sections apparently characterized by less active channel migration than is the case upstream, and the deltaic distributary zone. These reaches are characterized by fundamental differences in typical bank heights, floodplain widths and (especially) elevations, frequency of overbank flow, and sediment transport capacity.

Upland sediment production within the lower Trinity Basin is adequate to supply the river's transport capacity downstream of Romayor where the transport capacity is low. Much of the yield at Romayor is supplied by channel bed and bank erosion, as inputs from the local drainage area and "leakage" from the dam are inadequate to account for sediment measured at Romayor.

## BACKGROUND

Dams typically have significant geomorphic effects downstream, but these impacts vary substantially with size, hydrologic regime, environmental setting, history and channel morphology of the stream in question, as well as with the nature and operation of the impoundment (Williams and Wolman, 1984; Friedman and Osterkamp, 1998; Brandt 2000; Phillips, 2001; Graf 2001). Most previous studies were conducted relatively near the dam site and most examine visible changes such as channel patterns and indirectly sediment movement. While in some cases dams dramatically reduce sediment transport for a considerable distance downstream, in other cases there is no apparent impact on sediment regimes except in the reach immediately downstream of the dam. Phillips (1992; 1995) has documented this pattern in large rivers of the North Carolina coastal plain, and more recently on a small East Texas stream (Phillips 2001; Phillips and Marion 2001). The main implication is that impounded rivers must be examined individually, as no general conclusion can be compiled from the literature.

White and Calnan (1991) and Solis, Longley, and Malstaff (1994) have documented the sediment station history at the Trinity River gage at Romayor, downstream of Lake Livingston. This evidence suggests the dam has significantly reduced downstream sediment inputs and points to a need for a direct investigation. 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 percent of the shoreline has experienced erosion rates averaging 0.6 m/yr or more in recent years, while on Bolivar Peninsula the figure is 86 percent. In the Galveston Bay estuarine system, which includes the Trinity Bay and Trinity River delta, shoreline retreat of 1.5 to >3 m yr is common in recent years, and conversion of marshes to open water at a rate of 47 ha/yr has been documented for the Trinity Delta (Morton and Paine 1990; White and Calnan 1991; Morton 1993; GLO 2001). The erosion and land loss has, in many cases, accelerated within the past 50 years. White and others (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 (Davis 1997; Morton 1977, Morton and Paine 1990). 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 land loss.

## METHODS AND RESULTS

Additional background information, methods employed, and results are reported in subsequent sections. Sections 2 and 3 are based on journal articles (one accepted for publication, one in review). While there is some overlap, particularly in background material, these papers represent stand-alone analyses of the sediment budget and cross-sectional channel changes, respectively. Section 4 consists of appendices containing data not utilized in sections 2 and 3.

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# SECTION 2:
# SEDIMENT STORAGE AND TRANSPORT IN THE LOWER TRINITY RIVER BASIN

This section is a reproduction of:

Phillips, J.D., Slattery, M.C., Musselman, Z.A. In press. Dam-to-delta sediment inputs and storage in the lower Trinity River, Texas. *Geomorphology* (accepted for publication).

## Abstract

Livingston Dam on the Trinity River in SE Texas, U.S.A., 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 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).

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; 1992b; 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 U.S. 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 Brierley, 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/yr 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/yr is common in recent years, and conversion of marshes to open water at a rate of 47 ha/yr 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 yr. White et al. (2002) note that the Trinity River Delta was prograding through most of the twentieth 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 $m^3\ km^{-2}\ yr^{-1}$. 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 bedload. At the Romayor station on the Trinity River, on 12 occasions between 1972-1975 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%.

### *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 2.5m 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 made at the mouth of

Menard Creek, Romayor, and Port of Liberty (two sites).

## 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 $km^{-2}$ $yr^{-1}$. 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 $km^2$ $yr^{-1}$. 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 and 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 $km^2$ $yr^{-1}$, 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 $km^{-2}$ $yr^{-1}$, 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 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 $km^{-2}$ $yr^{-1}$. Loadings for the Trinity basin upstream of Lake Livingston are estimated as 265 t $km^{-2}$ $yr^{-1}$.

### *4.2. Alluvial storage*

Comparison of average annual sediment yields in Table 1 show the apparent effects of alluvial storage. Yields at Crockett are > 1.7 million t $yr^{-1}$ 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 $km^{-2}$ $yr^{-1}$ 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 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 $6.1 \times 10^9$ $m^3$. At a typical bulk density of 1.4 t $m^{-3}$, $8.52 \text{ X } 10^9$ tonnes are available. At recent rates of sediment yield at Liberty, this volume is equivalent to > 87,000 yr of sediment discharge.

From Romayor downstream, the mean annual alluvial storage is 5.4 to 9.1 million t $yr^{-1}$. The total amount of alluvium estimated above represents about 1,000 yr of net input at this rate (666 to 1,131 yr), 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 years. Typical accretion rates of 18 to 40 mm $yr^{-1}$ are consistent with vertical accretion rates in alluvial flood plains elsewhere in the U.S. Atlantic and Gulf coastal plains, which range from <1 to 61 mm $yr^{-1}$ over periods of 1 to 25 yr (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, 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, 6). 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 depressions (Fig. 4). This is evident from a number of flood plain cross sections derived from digital elevation models (Figs. 5, 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 $m^3$ $sec^{-1}$ discharge associated with the flood stage at Romayor has an annual exceedence probability of 29%. By contrast, the flood stage discharge of 989 $m^3$ $sec^{-1}$ 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 $km^{-2}$ $yr^{-1}$, this would yield 286,800 t $yr^{-1}$, 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):

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

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 $yr^{-1}$ would result. If 19% of this is transported through the lake, it could account for 1.14 million t $yr^{-1}$, about 34% of the yield at Romayor.

Unless trap efficiency of Lake Livingston is significantly over estimated or sediment input between Livingston Dam and Romayor is markedly under estimated, 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. Figures 7-9 show field evidence of channel scour between the dam and Romayor. Although such scour is clearly occurring at a significant 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/yr. Using the 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.

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

## Acknowledgements

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

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

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

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 km2 | Storage loss m3 | Years | Yield t/km2/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 |

Table 3 Alluvial storage by reach[a]

| Reach | Upstream input[b] | Local input | Down-stream 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) |

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

[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.

(1) An unrealistically high estimate based on the assumption of the 1.6 t $km^{-2}$ $yr^{-2}$ 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.

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

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

[a] In mm/yr.

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

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

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

| Reach | Total input (t yr$^{-1}$) | 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$^{-2}$ yr$^{-1}$)

| 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 |

## Figure Captions

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

Fig. 2. Tree on flood plain at Port of Liberty 2 site, with base buried by recent deposition. Note 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.

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.

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

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.

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

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

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

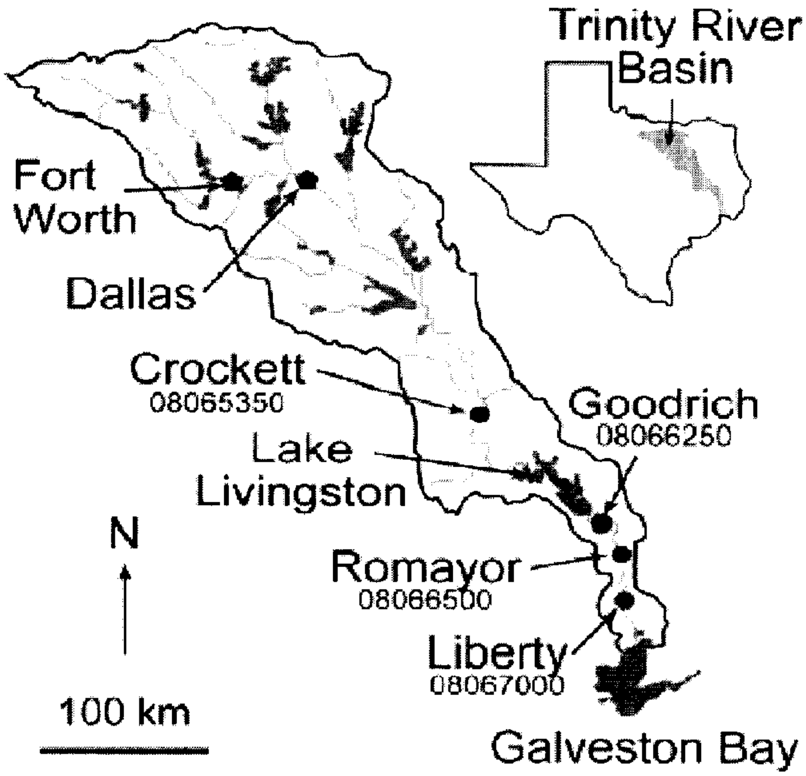

Trinity River
Basin
Fort
Worth
Dallas
Crockett
08065350
Goodrich
08066250
Lake
Livingston
N
Romayor
08066500
Liberty
08067000
100 km
Galveston Bay

figure 1

figure 2

figure 3

Figure 4

Figure 5

Figure 6

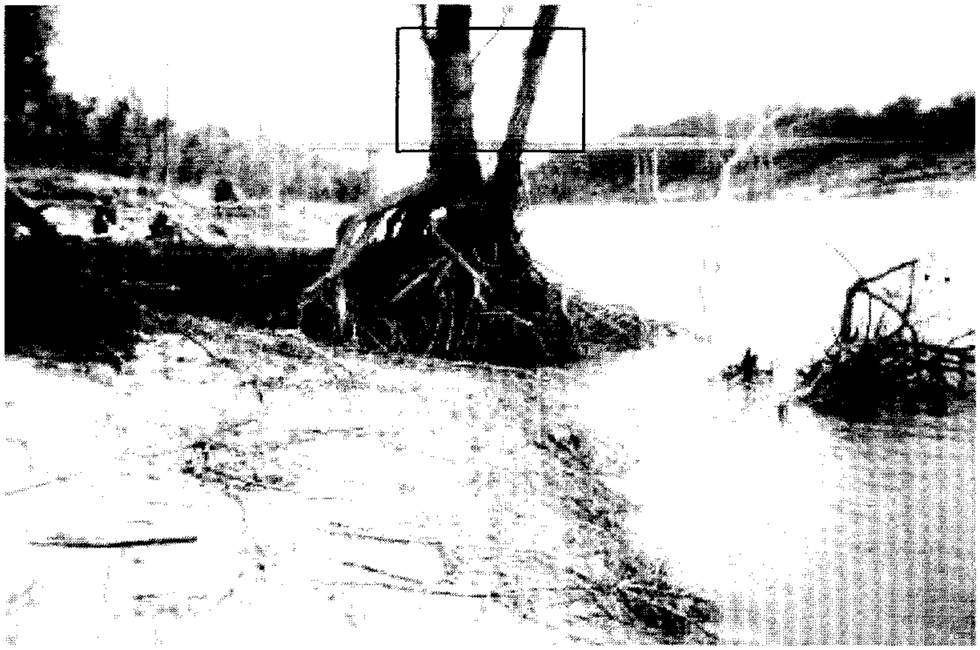


Figure 7

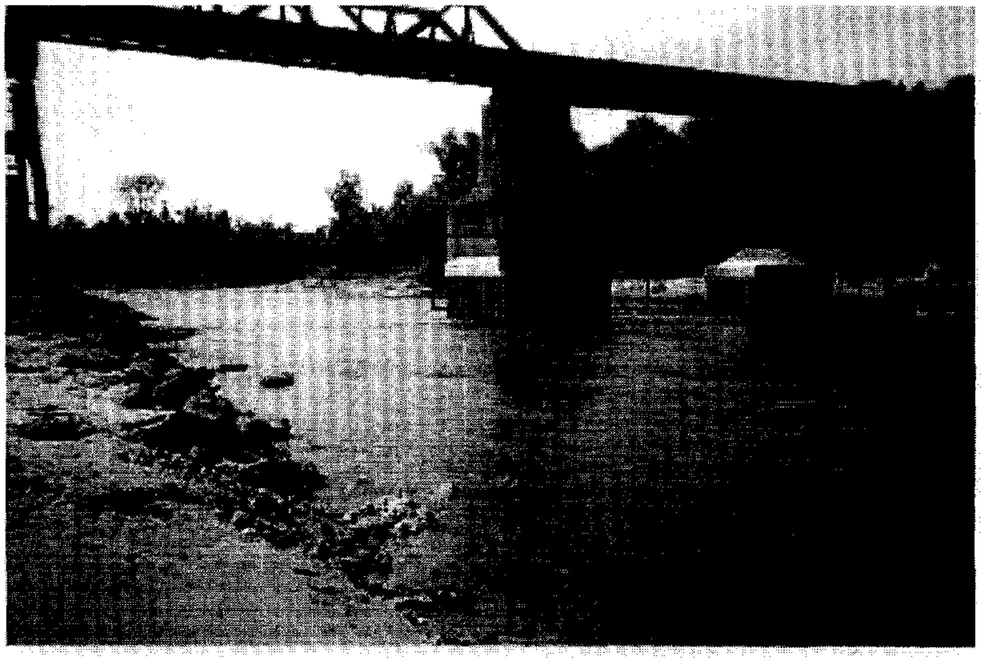


Figure 8

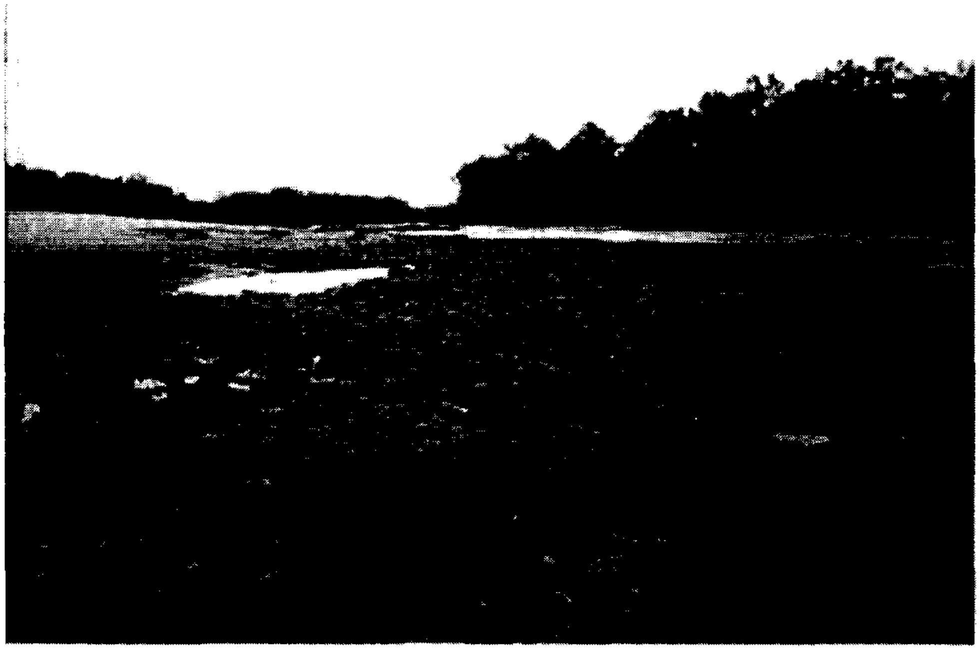
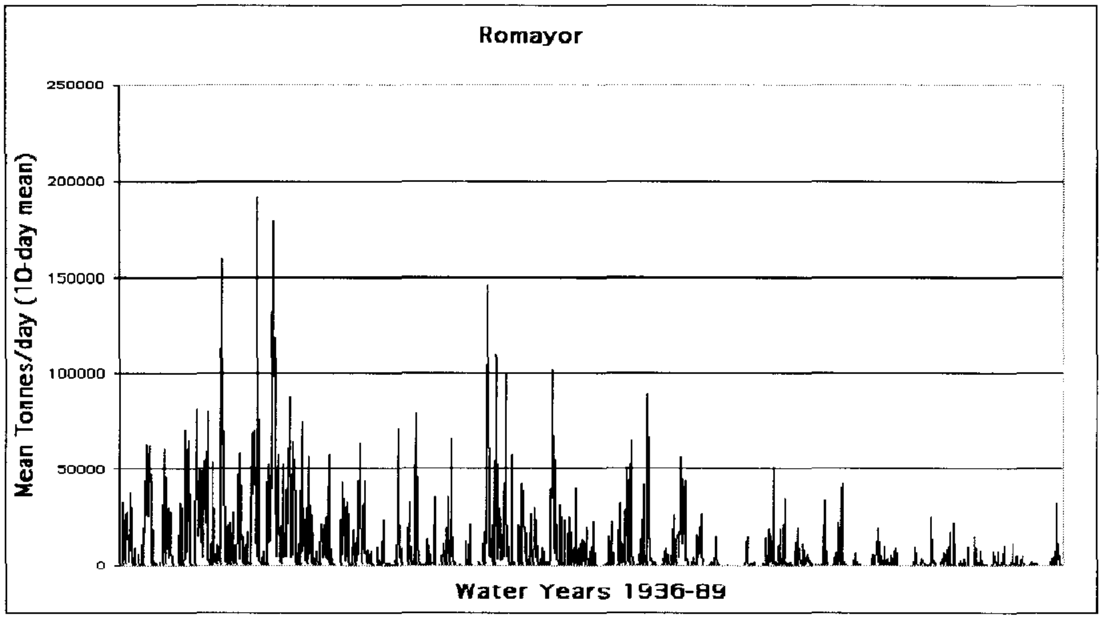


Figure 9


Romayor
250000
200000
150000
100000
50000
0
Mean Tonnes/day (10-day mean)
Water Years 1936-89

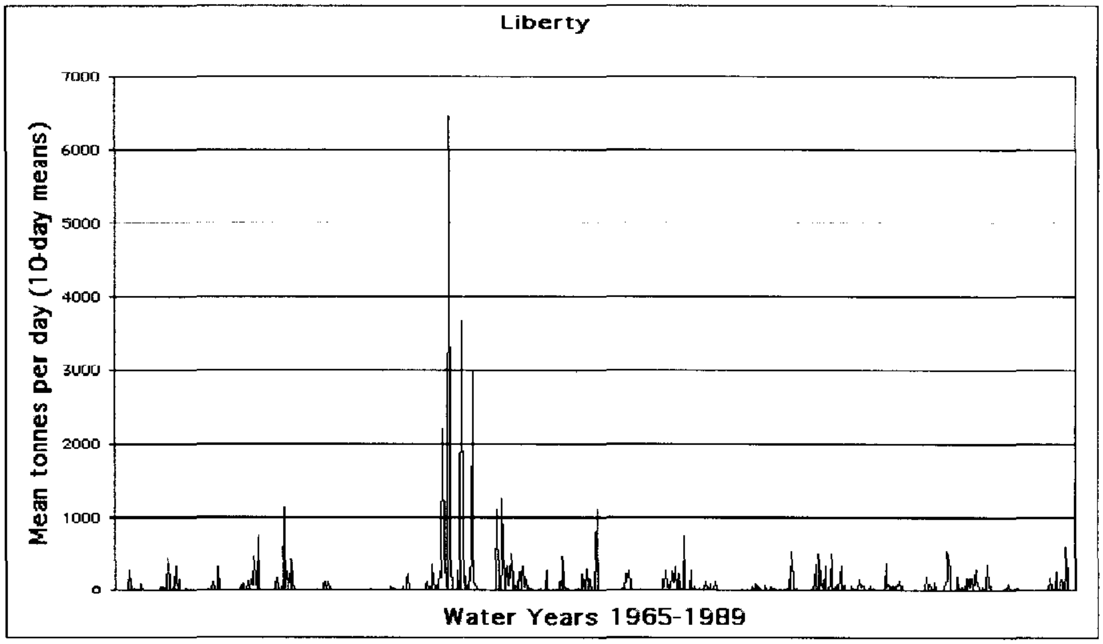

Liberty
Mean tonnes per day (10-day means)
7000
6000
5000
4000
3000
2000
1000
0
Water Years 1965-1989

figure 10

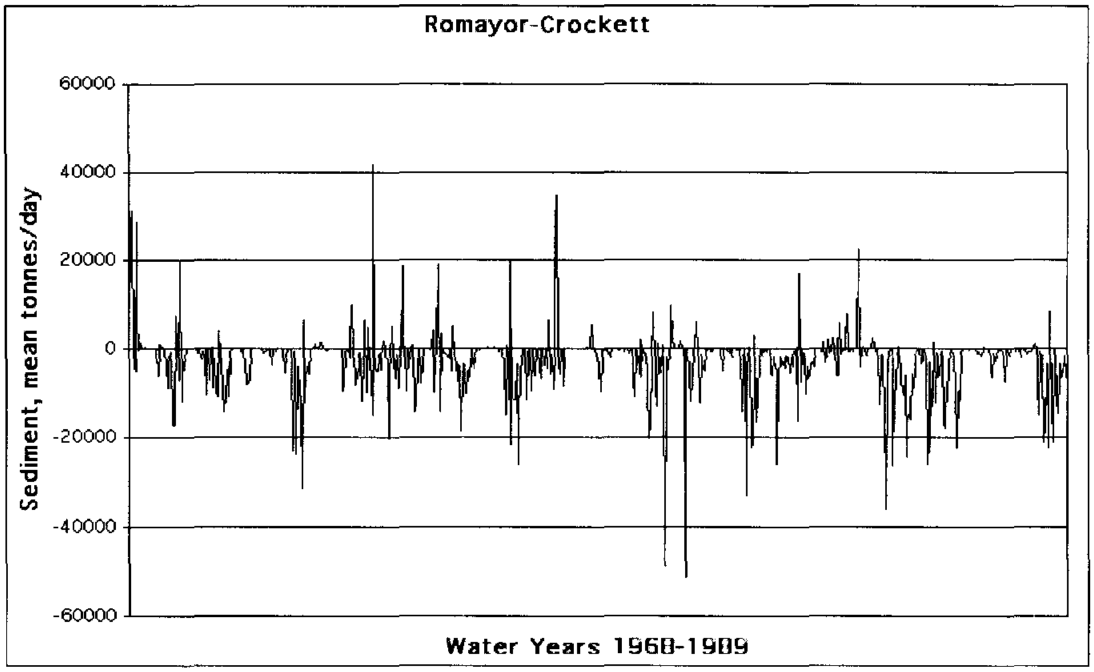

Romayor-Crockett
60000
40000
20000
0
-20000
-40000
-60000
Sediment, mean tonnes/day
Water Years 1968-1989

figure 11

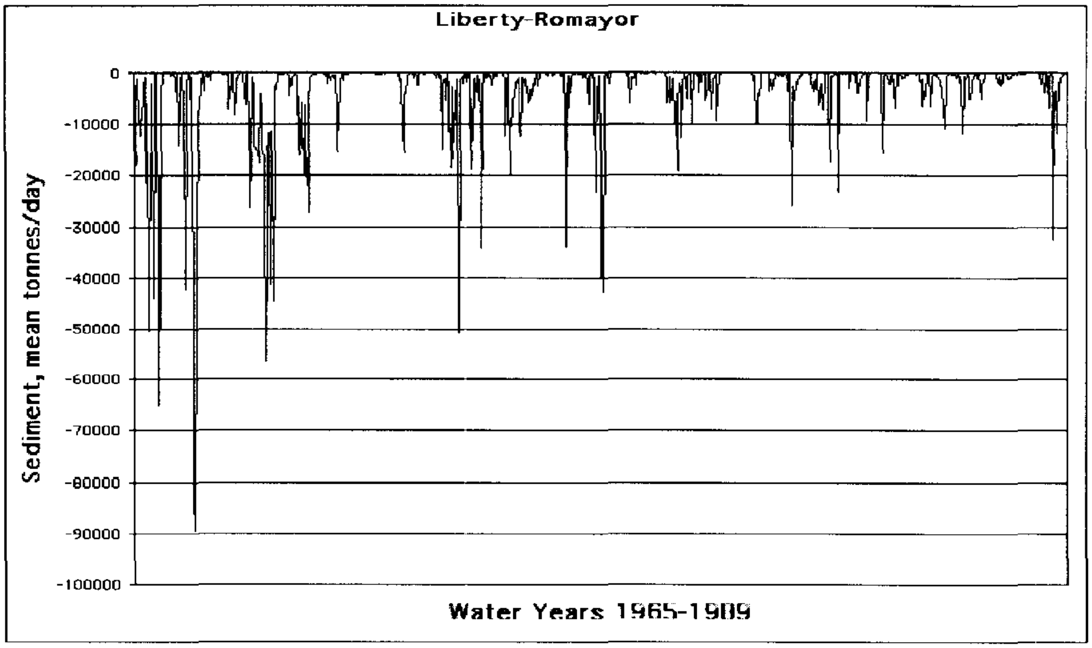

Liberty-Romayor
0
-10000
-20000
-30000
-40000
-50000
-60000
-70000
-80000
-90000
-100000
Sediment, mean tonnes/day
Water Years 1965-1989

figure 11

## SECTION 4: CROSS-SECTIONAL CHANNEL CHANGES

The following is a reproduction of an article currently under review by *Earth Surface Processes and Landforms*:

Phillips, J.D., Slattery, M.C., Musselman, Z.A. In review. Channel adjustments of the lower Trinity River Texas, downstream of Livingston dam.

### ABSTRACT

Channnel cross-sectional changes since construction of Livingston Dam and Lake Livingston in 1968 were studied in the lower Trinity River, Texas. High and average flows were not significantly modified by the dam, but sediment transport is greatly reduced by sediment trapping in the lake. The response in the channel for about 60 km downstream--incision, widening, coarsening of channel sediment, and a decrease in channel slope--are successfully predicted, in a qualitative sense, by standard models of channel response. Within these broad bounds, however, multiple modes of adjustment (qualitatively different combinations of increases, decreases, or no change in hydraulic variables) are found, as predicted by the unstable hydraulic geometry model. Between about 60 km and the Trinity delta 175 km downstream of the dam, no morphological response to the dam is observed or expected. This is due to the extensive sediment storage and reduced conveyance capacity, so that even after dam construction sediment supply still exceeds transport capacity. Further, the channel bed of much of this reach is near or below sea level, so that sea level rise and backwater effects from the estuary are more important controls on the fluvial system than upstream inputs. It is often assumed that major changes in fluvial sediment fluxes within a drainage basin are eventually communicated to the basin mouth. The lower Trinity results show that this is not necessarily the case.

KEY WORDS: channel adjustments, hydraulic geometry, dam effects, channel morphology, Lake Livingston, Trinity River

### INTRODUCTION

The purpose of this study is to describe and explain river channel cross-sectional change in the Trinity River, Texas, downstream of Livingston Dam. Dams and impoundments influence downstream geomorphology and hydrology--and, by extension, water resources, riparian land use, and stream ecology. Beyond studies of dam effects, however, the response of rivers to impoundment can also be seen as opportunistic field experiments. Fluvial geomorphologists have long been concerned with understanding the responses of stream channels to changes in imposed flow and sediment discharges. The impoundment of a river represents a spatially and temporally discrete, datable change in the flow and sediment transport regime of a channel. Thus, whatever the positive, negative, or equivocal social, economic, and environmental effects, dams represent potential opportunities for direct observation of channel changes.

The general issues of channel responses to changes in water and sediment inputs are discussed in fluvial geomorphology textbooks (e.g. Bridge 2003; Knighton 1998; Petts and Foster 1985; Richards 1982), and in particular in the literature on hydraulic geometry and regime theory (Ferguson 1986; Hey 1979; Huang and Nanson 2000; Lamberti 1992; Miller 1991a; 1991b; Simon and Thorne 1996; Yang 1992). Hydraulic geometry is explicitly concerned with adjustments at a cross-section (at-a-station) or downstream in response to changes in imposed flows and sediment inputs. A key issue is complexity and indeterminacy. There are many degrees of freedom for adjustments to changes in imposed flow, and the relative importance and efficacy of these responses is contingent on a number of time- and location-specific processes and controls. A related issue is that of multiple modes of adjustment, whereby, even within the constraints imposed by physical laws, there are numerous possible responses due to the complex mutual adjustments of basic hydraulic and geomorphic parameters (Phillips 1990; 1991). General governing conditions or laws, mostly based directly or indirectly on least-work principles, provide only broad constraints on possible channel responses (Huang and Nanson 2000; Ibbitt 1997; Lamberti 1992; Phillips 1990; 1991), as do general principles based on equable change (Miller 1991a; 1991b). The possibility and probability of specific responses may be further constrained based on local controls--for instance, the short-term prospects for increasing channel depth in a bedrock-controlled stream are nil.

There is another body of literature dealing with the downstream geomorphic impacts of dams; much of it is informed in at least a general way by the broader theory of channel responses to imposed changes. A few authors (e.g. Brandt 2000b; Xu 1990) have attempted to explicitly link principles of hydraulic geometry and regime theory to effects of dams. In general, the literature on downstream effects of dams on channel size, shape, and planform and the nature and rate of changes therein is equivocal (see reviews and syntheses by Brandt 2000a; Church 1995; Friedman et al. 1998; Graf 2001; Petts 1984; Petts and Gurnell 2004; Williams and Wolman 1984). That is, channels may get wider, narrower, deeper, shallower, more stable, less stable, and may degrade or aggrade depending on (among other things) the specific changes in flow regime, sediment trap efficiency of the impoundment, pre-dam conditions, and the local geological, ecological, hydrological, climate, and land use/management conditions. Responses will also vary with distance downstream from the dam and time since dam construction.

Beyond the study of dam effects in general, there are specific issues in the lower Trinity River. Channel scour and bank erosion has chronically threatened at least two bridge crossings in recent years, and bank erosion and channel migration have proved to be a recurring threat to property owners. Many local residents believe these geomorphic changes have accelerated since the completion of Livingston Dam in 1968, and thus suspect that the dam may be at least partly to blame. Even this apparently straightforward issue is complicated by the fact that the lower Trinity has been geomorphically active throughout the Quaternary, by anomalously high precipitation in the lower Trinity Basin during the post-dam period (Wellmeyer et al. 2004), and by the effects of a record flood in 1994. Changes in sediment transport and storage, and in planform change, are dealt with in separate studies (Phillips et al. 2004; Wellmeyer et al. 2004).

Examination of post-dam channel changes is not, then, a straightforward matter of applying rules of thumb or generalizations to a particular situation. Rather, it involves consideration of local context and constraints within a framework of fluvial geomorphology theory and physical principles. Specifically, this study first seeks to determine what changes in channel cross-sections have occurred in five channel reaches from Livingston Dam downstream to Trinity Bay, and the extent to which those changes are attributable to the effects of Livingston Dam. Second, we explore whether these changes are qualitatively predicted by several conceptual models. Finally, we interpret the results in the context of hydraulic geometry, particularly the role of complex responses and multiple modes of adjustment.

## STUDY AREA

The 46,100 km$^2$ Trinity River drainage basin has its headwaters in north Texas and drains to the Trinity Bay, part of the Galveston Bay system on the Gulf of Mexico (Figure 1). The lower basin, defined here as the drainage area downstream of Lake Livingston, has a humid subtropical climate, and a generally thick, continuous soil cover. Soils on stable upland sites are mainly Ultisols and Alfisols. Drainage area at Livingston Dam, which was completed in 1968 to form Lake Livingston, is 42,950 km$^2$. The primary purpose of the lake, which has a conservation pool capacity of more than 2.2 billion m$^3$, is water supply for Houston. The dam has no flood control function and Livingston is essentially a flow-through reservoir.

White and Calnan (1991) and Solis et al. (1994) examined sediment records for the Trinity River gage at Romayor, 51 km downstream of Lake Livingston, which suggest that the dam has significantly reduced downstream sediment transport. "Hungry water" downstream of dams, with unfilled sediment transport capacity, is known to result in channel degradation in some cases (Kondolf 1997), leading to suspicion that this is to blame for recent lateral and vertical channel erosion that has occurred in the lower Trinity. 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. A new splash basin was recently completed at the base of the dam due to the severe scour occurring there.

The Trinity River floodplain 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 floodplain and the lower alluvial terraces. The contemporary river has extensive evidence of bank erosion and point bar accretion. Thus the lower river is an actively migrating channel and has been throughout the Quaternary. 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 and Rodriguez 2000; Anderson et al. 1992; Blum et al. 1995; Phillips 2003; Phillips and Musselman 2003; Rodriguez and Anderson 2000; Rodriguez et al. 2001; Thomas and Anderson 1994). Thus one task is to disentangle dam effects from other factors influencing the geomorphology of the lower Trinity.

## PREDICTING EFFECTS

### *Dam Effects on Discharge and Sediment Transport*

As a water-supply reservoir with no flood control function, Lake Livingston has resulted in minimal changes in downstream discharge compared to pre-dam conditions. There is no evidence of post-dam reduction in mean discharges or annual peak flows at the gaging stations at Romayor (51 km downstream of the dam) or Liberty (120 km downstream). At Romayor, where the longest record is available, flow duration curves show that there is no pre- vs. post-dam change in the highest flows, while lower flows have increased in the post-dam period (Wellmeyer et al. 2004). Increases in low flows are common below dams, though in the case of the lower Trinity a general increase in precipitation in post-dam years is also present, thereby masking effects of the dam itself (Wellmeyer et al. 2004).

The capacity/inflow ratio of Lake Livingston is 0.316, which gives a trap efficiency estimate of 0.81, based on the curve of Brune (1953). Spillway effluent is indeed low in turbidity, and suspended sediment records for the Romayor station show evidence of a general post-dam decline in sediment loads (Fig. 2). A mass-balance study using sediment transport on the Trinity upstream of the lake and at Romayor, and estimating local inputs, also suggests extensive sediment storage in Lake Livingston, as well as channel scour in the river below the dam (Phillips et al. 2004). However, further downstream at Liberty, there is no evidence of any decline in sediment yield, and alluvial storage between Romayor and Liberty greatly exceeds sediment trapping in Lake Livingston (Phillips et al. 2004). Thus sediment starvation effects of the dam decline to insignificance somewhere between about 50 and 120 km downstream. Despite this, the long-term trend in sediment yields at Romayor (Figure 2) shows that "hungry water" scour might be expected between Lake Livingston and Romayor, at least.

In the lower Trinity River, then, discharge will be treated as unchanged by the dam, based on the lack of any flow reduction, and the lack of change to high flows, which are most important for sediment transport. Sediment inputs have clearly been reduced, and at least as far downstream as Romayor, sediment supply is less than transport capacity, based on the reduced load without accompanying discharge reductions, and the channel scour observed in the area (discussed below). Downstream of Romayor, however, sediment supply remains greater than transport capacity. This is apparent in the sediment budget (Phillips et al. 2004).

### *Model Predictions*

A number of models, generally in the category of hydraulic geometry or regime theory models, may be applied to predict or interpret downstream changes. These approaches vary markedly in their specifics (see general reviews by Ferguson 1986; Huang and Nanson 2000 and in the context of dam effects by Brandt 2000b) and in their quantitative predictions. In the qualitative sense, however, they are consistent with the conceptual models of Lane (1955) and Schumm (1969) (Brandt 2000b; Petts and Gurnell 2004). This is based on a steady-state equilibrium concept whereby

$$LD \sim QS \tag{1}$$

where L is sediment load, D is grain size, Q is discharge, and S is slope. If sediment load decreases and Q is unchanged, as is the case downstream of Livingston Dam at least as far as Romayor, the bed must become coarser and/or the slope should decrease.

Brandt (2000a) developed a classification and qualitative predictive model of channel changes downstream of dams based on a synthesis of the literature. He identified nine cases, based on changes in discharge (increased, constant, or decreased) and sediment load relative to conveyance capacity (load greater than, equal to, or less than capacity). In the lower Trinity, Brandt's model predicts channel erosion dominated by either bed or bank erosion. The cross-sectional area of flow should not change much, but the shape and position may change as "hungry water" erodes bed and/or banks. Further downstream, available sediment exceeds transport capacity (Phillips et al. 2004; Phillips and Musselman 2003). However, since this was the case before as well as after the dam, Brandt's model is not applicable.

Xu's (1990; 2001) model of complex response downstream from reservoirs predicts, for a case where clear water scour occurs, a three-stage adjustment process. First is a decrease in width/depth ratio and channel slope, coupled with an increase in sinuousity. Feedbacks in stage two lead to increasing w/d ratios and decreasing sinuousity, with a slowdown in the rate of slope change. Xu postulates a third stage characterized by a new stable equilibrium with w/d, slope, and sinuousity tending to constant values.

The unstable hydraulic geometry model of Phillips (1990; 1991) suggests that changes in channel geometry, slope, and roughness are likely to persist rather than to recover to pre-disturbance states, and that adjustment is characterized by multiple modes of adjustment rather than a single "equilibrium" response. Changes are likely to be characterized by qualitatively different modes of adjustment (defined as different combinations of increases, decreases, or negligible change in width, depth, slope, and roughness) within a single reach.

## METHODS

The primary sources of evidence are resurveys of channel cross-sections at highway bridge crossings, and field indicators of erosion, sedimentation, and channel change. Bridge crossings are not necessarily representative due to the tendency to choose, when possible, locally more narrow and stable channels and floodplains, and due to a tendency for scour to occur around pilings. However, such crossings do represent the only historical records of channel cross-sectional surveys. The bridge sites are supplemented with observations at 13 other cross-sections.

Channel cross-sections for five bridge crossings of the lower Trinity were obtained from the Texas Department of Transportation (TXDOT). These included channel surveys immediately prior (within two years) of bridge construction, and up to three additional surveys. In some cases cross-sections for two generations of bridges are available. These cross-sections were resurveyed in January, 2003 using the same methods employed by the bridge engineers, a weighted drop line. In flowing channel sections a 45 kg "torpedo" style suspended sediment sampler was used as the weight. The cross-sections were then compared to determine changes in width, cross-sectional area, mean depth, maximum depth, and width/depth ratio. The latter are all relative to a banktop-to-banktop datum determined for each survey. Channel sediments were sampled at each site. The TXDOT data also contains stratigraphic characterizations from test bores made before construction of each bridge.

At the five bridge sites, and an additional 13 sites (18 total), field evidence of geomorphic changes was assessed. These indicators include channel and bank morphology, vegetation, changes to cultural features such as bridges, boat ramps, and erosion control structures, dendrogeomorphic evidence (such as exposure or burial of tree roots), and comparisons of observations made during the study period (2001 - 2003) with earlier maps and aerial photographs.

These data are supported by data and observations on flow, suspended sediment transport, and sediment inputs collected in connection with related studies (Phillips 2003; Slattery 2003. Flow records from U.S. Geological Survey gaging stations at Goodrich (08066250), Romayor (08066500), and Liberty (08067000) were used to determine the discharge associated with bankfull stage. U.S. Geological Survey field measurements of velocity at each station at stages within 2 feet (0.6 m) of bankfull stage were used to calculate mean bankfull velocities. These measurements, combined with estimates of slope based on the channel bed slope upstream of each station as an approximation of energy grade slope, allowed stream power to be calculated at each station for the bankfull reference condition. Cross-sectional stream power is given by

$$\Omega = \gamma Q S \qquad (2)$$

where $\gamma$ is the specific weight of water, Q is discharge, and S the slope. This represents the total transport capacity of the river at a given cross-section as a rate of energy expenditure. The stream power per unit weight of water is

$$P_u = \gamma Q S / \gamma \; w \, d = VS. \qquad (3)$$

Each cross-section was characterized with respect to qualitative (e.g., increase, decrease or negligible change) responses of width, depth, slope, and roughness. Changes in width and mean depth were measured directly from the bridge cross sections. At other sites, increases in width were considered to occur if there was field evidence of erosion on both banks, and decreases where there was evidence of accretion or infilling on both banks (or on one bank, with the other stable). The latter was observed only at sites upstream of Lake Livingston that are not discussed in this paper. Indicators of cutbank erosion where there was also evidence of pointbar accretion were not considered evidence of channel widening. Vegetated banks without erosion scarps, slope failures, or toppled trees were considered stable.

Increases in depth were assumed to be due to channel scour, as indicated by downcutting relative to man-made objects such as bridge pilings, exposure of bedrock in low-water channels, and former bank positions higher than current banks. No evidence of channel aggradation, associated with decreasing depth, was observed.

Changes in slope were estimated based on channel thalweg elevations determined from maximum depths at bridge cross-sections, by dividing elevation differences by the channel distance between stations. These were therefore estimated on a reach basis (Camilla-Goodrich, Goodrich-Romayor, Romayor-Moss Hill, and Moss Hill-Liberty). All intervening cross-sections are assumed to have experienced the same qualitative change in slope of the thalweg.

Channel roughness varies with flow hydraulics, but it was assumed that within the context of the lower Trinity Channel the general roughness regime varies primarily as a function of large woody debris and major bedforms (bars). Thus indications of active delivery and accumulation of woody debris, or of growth of bars, was taken to indicate an increase in roughness. Bar or debris removal or flushing is taken to indicate a decrease in roughness.

There are no pre-dam sediment samples available for direct testing of whether coarsening has occurred. We attempted to get some indication of this by comparing grain size of several samples collected upstream of Lake Livingston, at the downstream-most accessible site which is unaffected by backwater effects from the Lake. This is the state highway 21 crossing, and nearby Pecan Landing. Samples were collected from the channel and from the bank/channel interface at SH 21, and from the surface of a point bar and the channel adjacent to the point bar at Pecan Landing. Channel samples were collected at Goodrich and Romayor, and point bar and bank edge samples from Romayor, for comparison. The upstream samples are assumed to approximate pre-dam sediments at the downstream sites.

Samples were oven-dried and disaggregated, and dry sieved using an ATM sonic sifter. To assess potential coarsening, samples were compared in terms of the percentages of silt and clay (all sub-sand size particles), percentage of grains of fine sand (0.125 mm or 3ø) or finer, and percentage of grains which were medium sand (0.24 mm or 2ø) or coarser.

## RESULTS

Results are presented on a reach-by-reach basis, starting at Livingston dam.

### *Livingston Dam (Camilla) to Long King Creek*

Predictably, the reach immediately downstream of the dam shows the greatest post-dam change. This is, of course, partly due to the engineering modifications of dam and reservoir construction itself, which locally rerouted the main channel in the vicinity of the dam spillway (Figure 3).

Based on channel elevations at Camilla at the time of dam construction, and in the 1948 survey at Goodrich (near the mouth of Long King Creek), the channel bed slope pre-dam was 0.000314. Based 2003 surveys, the slope had been reduced to 0.000283.

There is abundant evidence in this area of clear-water scour and both vertical incision and bank erosion. A splash basin below the spillway was recently completed to alleviate effects of scour immediately below the spillway. Boat ramps a short distance downstream of the dam--a popular and productive fishing spot--have been rendered useless by the channel scour. The lower ends of the concrete ramps are broken and undercut, and due to downcutting are no longer usable at normal water levels.

Dendrogeomorphic evidence of the channel scour is also apparent. Floodplain stripping is indicated by exposed roots on floodplain and bank trees, which bear evident watermarks from high flows. Measurements of the current 2002 ground surface to the root crown indicate at least 1.29 m of vertical erosional stripping. A lateral gully across the floodplain in this vicinity exposes cypress knees (normally above-ground root portions of the bald cypress tree, *Taxodium distichum*). Because the cypress germinates in wet soils at or near river levels, the presence of the species well above current water levels is indicative of downcutting.

The SH 3278 bridge was built a short distance downstream of the dam in 1997 (survey date 1995). For the 1995-2003 perid, surveys show both widening and scouring (Fig. 4; Table 1). The cross-sectional area increased 43 percent, reflecting a 40 m increase in banktop width, and increases of almost 3 m in maximum depth and 2 m in mean depth. While at least some of this change no doubt represents short-term adjustments and scour immediately following construction, it also suggests that scour in this zone is still occuring, more than 35 years after dam construction. Note that in all cases the channel dimensions are relative to bank tops, and are not necessarily indicative of changes in cross-sectional areas of flow.

The "bedrock" of the lower Trinity channel in this vicinity is a tight gray clay. In TXDOT drillings on the banks at the SH 3278 bridge site, this occurs more than 12 m below the surface. In the channel, test borings in 1995 showed less than 0.6 m of loose sand overlying the gray clay. In 2002 there was a thin veneer of sandy bed material overlying the clay on the channel margins. Scour into this material during high flows is indicated by gray watermarks on trees in the vicinity.

Additional cross-sections were observed further downstream in this reach. At the Camilla Twin Harbors community channel morphology was consistent with recent scour, including fresh erosion scarps on both sides of the channel. At Cedar Valley, a large, unvegetated--and therefore active--sandbar was present on the left bank. The right bank is an active cutbank, with fresh erosion scarps and recently toppled trees. The light-colored gray watermarks associated with scouring of channel-bed clays were evident at Cedar Valley as well.

### *Goodrich to Romayor*

This reach encompasses the area from the confluence of Long King Creek, the largest tributary downstream of Lake Livingston, to just upstream of the Romayor bridge crossing and gaging station. This reach also experienced slope reduction, based on comparing pre-dam and 2003 thalweg elevations at Goodrich and Romayor, from 0.000359 to 0.000250.

The bridge surveys at the U.S. 59 crossing near Goodrich, TX are difficult to compare because of multiple generations of bridges. Thus the 2003 survey focussed on replicating the earliest, 1948 cross-section as closely as possible. The comparison shows decreases in width and cross-sectional area, but these are primarily due to engineering and construction activities at the site (Fig. 4; Table 1). Vertical scour is evident, however, in a 5 m increase in mean depth and a slight (0.8 m) increase in maximum depth. Surface water measurements from the U.S. Geological Survey show a marked decline in width/mean depth ratios after 1982 (figure 5). This suggests a decreased frequency of overbank flow and a completion of most of the downcutting by the early 1980s.

Channel incision has been extensive at this site. A short distance upstream of the highway bridges is a railroad trestle constructed in 1917. Concrete pads on bridge pilings were constructed flush with the channel bed surface at that time. In 2002 these pads were at least 5.26 m above the bed surface. Channel downcutting has also triggered a downcutting response at the mouth of Long King Creek, where a recent "paleobank" is obvious above the current bank (Figure 6). The mean vertical distance between the current and contemporary bank top suggests 3.62 m of downcutting.

Banks at the bridge sites are well-protected with revetments. Immediately upstream, however, bank erosion and retreat is evident along the right bank. Slope failures are evident along the banks, and the remains of erosion control groins attest to failed erosion control efforts. Downstream of the bridges a resistant clay/shale layer outcrops in the nearly vertical channel banks, reflected in a distinctly narrower channel (Fig. 7). These banks are nonetheless actively eroding, as indicated by toppled trees in the channel along the left bank. Seven channel width measurements (based on the normal-water-level channel indicated by the vegetation line) 80 to 200 m upstream of the railroad crossing ranged from 129 to 150 m, with a mean of 138.3. Two measurements 50 and 75 m downstream of the lowermost of the bridges showed widths of 84 m.

The left bank upstream of the bridges (between Long King Creek and the railroad), by contrast, is characterized by active deposition. Dendrogeomorphic measurements of recent (one to 27 years) vertical accretion rates showed clear evidence of recent accretion at nine of 10 samples, with a mean rate of 18.5 mm $yr^{-1}$ (Phillips et al. 2004). The stratigraphy in this zone is also consistent with recent deposition. Two auger holes in 2002 show stratification, and limited pedogenic development to a depth of 3 m or more. Hiatuses in deposition occasionally occur, apparently, as indicated by thin, weakly-developed buried Bh horizons which occasionally occur. The alluvium is dominantly sandy, with occasional clay lenses.

A delta has developed at the mouth of Long King Creek since Livingston Dam was created. Tributary-mouth delta growth is not uncommon downstream of dams where flow in the main channel has been reduced, but this is not the case in the Trinity. While flow magnitudes have not been reduced, the lake creates asynchronicity in peak flows between Long King Creek and the Trinity. Peak sediment inputs from the creek, we speculate, are delivered before river discharge has increased enough to transport the coarser material. The delta is dominantly sandy, but characterized by alternating sand and clay layers. This suggests that at high flows there is backwater flooding, and perhaps recirculating eddies, in the creek mouth, facilitating the fine-grained depostion. At normal and low water levels there is an obvious flow from the creek into the river and a turbidity plume.

The mouth of Menard Creek, the second largest tributary in the lower Trinity, has also built a delta, and shows evidence of recent vertical accretion downstream of the creek mouth. No tree coring was done at this site, but there was obvious burial of basal flares and root crowns of trees of all ages and sizes. There were 9 mm of sediment (in August 2002) covering the previous winter's litter layer. A former channel bank position is marked by leaning trees. The top of this paleobank is 3.07 m above the accreted floodplain surface below, which is about 24 m wide from the former to the current bank. There is no other evidence of downcutting at the Menard Creek mouth, which is backwater flooded from the Trinity at normal and low water levels. An active pointbar across the river, combined with the sandy creekmouth delta, creates a highly variable, mobile channel at this site.

The railroad trestle near Romayor, upstream of the Romayor gaging station, appears to be a relatively stable cross-section. There is a cutbank with erosion scarps and toppled trees upstream on the left bank, on the outside of a meander bend, but with no point bar opposite. The east side (left bank) of the railroad trestle was recently reconstructed (concrete beams are date-stamped November, 2001), but there is no obvious evidence that bank erosion or channel scour is responsible.

*Romayor to Moss Hill*

This reach, from the vicinity of the Romayor gaging station at the SH 787 bridge to just upstream of the SH 105 crossing near Moss Hill, encompasses an apparent transition in river valley morphology and dynamics. Alluvial sediment storage increases dramatically downstream of Romayor, and floodplain morphology suggests that this transition occurs within a few km downstream of Romayor (Phillips et al. 2004). Channel slope here is very low; ~ 0 based on pre-dam surveys and 0.00001 in the 2003 survey.

The Romayor bridge cross-sections (Fig. 4; Table 1) reflect the effects of floods. The original profile of ca. 1923 has a banktop width of about 133 m, maximum depth of 17.2 m, and mean depth of 7.4 m. The next survey was in 1995, following a major flood in October 1994. There were also a series of floods in 1990, and a TXDOT engineer at the scene said the Romayor bridge had only three feet of one piling remaining unexposed following a 1993 flood. The 1995 profiles showed similar width, but a maximum depth of 19 m and mean depth of 11.7 m. Depths were similar in a 1999 survey, but width had increased some. In 2003 some recovery had apparently occurred. Cross-sectional area was 1043 $m^2$ (compared to 982 in 1923 and the maximum of 1715 in 1999). Depths were near 1923 levels (maximum 16.3 m; mean 9.3), but width (presumably due largely to infill associated with bridge repairs) was reduced to 112 m.

Channel downcutting at Romayor is obvious. The 787 bridge is chronically threatened by scour, and was under repair during fieldwork. Sandstone bedrock is exposed in the channel at low water immediately downstream of the bridge. Bank erosion is also evident. The left bank just upstream of the highway shows erosion scarps, slump scars, and evidence of multiple generations of erosion control structures (groins, rip-rap, revetments) and of recent fill of bank scallops along the road. The right bank downstream shows erosion scarps and slump scars, as well as toppled trees and large woody debris (Figure 8).

Tropical Storm Allison in June, 2001 illustrates the active sand transport that occurs in the lower Trinity. The storm deposited two left-bank sandbars in the vicinity, one upstream of the bridge and one immediately downstream (Figure 8). These bars were evident in October 2001, but were greatly diminished in size in May, 2002. By August, 2002, the upstream bar was no longer in evidence and the downstream bar was nearly gone.

A right bank sandbar upstream of the bridge is largely stable, as indicated by well-established vegetation, cross-bar gullies, and tributary stream incised more than 5 m at the upstream end. The upper surface shows clear evidence of recent sedimentation, however, in the form of buried vegetation. This bar is a direct result of efforts to control erosion of the right bank at and just upstream of the bridge. Bank-normal groins were emplaced to trap sediment, and have succeeded in building a sandbar. In one location where the former bank position could be clearly identified by the presence of a navigation warning sign (now invisible from the channel), the bar had built to a width of 52 meters in 2003. At least partially as a consequence, however, erosion on the opposite bank has been severe, chronically threatening highway 787. Further, the artificially-induced bar apparently captures sediment that would otherwise accrete as a point bar at and just downstream of the bridge site on the left bank. It is ironic that the upstream right-bank groins--the only successful example of several uses of this technique we observed in the study area--appear to have exacerbated the overall bank erosion problems in the vicinity of the bridge.

Bank erosion is evident at the Sam Houston Lakes site, mainly associated with active meander migration. An active, unvegetated sandbar on the left bank is across from an active cutbank with recently toppled trees, abundant large woody debris, and a house undermined and collapsed into the channel. Bank failures due to sliding on a clay layer are also evident.

The Cypress Lakes site is also one of active meander migration. A large, active, mostly unvegetated point bar on the right bank faces a cutbank wth erosion scarps. The bar is also migrating downstream, as the downstream end is backed by a small sloping scarp with tilted trees marking the recently-transgressed bank.

*Moss Hill to Liberty*

Changes at the SH 105 crossing near Moss Hill are marked mainly by bank erosion and recent channel widening. The original pre-1970 banktop width of 188 m was reduced by 156 in a 1992 survey, but had increased to 400 m in 2003 (Fig. 4; Table 1). The greater part of this widening likely occurred during a major 1994 flood, discussed below. Cross-sectional area increased more than 200 percent by 2003, due to the width increase. Though the maximum depth increased by 5.5 m, mean depth decreased slightly over the period. Pre-dam thalweg elevations indicate a channel slope of 0.000134; while the 2003 data indicate a negative slope (-0.000136). Because this reach includes sections where the channel is below sea level, it is unlikely that energy grade slopes are related to channel slope.

The erosion occurred on the left bank, a cutbank paired with a large sandy point bar. The bank is steep, mainly unvegetated, with toppled trees and large woody debris at the channel margin. Upstream of the bridge on both banks are pilings, remnants of failed erosion control groins. Local residents indicated that left bank erosion is constant, and said (in May 2002) that significant bank retreat had occurred within the previous year.

The right bank point bar is active, and deposition is evident on the upper bar and in the backswamp area behind it. Dendrogeomorphic estimates, covering periods of one to 16 years, show mean accretion rates of more than 45 mm $\mathrm{yr}^{-1}$ (Phillips et al. 2004).

Dayton Lakes is the site of another massive point bar. The lower part is unvegetated, and bedforms were evident on the lower portions. The size and extent of vegetation on higher portions of the bar suggest at least three episodes of growth and two of subsequent vegetation colonization and stabilization. The right bank cutbank has erosion scarps, toppled trees, and fresh slope failures. One of these was examined closely, with the failure surface occurring over a smectitic clay layer. This slump was observed on consecutive days, with more than 1 m of movement occurring overnight.

Kenefick was the site of a major oxbow cutoff that occurred in the October 1994 flood (Figure 9). Just downstream of the cutoff is an active cutbank-pointbar pair. The lower bar is active (unvegetated, bedforms on lower portion), while the partially-vegetated upper portion shows evidence of recent alluvial burial of vegetation.

*Liberty to Trinity Delta*

The Trinity River bed at Liberty is below sea level, so this reach is influenced by backwater effects from the Trinity Bay estuary. While lunar tides in the Galveston Bay system are small, ponding effects and wind set up may influence flow up to approximately Kenefick, and gages at Liberty and Moss Bluff show tidal fluctuations superimposed on fluvial flows.

At the U.S. 90 bridge crossing at Liberty, width, depth, and cross-sectional area declined between 1938 and 1992. The 1994 flood, however, created significant widening and about 6 m of incision as shown in a 1995 profile. Surveys in 2001 and 2003 show further increases in width, but decreases in depth (Fig. 4; Table 1). The width measurements are affected by construction of a boat ramp just upstream of the highway bridges.

Active point bars exist on the left bank just upstream of the bridges and on the right bank downstream, with recent sedimentation evident on the upper right bank point bar and adjacent floodplain. Mean recent accretion rates from dendrogeomorphic measurements are about 40 mm $yr^{-1}$ (Phillips et al. 2004). The left bank bar was not assessed in detail, but features *in situ* dead trees buried in unvegetated sand, suggesting rapid recent deposition. Otherwise, there is abundant evidence of bank erosion (Fig. 10), including remnants of failed erosion control groins.

The Old River near Liberty is not a recent cutoff, and was developed as a port facility in the 1970s. It was not navigable by commercial traffic in 2002, and at low water the mouth of Old River can be crossed on foot. On the left bank smectitic clays provide a sliding surface for several slump failures similar to, but larger than, those observed at upstream sites. Otherwise the banks appear relatively stable in this vicinity. Recent sedimentation is indicated by buried tree root crowns and basal flares in backswamp areas. The alluvium is, as at other sites, dominantly sandy but with a significant content of fines.

At Moss Bluff, erosion is evident on the left bank, where rip rap and debris filling of washouts are common. The right bank appears stable. Though the river meanders considerably in this reach, the large point bar-cut bank combinations common from Liberty upstream are absent in this vicinity.

The Trinity channel was also examined in the vicinity of the interstate 10 crossing, at the Wallisville Project tidal barrier, and at the river mouth at the delta at Anahuac, Texas. The delta and I-10 sites are low-bank with marsh and/or swamp shorelines and are dominated by coastal processes. No obvious evidence of fluvial change was noted. At the delta site some tree trunks in the channel are clearly larger than any of the local trees growing in the marsh areas and may thus be inferred to have been transported from upstream.

The Wallisville site is engineered. Between Liberty and Moss Bluff the intake for the Coastal Water Authority canal is an additional water supply for the Houston area. Between 1968 and 2000, the prevention of salt wedges during low flow at the canal intake was achieved by releasing flushing flows from Lake Livingston. The Wallisville barrier is designed to close when salinity reaches critical levels to prevent upstream intrusion, thus reducing or eliminating the need for flushing flows. No such releases have occurred since 2000.

### *Grain Size*

Grain size comparisons for sites upstream of Lake Livingston and downstream of Livingston Dam are shown in Table 2. In general, results do indicate coarsening, if the upstream sites are indeed representative of pre-dam grain size at the downstream sites. The channel sample at Goodrich has fewer fines and a greater percentage of medium sand-to-gravel sizes than the comparable SH 21 channel sample. The difference is even more pronounced at Romayor, which has less than 0.1 percent silt and clay (vs. 10.1 percent at SH 21) and 85 percent medium sand and coarser (10 times greater than SH 21). The bank edge sample at Romayor is likewise coarser than the comparable sample at SH 21. The point bar samples at Pecan Landing (one on the point bar surface, one in the immediately adjacent channel) are very low in fines, but the Romayor point bar sample was even lower. The sand was also finer at the Pecan Landing site. In general, results of the comparison are consistent with channel sediment coarsening after dam construction.

### *Stream Power*

Discharge, stream power, velocity, and sediment transport capacity are substantially less in the lower reach than in the dam-to-Romayor section. Table 3, based on a bankfull reference standard, shows that discharge increases from Goodrich to Romayor. However, $Q_{bf}$ at Liberty is less than that at Goodrich and less than half the value at Romayor. The mean velocity of near-bankfull flows at Liberty is also less than half the value at Romayor. Stream power values are based on the assumption that energy grade slope is approximated by the channel bed slope of the reach upstream of a given cross-section, and are thus subject to considerable quantitative uncertainty. However, the relative slope at the cross-sections is considered accurate, and thus the relative cross-sectional and unit stream powers are reflective of the relative transport capacities. These data indicate the greatly reduced transport capacity downstream of Romayor, as total bankfull stream power at Romayor is about 2.4 times that at Liberty, and units stream power 53 times higher.

### *Synthesis and Summary*

Geomorphic changes at each cross section are summarized in Tables 4 and 5. From the dam to Romayor post-dam channel scour is evident. Further downstream downcutting is less evident, though bank erosion is common. However, the bank erosion seems to be associated primarily with meander migration rather than adjustments associated with Livingston Dam. The effects of the 1994 flood are the dominant factor in channel changes downstream of Romayor. The October 17-21, 1994 flood is the worst on record in southeast Texas. The record discharge from Lake Livingston, 3113 $m^3sec^{-1}$ at the Goodrich gaging station, occurred during this event. Peaks were lower downstream at Liberty, which received about 76 mm of rain in less than 48 hours. Much of the city of Liberty was underwater in this event, as levee systems failed.

The sediment budget study of Phillips et al. (2004) showed that the lower Trinity contains two distinct reaches with respect to sediment storage. From the dam to approximately 60 km downstream (a few km past Romayor) there is evidence of a post-dam reduction in sediment loads. In the remainder of the river valley, alluvial storage increases and the sediment delivery ratio decreases dramatically, forming a sediment bottleneck that buffers the lower river and Trinity Bay from changes in upstream sediment transport. The fundamental difference in behavior is also reflected in valley morphology, with the lower section characterized by lower floodplain elevations, a wider floodplain, and larger and more numerous sloughs and oxbows (Phillips et al. 2004).

This fundamental difference is also reflected by the cross sections. The seven sites from Livingston Dam to Romayor are characterized by incision, widening, and a decrease in channel slope. Downstream cross-sections are generally characterized by stable widths even as channels actively migrate laterally and increasing slopes. Any channel erosion appears to be associated with the effects of the 1994 flood.

## DISCUSSION

### *Model Predictions*

Results above suggest that morphological effects of Lake Livingston and Livingston Dam apply to the approximately 60 km downstream of the dam, and the seven cross-sections from the dam to Romayor. Thus the predictive models are relevant mainly to these sites.

Hydraulic geometry or regime models based on the Lane/Schumm equilibrium concept predict that the Trinity River bed should become coarser and/or the slope should decrease. The channel slope, as indicated by the elevation of the thalweg, indeed decreased post dam as far downstream as Romayor. The grain size analyses are consistent with a post-dam coarsening, though this is based on an indirect approach assuming that sites upstream of Lake Livingston represent pre-dam grain size distributions at the downstream sites.

Brandt's (2000a) framework predicts widening and/or incision for the dam-to-Romayor reach, which is also evident. All seven cross sections show evidence of either widening or incision or both, though at one site (mouth of Menard Creek) the evidence is not strong. At five of seven channel widening is evident, while one shows no evidence of significant changes in width. The Romayor site has locally experienced increases and decreases in width, largely associated with construction and erosion control activities. Five of seven sites also have morphological evidence of incision.

Xu's (1990; 2001) model predicts a decrease in width/depth ratio and channel slope, coupled with an increase in sinuousity. Slopes have decreased, as described above, from the dam to Romayor. At the 3278 site w/d decreased slightly from 1995 to 2003, but the amount of change is small and interpretation confounded by bridge construction. At Romayor the w/d ratio has ranged from 7.73 in 1923 to 6.74 in 1995. The 1995 value following the 1994 flood (7.64) is near the original value, and in 2003 w/d = 7.64. Thus the ratio here is variable, with evidence of a slight post-dam decline. The Moss Hill and Liberty sites show increases in w/d in 2003 as compared to the earliest profiles, but these are likely attributable to the effects of the 1994 flood. The data presented by Wellmeyer et al. (2004) do not show any significant changes in sinuousity in the lower Trinity, though lateral channel migration is common.

The unstable hydraulic geometry model of Phillips (1990; 1991) suggests that changes in channel geometry, slope, and roughness are likely to persist rather than to recover to pre-disturbance states, and that adjustment is characterized by multiple modes of adjustment rather than a single "equilibrium" response. Changes are likely to be characterized by qualitatively different modes of adjustment (defined as different combinations of increases, decreases, or negligible change in width, depth, slope, and roughness) within a single reach. At the seven cross sections from the dam to Romayor, there are five qualitatively different modes of adjustment with respect to increases, decreases, or lack of change in width, depth, slope, and roughness. Downstream of Romayor there are at least four different modes of adjustment (the uncertainty arising from an absence of slope change data downstream of Liberty) at nine cross sections.

The equilibrium and Brandt models are very effective at predicting the qualitative channel responses, but in a very broad, general way. The multiple modes of adjustment model is also confirmed, and implies that within the broad constraints of the behaviors predicted by the equilibrium and Brandt models, that qualitatively different modes of adjustment will occur.

The sequence predicted by Xu's (1990; 2001) model is not supported by these data, but it should be noted that, first, this model is far more specific, detailed, and ambitious than the others; and second, that the time since dam construction may not be sufficient to fully evaluate the model.

### *Spatial and Temporal Propagation*

The response of a fluvial system to a point-centered perturbation such as a dam could be expected to begin the immediate vicinity of the disturbance and propagate downstream. In the Trinity the response is evident as far downstream as Romayor, while at sites further downstream the channel incision and/or widening and slope decrease is not evident. This raises the question of whether the lower reaches are unaffected by the dam, or whether the response has not propagated that far in 35 years.

The Trinity downstream of Romayor is distinct from reaches above both morphologically and in terms of sediment dynamics. Sediment budget studies indicate that the lower river is a much more effective sediment sink than upstream reaches (Phillips et al. 2004), and from about 95 km downstream of Livingston Dam the channel bed is below sea level. From this point downstream, and for some distance upstream, Holocene sea level rise in the longer term and water level changes in the estuary in the shorter term exert more influence on flow and sediment transport than the dam upstream.

Transport capacity (as indicated by mean bankfull discharge, velocity, total stream power, and unit stream power), is drastically reduced in the lower portions of the study section. The limited sediment conveyance capacity, coupled with additional sediment inputs downstream of the dam (estimated at 400 t $km^{-2}$ $yr^{-1}$ by Phillips et al. 2004), indicate that sediment supply exceeds transport capacity post-dam, as it did pre-dam. Significant morphological changes in the form of lower and wider floodplains and additional oxbows, are observed 8-10 km downstream of Romayor. Assuming that these changes correspond with the differing sediment transport regimes, it is likely that morphological responses to Livingston Dam will extend no more than about 60 km downstream, indicating that the river is currently at or near that downstream response limit.

While the downstream propagation of the disturbance effects can apparently occur in about 35 years or less, there is no sign that the scour from the dam to Romayor is abating. The rate of channel downcutting would presumably slow down as mobile alluvium is removed and bedrock is encountered. However, the Trinity was cut to near bedrock before the dam. The gray clay material downstream of dam continues to erode, as indicated by high water stains on trees. The sandstone exposed at Romayor was cut significantly during the Tropical Storm Allison flows of 2001, and appeared (based on visual observation) to have been further downcut in 2003. Channel widening is more difficult to assess, due to the confounding effects of construction activities at the bridge cross-sections. However, we believe the widening has slowed down. While there is morphological evidence of recent widening at some sites, field measurements of channel width in 2002 did not reveal any changes relative to 1994 aerial photographs that were significant given the 5 to 10 m uncertainty in the photogrammetric measurements.

Even if width increases are reduced, bank erosion is and will likely continue to be a significant source of sediment in the lower Trinity. The channel is actively migrating (Wellmeyer et al. 2004), and active cutbank-pointbar systems are common.

### *Speculations*

Livingston Dam controls about 95 percent of the Trinity River drainage area, and by conservative estimate traps 81 percent of the sediment delivered to it. Yet its influence on channel morphology is restricted to a relatively short distance downstream, with no effects evident or likely more than about 60 km downstream. This is consistent with some other case studies of dams, which show that the downstream effects are localized to a relatively short reach downstream. On the other hand, the low elevation, gradient, and transport capacity, and high sediment storage of the lower Trinity, while not atypical for coastal plain rivers, is not representative of rivers in general. This points to the need to consider the specific history and context of each stream and dam (or other disturbance).

While the general qualitative response of the channel is readily predicted, the specific response and configuration of each cross-section is likely to be idiosyncratic. This, along with the point above, suggests that a probabilistic, typological or synoptic approach to prediction of the effects of flow and sediment supply changes and disturbances might be more fruitful than deterministic model.

Finally, it is often assumed that major changes in fluvial sediment fluxes within a drainage basin are eventually communicated, in terms of both morphological changes and mass flux modifications, to the basin mouth. The lower Trinity results show that this is not necessarily the case, necessitating reconsideration of the completeness of sedimentary records in lakes, deltas, estuaries, etc. as indicators of upstream changes, and suggesting that for any given change or disturbance consideration should be given to where, along the course of the river, impacts are most likely to be manifested.

## CONCLUSIONS

Livingston Dam greatly reduced sediment input to the lower Trinity River without significantly modifying flows. The channel response is characterized by incision, widening, coarsening of channel sediment, and a decrease in channel slope. This response is limited to about 60 km downstream of the dam, however. Between about 60 km and the Trinity delta no morphological response to the dam is observed. This is due to the extensive sediment storage and reduced conveyance capacity, so that even after dam construction sediment supply still exceeds transport capacity. Further, the channel bed of much of this reach is near or below sea level, so that sea level rise and backwater effects from the estuary are more important controls on the fluvial system than upstream inputs.

Channel responses in the reach where sediment supply is reduced below conveyance capacity are successfully predicted, in a qualitative sense, by standard models of channel response. Within these broad bounds, however, multiple modes of adjustment (qualitatively different combinations of increases, decreases, or no change in hydraulic variables) are found, as predicted by the unstable hydraulic geometry model. The downstream propagation of change has been completed, or nearly so, in the 35 years since dam construction, though channel scour continues from 0 to about 60 km downstream of the dam.

Results suggest that the effects of even large changes in sediment fluxes may be relatively localized and not necessarily manifested at the basin mouth.

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Kristin Adams, Josh Lepawsky, and Linda Martin (University of Kentucky) helped out with fieldwork. Susan Chu and Nancy Smith of the Texas Department of Transportation provided bridge cross-section data. Greg Malstaff of the Texas Water Development Board helped out in ways too numerous to enumerate. This work is supported by Texas Water Development Board Contracts 2002-483-442 (University of Kentucky) and 2002-483-440 (Texas Christian University). The usual disclaimers apply.

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*Note to referees: Manuscripts of the same title are currently in review. Because we do not believe in citing "in preparation" or "submitted" material, we are currently citing the technical reports. If/when the manuscripts are accepted we will substitute the journal citations.

Table I. Channel dimensions at bridge cross-sections, lower Trinity River. 2003 surveys by the authors; earlier surveys from Texas Department of Transportation.

| *Cross section* | *Date* | *CX area ($m^2$)* | *Width (m)* | *Max depth (m)* | *Mean depth (m)* | *width/max depth* |
|---|---|---|---|---|---|---|
| 3278 | 1995 | 2139 | 257 | 15.2 | 8.3 | 16.9 |
| | 2003 | 3059 | 304 | 18.4 | 10.0 | 16.6 |
| Goodrich | 1948 | 2834 | 540 | 15.5 | 5.2 | 34.8 |
| | 2003 | 1971 | 187 | 16.3 | 10.5 | 11.5 |
| Romayor | 1923 | 982 | 133 | 17.2 | 7.4 | 7.7 |
| | 1995 | 1564 | 134 | 20.0 | 11.6 | 6.7 |
| | 1999 | 1715 | 149 | 19.4 | 11.6 | 7.6 |
| | 2003 | 1043 | 112 | 16.4 | 9.3 | 6.8 |
| Moss Hill | pre 1970 | 877 | 188 | 10.1 | 4.7 | 18.6 |
| | 1992 | 720 | 156 | 13.2 | 4.6 | 11.8 |
| | 2003 | 1667 | 400 | 15.6 | 4.2 | 25.6 |
| Liberty | 1938 | 573 | 108 | 8.5 | 5.3 | 12.7 |
| | 1992 | 300 | 96 | 6.4 | 3.1 | 15.0 |
| | 1995 | 1342 | 146 | 13.9 | 9.2 | 10.5 |
| | 2001 | 1271 | 189 | 11.5 | 6.7 | 16.4 |
| | 2003 | 1150 | 195 | 12.2 | 5.9 | 16.0 |

Table II. Grain size comparisons for sites upstream of Lake Livingston (State Highway 21 crossing, and Pecan Landing) and downstream of Livingston Dam.

| Site | Pct silt+clay | P ct ≤ fine sand | Pct ≥ medium sand |
|---|---|---|---|
| SH 21 channel | 10.1 | 91.6 | 8.4 |
| SH 21 bank edge | 25.5 | 56.6 | 43.4 |
| PL point bar | 0.25 | 59.1 | 40.9 |
| PL bar/channel | 0.4 | 31.5 | 68.5 |
| | | | |
| Goodrich channel | 7.5 | 75.1 | 24.9 |
| Romayor channel | 0.1 | 15.0 | 85.0 |
| Romayor point bar | 0.1 | 12.0 | 88.0 |
| Romayor bank edge | 14.6 | 44.4 | 55.6 |

Table III. Bankfull stream power. $Q_{bf}$ = discharge; $V_{bf}$ = mean velocity; S = channel bed slope; $\Omega$ = cross sectional stream power = $\gamma Q S$; $P_u$ = unit stream power = VS.

| Station | $Q_{bf}$ $m^3$/sec | $V_{bf}$ m/sec | S (X $10^{-4}$) | $\Omega$ | $P_u$ |
|---|---|---|---|---|---|
| Goodrich | 1400 | 1.23 | 2.834 | 3.89 | $3.49 \times 10^{-4}$ |
| Romayor | 2364 | 1.59 | 2.508 | 6.57 | $3.99 \times 10^{-4}$ |
| Liberty | 989 | 0.75 | 0.100 | 2.75 | $7.51 \times 10^{-6}$ |

Table IV. Summary of geomorphic changes at lower Trinity River cross-sections, based on field indicators.

| Site | Evidence of geomorphic change/activity |
|---|---|
| Camilla (FM 3278 just downstream of dam) | Channel incision, lateral channel migration, bank erosion |
| Camilla Twin Harbors | Bank erosion |
| Cedar Valley | Cutbank erosion, point bar migration, channel incision |
| Goodrich (US 59 crossing) | Channel incision, incision at mouth of Long King Creek, floodplain accretion, bank erosion |
| Mouth of Menard Creek | Floodplain accretion, creek delta and river sandbar migration and breaching |
| Romayor railroad bridge | Channel incision; bank erosion |
| Romayor (SH 787 crossing) | Channel incision; bank erosion; sand bar mobility, floodplain accretion |
| Sam Houston Lake Estates | Cutbank erosion; point bar accretion; slope failures on bank |
| Cypress Lakes (sandbar beach) | Cutbank erosion, point bar growth and migration, lateral channel migration |
| Moss Hill (SH 105 crossing) | Floodplain accretion, bank erosion, cut bank erosion, point bar migration |
| Dayton Lakes | Cut bank erosion; point bar growth and migration; slope failures on bank |
| Kenefick | Lateral channel migration and meander cutoff; cutbank erosion; point bar migration; floodplain accretion |
| Liberty (US 90 crossing) | Floodplain accretion; bank erosion; point bar growth and mobility; lateral channel migration |
| Port of Liberty 1 (upstream end of Old River) | Bank erosion; slope failures on bank; lateral channel migration |
| Port of Liberty 2 (downstream end of Old River) | Floodplain accretion; lateral channel migration; slope failures on bank |
| Moss Bluff | Bank erosion |
| Wallisville | Engineered site; no obvious fluvial changes observed |
| Trinity River mouth/Trinity Delta` | Engineered and coastal-dominated site; no obvious fluvial changes observed |

Table V. Qualitative pre-dam to 2003 changes in width, depth, slope, and roughness at lower Trinity River cross-sections.

| Site | Width | Depth | Slope | Rough-ness |
|---|---|---|---|---|
| Camilla (FM 3278 just | increase | increase | decrease | decrease |
| Camilla Twin Harbors | increase | increase | decrease | increase |
| Cedar Valley | increase | increase | decrease | increase |
| Goodrich (US 59 | increase | increase | decrease | increase |
| Mouth of Menard Creek | NSC | increase?[1] | decrease | increase |
| Romayor railroad bridge | increase | increase?[1] | decrease | NSC |
| Romayor (SH 787 | decrease[2] | increase | decrease | increase |
| Sam Houston Lake Estates | NSC | NSC | increase | NSC |
| Cypress Lakes (sandbar | NSC | NSC | increase | NSC |
| Moss Hill (SH 105 crossing) | decrease, increase[3] | NSC | increase | NSC |
| Dayton Lakes | NSC | NSC | increase | NSC |
| Kenefick | NSC | NSC | increase | increase |
| Liberty (US 90 crossing) | decrease, increase[3] | variable; negligible net change | increase | NSC |
| Port of Liberty 1 | NSC | NSC | no data | NSC |
| Port of Liberty 2 | NSC | NSC | no data | NSC |
| Moss Bluff | increase | NSC | no data | NSC |

NSC: no significant change.

[1] These sites occur within a reach where incision has clearly occurred, but there was no clear morphological evidence of incision at the sites.

[2] Width has decreased at the bridge cross-section, but has apparently increased and remained unchanged at other sites immediately up- and downstream of the bridge.

[3] Width decreased from pre-dam periods to the early 1990s, but increased following the 1994 flood.

## LIST OF FIGURES

Figure 1. Study area, showing study sites referred to in the text.

Figure 2. Sediment loads as 10-day means at the Romayor gaging station. Data from the Texas Water Development Board. Samples were taken with a point sampler (the Texas Sampler); results are multiplied by 2.37 to calibrate with depth-integrated samples as described by Phillips et al. (2004).

Figure 3. Channel changes at Camilla, just downstream of Livingston dam.

Figure 4. Surveyed cross-sections at five bridge crossings of the lower Trinity River.

Figure 5. Width/depth ratios at Goodrich, based on U.S. Geological Survey field measurements.

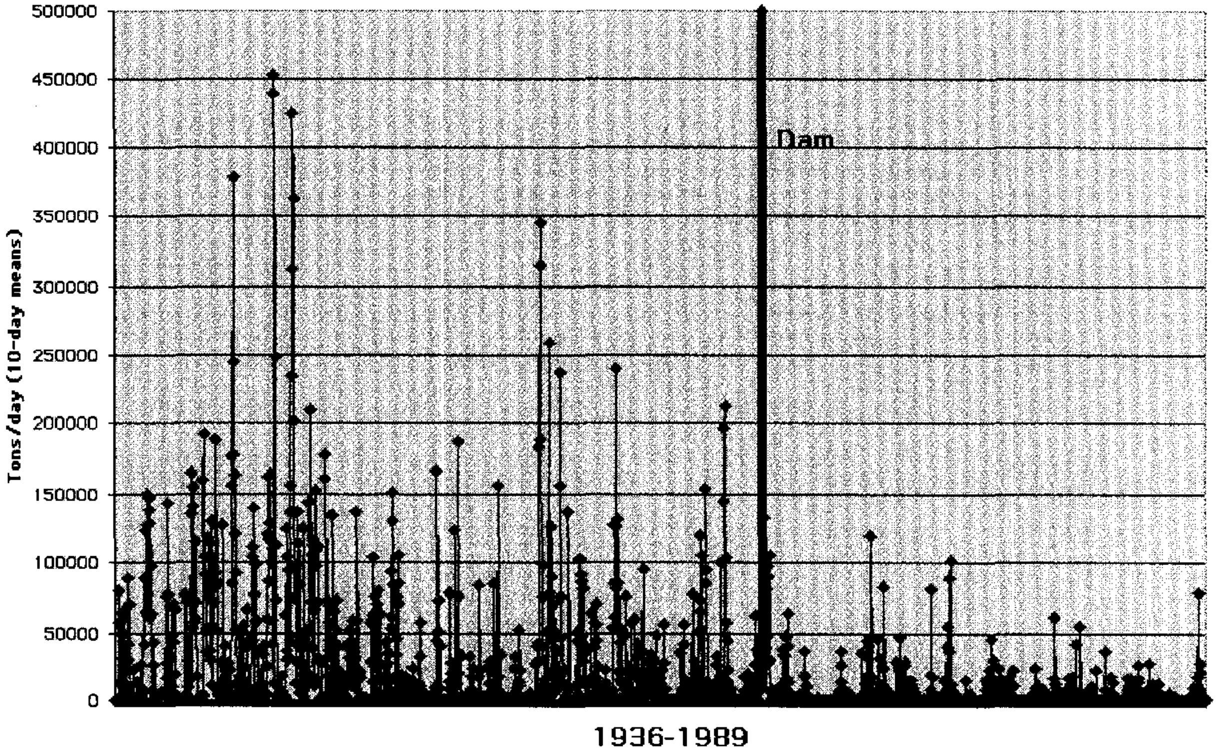
Figure 6. Bank near the mouth of Long King Creek. The line shows the approximate elevation of the pre-dam banktop, more than 3 m above the current bank top.

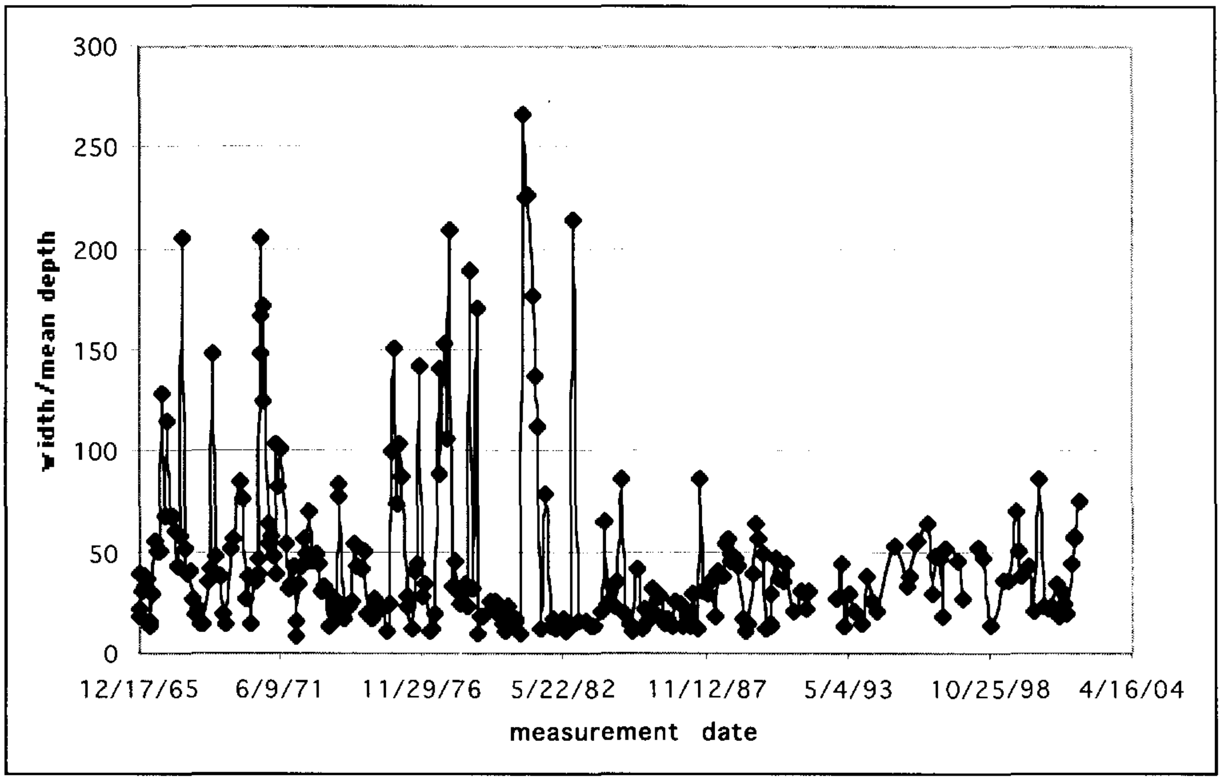
Figure 7. Channel morphology and change indicators at Goodrich.

Figure 8. Channel morphology and change indicators at Romayor.

Figure 9. Channel morphology and change indicators at Kenefick.

Figure 10. Channel morphology and change indicators at Liberty.


500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
Tons/day (10-day means)
Dam
1936-1989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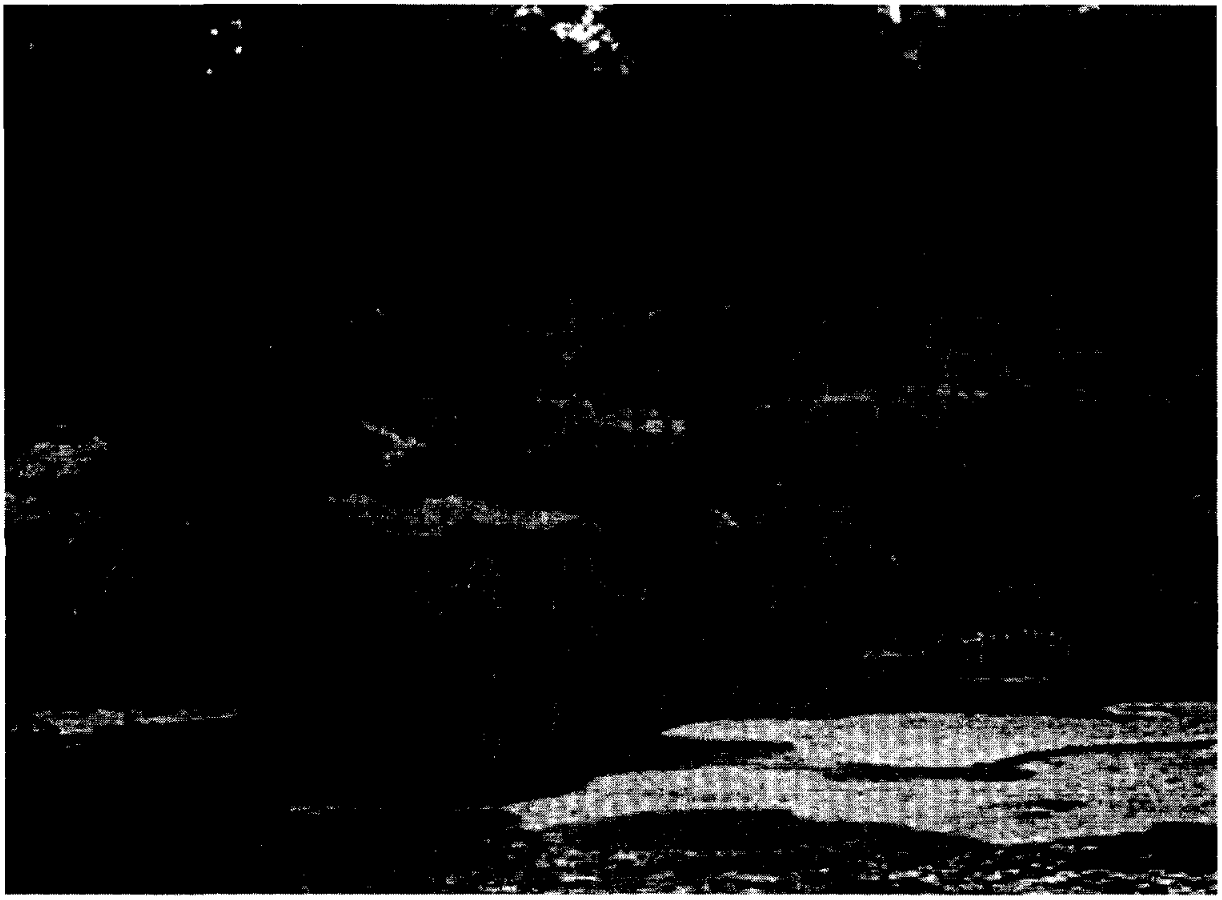


Figures 7, 8, 9, 10 here

# SECTION 5: ADDITIONAL DATA

## SEDIMENT CHARACTERIZATION

Grab samples of sediments were collected in the field from channel, channel bar (generally point bar), floodplain, and bank environments. A number of samples were also collected from potential upland source areas. These included erosion surfaces, rills, and gullies, and eroding ditches and minor tributaries. The sand fraction of samples was examined under a binocular microscope primarily for two properties--the degree of rounding or angularity, and the presence and abundance of iron oxide coatings.

Grains were classified as angular, subangular, subrounded, or rounded based on standard sedimentological categories. For each sample both the range of angularity and the dominant or modal angularity class was recorded. Iron-oxide stains or coatings on sand grain were recorded as none, rare, few, common, or many (0, <10, 10 to 25, 25 to 50, and >50 percent of grains with coatings, respectively) based on the proportion of sand grains which had oxide coatings. Residual upland soils in east Texas have dominantly angular and subangular grains, and iron oxide coatings are ubiquitous. The logic of the approach is that once such grains are delivered to the fluvial environment then angularity will decrease and rounding will increase; and iron oxide coatings will decrease as a function of transport distance and time in the channel environment. This occurs primarily due to grain abrasion, but removal of Fe coatings in solution by reduction in the aqueous environment is also possible.

Similar methods were used by Phillips (2003) in the Sabine River, and the principle of increasing in rounding as a function of the time or distance of transport is well established (Knighton 1998: 136-140; Mills 1979). Stanley, (2000) showed that iron-staining of sand grains could be used to distinguish between in situ Pleistocene deltaic sediments from reworked Holocene material. This suggests that the length or intensity of reworking results in the loss of iron stainings and coatings. Eriksson et al., (2000) used intact iron oxide coatings of sand grains in colluvial and alluvial deposits as an indicator transport has occurred over relatively short distances.

### *Fe coatings*

The examination of iron oxide coatings is summarized below.

1. No channel, sandbar, or floodplain samples have *many* coatings. This compares to 48 percent of upland source samples, 20 percent in tributariess, and 25 percent in bank samples.

2. 59 percent of channel, 67 percent of sandbar, and 50 percent of floodplain samples have rare or no oxide coatings. This compares to 16 percent of source samples. Fewer than half of the river bank and tributary samples lack oxides, but there are a significant number of samples in this category.

3. The channel, bar, and floodplain samples in the "common" coating category were disproportionately associated with finer material.

4. The two bank samples in the "rare" category seem to be clearly alluvium. The two in the "many" category occur in a well-defined soil. The other four (in the "common" class) are a mixture of alluvial and upland.

5. The five source samples where some fluvial transport has obviously occurred (ditch, gully, and small tibutary samples) fall into the "common" or "rare" (2) categories. But three "rare" and eight "common" source samples are not obviously recently fluvially transported.

Results indicate Fe coatings are inversely associated with abrasive bedload transport, which apparently removes the coatings. The rarity or absence of coatings in well-drained upland soils many indicate a geologically recent fluvial origin or local fluvial or aeolian transport. However, where this situation occurs it could also represent exposed E horizons or soils that do not aquire oxide stains or coatings.

The results indicate that Fe coatings are inversely associated with bedload, abrasive transport, which apparently removes the coatings. The absence or rarity of coatings in well-drained upland soils may indicate a geologically recent fluvial origin or local fluvial or aeolian transport. However, they may also be exposed E horizons or soils that do not acquire Fe coatings. The presence of numerous Fe coatings in fluvial sediments indicates recent delivery from uplands, but the absence of coatings does not necessarily imply long storage, reworking, or a lack of upland sediment delivery.

In general, results suggest a significant and perhaps dominant role for bank erosion and alluvial remobilization, and a relatively long residence time for alluvium. However, the erosion of older alluvium from terrace uplands cannot be ruled out.

### *Angularity and Rounding*

Assessment of angularity and rounding can be summarized as follows:

1. Dominantly angular sand grains are found only in the uplands, but are dominant in only two of 31 samples.

2. Angular grains make up a significant portion of 48 percent of upland samples, but make a significant portion of 62 percent of bank and floodplain samples, and 35 percent of channel samples.

3. Dominantly rounded sand grains are found in only two samples--one channel, and one bank sample that derives from alluvial terrace deposits of the Deweyville formation.

4. Rounded grains make up a significant portion of 41 percent of channel, 58 percent of sandbar, 60 percent of tributary, and 50 percent of bank and floodplain samples. This compares to 39 percent of source samples with a significant component of rounded sand grains.

5. Channel, sandbar, and tributary samples are dominantly subrounded--in 65, 67, and 70 percent, respectively of the samples the modal shape was subrounded.

6. Upland, bank, and floodplain samples are dominantly subangular--in 48, 75, and 75 percent, respectively of the samples the modal shape was subangular (upland = 15 subangular, 14 subrounded, two angular).

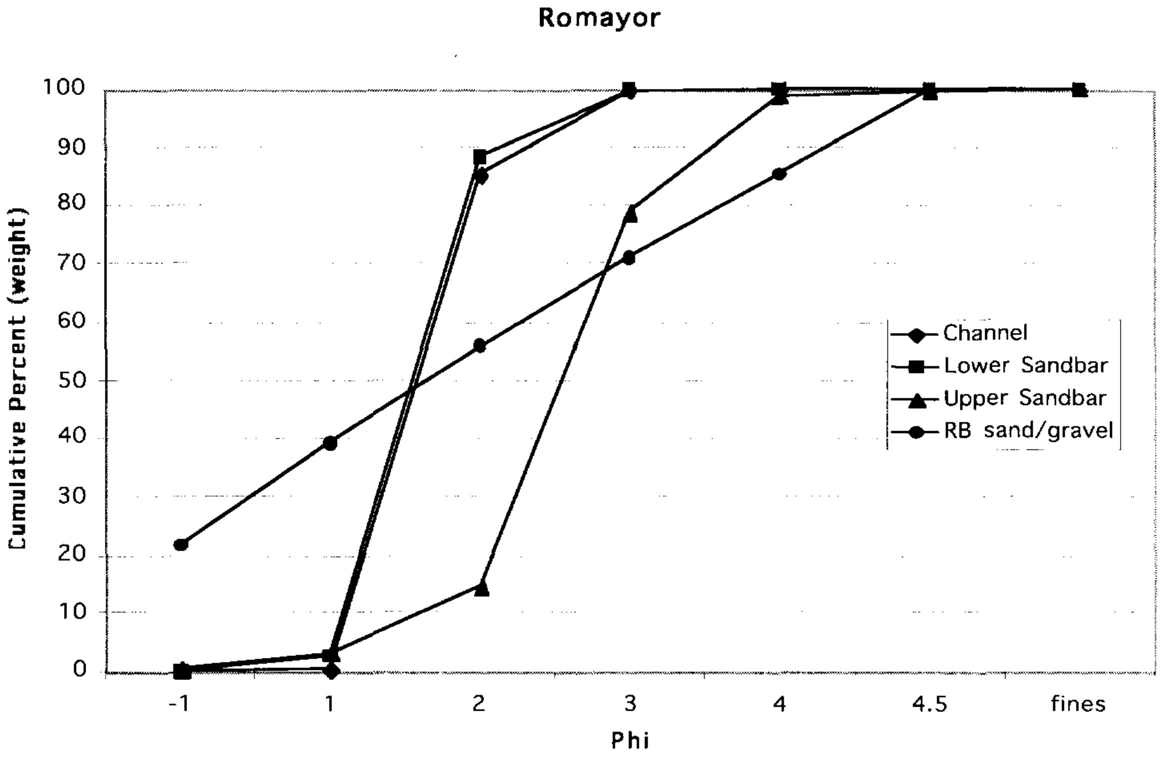
7. Rounding is irreversible. A grain can only follow the path angular - subangular - subrounded - rounded; it cannot become more angular.

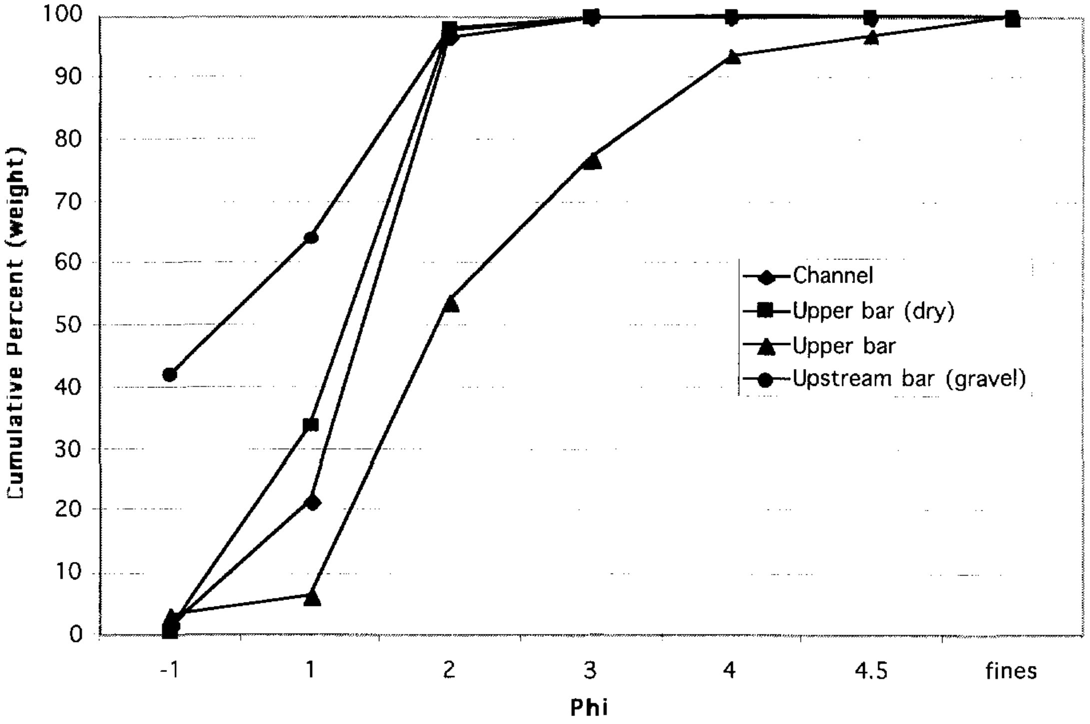
Results indicate that grain rounding is associated with bedload, abrasive transport. However, rounding observed in any setting may be ancient or recent. Rounding in upland grains indicates a fluvial source, but this is possibly ancient deposits. The presence of numerous angular and subangular grains in fluvial sediments indicates recent delivery from uplands, but the absence of angularity does not necessarily imply long storage, reworking, or a lack of upland sediment delivery.

Results are generally consistent with those of the Fe oxide coatings, and indicate a mixture of reworked alluvium and recently-eroded upland material. The irreversibility of rounding makes it difficult to distinguish geologically recent versus ancient fluvial transport.

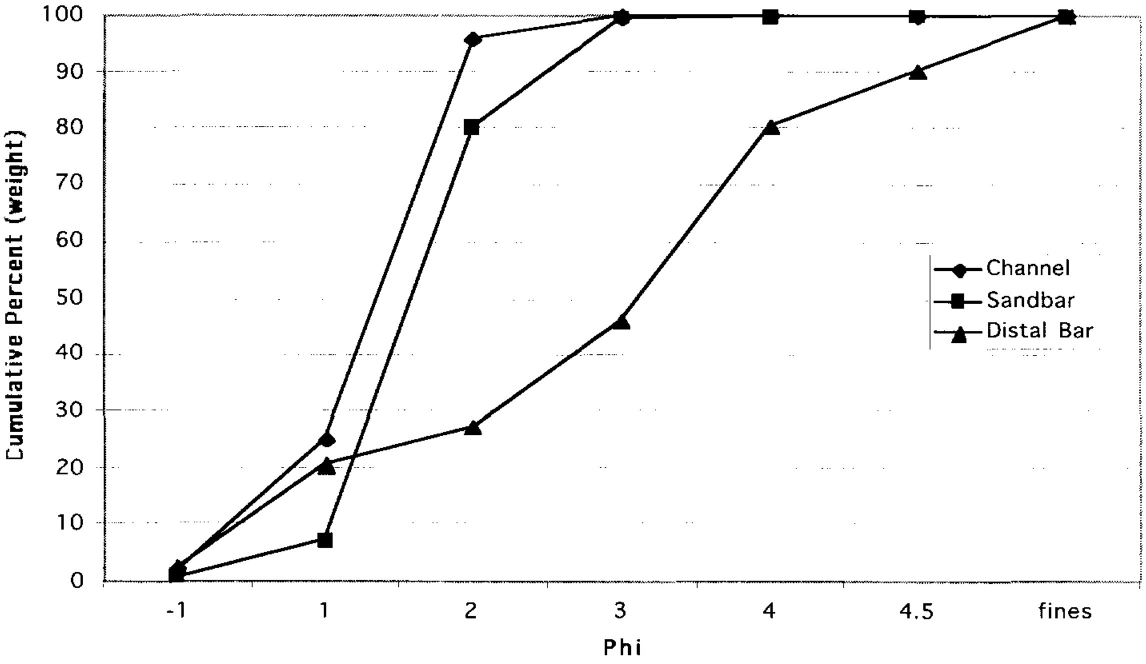
*Grain Size Distributions*

Grain size distributions focussing on the sand fraction were examined for sediments collected from channels and bars at four sites (Romayor, Cypress Lakes Beach, Moss Hill, and Liberty. Samples were air-dried, disaggregated, and sieved using at ATM sonic sifter. Sieve sizes represented -1, 1, 2, 3, 4, 4.5 phi units, corresponding with the gravel, and the very coarse, coarse, medium, fine, and very fine sand fractions. Grain size distribution curves are shown in Figure 9. Laboratory analyses of other samples have been completed, but are not presented here..





Cypress Lakes Beach



Moss Hill

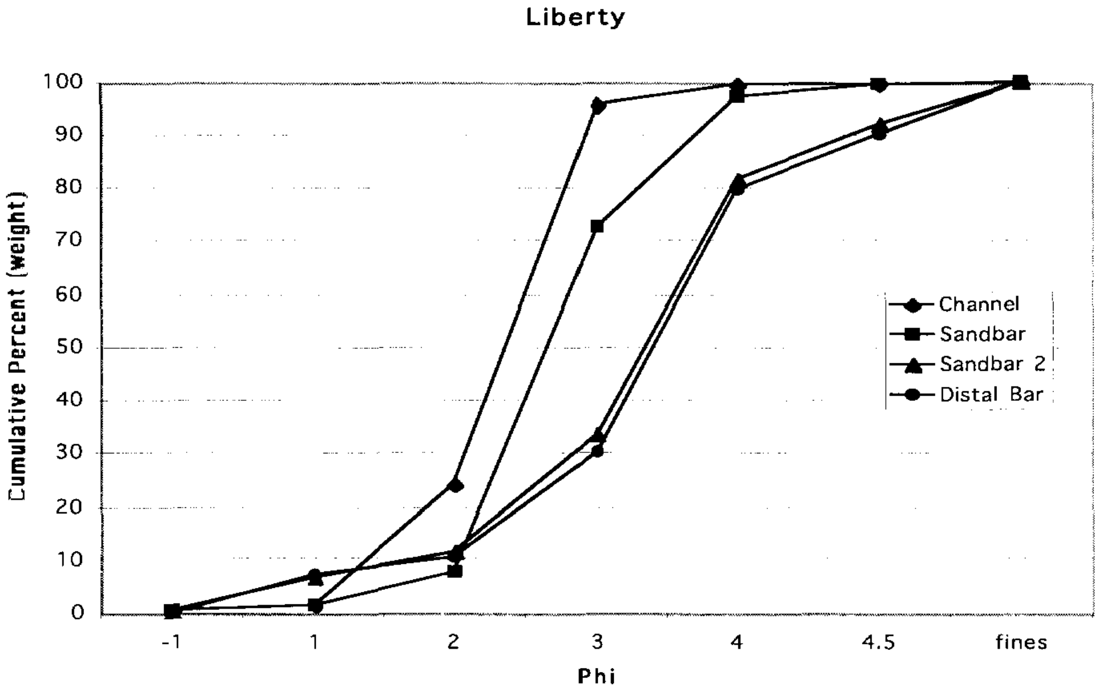


Figure 9 (continued from previous page). Grain size distribution curves.

## POTENTIAL SEDIMENT REPLENISHMENT SOURCES

One original study objective was to determine the sediment sources that could replenish the stream sediment supply that are near the river channel or in the lake. This objective appears to have limited relevance, given the lack of evidence of any dam-related reduction in sediment supplies to the estuary. More importantly, there is abundant mobile sand in the Trinity channel. Many alluvial and terrace soils of the lower Trinity have high sand contents. However, this objective will not be pursued further, given results obtained thus far.

## REFERENCES

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