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Downstream trends in discharge, slope, and stream power in a lower coastal plain river

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Summary Conceptual models of river-estuary interaction are typically based on a notion of systematic downstream change in the intensity of fluvial processes. Low slopes, backwater effects, and effects of antecedent topography and landforms may complicate downstream tends in water and sediment flux in coastal plain rivers. An analysis of the lower Trinity River, Texas shows no consistent downstream pattern of increases or decreases in the discharge, stream power, or water surface slope. Flows may decrease downstream due to coastal backwater effects in the lowermost reaches, and due to diversion of flow into valley-bottom depressions during high flows in both the fluvial and fluvial-estuarine transition reaches. In general, however, stream power and slope decrease in the lower reaches, consistent with earlier findings of limited fluvial sediment delivery to the coastal zone. Some tributaries may become distributaries at high but sub-bankfull flows, as backwater effects reverse flows into depressions associated with paleomeanders. The paleomeanders, and possibly the locations of these ''reversible'' channels, are related to antecedent topography associated with aggradation/degradation cycles over the past 100 Ka. Low-gradient coastal plain rivers may not function as simple conduits from land to sea. Further, the transition from fluvial to coastal dominance may be variable along the river, with the variability controlled not just by the relative magnitude of river and tidal or backwater forcing, but also by valley topography controlled in part by antecedent landforms.

Introduction

The conveyance of water and sediment from rivers to the sea is deceptively complex. As rivers approach the coast, particularly those crossing extensive coastal plains, fluvial dynamics change as channel and valley slopes decline and alluvial accomodation space increases. In the fluvial-estuarine transition zones backwater effects and lunar and wind tides influence water and sediment fluxes. Over longer timescales, these lower coastal plain reaches are also profoundly influenced by Quaternary and contemporary sea

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level changes. A common conceptual model of hydrodynamics applied to, e.g., stratigraphic facies models, is based on the interplay of coastal/marine processes, which generally decrease in intensity inland, and fluvial processes, which decline in strength downstream (Cattaneo and Steel, 2003; Dalrymple et al., 1992). However, a number of studies in fluvial systems show that there may not be consistent downstream trends in factors such as stream power (Graf, 1983; Jain et al., 2006; Knighton, 1999; Lecce, 1997; Magilligan, 1992; Reinfields et al., 2004). The goal of this project is to examine downstream changes in stream power and the determinants of the latter, discharge and slope, in the lower Trinity River in the southeast Texas coastal plain. Process linkages between hydrology, geomorphology and ecology in coastal plain rivers remain largely undocumented (Hupp, 2000). This work seeks to help fill that gap, for the particularly problematic lower coastal plain.

River discharge is an important determinant of estuarine circulation, water chemistry, and flushing or residence time, and is thus critical with respect to water quality, estuarine ecology and fisheries (Longley, 1994; Powell et al., 2003). Fluvial discharge and sediment fluxes are typically measured a considerable distance upstream from the coast. Variations in discharge occurring downstream of these gaging stations will thus not be reflected in these records. Because these gaging stations are often upriver from lower coastal plain sediment bottlenecks in some cases fluvial sediment delivery to the coast has been substantially overestimated (Brizga and Finlayson, 1994; Olive et al., 1994; Phillips, 1993, 1997; Phillips et al., 2004; Phillips and Slattery, 2006).

In tidally dominated river estuaries there may be a relatively straightforward downstream progression from fluvial to tidal domination, reflected in landforms, sedimentary environments, and hydrodynamic zones (e.g. Renwick and Ashley, 1984), the latter obviously varying with river discharge and tidal cycles. The transition from fluvial to coastal dominance may be considerably more complicated and subtle in wave- and wind-dominated estuaries such as the Trinity Bay/Galveston Bay system considered in this study (Nichols, 1989; Phillips and Slattery, 2006; Wells and Kim, 1987).

In addition to the systematic changes in channel and valley morphology, slope, and the relative importance of fluvial vs. coastal processes, recent field experience on the lower Trinity River in southeast Texas suggested that the downstream changes in flow and sediment transport capacity might be even further complicated by factors such as inherited valley morphology, extensive water storage on floodplains, and low-water tributaries that might function as distributaries at high flow. This paper investigates the downstream trends in discharge, slope, and stream power in the lower Trinity River. The study area was selected in part due to past and ongoing geomorphological studies in the area, but the Trinity is advantageous for this study in having a number of gaging stations in the lower fluvial reaches and fluvial-estuarine transition zone. The specific environmental settings, land and water use and management, sea level histories, and other controls vary between rivers, but in a broad general sense the Trinity is not atypical of rivers on the US. Atlantic and Gulf Coastal Plains.

Background

Stream power

In humid-region perennial streams such as the Trinity River, channel, valley, and energy grade slopes typically decline, on average, as base level is approached, as illustrated by the typically concave-upward longitudinal profile. Discharge generally increases downstream, often as a step function reflecting tributary inputs. Cross-sectional stream power (power per unit channel length; terminology follows Rhoads, 1987) is a function of the product of slope (S) and discharge (Q):

$$\Omega = \gamma Q S, \tag{1}$$

where γ is specific gravity.

Stream power does not necessarily increase systematically downstream because of the conflicting changes in discharge and slope, and local variations in width, depth, roughness, and other factors that may influence Q and S (Graf, 1983; Magilligan, 1992; Knighton, 1999). Nonlinear downstream changes in stream power were documented by Lecce (1997), who showed power peaking where drainage areas were 10–100 km^2 (in a 208 km^2 Wisconsin drainage basin) and decreasing rapidly downstream. The relative rates of change in discharge and slope determine the location of the Ω maximum, which in Knighton's (1999) model, applied to the Trent River, England, occurred at location intermediate between headwaters and lower reaches.

Downstream variations in stream power were assessed from digital elevation models (DEMs) in a small, steep Australian watershed by Reinfields et al. (2004), where longitudinal profiles were concave up, and channel gradients generally decreased downstream, with some localized variations. Channels with steep convex sections had locally steeper gradients in mid-profile, but still displayed lower gradients in the lower as compared to upstream reaches (Reinfields et al., 2004). Cross-sectional stream power exhibited no monotonic downstream trend, and in four study rivers was both higher, lower, and approximately the same in the lower as in the upper reaches. Specific stream power was uniformly lower in the downstream reaches, but also varied irregularly in the longitudinal direction. Jain et al. (2006) also used a DEM-based model for the upper Hunter River watershed, Australia, finding that stream power variations in headwaters were controlled mainly by discharge, while in the mid and lower reaches local variations in slope were the primary controls. Those results, and the theoretical models applied, showed irregular downstream trends in power, but with generally smoother, downward trends in the lowermost reaches (Jain et al., 2006).

In the lower Trinity River, Texas, Ω was found to be substantially reduced between upstream and downstream gaging stations at flood, bankfull, and near-bankfull flows (Phillips et al., 2005; Phillips and Slattery, 2006). This was attributed primarily to declines in slope (based on channel bed slope), though lower banks downstream and thus a tendency to reach bankfull at lower discharges also played a role.

In Magilligan's (1992) and Lecce's (1997) studies, discharge increased downstream, and in the other studies in perennial streams (Jain et al., 2006; Knighton, 1999;

Reinfields et al., 2004) discharge was assumed to increase downstream as a function of drainage area and/or total stream length. The latter is common and widely accepted, and Phillips et al. (2005) accordingly dismissed the apparent downstream decrease in bankfull flow in the lower Trinity as a function of bank height. Subsequent analysis of Trinity River flows during sub-bankfull events, however, suggested that a general downstream increase in discharge between gaging stations cannot necessarily be assumed.

While Lecce (1997) and Magilligan (1992) based their analyses on measured or modeled water surface slopes between stations, Phillips et al. (2005) used surveyed channel bed slope, and Jain et al. (2006), Knighton (1999), and Reinfields et al. (2004) assumed that downstream changes in energy grade slope reflect changes in channel slope. Magilligan (1988) showed that water surface slopes are a better approximation of energy grade slopes than either field-measured or map-derived channel bed slopes.

In some previous studies lithological control has been identified as a key determinant of factors such as valley width and valley slopes, which in turn help determine stream power (Graf, 1983; Lecce, 1997; Magilligan, 1992). Lithological controls are generally not thought to be strong, or even relevant, in coastal plain alluvial rivers such as the lower Trinity, however, where resistant, confining materials are rare. However, the Trinity (in common with other rivers of the region) has experienced a series of climate- and sea level-driven cycles of aggradation and degradation, such that inherited valley morphologies influence the contemporary river (Blum et al., 1995; Blum and Törnqvist, 2000; Morton et al., 1996; Rodriguez et al., 2005). While structural and lithological control in the usual sense is subtle at best in the lower Trinity River, antecedent topography may play a significant role in downstream variations in discharge, slope, and stream power.

Abrupt changes in the downstream trends of slope and stream power may represent critical transition points and foci of change (Reinfields et al., 2004). A critical transition zone has already been identified in the lower Trinity with respect to sediment transport and storage, and channel cross-sectional change (Phillips et al., 2004, 2005).

The mouth of the river

Generalizations about downstream changes in discharge and other hydrologic and hydraulic parameters are generally at least implicitly understood to apply to the portion of the river network which is both fluvially dominated (vs. influenced by coastal processes) and convergent. Convergent networks are dominated by net tributary inflows, while divergent networks are dominantly distributary, with net flow from the trunk stream into the tributary.

The seaward mouth of a river can be defined as the point at which a well-defined dominant channel can no longer be identified, at an open-water estuary or a delta apex. The mouth might also be defined as the point at which the dominant flow pattern becomes divergent or distributary rather than convergent. These points often do not coincide with the point at which channels are cut to below sea level, or with common upstream limits of backwater effects or salt wedges. Further, these ''mouths'' have been found to over channel distances of 50 to >100 km (Pierce and Nichols, 1986; Nichols et al., 1991; Phillips and Slattery, 2006).

In the Trinity, the transition to a distributary network occurs about 20 km upstream of the point at which the Trinity River enters Trinity Bay. Tidal influence is evident at the gaging station at Liberty, Texas, 85 km upstream, and the channel is cut to below sea level 110 km upstream. The lower coastal plain sediment storage bottleneck identified by Phillips et al. (2004) occurs about 130 km upstream of Trinity Bay. This suggests that downstream changes could be considerably more complex than a steady downstream increase in discharge and decrease in slope, followed by a gradual transition from fluvial to coastal dominance.

These issues are not only important for determination of sediment and water fluxes to the coast. The lower coastal plain reaches of rivers also typically contain large areas of ecologically and economically valuable wetlands such as bottomland hardwood forests, and both natural environments and anthropic features which are quite vulnerable to river floods, coastal storms, sea level change, subsidence, and other coastal plain dynamics.

Study area

The 46,100 km^2 Trinity River drainage basin, Texas, drains to the Trinity Bay, part of the Galveston Bay system on the Gulf of Mexico. The lower Trinity River basin (Fig. 1) has a humid subtropical climate and a generally thick, continuous soil and regolith cover. Most of the drainage area (95%) lies upstream of Livingston Dam, which was completed in 1968 to form Lake Livingston. The lake, a water supply reservoir for the city of Houston, has a conservation pool capacity of >2.2 billion m^3. The dam has no flood control function and Livingston is essentially a flow-through reservoir.

The contemporary and recent historical sediment budget, channel planform change, and changes in cross-sectional channel morphology between Lake Livingston and Trinity Bay have been analyzed elsewhere (Phillips et al., 2004, 2005; Wellmeyer et al., 2005). The alluvial morphology and stratigraphy of the lower Trinity (and the nearby and similar Sabine River) and the deposits and palaeochannels 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.

The Trinity/Galveston Bay has a mean volume estimated at about 2.7 billion m^3 and drainage area of 85,470 km^2. About 54 percent of the drainage area, and of the freshwater inflow, is accounted for the Trinity River. Though Lake Livingston's capacity is more than 80% of that of Galveston Bay, analysis of pre- and post-dam discharge records at Romayor found no significant post-dam decrease in flow, and limited discharge change of any kind (Wellmeyer et al., 2005).

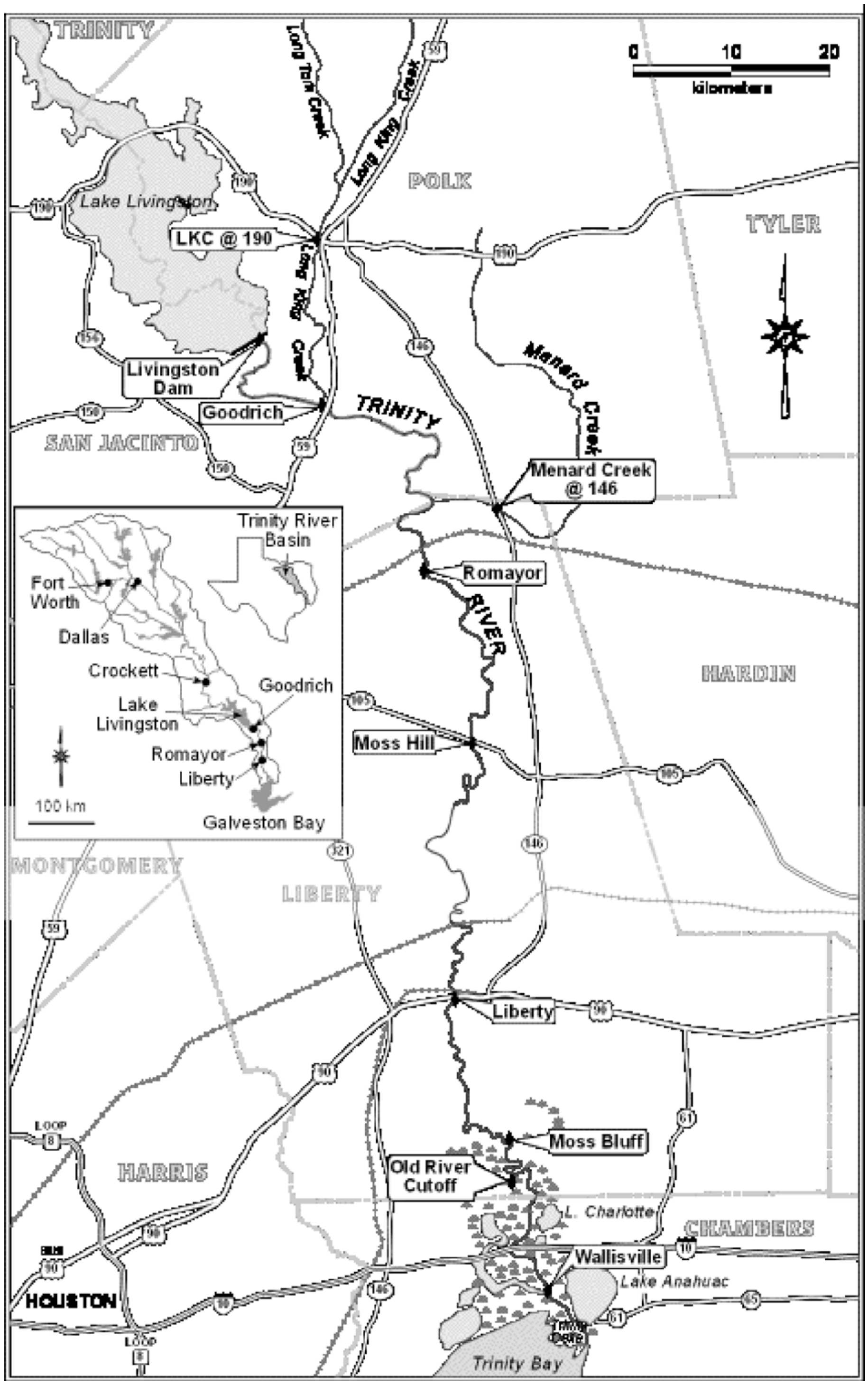

Figure 1 Study area, showing gaging stations and field sites.

Hydrodynamics of the Galveston Bay estuary have been studied in some detail (e.g. Powell et al., 2003), in part driven by concerns over potential effects of changes in freshwater inflow due to water diversions on salinity, water quality, and estuarine ecology. Work thus far has been focused almost entirely on the estuary, and driven chiefly by concern with fisheries production (GBFIG, 2003; Longley, 1994). The lower Trinity River has not been included in these studies, and is treated only as an input to Galveston Bay hydrology. Water diversions represent less than 10% of the mean discharge of the lower Trinity River, and a considerably lower proportion of high flows.

The details of sea-level history and coastal evolution in Texas are controversial (Blum et al., 2002), but most sources agree that Galveston Bay in its more-or-less modern position was formed about 4000 years ago. During lower

Quaternary sea level stands, the Trinity and Sabine Rivers converged on the continental shelf and cut an incised valley. From about 18,000 years BP to the present, the Trinity-Sabine incised valley has backfilled (Blum et al., 1995, 2002).

Methods

Data from nine gaging stations between Lake Livingston and Trinity Bay was used for this study. Five are Trinity River stations, and two (Long King and Menard Creeks) are stations on the two largest tributaries to the Trinity downstream of Livingston Dam. One station records changes in surface elevation and storage in Lake Livingston, and another (Old River cutoff) is a short distance from the river on a distributary channel in the Trinity River delta area. Station locations are shown in Fig. 1, and described in Table 1.

Discharge regime

For the three river stations with a sufficient period of record (Goodrich, Romayor, and Liberty), a number of reference flows were calculated using the standard formula

$$P = m/(n+1) \text{ or } T = (n+1)/m, \qquad (2)$$

where m is the rank of the flow in the series and n is the total length of the series. Daily mean flows (reported in $ft^3\ s^{-1}$) were used to calculate P, the probability of exceedence, and T, the return period or recurrence interval. Reference flows include those associated with 50%, 10%, and 1% probability of exceedence by mean daily flows, and annual peaks with recurrence intervals of 1, 2, and 10 years. In addition, the mean annual discharge was determined from the entire available record of mean daily discharge. Finally, peaks were determined for the October, 1994 flood, which is the flood of record in the lower Trinity River, and a smaller flood in November, 2002.

The upstream–downstream trends in these reference flows was examined based on direct comparisons and differences between downstream and upstream stations (Liberty–Romayor; Romayor–Goodrich).

Hurricane Rita event

Hurricane Rita struck the southeast Texas coast and areas of adjacent Louisiana in late September, 2005. The eye of the storm and the most intense rainfall passed to the east of the Trinity River valley, but there was extensive precipitation in the lower Trinity Basin. Furthermore, wind-wave related damage to the earthen and stone Livingston Dam forced the Trinity River authority to make a rapid release to lower lake levels for damage assessments and repairs. The event therefore provided an opportunity to determine response to a dam release and precipitation confined chiefly to the lower basin, as opposed to being transmitted through the lake.

Based on the hydrograph responses to this event, water surface elevations and flow responses (discharge and/or stage) were determined for times corresponding with the start of the rising hydrograph limbs of Long King Creek and the Trinity at Goodrich and Romayor, the peak elevation and beginning of drawdown of the lake, the completion of the lake drawdown, and the flow peaks at Long King Creek, and Goodrich, Romayor, Liberty, and Moss Bluff. Long King Creek is taken as representative of the local, lower-basin runoff and tributary input, as opposed to releases from Lake Livingston.

Stage elevations at these times, coded as R1 through R9, were combined with gage datums to determine instantaneous water surface elevations. These were combined with distances between stations measured from 10-m resolution DEMs to determine water surface slopes.

The National Oceanic and Atmospheric Administration data buoy at Morgan's Point on upper Galveston Bay was used (via barometric pressure records) to pinpoint the arrival of the storm in the lower Trinity valley.

Table 1 Lower Trinity River (TR) gaging stations and year of establishment

Name	Location	Number	Measurements
Livingston Reservoir (1969)	177	0866190	H, storage
Long King Creek at Livingston (1963)	145[a]	0866200	H, Q
Menard Creek at Rye (1963)	130[a]	0866300	H, Q
Trinity River (TR) nr Goodrich (1965)	144	0866250	H, Q
TR at Romayor (1924)	126	0866500	H, Q
TR at Liberty (1940)	83	0867000	H, Q[b]
TR at Moss Bluff (1959)	32.5	0867100	H, Q[c]
Old River cutoff near Moss Bluff (2003)	30[a]	0867215	H, velocity
TR at Wallisville (2003)	6.5	0867252	H

Location refers to distance upstream from Trinity Bay, in kilometers. Number is the US. Geological Survey station number. Measurements of interest here include discharge (Q) and stage or gage height (H). All are operated by the US. Geological Survey except Livingston Reservoir (Trinity River Authority) and Old River and Wallisville (US Army Corp. of Engineers).

[a] Approximate distance from the bay of creek/river confluence.

[b] Discharge measurements discontinuous.

[c] Discharge estimated from stage by National Oceanic and Atmospheric Administration, West Gulf River Forecast Center (http://www.srh.noaa.gov/wgrfc/statlist.php?funct=obs&shefid=MFT2).

Valley topography

Topography of the lower Trinity Valley was analyzed based on 10-m resolution DEMs from the USGS National Elevation Dataset (NED) obtained via the USGS seamless data distribution center. The RiverTools software was used for visualizations of the topography, to construct elevation profiles and to evaluate topographically controlled flow directions. The flow analysis was based on the imposed gradient method of Garbrecht and Martz (1997). The algorithm used arbitrarily fills local pixel-scale depressions, so any broader depressions attracting flow were taken to be real rather than data artefacts. Digital orthophotquads (DOQQs) at 1- and 2.5-m resolutions, many taken during high water conditions associated with the 1994 flood, were also used to identify key geomorphic features. DOQQs and fieldwork confirmed that larger depressions in the DEM are present on the ground.

Field observations

The field area was visited in early November, 2005. No further overbank flows occurred between the Rita event and this fieldwork. Flow indicators (flood debris and deposits) were examined at seven locations between the mouth of Long King Creek and the Wallisville station. In addition, field surveys were conducted at the junction of Pickett's Bayou and the Trinity River, a short distance upstream of Moss Bluff. This stream connects the Trinity River with Old River, one of the delta distributaries. It was unclear from maps and photography the extent to which the bayou functions as a tributary or distributary.

Results

Discharge regime

Reference flows are shown in Table 2. Mean annual flows and some relatively frequently exceeded events show slightly higher values at Romayor, as expected, than at Goodrich 18 km upstream. However, for six of the nine reference events discharge is higher at Goodrich than downstream at Romayor. This is despite the fact that two major tributaries (Menard and Big Creeks) join the Trinity between the two stations.

By contrast, every reference discharge for Liberty except the 2002 flood is higher – often substantially so – than at either of the upstream stations. The gage datum at Liberty is 0.67 m below sea level, and the thalweg elevation when measured in early 2003 was −5 m (Phillips et al., 2005). The gage also often shows tidal influences. Tidal and backwater effects influence the stage/discharge relationship so that discharges are not estimated or published continuously. This may bias the published data toward river flow domination and thus inflate the mean annual flow and relatively frequent discharges (50% and 10% daily exceedence, and Q1). In the two specific high flow events, the peak for the 2002 flood was lower than for the upstream stations, and for the 1994 flood only eight percent greater.

Overall, the data in Table 2 indicate that there is not necessarily a consistent downstream increase in discharge, even within the always fluvially dominated Goodrich-Romayor reach.

Peak flow differences (downstream station minus upstream station) for the annual peaks are shown for Romayor–Goodrich and Liberty–Romayor for the period of overlapping records in Fig. 2. In most cases, peaks were apparently associated with the same flow event, as indicated by peaks occurring within 5 days or less of each other at adjacent stations. Negative values indicate that the peak flow for the downstream station was lower than for the upstream. In some cases, these could be associated with downstream flood wave attenuation for events dominated by releases from Lake Livingston. This could account for the increasing range of differences observed after 1968. However, negative differences are approximately equally common in the pre- and post-dam records.

Table 2 Reference flows for lower Trinity River gaging stations, in $m^3 s^{-1}$

Reference flow	Goodrich	Romayor	Liberty
MAQ	231	246	509
50% exceedence	82	77	433
10% exceedence	677	640	1048
1% exceedence	1550	1541	822
Q1	2130	1970	2484
Q2	2400	2330	2835
Q10	3002	2925	3600
2002 flood	1872	2198	1602
1994 flood	3540	3455	3823

MAQ, mean annual discharge. Exceedence flows indicate the mean daily flow exceeded the indicated percentage of days. Q1, Q2, Q10 are peak flows with estimated recurrence intervals of 1, 2, and 10 years. The 2002 and 1994 floods are the maximum flow peaks.

Hurricane Rita discharge

The Morgan's Point station recorded its lowest pressure (983 mb) at 0900 on September 24, 2005 when the eye of Hurricane Rita passed closest to Trinity Bay. Clouds and rain bands preceded the eye of the storm. Though the most intense precipitation fell east of the Trinity River watershed, significant rainfall was recorded for September 23–24 at several locations in the region. The most at nearby stations was >170 mm at Beaumont, about 70 km east of the Trinity River. No meteorological stations within the lower Trinity basin directly recorded precipitation for this event, but 24-h precipitation estimates from the Lake Charles, Louisiana National Weather Service Radar indicated 25–100 mm in the lower Trinity basin.

Long King and Menard Creeks experienced steep rises in the hydrograph. Long King Creek showed an equally steep recession, whereas Menard Creek flow remained elevated for several days. This is consistent with the greater proportion of urban and agricultural land use in the Long King watershed, as opposed to the predominantly forested Menard watershed, much of which is within the Big Thicket National Preserve. The creeks began rising at about 0430 September 24 (Table 3), though the hydrograph had begun rising at

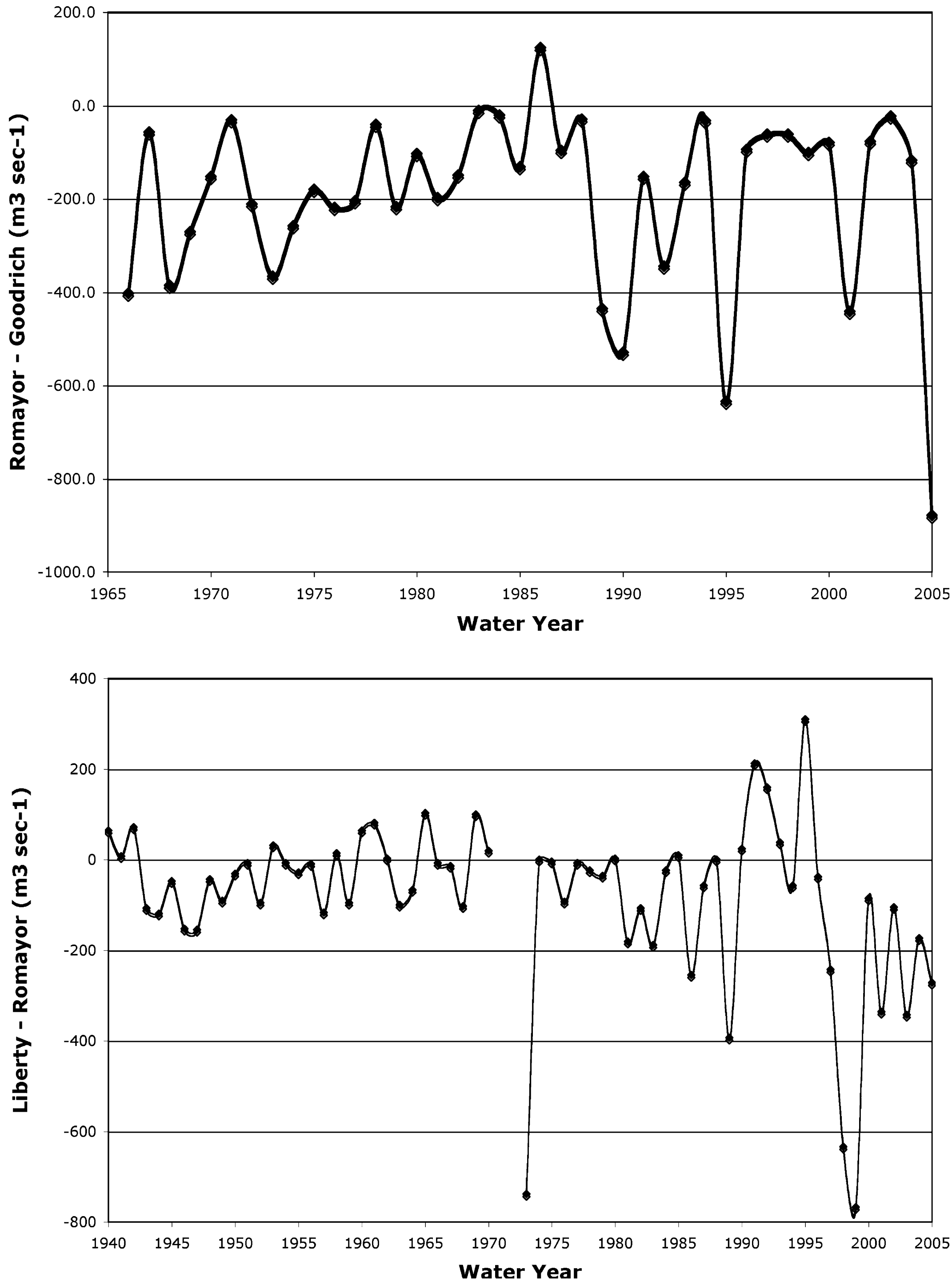

Figure 2 Annual peak discharge at the Romayor gaging station minus that at the Goodrich station 18 km upstream (top), and at the Liberty gaging station minus that at Romayor, 43 km upstream. Lines between points are included to facilitate visual comparisons and do not imply continuous change.

Romayor a bit earlier. Later the same morning the peak elevation of Lake Livingston occurred, and the drawdown began, along with the hydrograph rise at Goodrich. Long King Creek, Goodrich, and Liberty peaked on September 25, with Moss Bluff peaking early on September 27 (Table 3).

Storm runoff resulted in a roughly half-meter rise in the elevation of Lake Livingston. Wind-wave damage to Livingston Dam, however, required the Trinity River Authority to draw down the lake to inspect damage and begin repairs. Lake elevation peaked at 0800 on September 24, and was drawn down over the next three days, leveling off about 1 m below pre-storm water levels early on September 27 (Fig. 3).

The hydrograph responses of the river at Goodrich and Romayor (Fig. 4) show a rapid rise and recession similar to

Table 3 Key stages of the Hurricane Rita flow event, 2005

Code	Date & time		Significance
R1	9/24	0200	Start of hydrograph rise @ Romayor
R2	9/24	0430	Start of hydrograph rise @ Long King Creek
R3	9/24	0800	Peak elevation, Lake Livingston; start of drawdown
R4	9/24	0830	Start of hydrograph rise @ Goodrich
R5	9/25	0700	Peak @ Long King Creek
R6	9/25	1545	Peak @ Goodrich
R7	9/25	2330	Peak @ Romayor
R8	9/27	0200	Lake drawdown complete; Liberty near peak
R9	9/27	0315	Peak @ Moss Bluff

the Lake drawdown curve (Fig. 3), with the peak at Romayor occurring 7.75 h after Goodrich. In both cases, following recession the base flow remained only slightly elevated from the pre-storm flow.

By contrast, stations further downstream at Liberty and Moss Bluff (Fig. 5) showed a sustained rise in base flow. Note that while discharge at Liberty was partly estimated, the peak and recessional limb are based on published data. The Moss Bluff discharge, however, is entirely estimated. The West Gulf River Forecast Center of the National Oceanic and Atmospheric Administration sometimes estimates discharges for this station based on gage heights. An empirical equation based on such records for similar stages was used to estimate discharge for the Rita event. However, this station — even more so than Liberty — is affected by backwater effects and both lunar and wind tides, and there is thus some uncertainty in converting gage heights to discharge.

Water levels at Old River declined only slightly after the storm, as did those at the Wallisville station, where the tidal signal is clearly overprinted (Fig. 6).

Slope

Instantaneous water surface slopes for the nine key times during the Hurricane Rita event were determined by determining surface elevations based on gage heights and datums, and the channel distance between stations. Water surface profiles for the Rita event are shown in Fig. 7. At the highway 105 river crossing near Moss Hill flood debris and an interview with a local resident both suggested that the Rita water levels peaked just under the bridge. This implies a stage elevation of 16—17 m, consistent with the computed water surface slope between Romayor and Liberty.

The water surface slopes show that in all cases, slopes decrease substantially downstream of the Liberty station. Gradients from Goodrich to Romayor to Liberty are variable, but always positive and always >0.0011. Slopes between Liberty and Moss Bluff may be negligible or negative. From Moss Bluff to Wallisville water surface gradients are even more variable, ranging from +0.117 to −0.079, the steepest positive and negative slopes at any station. Negative slopes

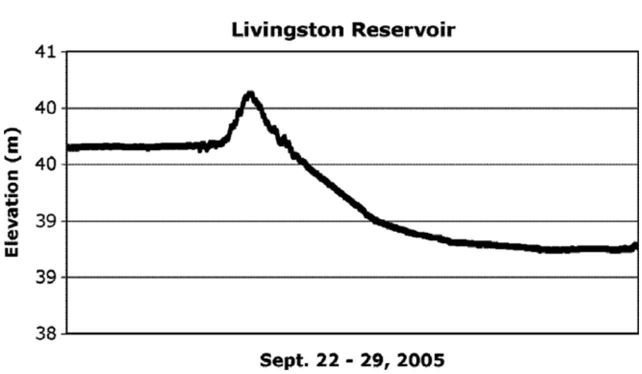

Figure 3 Water surface elevations for Lake Livingston for the week including Hurricane Rita, showing the rise in lake levels and subsequent drawdown via dam releases to assess and repair damages.

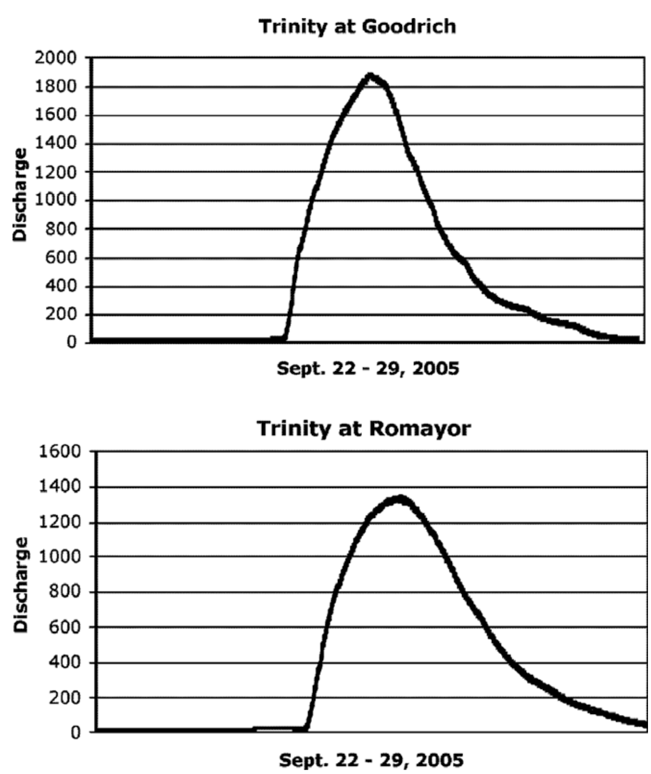

Figure 4 Hydrographs for the lower Trinity River at the Goodrich and Romayor gaging stations for the week including the Hurricane Rita flow event. Discharge was measured every 15 min.

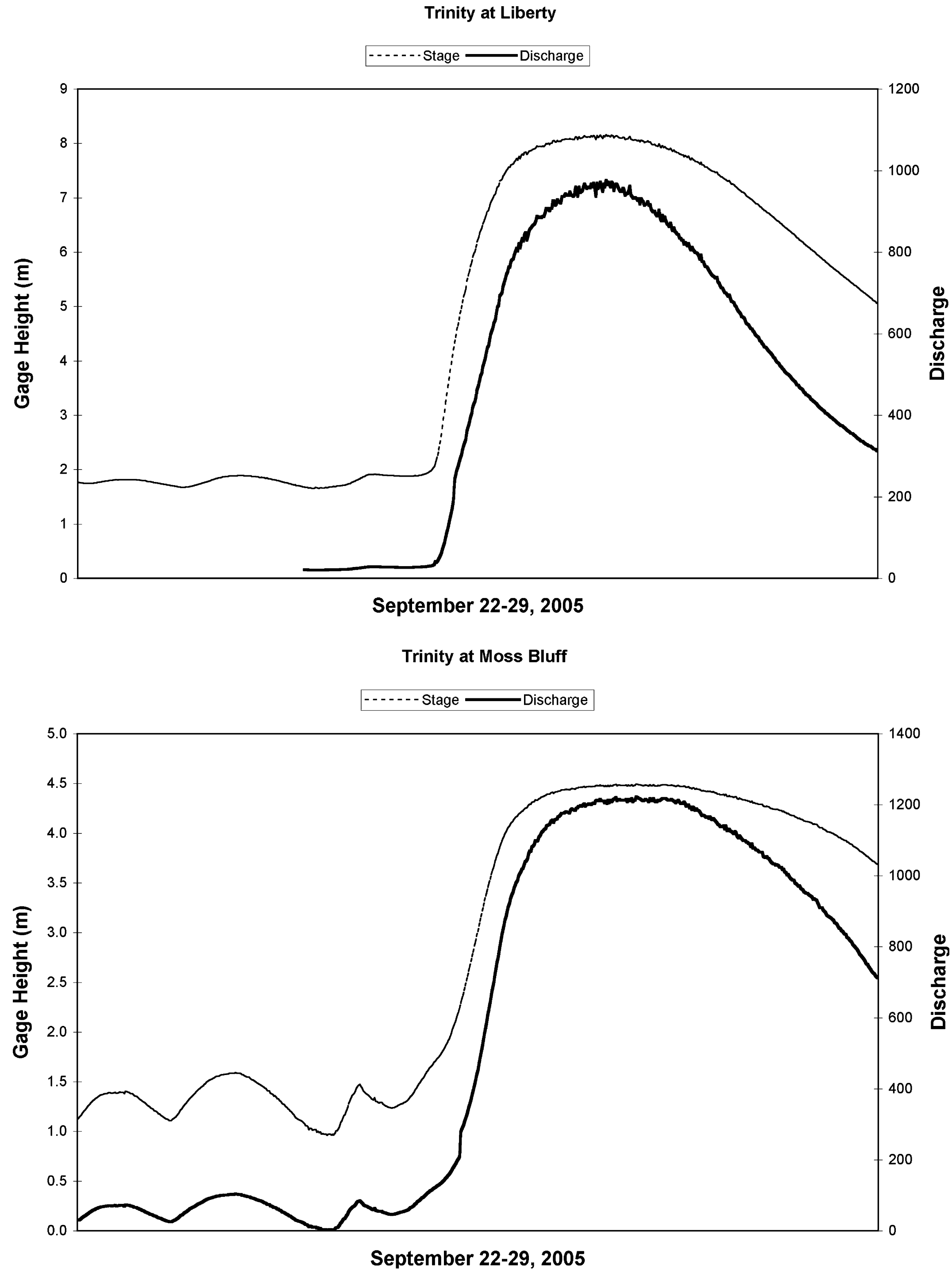

Figure 5 Stage (gage height) and discharge for the lower Trinity River at the Liberty and Moss Bluff gaging stations, with readings every 15 min. For the Liberty data, discharge was estimated by the author for the portion of the curve prior to the point indicated by the arrow. For Moss Bluff, discharge is entirely estimated by the author.

in the lower river can occur due to tidal effects and wind forcing.

Stream power

Cross-sectional stream power was estimated for a number of reference flows at the Goodrich, Romayor, and Liberty stations by Phillips and Slattery (2006) using channel thalweg slope as a surrogate for energy grade slope. As the previous section shows, water surface — and therefore energy grade — slopes may vary considerably between and within flow events. While water surface gradient is still only a surrogate for energy grade slope, and the distances between stations (18—50 km) are quite large, they allow a first-order assessment of the downstream variation of stream power during the Rita event.

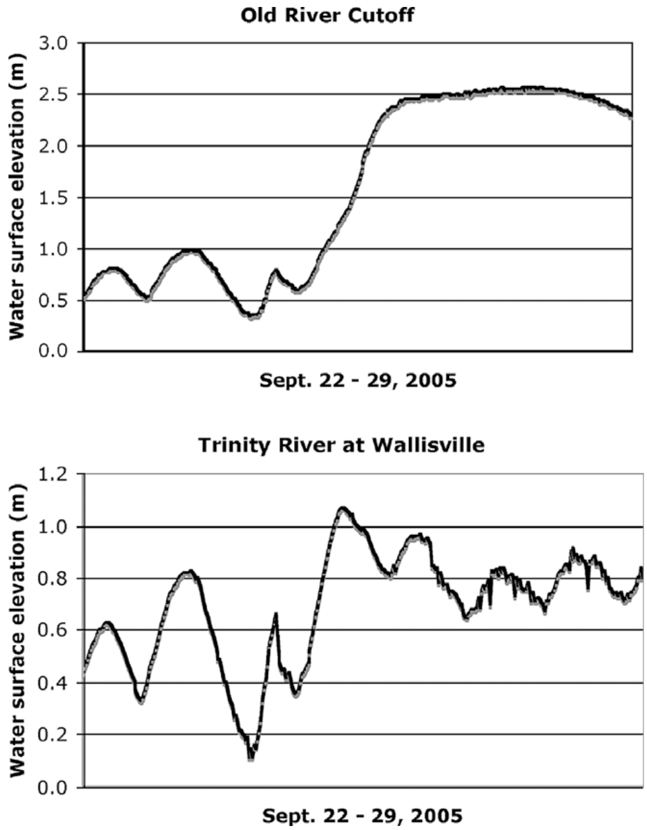

Figure 6 Water surface elevations for the week including the Hurricane Rita event at the Old River cutoff and Wallisville sites. Readings were taken every 15 min.

The data set allows calculation of either ''import'' or ''export'' stream power for each station (Fig. 8), using the instantaneous discharge and either the upstream or downstream water surface slope. During the first four samples of the Rita event (up to the start of the hydrograph rise at Goodrich), power is low at all cross sections. As the river peaks at Goodrich and Romayor, stream power increases substantially, and is much higher than at the downstream stations. As Liberty and Moss Bluff peak, the flood wave from the lake drawdown has passed the upstream stations, where stream power is now less than the downstream points (Fig. 9).

The stream power trends for the Rita event are consistent with previous work indicating a sediment storage bottleneck downstream of Romayor, whereby power is insufficient to transport the imposed sediment load, reduced though it is by trapping in Lake Livingston (Phillips et al., 2004).

Floodplain, tributary, and distributary morphology

The topography and geometry of the floodplain and tributaries were examined between the Goodrich and Romayor stations to investigate possible causes for the reduction in flow that sometimes occurs between the stations (Table 2). This was also noted in the Rita event, as the peak discharge at Goodrich was 39% higher than at Romayor.

Mussel Shoals Creek, which joins the Trinity downstream of the Goodrich station (Fig. 10), does so at an angle which is more characteristic of a distributary than a tributary channel. These are sometimes termed barbed tributaries, but to some geomorphologists the latter term implies

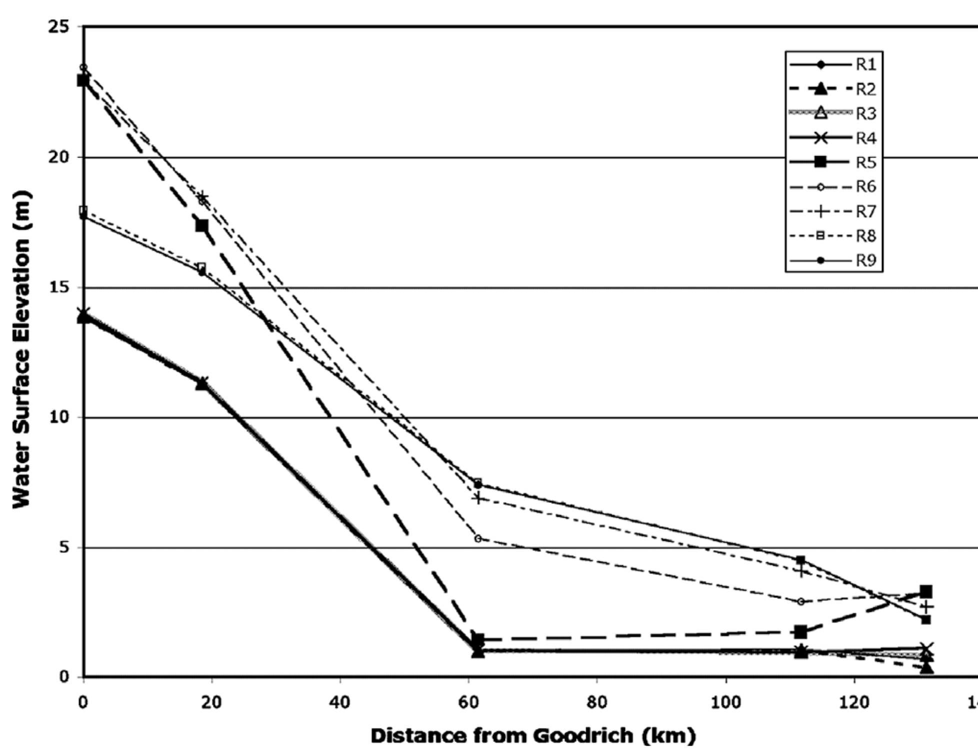

Figure 7 Water surface profiles from Goodrich to Wallisville for nine sample times during the Hurricane Rita flow event. Note the negative slopes for some measurements between Moss Bluff and Wallisville in the lowermost segment.

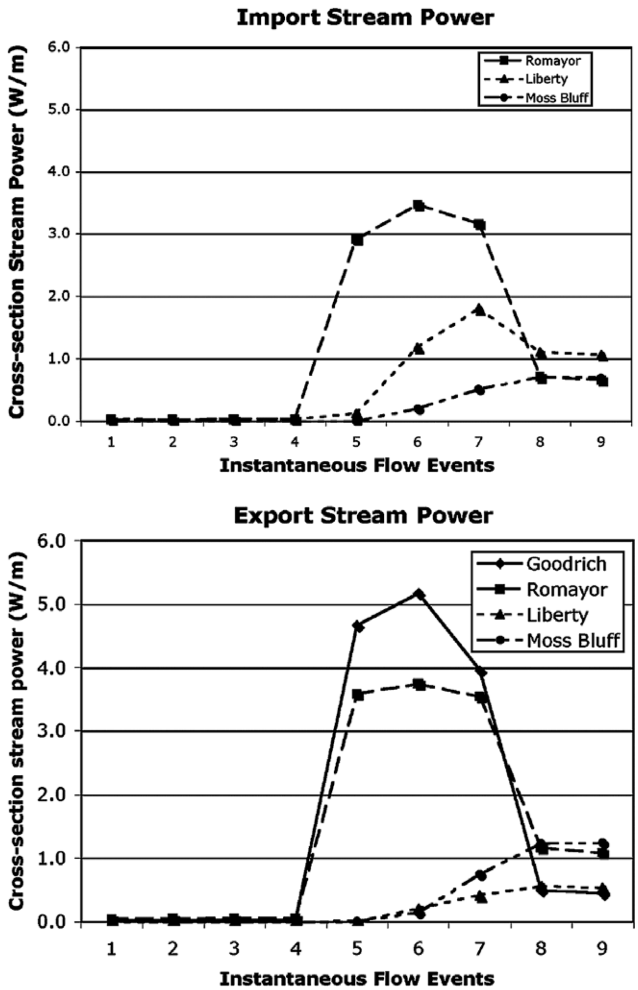

Figure 8 Stream power at Trinity River gaging stations for nine Hurricane Rita instantaneous flows, based on discharge and upstream (import) or downstream (export) slope.

stream capture, which is not the case here. Analysis of topographic gradients from the DEM indicate that portions of the channel drain away from the river, toward Grama Grass Bottom. Simulated flooding of the DEM to uniform depths indicates that (assuming water surface elevations at the confluence are approximately the same as at the Goodrich gage), that Mussel Shoals Creek begins backflooding from the river as water elevations at Goodrich rise from 21 to 23 m. This is below bankfull stage in this vicinity. During the Rita event stages at Goodrich reached this level late on September 24. The longitudinal profile of the creek channel suggests that backwater flooding to about 22 m could direct flow upstream.

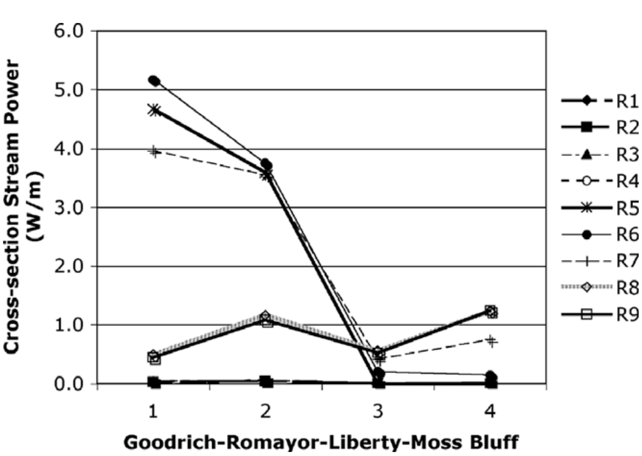

Figure 9 Stream power (export) at four stations for nine Hurricane Rita instantaneous flows.

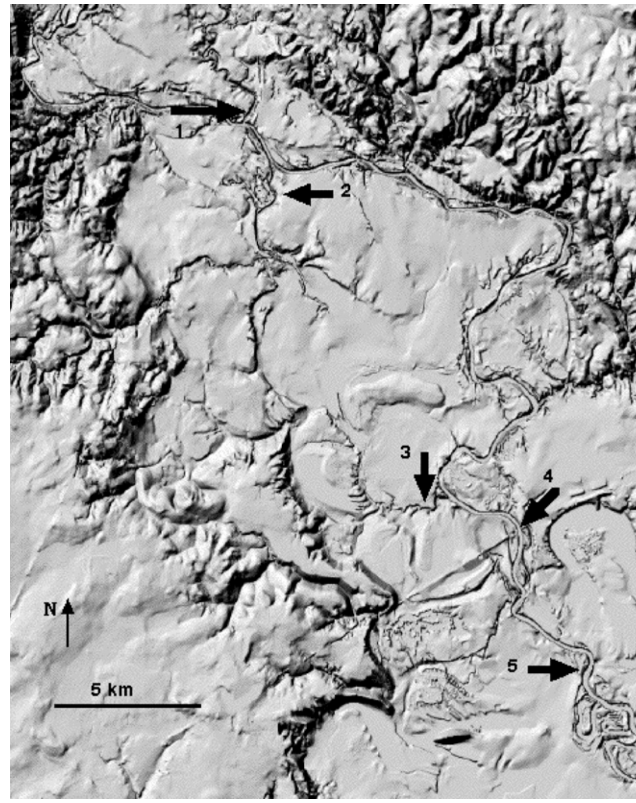

Figure 10 Shaded relief map (50× vertical exagerration) of the lower Trinity River valley in the vicinity of the Goodrich and Romayor gaging stations. Numbered arrows identify (1) Goodrich gage site; (2) Mussel Shoals Creek; (3) Big Creek at the southern end of Grama Grass Bottom; (4) Romayor gage site; and (5) approximate location of the morphological transition zone. The Romayor gage is located at 30°25′30″N and 94°51′02″W. Big Creek and lower Grama Grass bottom begin backflooding from the Trinity River as stages at Romayor rise from about 15 to 19 m amsl. Mussel Shoals Creek begins backflooding from the river as Goodrich stages rise from approximates 21 to 23 m amsl.

Big Creek, the largest tributary of the lower Trinity on the west side of the valley, joins the river at the expected acute angle, and flows through the southern end of Grama Grass bottom. The mouth of Big Creek, observed in the field at low flows, was not discharging water into the Trinity (though there was signifigant flow at several cross-sections of the upper reaches of the creek). A DEM analysis similar to that above indicates that Big Creek and lower Grama Grass bottom begin backflooding when stage elevations at Romayor rise from about 15 to 19 m. Again, this is well below bankfull levels. The Trinity at Romayor reached this stage late on September 24.

Thus, as river stages rise, Mussel Shoals and Big Creeks do not merely backflood, but become distributaries rather than tributaries of the Trinity, delivering water to the depressional areas of Grama Grass bottom, thus reducing the proportion of flow passing the Goodrich gage which is recorded at Romayor.

A short distance downstream of Moss Bluff, the Trinity clearly transitions to a dominantly divergent, distributary network at the confluence of Old River cutoff. Pickett's Bayou, which joins the Trinity upstream of Moss Bluff, connects the river with Old River in a marshy area of the Trinity River delta. It is not clear from maps the extent to which the bayou is a tributary of the Trinity or Old River. In the field, the confluence of Pickett's Bayou and the Trinity River has no single dominant mouth (or inlet). Rather, at least five subchannels dissect the river bank. Field surveys indicate the beds (Fig. 11) are 3.5—4 m above the river channel. Bayou channel slopes and flow indicators show the dominant flow pattern is clearly away from the river. Thus it appears that Pickett's Bayou serves as a tributary of Old River during low and normal water flows, draining a portion of the delta and adjacent terrraces. During high flows, however, the bayou becomes a distributary of the Trinity River. The elevation of the bayou channels at the river bank is approximately the same as that of the top of the point bar opposite the confluence. At this site, the distributary function comes into play at approximately bankfull flow. Shaded relief and surface images derived from the DEM (Fig. 12) show that topographic gradients lead generally away from the river toward the southeast.

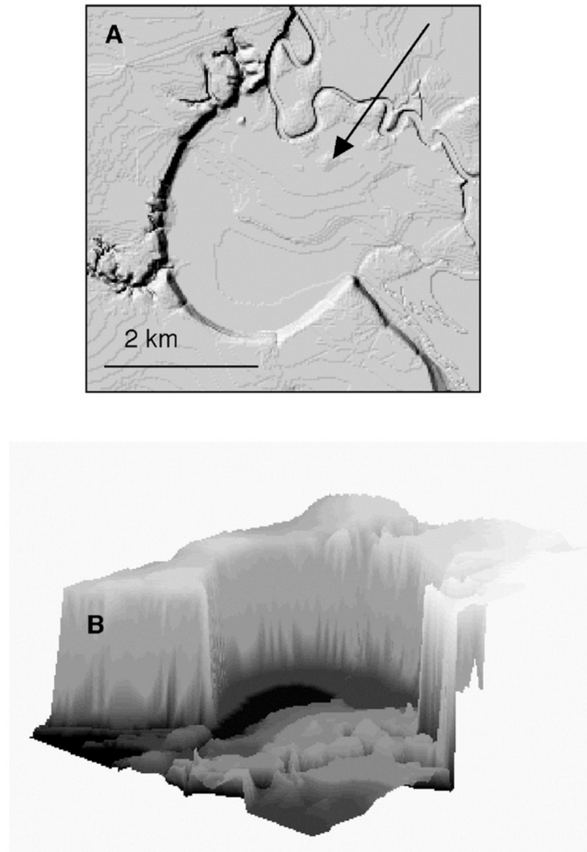

Figure 12 Trinity River Floodplain topography in the vicinity of Pickett's Bayou near Moss Bluff, Texas. A shaded relief map (A) shows the Trinity River, and the large palaeomeander defining the western valley wall. The arrow indicates the direction of view for the shaded surface model (B), which illustrates the topographic controls which tend to direct flow away from, rather than toward, the Trinity River channel.

Figure 11 (top) One of several channels at the confluence of Pickett's Bayou and the Trinity River. The elevation of the tributary channel is well above normal Trinity Water levels, but slopes away from the river bank, so that the bayou functions as a distributary during high flows. (bottom) Two of at least five channel inlets at the confluence of Pickett's Bayou and the Trinity River.

Both Grama Grass bottom and the depression shown in Fig. 12 are palaeomeanders of the ancestral Trinity River. The role of this inherited valley morphology in determining modern flow patterns will be addressed in the discussion.

Discussion

Despite being a humid perennial stream with no significant transmission losses, and despite numerous tributary inputs, discharge as recorded at gaging stations does not necessarily increase downstream in the lower Trinity River. In the clearly fluvially dominated reach from Goodrich to Romayor, while mean annual discharge is slightly higher at the downstream station, discharges associated with six reference flows (1%, 10%, and 50% exceedence probability, and recurrence intervals of 1, 2, and 10 years) are actually lower at the downstream station. Peaks associated with a moderate 2002 flood were higher at Romayor, but the peak for the 1994 flood of record was higher at Goodrich. Peak flows in the 2005 Hurricane Rita event also showed an apparent decline in flow between Goodrich and Romayor. Annual peak flows are often higher at the Romayor station.

The apparent cause of the discrepancy is backflooding and flow reversal in two tributaries, Mussel Shoals and Big Creeks. At higher than average but less than bankfull flows these creeks are backflooded by the river, and local topographic gradients lead to Grama Grass bottom, a depression within the river valley. This flow diversion may reduce discharge recorded at Romayor. If the magnitude or duration of high water is sufficient to fill the depressions, however, no peak flow reduction downstream of Goodrich is likely to occur.

Gaging stations further downstream are influenced by tidal and coastal backwater effects. Mean and reference flows at Liberty are substantially higher than at the upstream stations, but the discharge data are biased towards fluvially dominated events. Event peaks at Liberty may be lower than at the upstream stations, as shown by the 2002 flood and the Rita event.

Water surface slopes decline systematically from Goodrich to Romayor to Liberty, but further downstream slopes may be negative due to tidal and backwater effects. Slopes in the lowermost reach from Moss Bluff to Wallisville are the most variable, including the steepest positive and negative water surface slopes, reflecting the downstream translation of the Lake Livingston dam release and the backwater flooding effects of the storm.

Downstream of Moss Bluff the Trinity River is clearly dominantly divergent and distributary at all times, discounting periods of backwater effects and upstream flows. At least one upstream confluence is also distributary at high flows. Pickett's Bayou diverts water from the river at flow stages slightly less than bankfull. The bayou thus serves as a tributary of local runoff to Old River most of the time, but as part of the Trinity distributary network at high flows.

The depressional areas of both Grama Grass bottom and the Pickett's Bayou area are associated with palaeomeanders. The Trinity River is flanked by a modern floodplain and flights of several Pleistocene terraces. The oldest and highest are termed the Beaumont terrace, correlative with the Prairie surface in Louisiana. The modern lower Trinity River valley is cut into the Beaumont surface. Dates for the Prairie-Beaumont terrace in Louisiana and Texas range from 33 to 195 Ka, with a date from Winnie, Texas (the closest site to the Trinity) of 102.3 ± 8.3 Ka (Otvos, 2005). Blum et al. (1995) date the incision into the Beaumont terraces at about 100 Ka, broadly consistent with Thomas and Anderson's (1994) date of about 110 Ka, and within the range of Beaumont dates indicated by Otvos' (2005) synthesis (74–116 Ka).

Below the Beaumont surface, and often merging into the modern floodplain, are a series of up to three alluvial terraces, traditionally referred to as Deweyville, though they are not now generally believed to be part of a single terrace system (Blum et al., 1995; Morton et al., 1996). The paleomeanders in the lower Trinity Valley, often expressed as swampy depressions or meander scrolls, occur on the Deweyville surfaces, with radii of curvature and amplitudes suggesting significantly larger paleodischarges than at present (Alford and Holmes, 1985; Blum et al., 1995). These are generally cut laterally into Beaumont sediments. Between incision into the Beaumont and the current Holocene sea level rise, the Trinity underwent several entrenchment/aggradation cycles (Blum et al., 1995; Morton et al., 1996; Thomas and Anderson, 1994).

While the antecedent topography associated with incision into the Beaumount surface, and the Deweyville terraces and paleomeanders, does not constitute geological control in the traditional sense, it does apparently exert important influences on the modern river. Rodriguez et al. (2005) emphasized the importance of alluvial terrace inundation in creating flooding surfaces during transgression of the Galveston/Trinity Bay/Trinity delta area. Phillips et al. (2005) related the morphological and process transition zone in the river to the upstream limits of the effects of Holocene sea level rise. This study suggests that the location and gradient of tributaries and distributaries is strongly influenced by the antecedent landforms, and that water and other mass fluxes may be diverted from the river channel at high river flows.

Conclusions

There are no systematic downstream patterns of increases or decreases in the discharge, stream power, or water surface slope of the lower Trinity River. Discharge in the river channel may decrease downstream due to coastal backwater effects in the lowermost reaches, and due to diversion of low into valley-bottom depressions during high flows in both the fluvial and fluvial-estuarine transition reaches. In general, however, stream power and slope decrease in the lower reaches, consistent with earlier findings of limited fluvial sediment delivery to the coastal zone.

Some river tributaries may become distributaries at high but sub-bankfull flows, as backwater effects reverse flows into depressions associated with paleomeanders. The paleomeanders, and possibly the locations of these ''reversible'' channels, are related to antecedent topography associated with aggradation/degradation cycles over the past 100 Ka or so.

Results reinforce the notion that coastal plain rivers may not function as simple conduits from land to sea, and that the transition from fluvial to coastal dominance may be variable along the river, with the variability controlled not just by the relative magnitude of river and tidal or backwater forcing, but also by valley topography controlled in part by antecedent landforms.

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