Field Data Collection In Support of Geomorphic Classification of the lower Brazos And Navasota Rivers

Phase 2 of the project:
Geomorphic Context, Constraints, and Change in the lower Brazos and Navasota Rivers, Texas

Texas Water Development Board
Contract number 0604830639

FINAL REPORT

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Preface

This report is submitted in fulfillment of contract no. 0604830639 between the Texas Water Development Board and Jonathan Phillips (doing business as Copperhead Road Geosciences).

The study area is the lower Brazos River (Bryan to Gulf of Mexico) and Navasota River (Lake Limestone to confluence with the Brazos). The objectives were to refine the river styles-based geomorphic assessment to characterize the character, behavior, and current geomorphic condition of the rivers; and determine trends of river evolution and future trajectories of change. Additional objectives include:

•Identification of critical process/form transition points and zones.

•Resolution of geomorphic questions arising from earlier work, particularly the cause and timing of avulsion events; hydrologic and geomorphic relationships between the Brazos River and tributaries (including portions of the Navasota) current occupying former Brazos channels; potential bedrock controls on channel incision, and causes of and future potential for bed degradation and lateral channel migration.

•Development of guidelines and protocols for applying a river styles-based geomorphic assessment approach in alluvial rivers in Texas.

Acknowledgements are due to Greg Malstaff and Mark Wentzel of the TWDB for support and encouragement of various kinds, to Sarah McCormack for field assistance, and to Lynn Phillips for an inordinate level of logistic, project, and personal support.

Opinions and recommendations herein are the sole responsibility of the author and may or may not reflect the views of the TWDB, Texas Instream Flow Program, or individuals acknowledged above.

PART 1

Geomorphic Classification and Environmental Context Of the Lower Brazos and Navasota Rivers

INTRODUCTION

This work is undertaken in the context of the Texas Instream Flow Program. Instream flow programs (IFP) are intended to balance human and non-human uses of water, the latter usually summarized in terms of ecosystem requirements. IFPs are typically instituted to assess surface water withdrawals and flow modifications with respect to flow regimes required to maintain aquatic and riparian ecosystems (and sometimes instream recreational and economic activities). As a National Academy of Sciences report put it, IFPs "are being developed to answer the often politically-charged question, 'how much water should be in the river?'" (NAS, 2005: vii).

The Texas IFP has its roots in legislation establishing a state water planning process which considers environmental values in water development and allocation. The Texas Water Development Board (TWDB), Parks and Wildlife Department (TPWD) and Council on Environmental Quality (TCEQ) were directed to jointly establish and maintain an instream flow data collection and evaluation program, and to determine flow conditions in Texas streams necessary to support, in the words of the enabling legislation, "a sound ecological environment." The IFP work plan and technical overview developed by the three agencies are available from http://www.twdb.state.tx.us/instreamflows/.

The National Academy of Sciences established a committee to review methods for establishing instream flows for Texas rivers,which published an extensive review and recommendations (NAS, 2005). The review found that the existing technical overview document was "notably brief" in its discussion of hydrogeomorphic processes, "compact in its discussions of river classification, assessment of the current status of a river in terms of its geomorphology, and sediment transport processes," and "only scantly mentions some general methods that can be employed to assess and measure physical processes in an instream flow study" (NAS, 2005: 60).

The NAS review explicitly addresses the issue of geomorphic classification, noting that classification "is an important component . . . useful for documenting and analyzing physical processes, for selecting representative reaches and study reaches for instream habitat analysis, and for water quality analyses" (NAS, 2005: 71). The report also recommends identification of the river's geomorphic equilibrium status as part of a geomorphic classification (p. 72).

The first phase of the current project (Phillips, 2006) reviewed the theory and practice of geomorphological classification, existing classification schemes, and the relationships beween fluvial geomorphology and aquatic and riparian ecology. The "river styles" framework for assessment (Brierly and Fryirs, 2005) was determined to be most applicable to the Texas coastal plain, and an initial river styles classification was applied to the study area, the lower Brazos and Navasota Rivers.

River Styles

The river styles framework developed by Brierly and Fryirs (2005) is not a classification scheme *per se*, but a flexible, dynamic approach to river characterization. The lower case term river styles (or RS) will be used here in reference to the basic logic and scientific approach espoused by Brierly and Fryirs (2005), as opposed to the trademarked assessment algorithm, indentified as River Styles™. RS, in contrast to a categorical classification scheme, is specifically intended to incorporate evolutionary pathways of the fluvial system, rather than static conditions that are presumed to be related to stable equilibrium states. Rather than geomorphological taxonomy into which specific features are categorized, RS "provides a geomorphic template upon which spatial and temporal linkages of biophysical processes are assessed within a catchment context" (Brierly et al., 2002).

RS was developed as a research tool by geomorphologists working with the New South Wales (NSW, Australia) Department of Land and Water Conservation. It has been applied in NSW for a variety of river management applications, including rehabilitation programs, aquatic and riparian habitat assessments, and prioritization of rare or unusual features for preservation (Brierly et al., 2002; Brierly and Fryirs, 2000). The ecological significance of the river styles framework was specifically assessed by comparing macroinvertebrate assemblages and habitat characteristics of specific geomorphic units for three different river style units in NSW (Thomson et al., 2004).

RS has a nested hierarchical structure and incorporates assessment of river structure at the catchment, reach and geomorphic unit levels. Geomorphic units are analyzed and organized into reaches, which are amalgamated to form source, transfer, throughput and accumulation zones, based on the assemblage of geomorphic units and associated sediment relations along reaches. Watershed characteristics are used to determine the nature of the controls on river character and behaviour in each process zone. The evolution of the river is then assessed in a historical context, and provides an indication of pre-disturbance stream characteristics. Lastly, the direct controls on habitat availability are assessed by analysis of changes to channel geometry and planform, the assemblage of geomorphic units within each process zone and the nature of altered associations that each of these geomorphic features have with riparian vegetation (Brierley and Fryirs, 2005).

RS is not a taxonomic scheme, but can be used as the basis for categorizing specific fluvial systems. Despite its attractive grounding in geomorphology and river science, Parsons et al. (2002) note some potential disadvantages. These include assumptions that the units considered are relevant to biota (presumably a disadvantage to all classifications not based directly on biota), the requirement of a high level of geomorphological expertise, and the reliance on aerial photography and specialized field equipment.

The utility of any characterization must be evaluated with respect to the intended purpose (in this case the Texas IFP), and the environmental context. The scientific and technical basis of the Texas IFP has already been reviewed by NAS (2005), who gave considerable attention to geomorphic classification issues.

Taken together, the needs of the IFP and the environmental context of the study area imply the need for a classification or characterization scheme which (Phillips, 2006):

- is not based on any single reference or design flow;

- includes floodplains and riparian areas;

- is based on links between hydrology, geomorphic processes, and channel/valley morphology;

- can incorporate trends or trajectories of change;

- is applicable to meandering floodplain rivers; and

- is sensitive to geologic context, antecedent topography, and other manifestations of the legacy of Quaternary climate and sea level change.

The river styles approach was selected as the system which best meets these criteria (Phillips, 2006). Further, RS does not implicitly or explicitly assume any design or normative steady-state equilibrium forms or states, as some other common classification systems do (Phillips, 2006). Stable, steady-state equilibrium assumptions are problematic both in general and in the Texas context, as discussed in detail in a parallel project (Phillips, 2007c).

River Styles Stages

A detailed description of River Styles, including the underlying theory and philosophy, methods, and protocols, given by Brierly and Fryirs (2005). In this section a brief overview is presented, along with the general procedure used in the study area.

Application of the RS framework involves four stages. Stage 1 is a basin-wide baseline survey of river character and behavior which includes the identification and designation of river styles. The second stage is an assessment of river evolution and the contemporary geomorphic condition. Stage 3 involves elucidating possible and probable future trajectories of change, and the geomorphic recovery potential for reaches judged to be in poor or undesirable conditions. This study encompasses stages 1, 2, and part of stage 3. Determination of poor or undesirable conditions, and the final stage (4) of management applications, involves utilization of the geomorphic characterization in the instream flow program, and is beyond the scope of this study.

Site-level surveys, planning, assessment, and management requires consideration of geomorphic and hydraulic units. However, the river style is the key element of the hierarchy, as each designated style should contain a reasonably consistent and predictable set of such units.

An ideal, full RS report as described by Brierly and Fryirs (2005) is a major undertaking requiring a significant amount of expertise in fluvial geomorphology. The 13,115 km^2 of drainage area in this study (Brazos watershed downstream of Bryan, and the Navasota downstream of Lake Limestone) is almost seven times the size of the Bega catchment used as a case study by Brierly and Fryirs (2005). However, it is feasible to delineate and map river styles and reaches, and to describe the key characteristics of each style (termed a proforma by Brierly and Fryirs, 2005).

STUDY AREA

The study area is the lower Brazos and Navasota Rivers, defined for purposes of this study as the Brazos downstream of the SH 21 crossing west of Bryan, and the Navasota downstream of Lake Limestone (Fig. 1).

The Brazos River is the largest in Texas, with a drainage area of about 118,000 km^2, and flows more than 1,900 km from its headwaters in New Mexico to the Gulf of Mexico at Freeport (Figure 2). The 320 km Navasota River is the largest tributary of the lower Brazos, joining the latter at Washington, Texas.

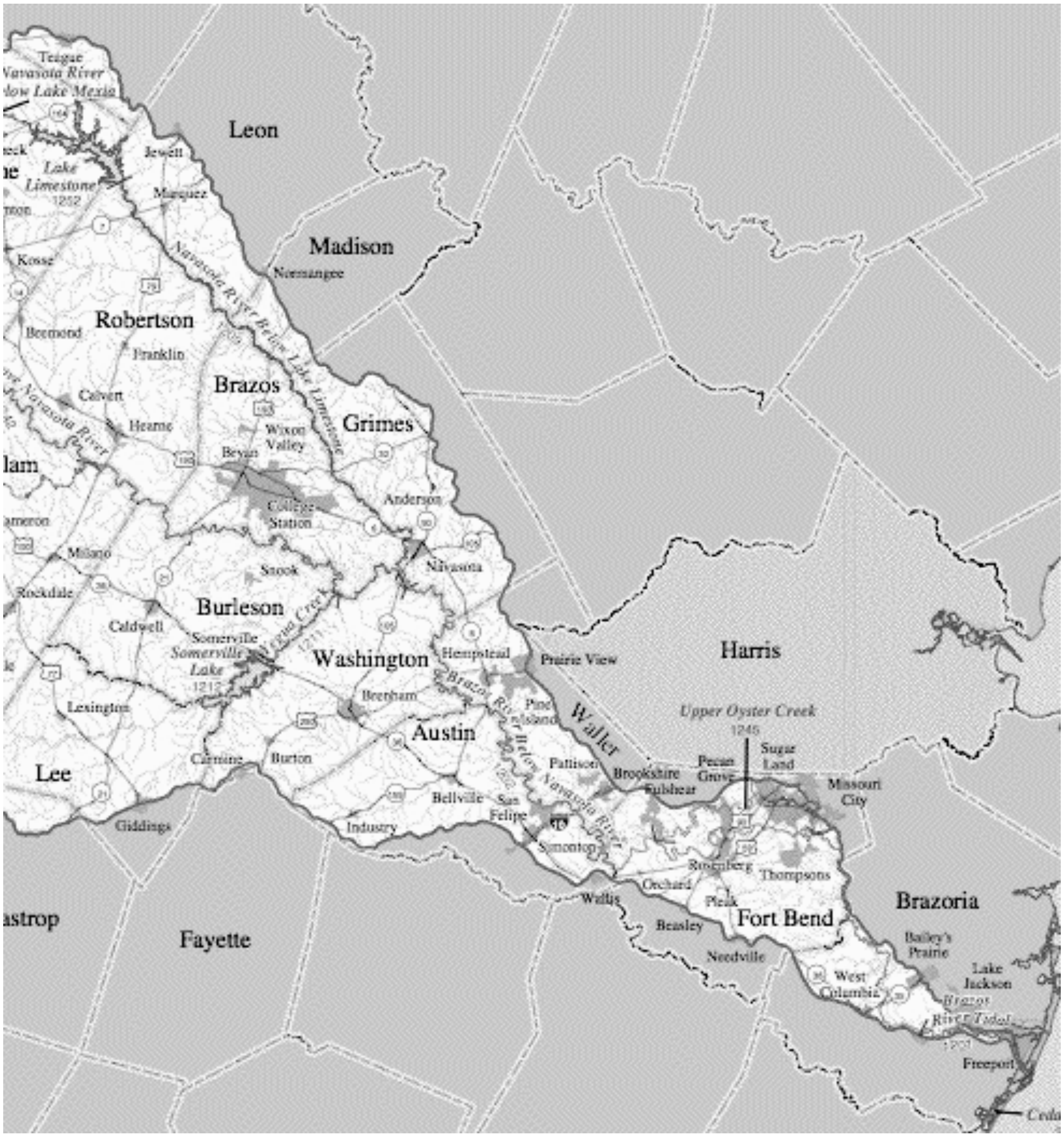


Figure 1. Study area, showing drainage basin boundary, county boundaries, and main channels.

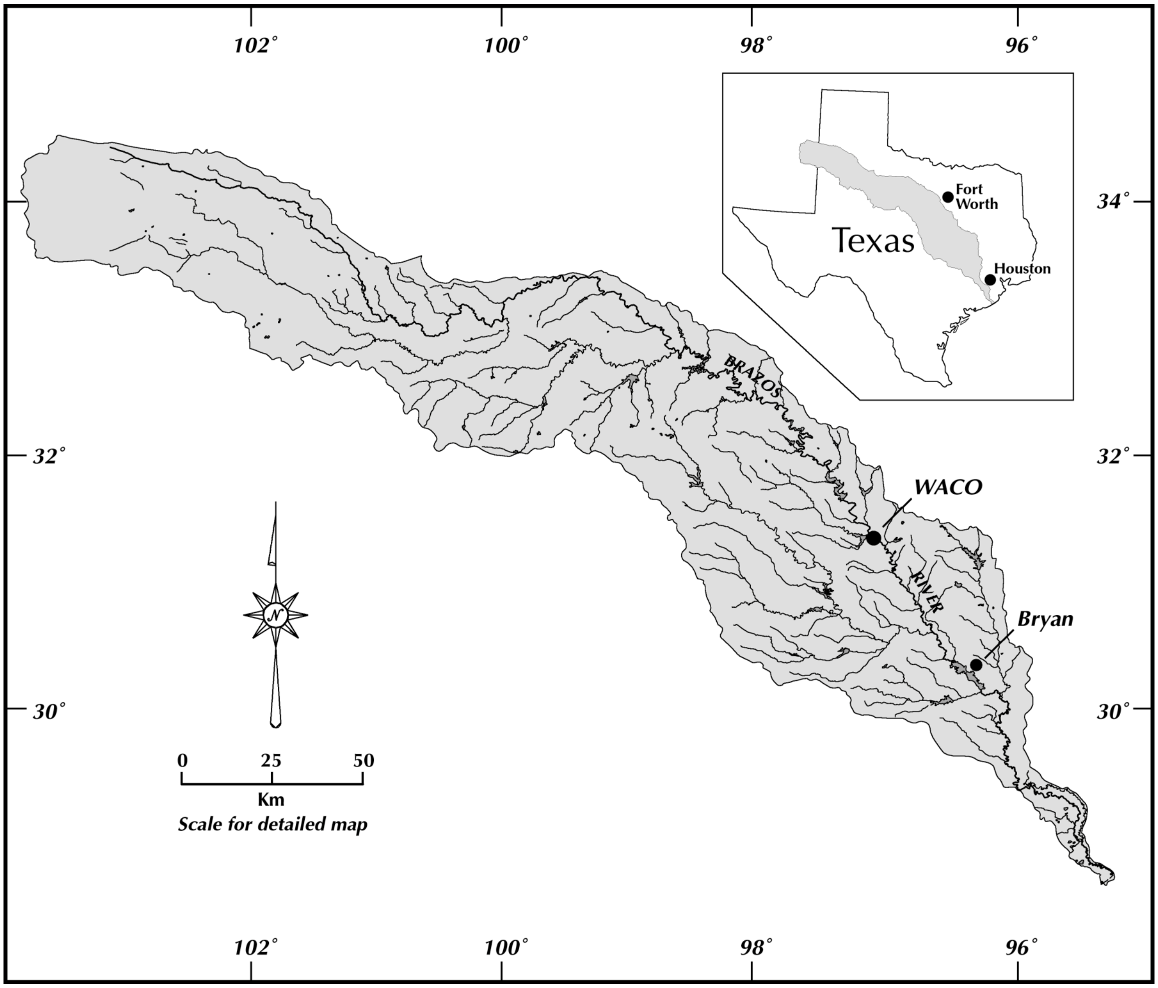


Figure 2. Brazos River basin.

Climate

The study area climate is humid subtropical. Mean annual precipitation is about 990 mm in Brazos County, and 1,320 mm in Brazoria County. Though precipitation occurs year-round, summer droughts and low-flow periods are common, due to high evapotranspiration. Average daily maximum temperatures in College Station range from 35° C in August to 14^0 in January, with an annual mean daily high of 25.5°C. Average daily minima are 23° in midsummer and 4° in January, with an annual mean of 14^O C.

Nordt et al. (1994) inferred late Pleistocene and Holocene climate change in the region from vegetation changes reflected in stable carbon isotopes in alluvial deposits and soils. Conditions in the late Pleistocene appear to have been cooler and moister than at any other time in the past 15 ka. Between 11 and 8 ka, a transition to warmer and drier Holocene conditions is inferred. In the mid-Holocene (~8 – 6 ka), expansion of warmer, drier conditions occurred, followed by a shift to a cooler and wetter regime about 4 ka. (Nordt et al. 1994).

Hydrology

Stream discharge and sediment transport at the Richmond station, the longest established in the area with records beginning in 1903, have been extensively analyzed elsewhere (Hudson and Mossa, 1997; Dunn and Raines, 2001; Osting et al., 2004).

Discharge and river stage data from the U.S. Geological Survey were used to establish hydrologic regimes. The stations used are shown in Table 1. Mean daily streamflows were used to determine average discharges, and flows with recurrence probabilities of 1, 10 and 50 percent. Bankfull levels at each station and historic flood peaks were determined from the National Weather Service Advanced Hydrologic Prediction Service records for each station, along with the USGS record of annual peak flows.

Table 1. US Geological Survey gaging Stations used in this study. Datum refers to the elevation of the gage above mean sea level; date is the beginning of regular recording at the site. The Bryan, Hempstead, Richmond, and Rosharon stations are on the Brazos River. The Easterly and Normangee stations are on the Navasosta.

Name	*Location*	*Number*	*Drainage area (km^2)*	*Datum (m)*	*Date*
Bryan	SH 21 W of Bryan	08108700	101,137	189.3	1993
Hempstead	US 290 W of Hempstead	08111500	113,649	33.5	1938
Richmond	US 90	08114000	116,827	8.7	1903
Rosharon	FM 1462 nr Brazos Bend State Park	08116650	117,428	~0	1967
Easterly	US 79 btwn Easterly & Marquez	08110500	2,507	84.4	1924
Normangee	Old San Antonio Rd. btwn Normangee & Bryan	08110800	3,333	76.1	1997

Table 2. Reference flows for Brazos and Navasota River gaging stations, calculated from mean daily flows. Note that the Bryan and Normangee stations have short periods of record. Flood of record indicates the highest flow for which discharge has been measured or estimated by the U.S. Geological Survey.

Flow	$ft^3\ sec^{-1}$	$m^3 sec^{-1}$
Brazos at Bryan		
Mean daily	4727	134
1%	40500	1147
10%	12400	351
50%	1770	50
Flood of record (2007)	85500	2421
Brazos at Hempstead		
Mean daily	6916	196
1%	56600	1603
10%	17900	507
50%	2570	73
Flood of record (1957)	143000	4049
Brazos at Richmond		
Mean daily	7480	212
1%	62800	1778
10%	18900	535
50%	2950	84
Flood of record (1929)	123000	3483
Brazos at Rosharon		
Mean daily	8186	232
1%	61900	1753
10%	21400	606
50%	3450	98
Flood of record (1994)	84400	2390
Navasota at Easterly		
Mean daily	422	12
1%	7440	211
10%	846	24
50%	27	0.8
Flood of record (1899)	90000	2549
Navasota at Normangee		
Mean daily	570	16
1%	8570	243
10%	1290	37
50%	67	2
Flood of record (1999)	30100	852

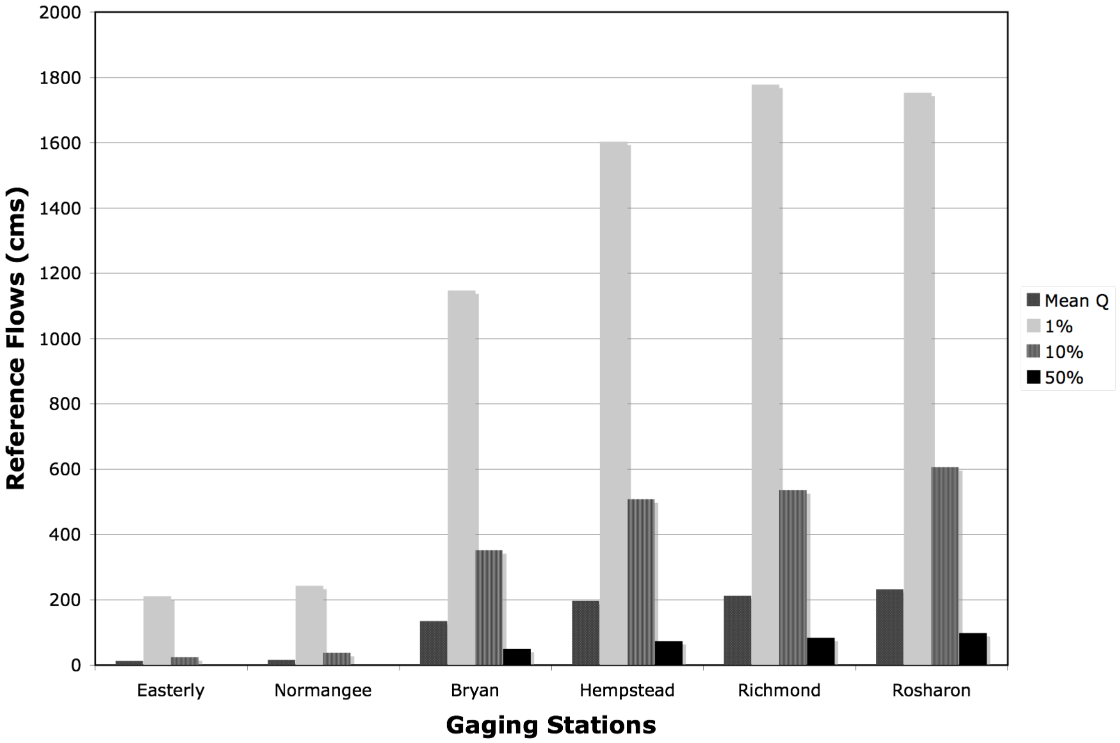


Figure 3. Reference flows: mean daily discharge, and average daily flows with recurrence probabilities of 1, 10, and 50 percent. Stations are arranged (L-R) in order of increasing drainage area.

Specific discharge (mean daily discharge per unit drainage area) is shown in Fig. 4. The difference between the Brazos and Navasota gages may reflect a significant portion of the drainage area in the uppermost Brazos basin which contributes little or no runoff, and the drier climates in some of the upper Brazos.

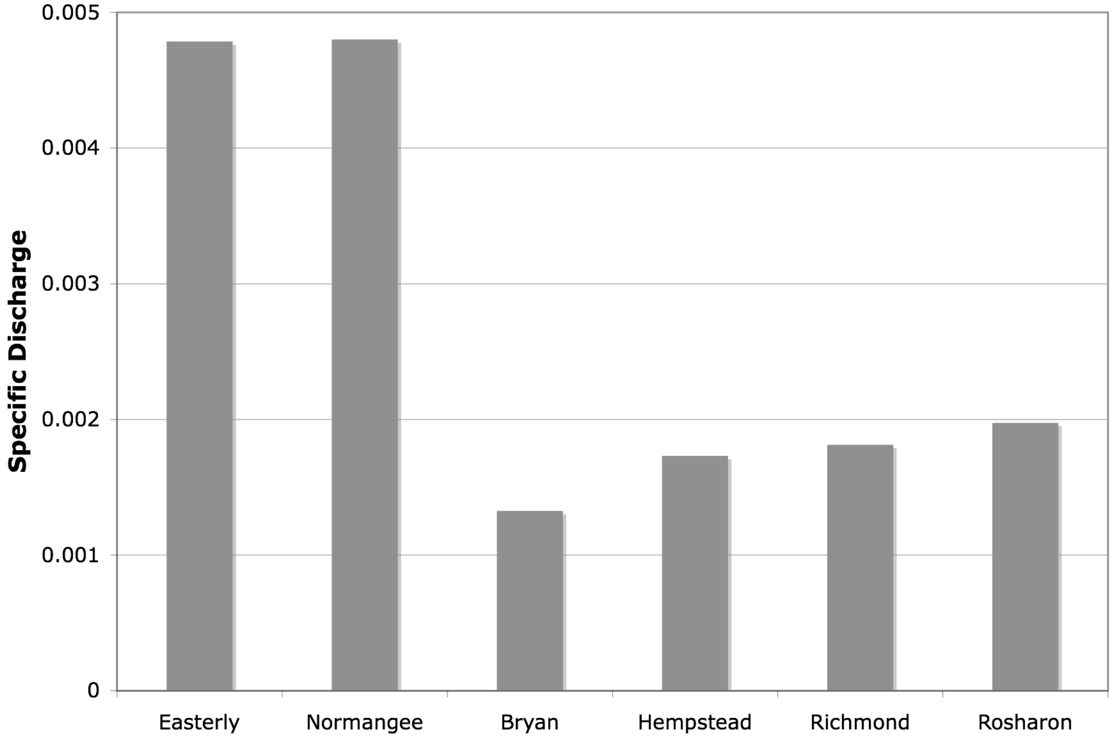


Figure 4. Specific mean daily discharge (m^3 sec^{-1} km^{-2}).

Major floods occurred on the Brazos River downstream of the Navasota in 1833 and 1841. The major floods of 1913 (the flood of record at the Hempstead and Rosharon stations) and 1921 spurred development of flood protection and mitigation measures throughout the Brazos River basin. Many reaches in the study area experience regular (annual or more frequent) minor flooding, though this is not always evident from gaging station data, as gaging stations are located at bridge crossings which in turn are not generally representative cross-sections.

Table 3 shows the designated flood stages for the gaging sites, the estimated discharge associated with this stage, and information on historic flood peaks. The estimated recurrence intervals of flood stage flows at the Brazos stations are 2.5, 22, 1, and 0.33 years, respectively, at Bryan, Hempstead, Richmond, and Rosharon. Note that in some cases flood stages were recorded or estimated before discharge measurements began.

Table 3. Flood regimes at gaging stations. Flood stages are given in feet based on local gage heights (meters in parentheses), as indicated by the National Weather Service Advanced Hydrologic Prediction Service (AHPS; Galveston site: http://ahps.srh.noaa.gov/index.php?wfo=hgx). Estimated discharge (m^3 sec^{-1}) at bankfull is based on AHPS data and analysis of stage-discharge curves for high flows by the author.

Station	*Flood stage*	*Estimated Q*	*Historic Peaks*
Easterly	19 (5.8)	~ 85	2548 m^3 sec^{-1}, 1899
Normangee	15 (4.6)		21 ft, 1999; 20 ft, 2000
Bryan	43 (13.1)	1853	54 ft, 1921; 51 ft, 1913; 2421 m^3 sec^{-1}, 2007
Hempstead	50 (15.2)	2888	66 ft, 1913; 54 ft, 4049 m^3 sec^{-1}, 1957
Richmond	48 (14.6)	2265	50 ft, 1994; 3483 m^3 sec^{-1}, 1929
Rosharon	43 (13.1)	1812	56 ft, 1913; 52 ft, 2390 m^3 sec^{-1}, 1994

Flood discharges tend to decrease downstream from Hempstead to Rosharon (the Bryan station's short data record make it difficult to generalize for this location). This is largely due to backwater flooding of tributaries and flow diversions into Oyster Creek and other streams occupying Brazos River paleochannels. At Richmond, backwater flooding of tributaries begins at flood stage, and flow occurs across the floodplain into Oyster Creek.

Geologic Setting

The study area is within the Gulf Coastal Plain physiographic province. The Brazos River valley is situated on a portion of the Gulf of Mexico margin which has been gradually subsiding since the mid-Mesozoic, allowing nearly continuous sedimentation since that time. Sediment supplied to the coast has generally exceeded available accommodation space on the continental shelf, leading to a prograding and aggrading shelf margin, and the seaward expansion of depositional environments. This overall trend is overprinted by shorter-term aggradation/degradation fluctuations associated with variations in sediment supply, sea level, and shelf subsidence (Yancey and Davidoff, 1994).

Geologic units can be broadly grouped into Tertiary formations and Quaternary sediments. Tertiary formations are about 2 to 45 million years old. Quaternary sediments include Pleistocene deposits (up to nearly 2 million years old), Holocene sediments deposited within the last 10 ka, and recent (historical and contemporary) deposits.

Tertiary formations are exposed at the surface in roughly coast-parallel patterns in the Navasota basin and the Brazos basin upstream of the Navasota confluence, and dip gently toward the Gulf. This structure locally deflects southeast-flowing tributaries eastward when resistant beds are encountered, resulting in several northeast-southwest strike-oriented cuestas where relatively resistant sandsones underlie the ridges. Tertiary formations include the Miocene Fleming, Oakville, and Catahoula Formations; and the Eocene Manning, Wellborn, Caddell, Yegua, and Cook Mountain Formations. Late

Pleistocene and Holocene alluvium occupy the Brazos and Navasota valleys, with older Quaternary alluvial terraces along the margins of both rivers and major tributaries.

Downstream of the Navasota confluence, Quaternary formations comprise the uplands, the oldest of which are the Willis formation. The Lissie formation is of particular importance, as it creates a valley constriction near Hempstead, locally reducing valley width by about 50 percent.

The incised valley of the Brazos is cut into the Willis and Lissie formations downstream as far as Richmond. From this point, the Pleistocene Beaumont formation bounds the valley. The Beaumont slopes gulfward at a gradient of about 0.0004, slightly greater than that of the average gradient of the Holocene alluvium and late Pleistocene alluvial terraces.

The Brazos River is flanked by a modern floodplain and flights of several Pleistocene Terraces. The Beaumont terrace is correlative with the Prairie surface in Louisiana. Dates for the Prairie-Beaumont terrace in Louisiana and Texas compiled by Otvos (2005) range from 33 to 195 ka. Otvos' (2005) analysis places the deposition of the Beaumont terraces in Texas, which are 50 to 100 km wide from the coast, at 74 to 116 ka--broadly consistent with Blum et al. (1995) and Thomas et al. (1994).

Between the Beaumont surface and often merging into the modern floodplain are a series of up to three alluvial surfaces. These are usually 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). In most locations two or three separate "Deweyville" surfaces are recognized (Blum et al. 1995; Blum and Price, 1998; Morton et al. 1996; Rodriguez et al., 2005). The lowermost Deweyville surfaces are only slightly higher than the modern floodplain, and in some cases are buried by the latter, with natural levees of the modern floodplain higher than backswamps of the lower Deweyville (Alford and Holmes 1985; Blum et al. 1995; Rodriguez et al., 2005). The youngest of the Deweyville surfaces has been termed the Eagle Lake Alloformation by Blum and Price (1998). The three Deweyville surfaces are designated (youngest to oldest) the Fredonia, Sandjack, and Merryville alloformations by the Louisiana Geological Survey (Heinrich et al., 2002).

In the Colorado River, Texas, deposition of the youngest Deweyville alloformation from 20-14 ka was followed by bedrock valley incision 14-12 ka, with Holocene valley filling since (Blum and Price 1998). Waters and Nordt (1995), working in the Brazos River between Hearne and Navasota, found that the Brazos was a competent meandering stream from 18 to 8.5 Ka, leaving thick coarse lateral accretion deposits (such as those associated with Deweyville terraces) as it migrated across the floodplain. The transition to an underfit stream incised into those deposits and dominated by vertical accretion is dated to 8.5 Ka, with avulsions in narrow and unstable meander belts occurring on several occasions since (Waters and Nordt, 1995). Further downstream, in the lowermost 160 km of the Brazos, Taha (2007) reckons incision beginning about 7.5 ka, with the maximum horizontal separation between the channel and floodplain occurring about 1.5 ka.

Nordt and Aronow (2002) report that the highest alluvial deposits of the Brazos River are more than 20 m (65 ft) above the modern floodplain in Brazos County, and occur across all Tertiary formations (though many such deposits are too small to be shown on soil maps, and none are shown on geologic maps). Field work for this project discovered alluvial deposits along the Navasota River/Trinity River drainage divide in Leon County.

Unlike smaller rivers such as the Trinity, Neches, and Sabine, the Brazos has essentially filled its estuary and has an actively prograding delta. The location of the delta shifted in 1929 (see below) with the rerouting of the lowermost channel. While the delta is wave-dominated in general, during periods of high flow the Brazos delta is fluvially-dominated (Rodriguez et al., 2000).

Landscape Units

The topography, geology, and geologic history of the study area are reflected in six different landscape units within which fluvial channels and valleys occur. These are shown in figure 5 and described below:

- *Lower Coastal Plain*. Low relief, low elevation (mainly < 3 m) minimally dissected surfaces composed entirely of Quaternary and largely of Holocene coastal, marine, deltaic, and alluvial sediments.

- *Quaternary Coastal Plain—Beaumont*. Gently-rolling, low relief minimally dissected uplands primarily on the Pleistocene Beaumont formation in the lower and middle coastal plain.

- *Quaternary Coastal Plain—Lissie*. Gently-rolling, moderately dissected uplands primarily on the Lissie (and to a lesser extent the Willis) formation, middle and upper coastal plain.

- *Miocene Uplands*. Gently-rolling to moderately steep, strongly dissected uplands, primarily on the Fleming and Catahoula formations, and the Oakville sandstone.

- *Eocene Uplands*. Gently-rolling to moderately steep, strongly dissected uplands, in generally northeast-southwest bands, with more resistant layers forming cuestas. Includes eight different Eocene formations.

Pleistocene alluvial terraces and Holocene alluvial floodplains are also prominent within the study area, but as these occur within the river valleys they are not considered part of the landscape units providing the broader context for river styles.

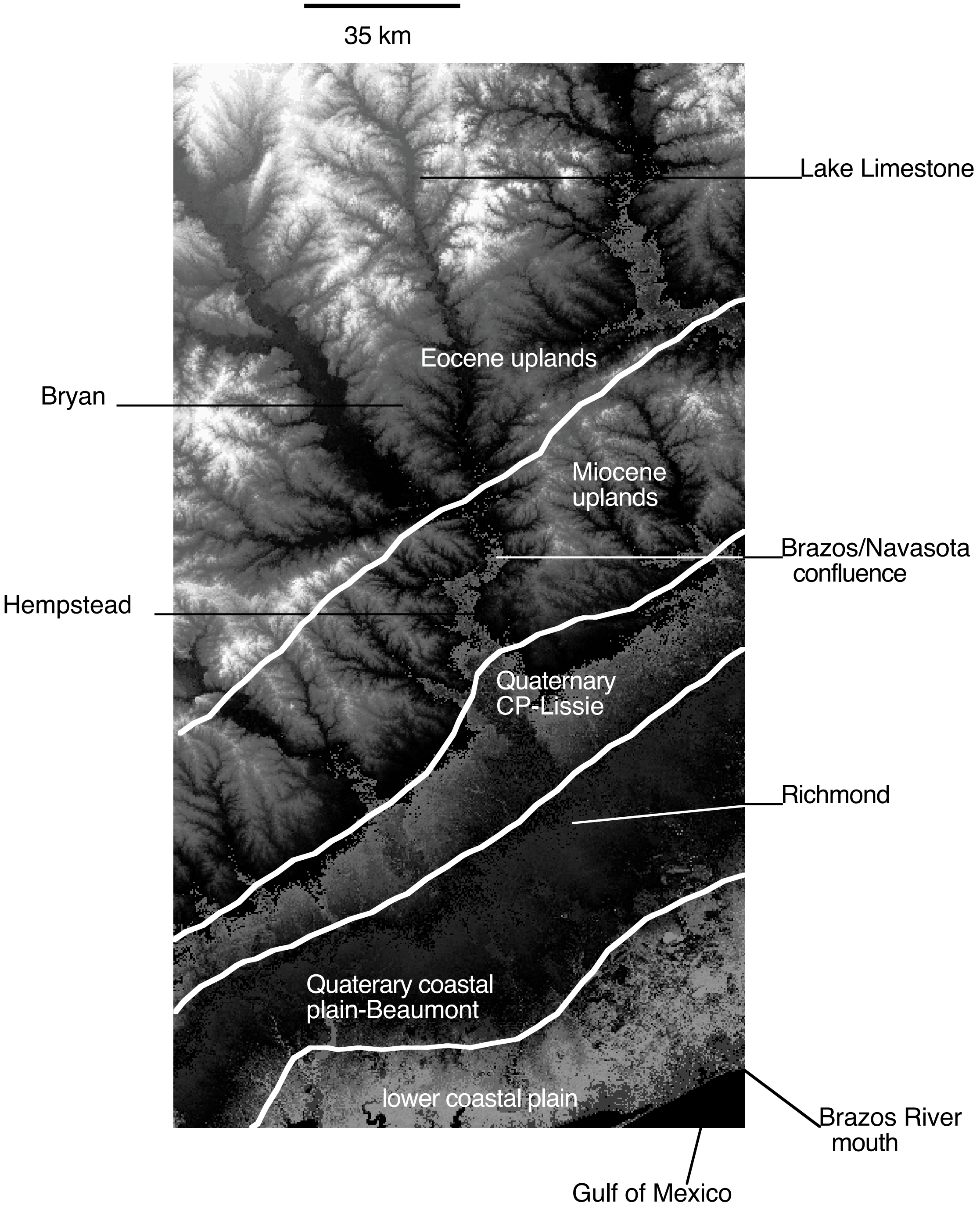


Figure 5. Landscape units are shown on a density-plot base map derived from 90-m DEM data. Landscape unit boundaries are generalized and approximate.

Human Impacts

The Brazos watershed is home to an estimated 3.5 million people, and the lowermost Brazos basin is adjacent to the Houston metropolitan area, with a population of more than four million. Within the basin, however, land use is predominantly agricultural, though large petrochemical complexes exist near the mouth of the river. A few specific impacts deserve special mention.

Dams and Reservoirs

Nearly 1,200 reservoirs with storage capacities of ≥ 50 acre-feet (61,700 m^3) and/or dam heights of ≥ 8 m exist within the Brazos River basin (Dunn and Raines, 2001), along with numerous smaller farm ponds and stock tanks. The first major dam, creating Possum Kingdom reservoir, was completed in 1941. Lake Whitney was impounded in 1951, Lake Somerville in 1967, and Lake Limestone in 1978. Nearly 90 percent of the controlled storage is in 13 reservoirs. The two most directly affecting the study area are Lake Limestone, at the upper end of the Navasota study area, and Lake Somerville, on Yegua Creek. Reductions in peak discharges, sediment transport, and lateral channel migration in the lower Brazos have been attributed to the effects of dams by various authors (Gillespie and Giardino, 1997; Hudson and Mossa, 1997; Dunn and Raines, 2001; Chin et al., 2002; Chin and Bowman, 2005).

However, reservoir entrapment apparently has little effect on sediment transport in the lower Brazos. The farthest downstream main-channel reservoir (Lake Whitney) is more than 560 km upstream of Richmond. Dunn and Raines (2001) found that reservoirs had no discernible impact on sand transport in the lower Brazos, consistent with studies on the Trinity River which showed minimal downstream geomorphic impacts of Lake Livingston beyond about 55 km downstream of the dam (Phillips et al., 2004; 2005).

Sand Mining

Several sand and gravel mining operations exist on the lower Brazos River between Hempstead and Rosharon. Dunn and Raines (2001) estimated that extractions may amount to 11 to 25 percent of the total sand transported by the Brazos, but they could not quantify the effects.

Flood Control and Navigation

In 1913 a major flood on both the Brazos and the Colorado Rivers reportedly caused the mouths to join and temporarily create a channel/lake more than 100 km wide. Impacts of this and other floods prompted several flood control efforts. In 1929, to alleviate flooding in the Freeport area and sedimentation in the Freeport harbor and ship channel, the Brazos River was rerouted to the southwest. The river now takes a straight path from the Freeport/Lake Jackson area toward the Gulf, where the old, meandering channel (cut off from the river) is the Freeport Ship Channel. The new route has built a delta.

Part 2
Methods, Data, and Results

METHODS

Geologic information was derived from 1:250,000 scale geologic maps from the Texas Bureau of Economic Geology (Geologic Atlas of Texas) from the Houston, Seguin, Austin, and Waco sheets. The Tectonic Map of the Texas Coastal Zone (Gulf Coast Association of Geological Societies) and the Tectonic Map of Texas (Ewing et al., 1991) were used to identify potential tectonic influences. Several published studies also allowed the identification of previously unmapped features, and the dating of several events (Waters and Nordt, 1995; Nordt and Aronow, 2002; Sylvia and Galloway 2007; Taha and Anderson, 2007)

Discharge and river stage data from the U.S. Geological Survey were used to establish hydrologic regimes, as described earlier. Digital elevation data at 10 m resolution, obtained from the U.S. Geological Survey Data Distribution Center proved to be prohibitively large in terms of file size and processing time for so large a study area. While 10 m digital elevation models (DEM) were used to analyze specific sections of subtle relief, 30 m data were used for the study area as a whole. DEM data were analyzed using the RiverTools program for general visualization of topography, identification of geomorphic surfaces, and computation of morphometric parameters.

Soil data from the U.S. Department of Agriculture Natural Resources Conservation Service was obtained for the study area from the STATSGO database. Published surveys for several counties were also consulted. While the soil maps are useful in establishing the general environmental framework, their primary purpose in this study was to aid in distinguishing modern Holocene floodplains from Pleistocene alluvial terraces that also occupy the river valleys. For each series mapped in the study area, the USDA-NRCS Official Series Descriptions database was consulted to identify soils occurring on floodplains and alluvial terraces. Series were included in the floodplain group if the database indicated the soils occurred on floodplains, with the modifiers fluvial, alluvial, modern, Holocene, river, or stream. The alluvial terrrace group included soils identified as occurring on terraces, with the modifiers alluvial, fluvial, river, or Pleistocene. Soils identified as occurring on coastal or marine terraces were not included. These interpretations from the database where then crosschecked with published soil surveys for counties within the study area. While some minor differences were found in the landscape interpretations, none were sufficient to modify placement in the floodplain, alluvial terrace, or “other” classes. Arcview GIS was used to aggregate the soil map units according to the scheme above, to produce a map showing the alluvial floodplain and terrace soils.

U.S. Geological Survey 1:24,000 topographic maps in DLG (digital line graph) form obtained from the Texas Natural Resources Information Service (TNRIS) were useful in assisting with the identification of landscape units and general geographic referencing. Further, the maps in the study area were generally originally surveyed in the 1959-1963 time frame and photorevised in the 1980s. Both originally surveyed channel positions and those at the time of photorevision are shown, allowing some assessment of change over a roughly two-decade period.

Contemporary conditions, and further evidence of change, was discerned from 1-m resolution digital orthophotoquads (DOQQ) obtained from TNRIS. These are based on high-altitude aerial photography flown in 1994-1997. While these are the primary basis of assessments of current conditions and recent changes, more recent imagery (1-m National High Altitude Aerial Photography and 1 to 10 m resolution sattelite images) from the 2004-2006 period was used to cross-check the general interpretations and provide further information on difficult-to-interpret sites.

Numerous sites were visited in the field in November, 2006; March, 2007; and July-August, 2007 to address issues raised by the GIS- and map-based analyses, and to further refine the initial classification. Field sites were selected based on locations or areas where conditions suggested in the secondary data were uncertain, and where critical geomorphic questions or transitions were evident, further supplemented by additional sites offering convenient access to the river. A total of 52 Brazos and 15 Navasota River field sites were visited at least once. General bank conditions, presence/absence of key morphological features, and geomorphic indicators of recent trends and changes were recorded, along with measurements of channel width and bank heights using a laser level.

Morphological indicators of bank erosion and retreat include cutbanks; erosion scarps; slump scars, displaced masses, friction cracks, and other evidence of mass wasting failures; undercut banks; exposed tree roots; and indications of recent tree toppling into the river. Bank stability is indicated by general slope shape (stable banks are generally convex-outward as opposed to concave), vegetation cover, and presence or absence of indicators of erosion or deposition. Indicators of recent deposition on banks or floodplain surfaces include fresh sediment deposits, burial or partial burial of vegetation, and burial of the most recent litter layer. The extent to which point bars are active is indicated by vegetation cover, cross-bar rills or gullies, superimposed bedforms, and evidence of encroachment downstream. Channel incision is indicated by high, steep banks, exposure of bedrock, the presence of “paleobanks” indicating recent higher bed levels, and scour around cultural features (though some local scour around bridge pilings is common independently of reach-scale incision).

Avulsions

Sites which might represent past avulsions were indentified from DOQQs and satellite imagery. Sites considered to represent possible avulsions met the following criteria:

•Anabranches, tributaries, distributaries, or linear channel-like depressions which join (or appear to have once joined) the modern river at a non-acute angle.

•Channel width and meander amplitude and wavelength consistent with the Brazos or Navasota River rather than lower-order streams.

Five apparent sites of Brazos River avulsions were visited in the field to confirm the presence of paleochannels of appropriate size. On the Navasota River, where avulsions and anabranching are ubiquitous, the focus was on field measurements at three sites to determine the relative ages and current state of anabranches and paleochannels.

Boundary Coincidence Analysis

Boundary coincidence analysis (BCA), is an approach to implementing river styles recently employed on the Sabine River, Texas/Louisiana (Phillips, 2007a;b). The basic steps in BCA are:

1. Based on published literature, analysis of maps, GIS and other secondary data sources, and field investigations, identify the key geomorphological controls and variables in the study area.

2. For each selected criterion, determine boundaries or transition zones along the river valley.

3. Identify points or zones characterized by multiple boundaries as potential critical transition zones.

4. Identify individual boundaries within the key points identified in 3 for potential subdivision.

5. Interpret transition zones in terms of environmental controls and sensitivity to change.

Nine criteria were initially selected for BCA, based on phase 1 studies (Phillips, 2006), experience in the lower Sabine and Trinity River basins, and the literature on the fluvial geomorphology of Gulf Coastal Plain rivers: surficial geology, valley width, valley confinement, network characteristics (divergent vs. convergent), sinuousity, slope, paleomeanders, avulsions, and point bars. Several additional criteria were added (channel/flow pattern, and channel-floodplain connectivity) and two of the original criteria dropped (divergent/convergent flow, and paleomeanders) after the initial phases of work.

Structure and lithology do no exert the same level of control in coastal plain rivers such as the lower Brazos as they do in other geological settings. Nevertheless, geologic constraints on channel and valley processes, specific inherited features, and the recent geologic history can exert significant controls over river morphology and processes in the Gulf coastal plain. In the Trinity River, for example, inherited features and antecedent morphology formed during lower sea levels earlier in the Quaternary have important influences on the modern Trinity River and Bay (Morton et al., 1995; Rodriguez et al., 2005; Phillips et al., 2005; Phillips and Slattery, 2007).

Valley confinement refers to the extent to which lateral migration and channel change is inhibited by contact with the walls of the alluvial valley. Following Brierly and Fryirs (2005), valley segments were classified as confined if the channel is in contact with the valley wall for 90 percent or more of its length, partly confined if the contact is 10 to 90 percent, and unconfined if the channel is in contact with the valley wall over less than 10 percent of its length.

Network characteristics refers to convergent or divergent connections between the trunk stream and tributaries (or distributaries), and single- vs. multi-thread channel patterns. Low-gradient coastal plain rivers often have a transition point or zone in which they change from a convergent, flow-collecting network to a divergent, flow-distributing network. Rivers characterized by avulsions may also develop anabranching or distributary patterns. There may also be important transitions with respect to the presence of multiple high flow channels. This was determined from DOQQs, digital elevation models, and field observations of flow patterns. Rather than the convergent-to-divergent transition, a modified criterion called channel-floodplain connectivity was assessed after initial reconnaissance work. The degree of connectivity between the active channel and floodplain is critical with respect to creation and maintenance of wetland habitats, and the storage, flux, and exchange of water, sediment, and nutrients. Connectivity was assessed on the basis of overbank flooding frequency at gaging stations, information on inundation and flow patterns as river stages increase beyond flood stage at gaging stations, and the presence of oxbow lakes.

Sinuousity is the “curviness” of the river, computed by dividing river channel distance by straight-line valley distance. Beyond being a distinctive geometric characteristic of rivers, sinuousity changes in coastal plain rivers often represent different forms of adjustment to base (sea) level change. In response to sea level rise or fall, coastal plain streams with limited capacity to degrade or aggrade their channels can adjust the hydraulic slope by increasing or decreasing the channel length. Zones of varying sinuousity were identified visually from DOQ and satellite imagery, and the sinuousity was calculated from DEM data.

On an instantaneous basis, the relevant slope in fluvial hydraulics is the energy grade or friction slope, typically approximated by water surface slope. Over longer time scales, these are controlled by channel bed and valley slopes. Water surface slopes can be determined from gaging station data for a given time (see Phillips and Slattery, 2006), but given the paucity of gaging stations the resolution is not particularly good, and the representativeness questionable. For this study valley and channel slopes were calculated from the DEM for reaches of distinct slope identified from the longitudinal profiles of the lower Brazos and Navasota Rivers. Adjacent reaches where channel and valley slopes were both within 25 percent were aggregated to produce the slope zonation.

The rivers of southeast Texas in general are characterized by large (relative to the modern river) meander scars in the river valley (Alford and Holmes, 1985; Blum et al., 1996). Evidence of at least three different sets of these paleomeanders can be seen in the lower Trinity and Sabine valleys. The paleomeanders, often associated with flats or depressions in the alluvial valley, may also significantly influence floodplain connectivity and flow patterns at high flows (Phillips, 2007b; Phillips and Slattery, 2007). The presence or absence of different "generations" of paleomeanders may also reflect the aggradational history of the valley. DOQs and DEMs were examined to determine how many distinct sets of paleomeanders could be identified, in terms of relative distance from the modern river and valley side, size or magnitude, and juxtaposition and geometry indicating separate meander trains. However, these paleomeanders are less common and influential in the Brazos and Navasota Rivers, as they are apparently largely buried by Holocene alluvium.

Point bars—typically sand in the lower Brazos—are important fluvial bed forms, and key indicators of lateral channel migration. They also reflect the type and general supply of sediment in the river. DOQQs and field observations were used to identify the number of point bars (i.e., whether they occur on the inside of all, most, some, few, or none of the channel bends), general size (small bars occurring only at the apex; large bars extending to both the up- and downstream limbs), composition (sand vs. mud), and stability, primarily indicated by vegetation establishment, but also by the formation of secondary features such as transverse gullies on the point bars.

For each BCA criterion, the identified reaches and zones were identified by latitude-longitude coordinates, approximate distance upstream from the Gulf of Mexico (Brazos) or junction with Brazos (Navasota), based on DEM-derived flow paths, and any nearby prominent landmarks such as tributaries and bridge crossings.

BOUNDARIES

Geologic Zones

The geologic boundaries reflect in large measure the landscape units described earlier, and incorporated into the phase 1 classification (Phillips, 2006). In the Navasota, and to a lesser extent the Brazos, the Tertiary formations are so narrowly-banded, geometrically complex, and poorly-exposed within the river valleys that few subdivisions within the Miocene Uplands and Eocene Uplands landscape units could be identified. Thus the units between the boundaries are relatively coarse, encompassing 20 to 128 km (river distance).

Seven geologically-defined reaches were delineated in the Brazos and four in the Navasota River. These generally reflect the formations bounding the alluvial valley and the presence of extensive (i.e., large enough to be depicted on soil maps) alluvial terrace remnants (Table 4).

Table 4. Geologically-defined zones on the lower Brazos and Navasota Rivers. The upstream and downstream columns indicate the distance (km) upstream of the river mouths of the up- and downstream portions of each reach.

Reach	*Upstream*	*Downstream*	*Geological Setting*
Brazos			
1	469	400	Eocene, with terrace remnants
2	400	370	Miocene, with terrace remnants
3	370	280	Miocene/Lissie with terrace remnants
4	280	260	Lissie with terrace remnants
5	260	165	Lissie/Beaumont with terrace remnants
6	165	041	Beaumont
7	041	000	Quaternary alluvial, coastal, marine
Navasota			
1	185	057	Eocene, with terrace remnants
2	057	052	Salt dome; Eocene, with terrace remnants
3	052	025	Eocene, with terrace remnants
4	025	000	Miocene, with terrace remnants

Valley Width

Valley width at individual cross-sections ranged from less than 2 to 17.5 km on the Brazos River, and 1 to 4.5 km on the Navasota. Zones of consistent width are shown in Table 5. Note that the lowermost Navasota zone (reach 7) crosses the Brazos River floodplain.

Table 5. Valley width zonation.

Reach	*Upstream*	*Downstream*	*Mean (km)*	*Range (km)*
Brazos				
1	469	399	8.75	8.0 – 10.00
2	399	376	5.83	5.5 - 6.0
3	376	372	2.25	2.0 - 2.5
4	372	318	5.10	3.5 - 8.0
5	318	283	2.00	1.75- 2.25
6	283	261	8.08	5.0 - 10.0
7	261	212	12.67	11.0 - 15.0
8	212	164	7.40	5.5 - 9.0
9	164	71	12.32	8.0 - 14.5
10	71	0	13.30	8.0 - 17.5
Navasota				
1	185	135	2.14	1.8 - 3.0
2	135	133	1.13	1.0 – 1.3
3	133	50	3.19	2.0 - 4.5
4	50	42	1.30	1.0 – 1.7
5	42	34	3.37	2.7 – 4.0
6	34	18	2.08	1.4 – 3.0
7	Brazos floodplain			

Valley Confinement

Valley confinement zones are shown in Table 6. The narrower valley width of the Navasota results in a generally partially confined status. The only apparently unconfined reach is a portion of the river which occupies a Brazos paleochannel and is therefore underfit and unlikely to undergo extensive lateral migration. The Brazos exhibits are more complex sequence of 12 confined, partially confined, and unconfined reaches.

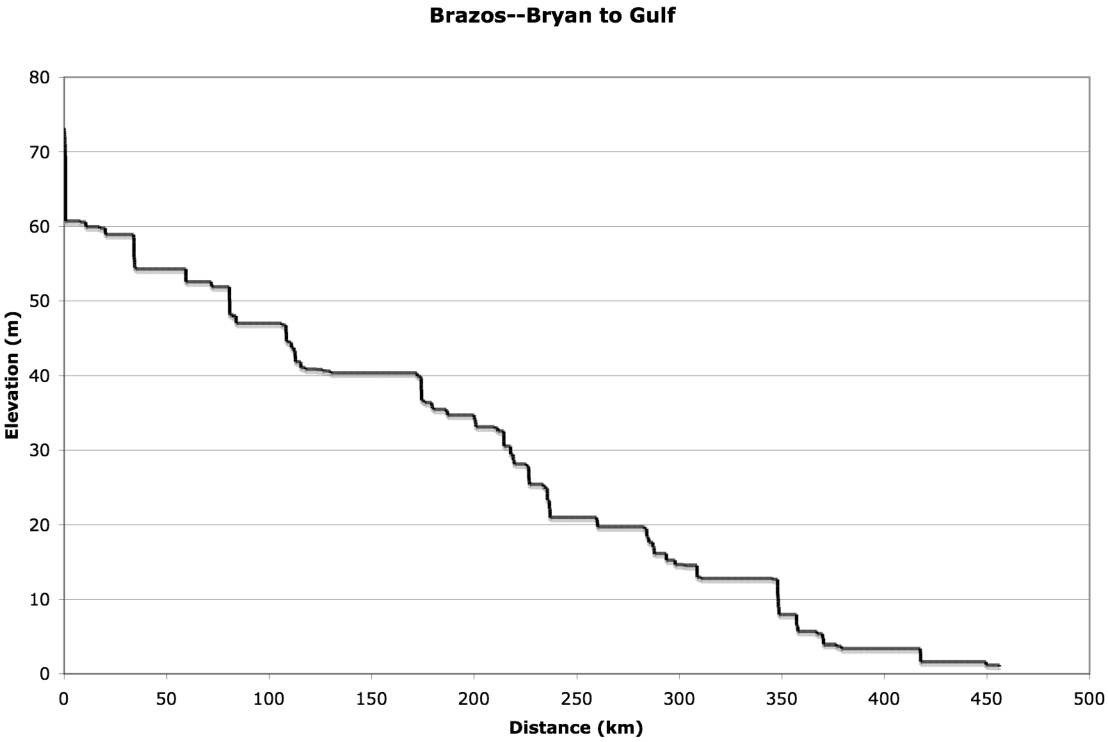
Table 6. Valley confinement zones.

Reach	*Upstream*	*Downstream*	*Valley Confinement*
Brazos			
1	469	444	Unconfined
2	444	411	Confined
3	411	399	Unconfined
4	399	365	Confined
5	365	318	Partially confined
6	318	283	Confined
7	283	252	Unconfined
8	252	212	Partially confined
9	212	145	Confined
10	145	094	Unconfined
11	094	034	Partially confined
12	034	000	Unconfined
Navasota			
1	185	018	Partially confined
2	018	005	Confined
3	005	000	Paleochannel/Unconfined

Slope

Longitudinal profiles of the studied portions of the rivers are shown in Figure 6. Note that these do not extend from drainage divides at the upper end, and were used in this context to help identify slope zonations (Table 7).

Slopes in the eight defined reaches of the Brazos vary over three orders of magnitude. As might be expected, the steepest slope is in the uppermost 12 km of the study area, and the lowest gradient in the lower coastal plain portion. In between, however, the pattern is more complex. The Navasota River exhibits a general decrease in gradient over the four identified reaches, with less variation than the Brazos.



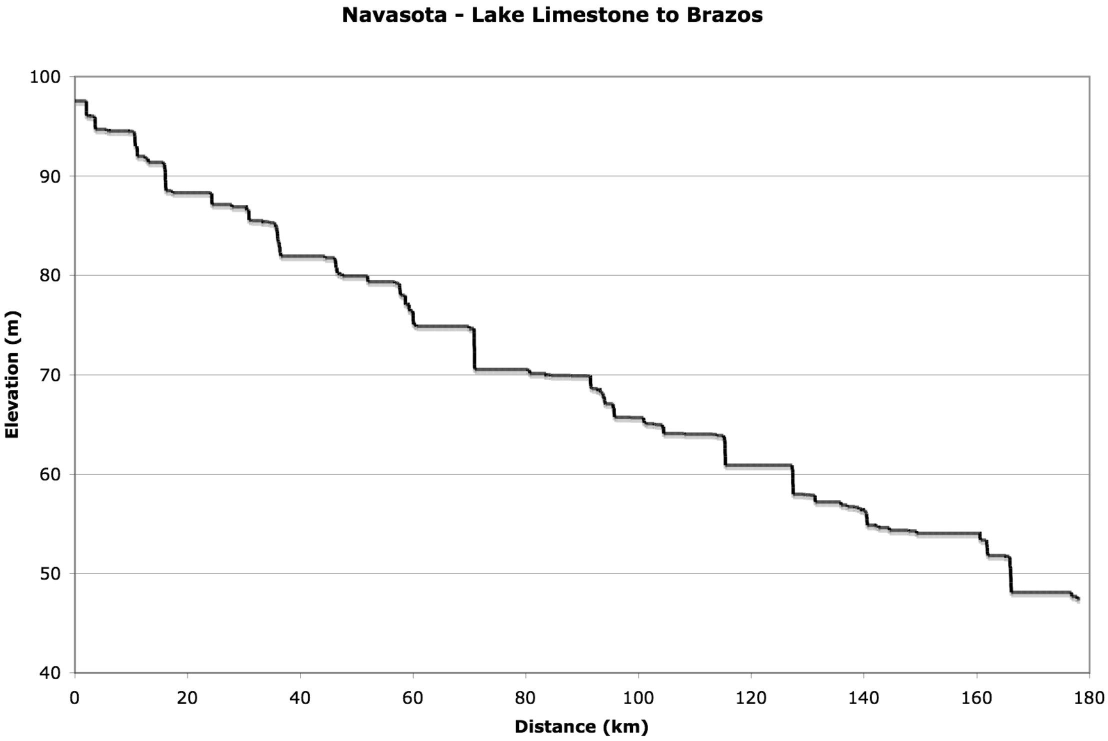


Figure 6. Longitudinal profiles of the lower Brazos and Navasota Rivers. The step-like appearance is an artifact of the digital elevation model used to develop the profiles, but general slope trends are evident.

Table 7. Slope zonation.

Reach	*Upstream*	*Downstream*	*Slope*
Brazos			
1	469	457	0.020459
2	457	379	0.000164
3	379	311	0.000183
4	311	237	0.000077
5	237	176	0.000251
6	176	118	0.000111
7	118	084	0.000138
8	084	000	0.000031
Navasota			
1	185	165	0.000702
2	165	146	0.000330
3	146	019	0.000259
4	019	000	0.000121

Sinuousity

Sinuousity in the lower Navasota River does not vary greatly, producing only two zones which themselves are both in the meandering category (sinuousity between 1.5 and 2.0), one of which occupies 92 percent of the study area. The Brazos, by contrast, includes 14 identifiable zones, ranging from 1.0 in the lowermost straightened zone to strongly meandering and tortuous sections with sinuousity values >2, and up to 4.41

Table 8. Sinuousity zonation.

Reach	*Upstream*	*Downstream*	*Sinuousity*
Brazos			
1	469	457	1.26
2	457	450	1.56
3	450	407	1.76
4	407	268	2.40
5	268	223	1.70
6	223	208	4.41
7	208	168	1.81
8	168	142	2.19
9	142	125	1.36
10	125	101	2.09
11	101	075	1.47
12	075	045	1.92
13	045	007	1.43
14	007	000	1.00
Navasota			
1	185	015	1.68
2	015	000	1.80

Avulsions and Channel Pattern

While the Trinity and Sabine Rivers show relatively clear transitions from entirely convergent to divergent (distributary) networks, with intermediate zones characterized by channels which may serve as high flow distributaries and as tributaries otherwise (Phillips and Slattery, 2006b; 2007a; 2007b). The Brazos/Navasota system does not show similar trends, with multiple high flow channels common in much of the Navasota study area, and limited distributary development in the Brazos.

The reaches were characterized on the basis of single-thread vs. multi-thread or anabranching channel patterns, and the presence or absence of former river channels (avulsion channels) still actively conveying flow in non-flood conditions. The latter were further subdivided according to whether the avulsion channels are currently tributaries to the modern (Brazos) river, or part of the Bessie's Creek/Oyster Creek system, which maintains partial connections to the Brazos but follows an independent path to the sea.

Table 9. Zonation of the lower Brazos and Navasota Rivers based on channel pattern and avulsion channels.

Reach	*Upstream*	*Downstream*	*Channel Characteristics*
Brazos			
1	469	411	single thread w/ tributary avulsion channel
2	411	399	single thread
3	399	373	single thread w/ tributary avulsion channel
4	373	252	single thread
5	252	212	single thread w/ tributary avulsion channel
6	212	146	single thread
7	146	076	single thread w/ distributary avulsion channel
8	076	000	single thread w/ distributary avulsion channel and deltaic/tidal distributaries
Navasota			
1	185	025	anabranching
2	025	000	single thread

Point Bars

Point bars in the Navasota River are generally fine-grained, though often with some sandy lenses or veneers, and vegetated. The mobile, sandy bars found in the Brazos, Sabine, Trinity, and other regional rivers are rare.

Mobile, active, predominantly sandy point bars are common in the lower Brazos River. Reaches were characterized according to the presence or absence of active bars, and their general size. Presence/absence was assessed on the basis of the extent to which bends or meanders exhibited active bars. Bars were considered active if vegetation cover was minimal and bare sediment widely exposed. “Large” bars occur on both the upstream and downstream axes as well as the apex of a bend; while “small” bars occur over only part of the bend. Results are shown in Table 10. Five distinctive zones were found (reaches 1-4, 6), and one long reach (reach 5, 187 km in length) which was highly variable with respect to the occurrence and size of active bars.

Table 10. Zonation of the lower Brazos River based on point bar occurrence and characteristics.

Reach	*Upstream*	*Downstream*	*Point Bar Characteristics*
1	469	411	Large or small sandy bars on many, but not all, bends
2	411	395	Large sandy bars on all bends
3	395	358	Few to no active bars
4	358	273	Large or small sandy bars on all bends
5	273	086	Mixed: bends may have large or small sandy bars or no active bars
6	086	000	Few to no active bars

Channel-Floodplain Connectivity

The frequency of overbank flooding was assessed by using stage-discharge relationships to estimate the discharge associated with official National Weather Service (NWS) flood stages at each gage site in the study area, as described earlier. The recurrence interval (RI) and exceedence probability were calculated using the standard formula

$$RI = [(n+1)/m]/365.25$$

Where n is the number of days in the record and m is the rank of the event. The constant is to express the RI in years. The probability of exceedence for a given flow is the inverse of the RI in days. Mean daily flows were used rather than peak flows because the focus here is on any period where flows are overbank for at least several hours.

Table 11 shows that overbank flow is relatively rare at the Bryan station and very rare at Hempstead. This reflects the incised nature of the Brazos River channel, and at Hempstead, a degree of geological constriction which inhibits floodplain development and tends to confine almost all flows in a relatively deep, narrow channel. Mean daily flows of bankfull or above occur annually, on average, at Richmond, and more often at Rosharon. Data from the two Navasota River gages shows that overbank flows are quite common in the highly aggraded Navasota valley.

Table 11. Frequency of overbank flooding at gaging stations, based on official National Weather Service flood stages. Recurrence interval (RI) and probability (daily) are based on mean daily flow greater than or equal to estimated flood discharge; minor overbank peaks may occur more frequently.

Station	*Estimated discharge* (m^3 sec^{-1})	*RI* (years)	*Exceedence probability* (%)
Brazos River			
Bryan	1853	2.5	0.10
Hempstead	2888	22.0	0.01
Richmond	2265	1.0	0.30
Rosharon	1812	0.3	0.82
Navasota River			
Easterly	85	0.08	3.33
Normangee	229	0.25	1.10

The NWS Advanced Hydrologic Prediction Service provides descriptions of potential flood impacts at various stages at the same gaging stations. These show (Table 11) that at the Bryan station, flows less than bankfull do cause significant backwater flooding in tributaries such as the Little Brazos River. While major overbank flooding of alluvial lowlands is rare, a significant degree of hydrologic connectivity is suggested by the backwater flooding, which occurs at sub-bankfull flows. At Hempstead, the relatively rare flood stage produces only minor overbank flooding, and stages about 1 m higher are necessary to produce widespread floodplain inundation in the vicinity of the gage. At Richmond, stages about 1.5 m below flood stage trigger some backwater flooding and minor flow toward Oyster Creek, while stages at or just below flood stage initiate cross-floodplain flow into Oyster Creek. Flood stage and slightly higher stages trigger significant inundation and cross-valley flows. The Rosharon gage site also experiences cross-valley flows at higher flood stages (Table 12).

The Navasota gages experience only minor overbank flow at designated flood stages, but more significant floodplain inundation is triggered stages only about 0.6 m higher (Table 12). Still higher stages result in the coalescence of anabranches and high flow channels and flooding of the entire valley.

Table 12. Hydrologic impacts at various flood stages at gaging stations. Information based on the National Weather Service (NWS) Advanced Hydrologic Prediction Service for the Galveston, TX office (URL: http://ahps.srh.noaa.gov/index.php?wfo=hgx). Stages are local gage heights, reported in feet.
*Official NWS flood stage.

Station	*Flood Stage* (ft)	(m)	*Impacts*
Bryan	21	6.4	backwater effects, Little Brazos River
	32	9.8	major backwater flooding of Little Brazos
	43*	13.1	minor lowland flooding
	48	14.6	moderate lowland flooding; left bank floodplain inundated
	54	16.5	major lowland flooding
Hempstead	50*	15.2	minor overbank flow
	53	16.2	widespread floodplain inundation
	55	16.8	major lowland flooding
Richmond	46.1	14.1	backwater creek flooding; minor culvert flow to Oyster Creek
	47.6	14.5	cross-floodplain flow into Oyster Creek
	48*	14.6	significant overbank flow and floodplain inundation
	49.8	15.2	massive lowland flooding; major cross-floodplain flow into Oyster Cr.
	50.7	15.5	major lowland flooding
Rosharon	43*	13.1	minor overbank flow
	50.7	15.5	minor culvert flow into Oyster Creek
	50.8	15.5	cross-floodplain flow into Oyster Cr.
Easterly	17*	5.2	minor overbank flow
	19	5.8	minor lowland flooding
	23	7.0	moderate lowland flooding
	26	7.9	major lowland flooding; bridge inundation
Normangee	15*	4.6	minor overbank flow
	17	5.2	widespread floodplain inundation
	18	5.2	merger of subchannels
	20	6.1	entire valley flooded

With respect to oxbow lakes and swamps, which may be connected to the river by tie channels or high flow channels, the lower Brazos has several distinct zones. From SH 21 to Yegua Creek (469 to 399 km) occasional oxbows exist, along with several Brazos River paleochannels. From Yegua Creek to the Navasota River the paleochannels are present, but no oxbows (399-373 km). Downstream of the Navasota, to Allens Creek

(373-212 km), oxbows are numerous, while from Allens Creek to Richmond (212-145 km) there are none associated with the Brazos, though creeks occupying Brazos paleochannels exhibit cutoffs. From Richmond to Freeport (145-0 km), Oyster Creek has numerous oxbows, but the Brazos has only a few.

Based on the information above, the lower Brazos can be divided into channel-floodplain connectivity zones as described in Table 13.

Table 13. Channel-floodplain connectivity zonation of the lower Brazos River.

Reach	*Upstream*	*Downstream*	*Description*
1	469	399	Moderate connectivity with relatively rare overbank flooding, but backwater tributary flooding common, and a few oxbows
2	399	373	Low connectivity; as above but no oxbows
3	373	318	Moderate to high connectivity. Relatively rare overbank flooding, but backwater tributary flooding common, and numerous oxbows
4	318	283	Low connectivity. Some oxbows, but overbank flow is rare.
5	283	145	High connectivity. Relatively common overbank flow, numerous oxbows.
6	145	0	High connectivity. Few oxbows, but common overbank flow, cross-floodplain flow to Oyster Cr.

Much of the Navasota River is an anabranching system characterized by frequent shifts in the main channel and multiple high flow channels. Overbank flow is frequent as the channel is not incised and the valley is apparently aggraded. Nine cross-valley transects of the Navasota were made to observe the nature of the anabranches. All but the SH 7 crossing were observed at or shortly following overbank flow levels in addition to near-normal (within one standard deviation of the mean at the nearest gaging station) flows. In addition to direct observations of flow, the channels were assessed in terms of bank conditions, vegetation (in-channel and bank), woody debris and sediment accumulations, and flow indicators such as flood debris, wrack lines, bedforms, and scour pits. Evidence for along- or cross-floodplain flow between channels was also assessed.

Channels other than the main river channel were classified as active or semi-active subchannels, or as paleochannels. Active subchannels are those which convey at least some downstream flow at normal water levels. Semi-active subchannels are inundated at normal water levels, but convey little or no flow, and are activated at high flows. Paleochannels are depressions indicating former channel positions which may be inundated during wet periods and convey flow during floods. Results are in Table 14.

Table 14. Characteristics of subchannels and floodplain flow at several crossings of the lower Navasota River valley. Cross-sections are arranged in downstream-upstream order.

Crossing	*Channels*	*Floodplain flow*
SH 105	No subchannels or paleochannels	No obvious flow indicators; may be subject to backwater flooding from Brazos River
Sulphur Springs	2 semi-active subchannels, one of which conveys tributary flow; 1 paleochannel.	Downvalley along floodplain; subchannel exchange
Ferguson Crossing	1 semi-active subchannel; 2 paleochannels	Limited flow downvalley along floodplain; limited subchannel exchange except when entire valley flooded
Channey Crossing	2 active; 2 semi-active subchannels. Possible older paleochannels near both valley margins.	Downvalley floodplain flow along floodplain; subchannel exchange
Democrat Crossing	1 active subchannel; 3 semi-active subchannels; 1 paleochannel	Downvalley floodplain flow along floodplain; subchannel exchange
SH 21/US 190	1 active, 1 semi-active subchannel	Subchannel coalescence at high flows
Old San Antonio Rd. (Normangee gage)	2 active subchannels	Subchannel coalescence at high flows
US 79 (Easterly gage)	2 semi-active subchannels	Limited flow downvalley along floodplain; limited subchannel exchange except when entire valley flooded
SH 7	3 paleochannels	Limited flow downvalley along floodplain; limited subchannel exchange except when entire valley flooded

Based on the gaging station information, data in Table 14, and valley morphology, the lower Navasota can be divided into channel-floodplain connectivity zones as described in Table 15.

Table 15. Channel-floodplain connectivity zonation of the lower Navasota River.

Reach	*Upstream*	*Downstream*	*Description*
1	185	168	High connectivity with frequent overbank flow and numerous semi-active subchannels, paleochannels, and oxbows.
2	168	56	Very high connectivity with frequent overbank flow and numerous active and semi-active subchannels, paleochannels, and oxbows
3	56	25	High connectivity with frequent overbank flow and numerous semi-active subchannels, paleochannels, and oxbows.
4	25	5	Moderate to high connectivity with frequent overbank flow and oxbows.
5	5	0	Low connectivity. Underfit stream occupying Brazos paleochannel.

Other Geomorphic Factors

Because the Brazos River has undergone Holocene incision, many tributaries have downcut significantly in response to the lower base level. With the exception of the lowermost 70 km of the river, all major tributaries, and many minor ones, are incised in at least their lower reaches. The Navasota River and its tributaries are not generally incised.

Rivers of the southeast Texas coastal plain draining to the Gulf of Mexico are typically cut to below contemporary sea levels some distance upstream of the coast. According to the profile presented by Morton and Donaldson (1978), the thalweg of the Brazos River channel is below sea level in the lower 90 km of channel.

Part 3
River Styles and Reaches

INTRODUCTION

The boundaries and zonations described in the previous section were combined and synthesized to produce 30 distinct reaches of the Brazos and 11 of the Navasota River. In some cases several criteria indicated boundaries at the same location—for example boundaries in valley width, valley confinement, channel-floodplain connectivity, and channel pattern all occur at the Brazos River confluence with Yegua Creek. In additional cases other boundaries were independently found to occur in the same vicinity—for instance, boundaries in geologic setting and point bars were found within 4 km of the Yegua Creek confluence. Where these were judged to be within a transitional zone, or within the uncertainty associated with boundary delineations, these "near misses" were considered to be part of the same boundary/transition. For example, given the very broad scale and coarse resolution of the geologic maps, or the judgment necessary in determining precisely where to divide a higher from a lower sinuousity reach, differences of a few river kilometers cannot be judged significant unless they correspond with some obvious, local change in environmental controls. An example of the latter occurs at the confluence of the Navasota River and Holland Creek, where the Navasota exits its own valley and begins crossing the Brazos River alluvial plain.

The reaches identified in this section are thus combinations of the zonations described above. For each geomorphologically distinct reach, a river style was determined. In many cases each reach constituted a distinct river style. The lower Brazos River was found to have 19 different styles and the lower Navasota seven. In most cases reaches of the same style are contiguous, but differ with respect to at least one of the geomorphic criteria. These reaches represent subdivisions of the initial classification presented in phase 1 of this work (Phillips, 2006).

LOWER BRAZOS RIVER

The locations of the identified reaches and their styles are shown in table 16. Figures 7 to 11 are a series of maps showing the identified reaches and river styles.

Table 16. Geomorphic reaches of the lower Brazos River. Distance is given in km upstream of the mouth. Latitude and longtitude coordinates (Lat-Long) are for the downstream end of the reach and also constitute coordinates of the upstream end of the next reach. The nearest identifiable map or landscape landmark is also indicated.

Reach	Distance	Lat-Long	Landmark	River Style
		30.6767,-96.5933	State Highway (SH) 21 bridge	(upstream end of study area)
1	469-457	30.6048,-96.4666	Thompson's Creek	Steeply Incised Valley Fill
2	457-444	30.5643,-96.4304	Upstream of SH 60 bridge	Meandering Incised Valley Fill
3	444-411	30.4432,-96.2899	Boggy Creek	Meandering Confined Incised Valley Fill
4	411-399	30.3799,-96.2999	Yegua Creek	Strongly Meandering Incised Valley Fill
5	399-379	30.3956,-96.1791	Hidalgo Falls	Confined Strongly Meandering Incised Valley Fill
6	379-372	30.3599,-96.2999	Navasota River	Hidalgo Falls
7	372-365	30.3085,-96.1033	Rocky Creek	Confined Strongly Meandering Incised Valley Fill II
8	365-318	30.1365,-96.1899	New Year Creek	Partly Confined Strongly Meandering Incised Valley Fill
9	318-311	30.1090,-96.1710	Austin Branch Road	Bedrock Confined Valley
10	311-283	29.9999,-96.1199	Clear Creek	Bedrock Confined Valley
11	283-268	29.9235,-96.1128	SH 529 bridge	Unconfined Alluvial Valley
12	268-260	29.8890,-96.1119	Hannay and Palmer Lakes	Unconfined Alluvial Valley
13	260-252	29.8499,-96.1065	Garrett Lake	Unconfined Wide Alluvial Valley
14	252-237	29.7883,-96.0413	Irons Creek	Avulsed Alluvial Valley
15	237-223	29.7033,-96.0157	Buckintin Road	Avulsed Alluvial Valley
16	223-212	29.6512,-95.9076	Allens Creek	Avulsed Alluvial Valley
17	212-176	29.5937,-95.8789	Dyer Moore Ranch Road	Confined Avulsed Alluvial Valley
18	176-164	29.5668,-95.8103	Houston Street bridge, Rosenberg	Confined Avulsed Alluvial Valley
19	164-145	29.5799,-95.7565	US 90A bridge, Richmond	Confined Avulsed Alluvial Valley

20	145-125	29.5098,-95.5730	Thompson Ferry Road	Unconfined Low-Sinuosity
21	125-118	29.4753,-95.5465	Rabbs Ridge oil field	Avulsed Alluvial Valley II
22	118-100	29.3681,-95.5777	Big Creek	Avulsed Alluvial Valley II
23	100-094	29.3274,-95.5904	Cow Creek	Unconfined Low-Sinuosity
24	094-084	29.2767,-95.5775	Otey	Partly Confined Low-Sinuousity
25	084-076	29.2544,-95.5622	Harris Reservoir north	Partly Confined Low-Sinuousity II
26	076-071	29.2294,-95.5413	Harris Reservoir south	Lower Coastal Plain
27	071-045	29.0900,-95.5880	Middle Bayou	Lower Coastal Plain
28	045-035	29.0356,-95.5246	Cutoff Lake	Low-Sinuousity Lower Coastal Plain
29	035-007	28.9646,-95.3751	Freeport ship channel	Low-Sinuousity Lower Coastal Plain
30	007-000	28.8767,-95.3792	Gulf of Mexico	Low-Sinuousity Lower Coastal Plain

(Table 16, continued from previous page).

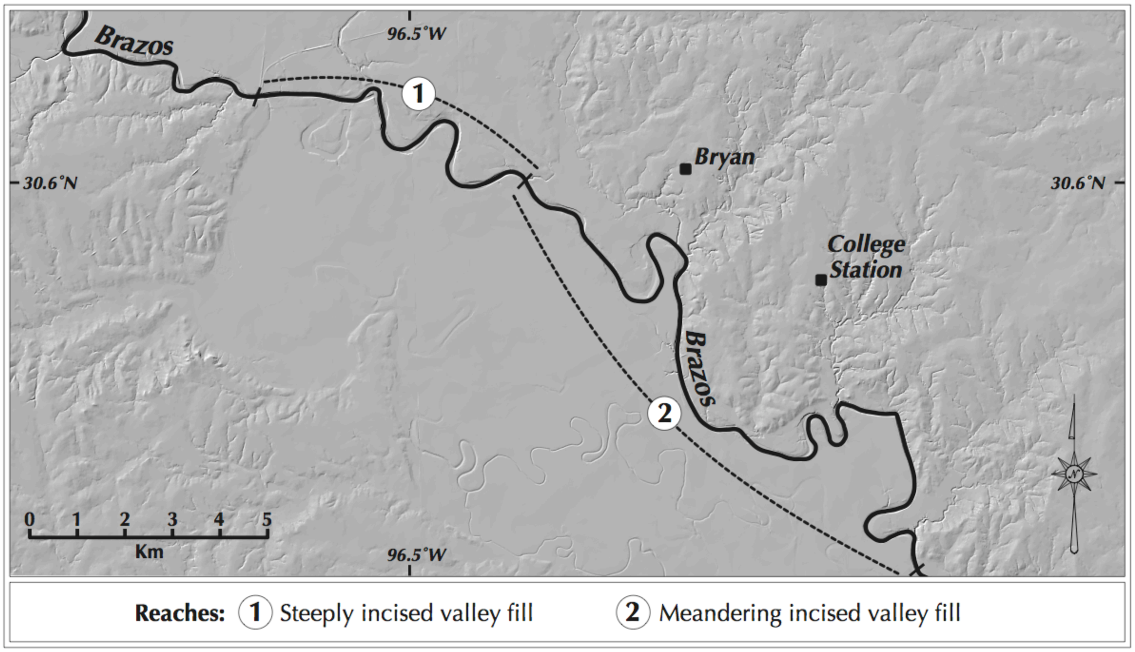


Figure 7. Geomorphic reaches and river styles, Brazos River near Bryan and College Station.

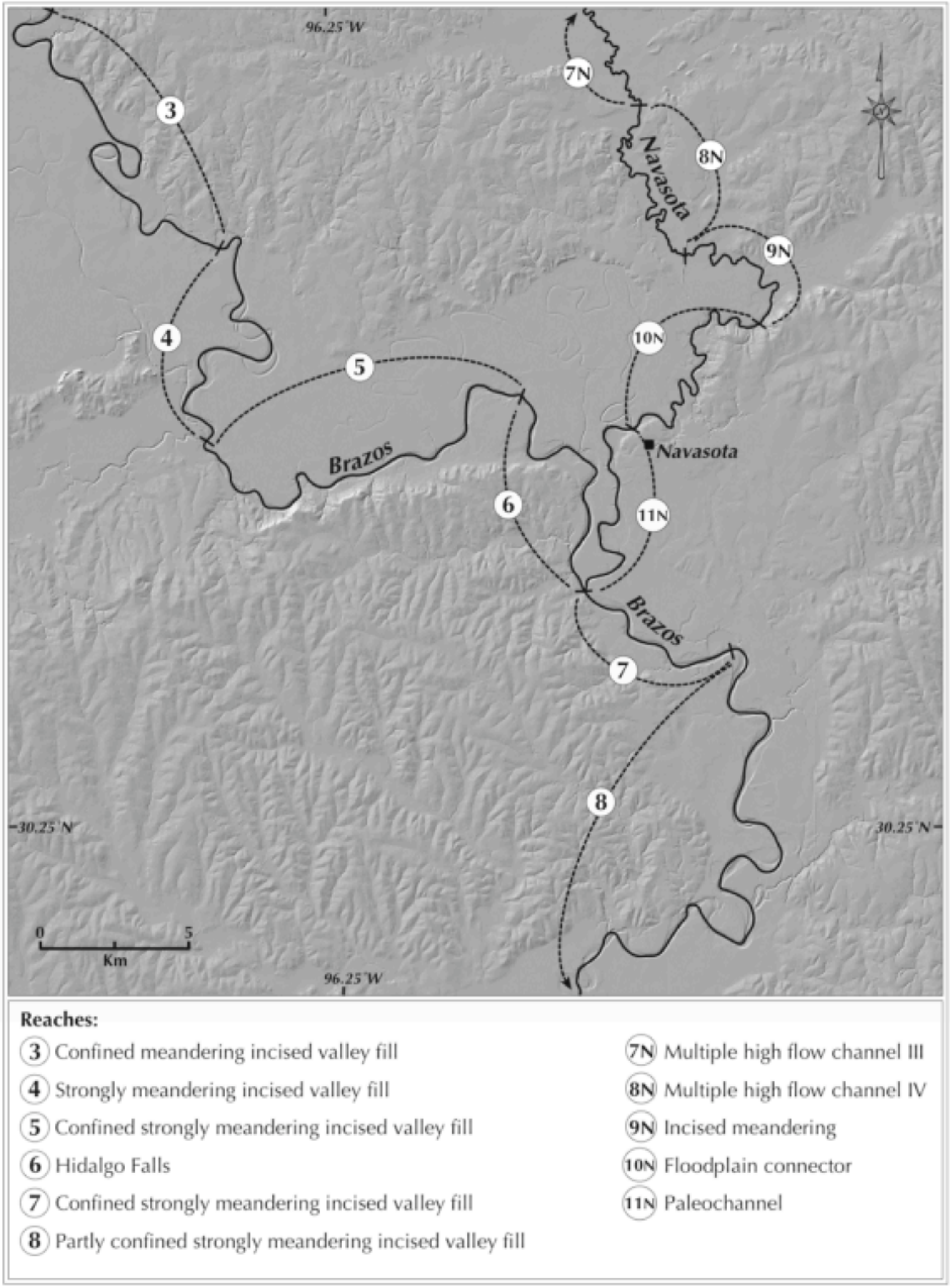


Figure 8. Geomorphic Reaches and river styles, Brazos River near College Station, Navasota, and Washington; and Navasota River, Gibbons Creek to Brazos River.

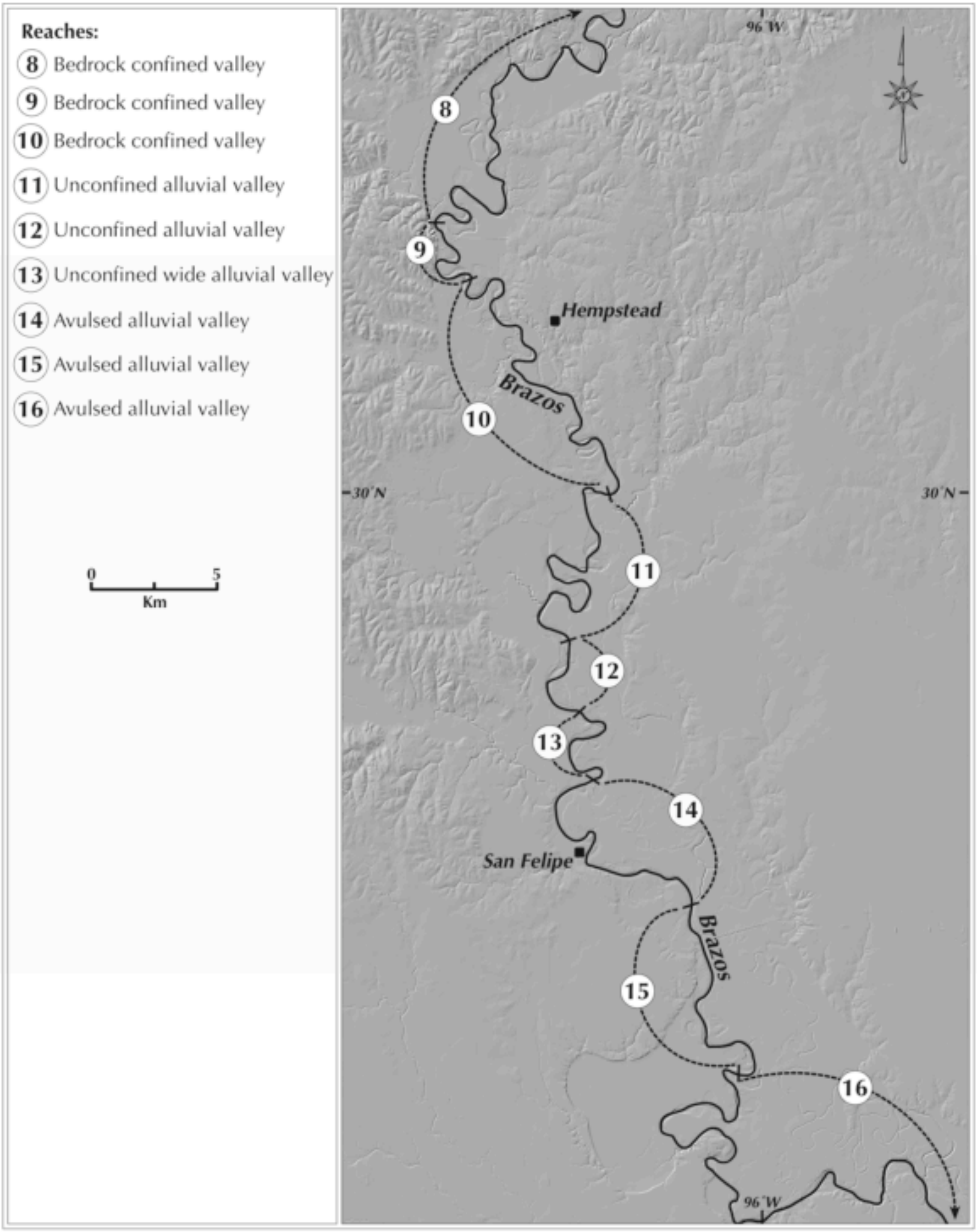


Figure 9. Geomorphic reaches and river styles, Brazos River near Hempstead and San Felipe.

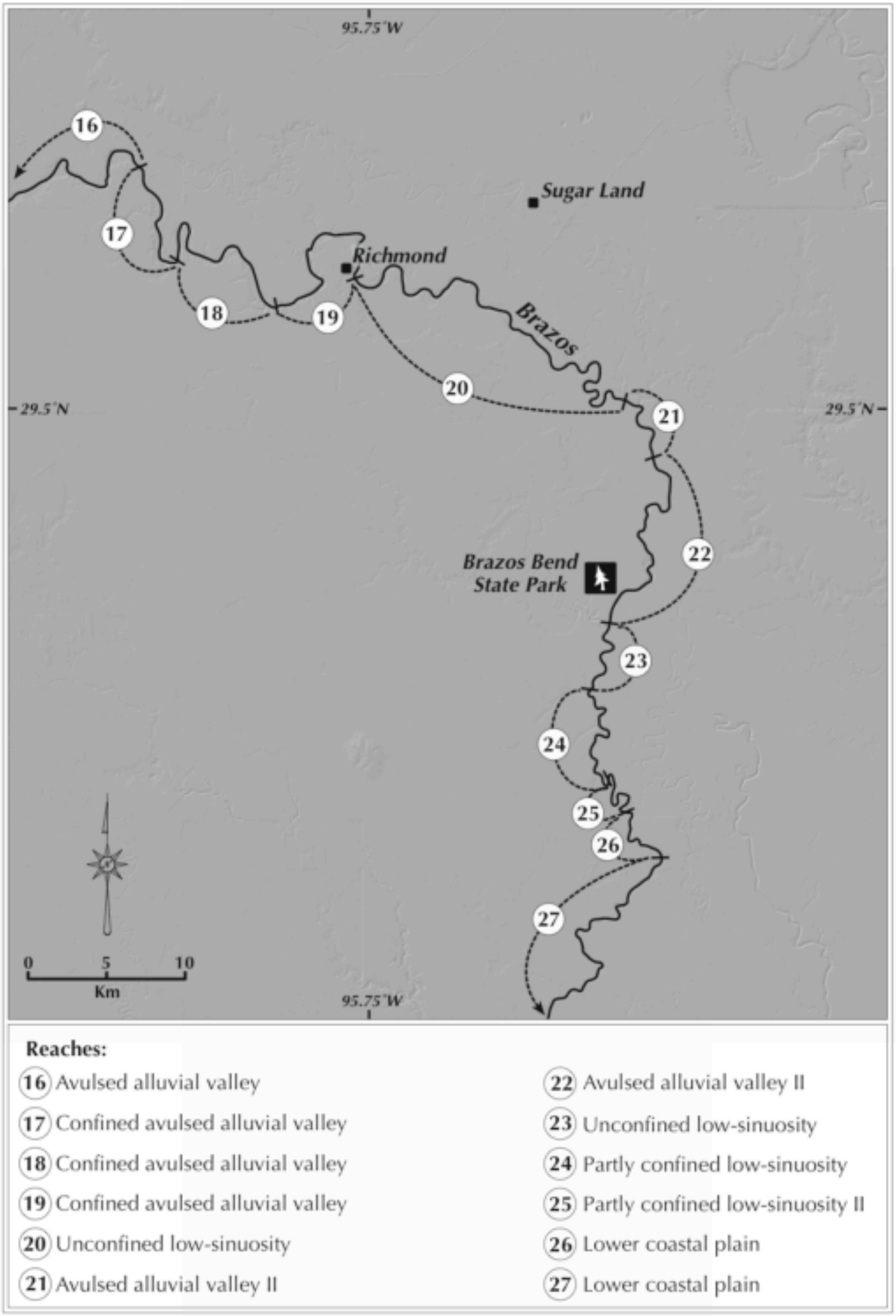


Figure 10. Geomorphic reaches and river styles, Brazos River near Rosenberg, Richmond, Brazos Bend State Park, and Harris Reservoir.

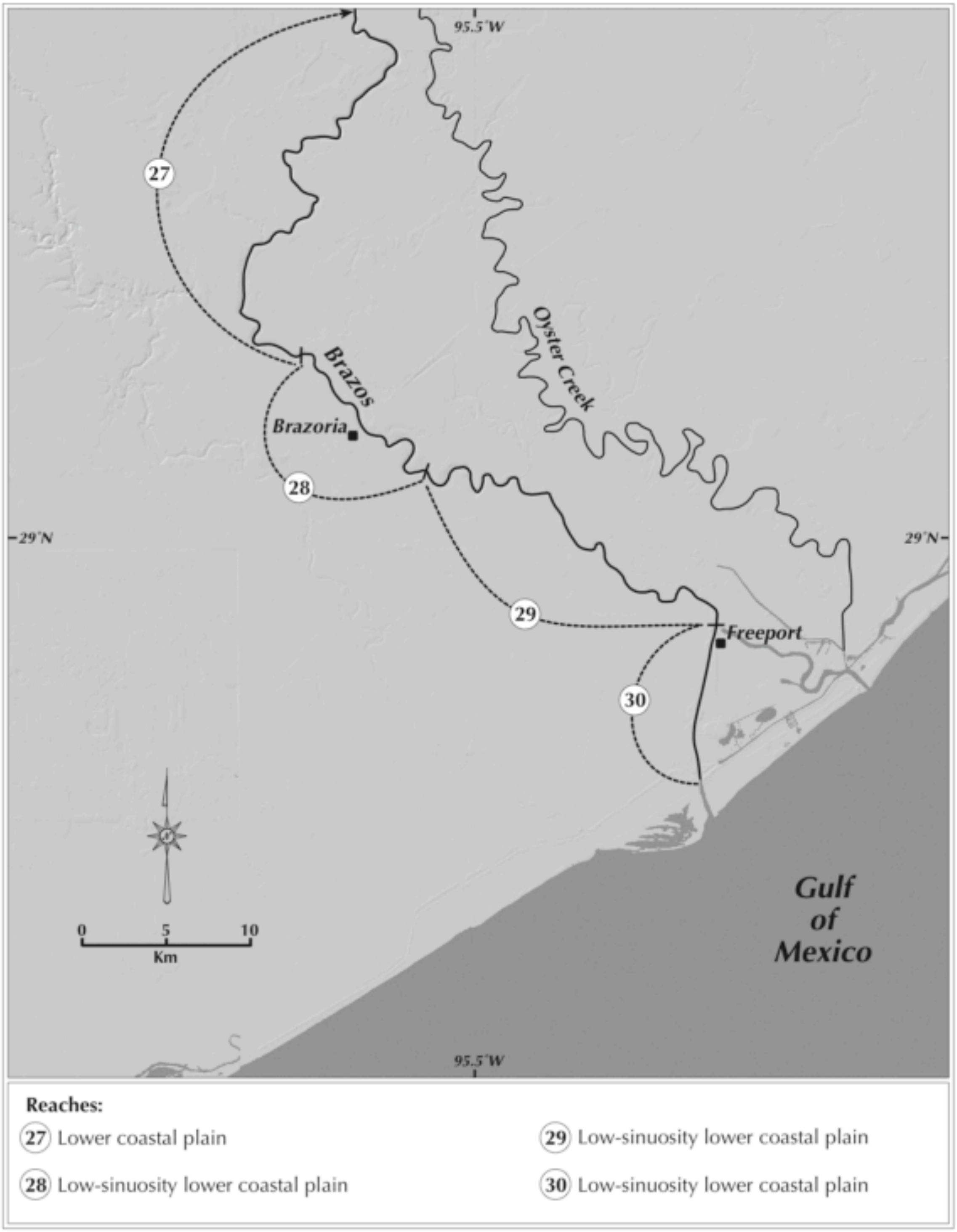


Figure 11. Geomorphic reaches and river styles, Brazos River near Brazoria, Lake Jackson, and Freeport.

In Table 17 below, abbreviated descriptions of the geomorphic criteria for each reach are given. Sinuousity values were classified as follows: 1.0 – 1.25, straight; 1.25-1.49; low-sinuousity; 1.50 – 1.99, meandering; 2.0 – 3.0, strongly meandering; >3.0, tortuous.

Table 17. Geomorphic characteristics of lower Brazos River reaches.

RR	Geology	VW	VC	Slope	Sinuousity	CP	Bars	CPC
1	Eocene	8.75	UC	0.020459	low sin	ST tac	many	mod
2	Eocene	8.75	UC	0.000164	mean	ST tac	many	mod
3	Eocene	8.75	C	0.000164	mean	ST tac	many	mod
4	Eocene	8.75	UC	0.000164	str mean	ST	all	mod
5	Miocene	5.83	C	0.000164	str mean	ST tac	few/no	low
6	Miocene	2.25	C	0.000183	str mean	ST tac	few/no	low
7	Miocene	5.18	C	0.000183	str mean	ST	few/no	mod/hi
8	Miocene	5.18	PC	0.000183	str mean	ST	all	low
9	Miocene	2.00	C	0.000183	str mean	ST	all	low
10	Miocene	2.00	C	0.000077	str mean	ST	all	low
11	Miocene	8.08	UC	0.000077	str mean	ST	all	high 1
12	Lissie	8.08	UC	0.000077	mean	ST	mixed	high 1
13	Lissie/Beaumont	12.67	UC	0.000077	mean	ST	mixed	high 1
14	Lissie/Beaumont	12.67	PC	0.000077	mean	ST tac	mixed	high 1
15	Lissie/Beaumont	12.67	PC	0.000251	mean	ST tac	mixed	high 1
16	Lissie/Beaumont	12.67	PC	0.000251	tort	ST tac	mixed	high 1
17	Lissie/Beaumont	7.40	C	0.000251	mean	ST	mixed	high 1
18	Lissie/Beaumont	7.40	C	0.000111	mean	ST	mixed	high 1
19	Beaumont	12.32	C	0.000111	str mean	ST	mixed	high 1
20	Beaumont	12.32	UC	0.000111	low sin	ST dac	mixed	high 2
21	Beaumont	12.32	UC	0.000111	str mean	ST dac	mixed	high 2
22	Beaumont	12.32	UC	0.000138	str mean	ST dac	mixed	high 2
23	Beaumont	12.32	UC	0.000138	low sin	ST dac	mixed	high 2
24	Beaumont	12.32	PC	0.000138	low sin	ST dac	mixed	high 2
25	Beaumont	12.32	PC	0.000031	low sin	ST dac	few/no	high 2
26	Beaumont	12.32	PC	0.000031	mean	ST dac*	few/no	high 2
27	Beaumont	13.30	PC	0.000031	mean	ST dac*	few/no	high 2
28	Late Quaternary	13.30	PC	0.000031	low sin	ST dac*	few/no	high 2
29	Late Quaternary	13.30	UC	0.000031	low sin	ST dac*	few/no	high 2
30	Late Quaternary	13.30	UC	0.000031	straight	ST dac*	few/no	high 2

RR: river reach number
Geology: dominant valley margin geology
VW: mean valley width, km
VC: valley confinement—confined (C), partly confined (PC), unconfined (UC)
Slope: mean channel slope
CP: channel/flow pattern. ST = single thread; tac = tributaries occupying avulsion channels; dac = distiributaries occupying avulsion channels; *coastal backwater or tidal influence
Bars: presence of active sandy point bars at meander bends
CPC: channel-floodplain connectivity. Mod=moderate; mod/hii=moderate to high; high 1=high connectivity primarily due to flooding of oxbows, sloughs, and flood basins; high 2 = high connectivity primarily due to cross-floodplain flow.

RIVER STYLE DESCRIPTIONS—LOWER BRAZOS

The river styles are described below using the proforma recommended by Brierly and Fryirs (2005). Note that geomorphic units which are ubiquitous in all styles, such as pool-riffle sequences, and minor alluvial ridges and depressions associated with meander scars on the floodplain, are not listed. River styles are listed in the order they are first encountered in the upstream-downstream direction.

Steeply Incised Valley Fill

Defining attributes: Steep channel slope, low sinuousity channel incised into Quaternary valley fill, with tributaries occupying river paleochannels. Unconfined channel in moderately wide (8-10 km) valley. Rare overbank flooding, but moderate channel-floodplain connectivity due to back water flooding of tributaries. Sandy point bars on many, but not all bends.

Landscape unit(s): Eocene Uplands

Representative reach: Reach 1, Brazos/Burleson County near Bryan.

Valley setting: Unconfined.

Channel planform: Continuous floodplain on both margins; low-sinuousity single-thread channel.

Bed material: Sand, bedrock

Geomorphic units:
- Meander cutoffs/oxbows.
- Cutbanks.
- Stable, convex, vegetated banks.
- Point bars
- Alluvial terraces
- Paleochannels occupied by tributaries.
- Infilled paleochannel depressions.
- Bedrock channel outcrops.

Meandering Incised Valley Fill

Defining attributes: Moderate channel slope, meandering channel incised into Quaternary valley fill, with tributaries occupying river paleochannels. Unconfined channel in moderately wide (8-10 km) valley. Rare overbank flooding, but moderate channel-floodplain connectivity due to back water flooding of tributaries. Sandy point bars on many, but not all bends.

Landscape unit(s): Eocene Uplands

Representative reach: Reach 2, Brazos/Burleson County near Bryan & College Station.

Valley setting: Unconfined.

Channel planform: Continous floodplain on both margins; meandering single-thread channel.

Bed material: Sand, bedrock

Geomorphic units:

- Meander cutoffs/oxbows.
- Cutbanks.
- Stable, convex, vegetated banks.
- Active point bars
- Alluvial terraces
- Paleochannels occupied by tributaries.
- Infilled paleochannel depressions.
- Bedrock channel outcrops.

Meandering Confined Incised Valley Fill

Defining attributes: Moderate channel slope, meandering channel incised into Quaternary valley fill, with tributaries occupying river paleochannels. Channel against left (northeast) valley margin in moderately wide (8-10 km) valley. Rare overbank flooding, but moderate channel-floodplain connectivity due to back water flooding of tributaries. Sandy point bars on many, but not all bends.

Landscape unit(s): Eocene Uplands

Representative reach: Reach 3, Brazos/Burleson County near College Station.

Valley setting: Confined.

Channel planform: Continuous floodplain on right margin; meandering single-thread channel.

Bed material: Sand, bedrock

Geomorphic units:

- Meander cutoffs/oxbows.
- Cutbanks.

- Stable, convex, vegetated banks.
- Active point bars
- Alluvial terraces
- Paleochannels occupied by tributaries.
- Infilled paleochannel depressions.
- Bedrock channel outcrops.

Strongly Meandering Incised Valley Fill

Defining attributes: Moderate channel slope, strongly meandering channel incised into Quaternary valley fill. Unconfined channel in moderately wide (8-10 km) valley. Rare overbank flooding, but moderate channel-floodplain connectivity due to back water flooding of tributaries. Sandy point bars on all bends.

Landscape unit(s): Eocene Uplands

Representative reach: Reach 4, near College Station to Yegua Creek confluence.

Valley setting: Unconfined.

Channel planform: Continuous floodplain on both margins; strongly meandering single-thread channel.

Bed material: Sand, bedrock

Geomorphic units:

- Meander cutoffs/oxbows.
- Cutbanks.
- Tributary mouth bars
- Stable, convex, vegetated banks.
- Active point bars
- Alluvial terraces
- Infilled paleochannel depressions.
- Bedrock channel outcrops.

Confined Strongly Meandering Incised Valley Fill

Defining attributes: Moderate channel slope, strongly meandering channel incised into Quaternary valley fill. Channel confined mainly to right (southwest) valley margin in relatively narrow (5-8 km) valley. Low channel-floodplain connectivity. Active point bars rare to absent.

Landscape unit(s): Miocene Uplands

Representative reach: Reach 5, Yegua Creek to Hidalgo Falls.

Valley setting: Confined.

Channel planform: Continous floodplain on left margin; strongly meandering single-thread channel with tributaries occupying former river channels.

Bed material: Sand, bedrock

Geomorphic units:

- Cutbanks.
- Tributary mouth bars
- Stable, vegetated point bars.
- Stable, convex, vegetated banks.
- Alluvial terraces
- Tributaries occupying river paleochannels
- Infilled paleochannel depressions.
- Bedrock channel outcrops.

Hidalgo Falls

Defining attributes: Moderate channel slope, strongly meandering channel incised into Quaternary valley fill. Channel confined within narrow (1.5-2.5 km) valley. Low channel-floodplain connectivity. Active point bars rare to absent.

Landscape unit(s): Miocene Uplands

Representative reach: Reach 6, Hidalgo Falls to Navasota River.

Valley setting: Confined.

Channel planform: Discontinuous floodplain on both margins; strongly meandering single-thread channel with tributaries occupying former river channels.

Bed material: Bedrock, sand

Geomorphic units:

- Cutbanks.
- Stable, convex, vegetated banks.
- Stable, vegetated point bars.
- Alluvial terraces
- Tributaries occupying river paleochannels
- Infilled paleochannel depressions.

•Bedrock channel outcrops.
•Bedrock/boulder rapids

Confined Strongly Meandering Incised Valley Fill II

Defining attributes: Moderate channel slope, strongly meandering channel incised into Quaternary valley fill. Channel confined mainly to right (southwest) valley margin in relatively narrow (5-8 km) valley. Moderate to high channel-floodplain connectivity. Active point bars rare to absent. Differs from reach 5 primarily with respect to geologic setting, absence of river paleochannels, and greater degree of channel-floodplain connectivity, associated with more oxbows and cutoffs and backwater tributary flooding.

Landscape unit(s): Miocene Uplands and upper Coastal Plain

Representative reach: Reach 7, downstream of Navasota River.

Valley setting: Confined.

Channel planform: Continuous floodplain on left margin; strongly meandering single-thread channel.

Bed material: Sand, bedrock

Geomorphic units:

•Cutbanks.
•Cutoffs/oxbows
•Stable, convex, vegetated banks.
•Alluvial terraces
•Stable, vegetated point bars.

Partly Confined Strongly Meandering Incised Valley Fill

Defining attributes: Moderate channel slope, strongly meandering channel incised into Quaternary valley fill. Channel partly confined in relatively narrow (5-8 km) valley. Low channel-floodplain connectivity. Active point bars on nearly all bends.

Landscape unit(s): Miocene Uplands and upper Coastal Plain

Representative reach: Reach 8, Rocky Creek to New Year Creek near Hempstead.

Valley setting: Partly confined.

Channel planform: Mostly continuous floodplain on both margins; strongly meandering single-thread channel.

Bed material: Sand.

Geomorphic units:

- Cutbanks.
- Cutoffs/oxbows
- Sandy point bars.
- Sloughs.
- Tributary mouth bars.
- Alluvial terraces
- Stable, vegetated point bars.

Bedrock Confined Valley

Defining attributes: Strongly meandering incised channel confined within narrow (~2 km) bedrock-controlled valley. Moderate to low slope, low channel-floodplain connectivity, active point bars on nearly all bends.

Landscape unit(s): Miocene Uplands; Quaternary Coastal Plain Uplands--Lissie

Representative reach: Reach 9, New Year Creek to Austin Branch near Hempstead (moderate slope); Reach 10, Austin Branch to Clear Creek near Hempstead (low slope).

Valley setting: Laterally unconfined within relatively narrow bedrock-controlled valley.

Channel planform: Continuous floodplains and occasional terrace remnants along both margins. Meandering single-thread channel.

Bed material: Sand.

Geomorphic units:

- Meander cutoffs/oxbows.
- Sloughs
- Cutbanks.
- Sandy point bars
- Alluvial terraces
- Stable, convex, vegetated banks

Unconfined Alluvial Valley

Defining attributes: Strongly meandering to meandering incised channel in a moderately wide (5-8 km) alluvial valley. Low slope, high channel-floodplain connectivity.

Landscape unit(s): Miocene Uplands; Quaternary Coastal Plain Uplands--Lissie

Representative reach: Reach 11, Clear Creek to SH 529 bridge (Miocene/Lissie; strongly meandering; active point bars on all bends); Reach 12, SH 529 Bridge to Hannay & Palmer Lakes (Lissie; meandering; mixture of active and stable point bars).

Valley setting: Laterally unconfined within alluvial valley.

Channel planform: Continuous floodplains and occasional terrace remnants along both margins. Meandering single-thread channel.

Bed material: Sand, bedrock

Geomorphic units:

- Meander cutoffs/oxbows.
- Sloughs
- Cutbanks.
- Sandy point bars
- Alluvial terraces
- Stable, vegetated point bars
- Bedrock channel outcrops

Unconfined Wide Alluvial Valley

Defining attributes: Meandering incised channel in a wide (10-15 km) alluvial valley. Low slope, high channel-floodplain connectivity. Mixture of active and stable point bars

Landscape unit(s): Quaternary Coastal Plain Uplands—Lissie & Beaumont

Representative reach: Reach 13, Hannay & Palmer Lakes to Garrett Lake near San Felipe.

Valley setting: Laterally unconfined within alluvial valley.

Channel planform: Continuous floodplains and occasional terrace remnants along both margins. Meandering single-thread channel.

Bed material: Sand, bedrock

Geomorphic units:

- Meander cutoffs/oxbows.
- Sloughs
- Cutbanks.
- Sandy point bars
- Alluvial terraces
- Stable, vegetated point bars
- Bedrock channel outcrops

Avulsed Alluvial Valley

Defining attributes: Meandering to tortuous incised channel in a wide (10-15 km) alluvial valley. Low to high slope, high channel-floodplain connectivity. Mixture of active and stable point bars. Tributaries occupying river paleochannel.

Landscape unit(s): Quaternary Coastal Plain Uplands—Lissie & Beaumont

Representative reach: Reach 14, Garrett Lake to Irons Creek near San Felipe (low slope, meandering); Reach 15, Irons Creek to Buckintin Road (high slope, meandering); Reach 16, Buckintin Road to Allens Crrek near Simonton)

Valley setting: Partly confined within alluvial valley.

Channel planform: Continuous floodplains on right; discontinuous on left. Meandering single-thread channel.

Bed material: Sand, bedrock

Geomorphic units:

- Meander cutoffs/oxbows.
- Sloughs
- Cutbanks.
- Sandy point bars
- Alluvial terraces
- Stable, vegetated point bars
- Tributaries occupying paleochannels.
- Infilled and partially infilled paleochannels.
- Bedrock channel outcrops

Confined Avulsed Alluvial Valley

Defining attributes: Meandering to strongly meandering incised channel pinned to right bank of a moderately wide (5.5 to 9 km) to wide (8 to 14.5 km) alluvial valley. High to moderate slope, high channel-floodplain connectivity. Mixture of active and stable point bars.

Landscape unit(s): Quaternary Coastal Plain Uplands—Lissie & Beaumont (reaches 17, 18); Beaumont (19).

Representative reach: Reach 17, near Fulshear (meandering, high slope; moderate valley width); Reach 18, upstream of Rosenberg (meandering, moderate slope and valley width); Reach 19, Rosenberg-Richmond (strongly meandering, moderate slope, wide valley).

Valley setting: Confined within alluvial valley.

Channel planform: Continuous floodplains on left. Meandering single-thread channel pinned to right valley side.

Bed material: Sand.

Geomorphic units:

- Meander cutoffs/oxbows.
- Sloughs
- Cutbanks.
- Sandy point bars
- Alluvial terraces
- Stable, vegetated point bars

Unconfined Low-Sinuousity

Defining attributes: Low sinuousity channel in a wide (8 to 14.5 km) alluvial valley. Moderate slope, high channel-floodplain connectivity. Distributary channels occupying river paleochannel. Mixture of active and stable point bars.

Landscape unit(s): Quaternary Coastal Plain Uplands—Beaumont

Representative reach: Reach 20, downstream of Richmond near Thompsons; Reach 23, Big Creek to Cow Creek near Rosharon.

Valley setting: Unconfined within alluvial valley.

Channel planform: Continuous floodplains on both banks. Low-sinuousity (1.36) single-thread channel.

Bed material: Sand.

Geomorphic units:

- Meander cutoffs/oxbows.
- Sloughs
- Cutbanks.
- Sandy point bars
- Alluvial terraces
- Stable, vegetated point bars
- Distributaries occupying paleochannels.
- Infilled paleochannels

Avulsed Alluvial Valley II

Defining attributes: Strongly meandering incised channel in a wide (8-14.5 km) alluvial valley. Moderate slope, high channel-floodplain connectivity. Mixture of active and stable point bars. Tributaries & distributaries occupying river paleochannel.

Landscape unit(s): Quaternary Coastal Plain Uplands—Beaumont

Representative reach: Reach 21, near Thompsons; Reach 22, Brazos Bend State Park.

Valley setting: Unconfined within alluvial valley.

Channel planform: Continuous floodplains both banks. Meandering single-thread channel.

Bed material: Sand.

Geomorphic units:

- Meander cutoffs/oxbows.
- Sloughs
- Cutbanks.
- Sandy point bars
- Alluvial terraces
- Stable, vegetated point bars
- Tributaries/distributaries occupying paleochannels.
- Infilled and partially infilled paleochannels.

Partly Confined Low-Sinuousity

Defining attributes: Low sinuousity channel in a wide (8 to 14.5 km) alluvial valley. Moderate slope, high channel-floodplain connectivity. Distributary channels occupying river paleochannel. Mixture of active and stable point bars.

Landscape unit(s): Quaternary Coastal Plain Uplands—Beaumont

Representative reach: Reach 24, near Otey.

Valley setting: Partly confined within alluvial valley.

Channel planform: Continuous floodplain on left bank; intermittent on right bank. Low-sinuousity single-thread channel.

Bed material: Sand.

Geomorphic units:

•Meander cutoffs/oxbows.
•Sloughs
•Cutbanks.
•Sandy point bars
•Alluvial terraces
•Stable, vegetated point bars
•Distributaries occupying paleochannels.
•Infilled paleochannels

Partly Confined Low-Sinuousity II

Defining attributes: Low sinuousity channel in a wide (8 to 14.5 km) alluvial valley. Low slope, high channel-floodplain connectivity. Distributary channels occupying river paleochannel. Active point bars rare.

Landscape unit(s): Quaternary Coastal Plain Uplands—Beaumont

Representative reach: Reach 25, upstream of Harris Reservoir.

Valley setting: Partly confined within alluvial valley.

Channel planform: Continuous floodplain on left bank; intermittent on right bank. Low-sinuousity single-thread channel.

Bed material: Sand.

Geomorphic units:

- Meander cutoffs/oxbows.
- Sloughs
- Cutbanks.
- Alluvial terraces
- Stable, vegetated point bars
- Distributaries occupying paleochannels.
- Infilled paleochannels

Lower Coastal Plain

Defining attributes: Meandering channel in a wide (8 to 17 km) alluvial valley. Low slope, high channel-floodplain connectivity. Distributary channels occupying river paleochannel. Active point bars rare. Influenced by coastal backwater effects.

Landscape unit(s): Quaternary Coastal Plain Uplands—Beaumont

Representative reach: Reach 26, Harris Reservoir; Reach 27, near East Columbia.

Valley setting: Partly confined within alluvial valley.

Channel planform: Continuous floodplain on left bank; intermittent on right bank. Meandering single-thread channel.

Bed material: Sand.

Geomorphic units:

- Meander cutoffs/oxbows.
- Sloughs
- Cutbanks.
- Alluvial terraces
- Stable, vegetated point bars
- Distributaries occupying paleochannels.
- Infilled paleochannels.

Low-Sinuousity Lower Coastal Plain

Defining attributes: Low-sinuousity to straight channel in a wide (8 to 17 km) alluvial valley. Low slope, high channel-floodplain connectivity. Distributary channels occupying river paleochannel. Active point bars rare. Influenced by coastal backwater effects.

Landscape unit(s): Late Quaternary Coastal Plain Uplands

Representative reach: Reach 28, near Brazoria (partly confined, low sinuousity); Reach 29, near Lake Jackson (unconfined, low sinuousity); Reach 30, Freeport (unconfined, straight).

Valley setting: Unconfined or Partly confined within alluvial valley.

Channel planform: Continuous floodplain on left bank; nearly-continuous on right bank. Low-sinuousity single-thread channel.

Bed material: Sand.

Geomorphic units:

- Meander cutoffs/oxbows.
- Sloughs
- Cutbanks.
- Alluvial terraces
- Stable, vegetated point bars
- Distributaries occupying paleochannels.
- Infilled paleochannels.
- Delta
- Constructed channel
- Artificial levees
- Tidal channels
- Intertidal marshes and mudflats

LOWER NAVASOTA RIVER

The locations of the identified reaches and their styles are shown in table 18. Maps showing the reaches and associated river styles are shown in figure 12 below and in fig. 8 in the previous section. Table 19 shows the geomorphic characteristics of the reaches.

Table 18. Geomorphic reaches of the lower Navasota River. Distance is given in km upstream of the mouth. Latitude and longtitude coordinates (Lat-Long) are for the downstream end of the reach and also constitute coordinates of the upstream end of the next reach. The nearest identifiable map or landscape landmark is also indicated.

RR	Distance	Lat-Long	Landmark	River Style
		31.3229,-96.3201	Lake Limestone Dam	(upstream end of study area)
1	185-165	31.2020,-96.3099	Marquez salt dome	Steep anabranching
2	165-146	31.0912,-96.2778	Clear Cr	Low-Gradient anabranching
3	146-133	31.0331,-96.2497	FZ upper	Anabranching
4	133-057	30.6203,-96.1805	Wickson Cr	Anabranching
5	057-050	30.5822,-96.1757	Carters Cr	Anabranching II
6	050-042	30.5711,-96.1668	Sulphur Spr	Anabranching II
7	042-034	30.4919,-96.1324	Gibbons Cr	Anabranching II
8	034-025	30.4382,-96.1132	Old RR nr Navasota	Anabranching II
9	025-018	30.4229,-96.0832	Holland Cr.	Incised meandering
10	018-005	30.3897,-96.1464	Big Cr	Floodplain connector
11	005-000	30.3599,-96.2999	Brazos R.	Paleochannel

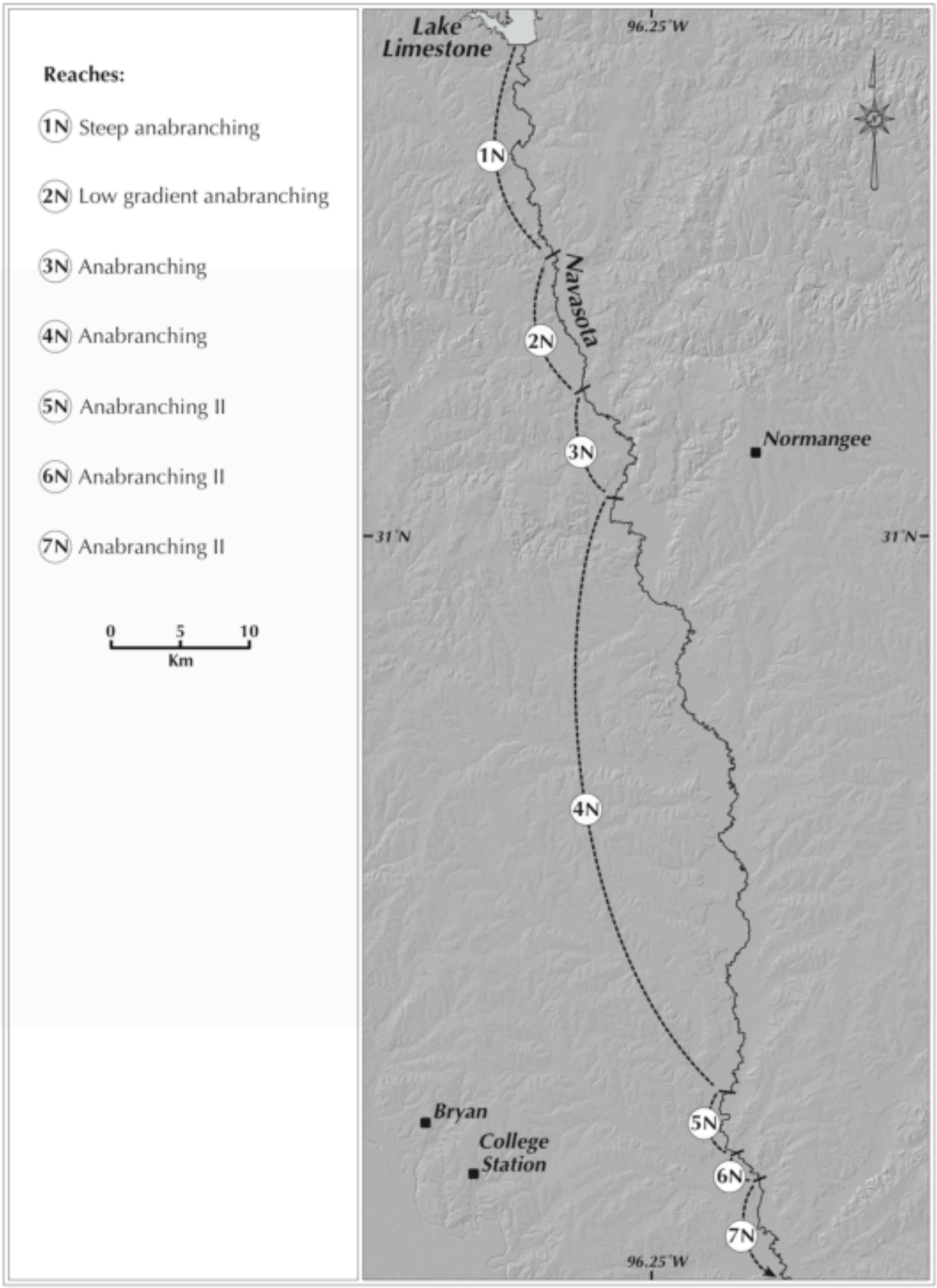


Figure 12. Geomorphic reaches and river styles, Navasota River from Lake Limestone to Gibbons Creek.

Table 19. Geomorphic characteristics of lower Navasota River reaches.

RR	Geology	VW	VC	Slope	Sinuousity	CP	CPC
1	Eocene	2.14	PC	0.000702	mean	ana	high
2	Eocene	2.14	PC	0.00033	mean	ana	very high
3	Eocene	2.14->1.13	PC	0.000259	mean	ana	very high
4	Eocene	3.19	PC	0.000259	mean	ana	very high
5	Eocene	3.19	PC	0.000259	mean	ana	high
6	Eocene	1.3	PC	0.000259	mean	ana	high
7	Eocene	3.37	PC	0.000259	mean	ana	high
8	Eocene	2.08	PC	0.000259	mean	ana	high
9	Miocene	2.08	PC	0.000259	mean	ST	mod/hi
10	Miocene	BFP	C	0.000121	mean	ST	mod/hi
11	Miocene	BFP	UC	0.000121	mean	ST	mod/hi

RR: river reach number
Geology: dominant valley margin geology
VW: mean valley width, km
VC: valley confinement—confined (C), partly confined (PC), unconfined (UC)
Slope: mean channel slope
CP: channel/flow pattern. ST = single thread; ana = anabranching
CPC: channel-floodplain connectivity. Mod=moderate; mod/hii=moderate to high

RIVER STYLE DECRIPTIONS—LOWER NAVASOTA

Steep Anabranching

Defining attributes: Very high gradient meandering channel with anabranches and high channel-floodplain connectivity. Partly confined within moderately wide (1.8 to 3 km) valley.

Landscape unit(s): Eocene Uplands

Representative reach: Reach 1, downstream of Lake Limestone dam.

Valley setting: Partly confined.

Channel planform: Meandering single-thread channel with multiple high-flow anabranches.

Bed material: Mud/sand

Geomorphic units:

- Cutbanks.
- Cutoffs, oxbows.
- Stable, vegetated point bars.
- Swamp/backswamp islands between anabranches.
- Semi-active subchannels
- Partially-infilled paleochannels
- Sloughs

Low-Gradient Anabranching

Defining attributes: Low gradient meandering channel with anabranches and very high channel-floodplain connectivity. Partly confined within moderately wide (1.8 to 3 km) valley.

Landscape unit(s): Eocene Uplands

Representative reach: Reach 2, near Marquez.

Valley setting: Partly confined.

Channel planform: Meandering single-thread channel with multiple active subchannels and high-flow anabranches.

Bed material: Mud/sand

Geomorphic units:

- Cutbanks.
- Cutoffs, oxbows.
- Stable, vegetated point bars.
- Swamp/backswamp islands between anabranches.
- Active subchannels
- Semi-active subchannels
- Partially-infilled paleochannels
- Sloughs

Anabranching

Defining attributes: Meandering channel with moderately high slope, anabranches and very high channel-floodplain connectivity. Partly confined within wide (2-4.5 km km) to locally narrow (1 -1.3 km) valley.

Landscape unit(s): Eocene Uplands

Representative reach: Reach 3, near Normangee (moderately wide valley with constriction to narrow valley in downstream end); Reach 4, near Normangee to Wickson Creek near Bryan (wide valley).

Valley setting: Partly confined.

Channel planform: Meandering single-thread channel with multiple active subchannels and high-flow anabranches.

Bed material: Mud/sand

Geomorphic units:

- Cutbanks.
- Cutoffs, oxbows.
- Stable, vegetated point bars.
- Swamp/backswamp islands between anabranches.
- Active subchannels
- Semi-active subchannels
- Partially-infilled paleochannels
- Sloughs

Anabranching II

Defining attributes: Meandering channel with moderately high slope, anabranches and high channel-floodplain connectivity. Partly confined within wide (2-4.5 km km) to narrow (1 -1.7 km) valley.

Landscape unit(s): Eocene Uplands

Representative reach: Reach 5, Wickson Creek to Carters Creek near College Station (wide valley); Reach 6, Carters Creek to Sulphur Spring near College Station (narrow valley); Reach 7, Sulphur Springs to Gibbons Creek near College Station (wide valley); Reach 8, Gibbons Creek to Holland Creek near Navasota (moderately wide valley).

Valley setting: Partly confined.

Channel planform: Meandering single-thread channel with multiple high-flow anabranches.

Bed material: Mud/sand

Geomorphic units:

- Cutbanks.

- Cutoffs, oxbows.
- Stable, vegetated point bars.
- Swamp/backswamp islands between anabranches.
- Semi-active subchannels
- Partially-infilled paleochannels
- Sloughs

Incised Meandering

Defining attributes: Incised meandering single-thread channel; relatively steep slope; moderate to high channel-floodplain connectivity.

Landscape unit(s): Miocene Uplands

Representative reach: Reach 9, old rail crossing to Holland Creek upstream of Navasota.

Valley setting: Partly confined.

Channel planform: Continuous floodplain on right margin; discontinuous on left margin. Meandering single-thread channel.

Bed material: Mud/sand

Geomorphic units:

- Cutbanks.
- Cutoffs, oxbows.
- Stable, vegetated point bars.
- Swamp depression in meander cutoff.
- Alluvial terraces;

Floodplain Connector

Defining attributes: Incised channel crossing floodplain of larger river. Meandering, single-thread channel with moderate to high channel-floodplain connectivity.

Landscape unit(s): Miocene Uplands

Representative reach: Reach 10, Holland Creek to Big Creek. near Navasota.

Valley setting: Confined.

Channel planform: Continuous floodplain on both margins. Meandering single-thread channel.

Bed material: Mud/sand

Geomorphic units:

- Cutbanks.
- Stable, vegetated point bars
- Alluvial terraces

<u>**Paleochannel**</u>

Defining attributes: Incised channel confined within abandoned paleochannel of larger stream.

Landscape unit(s): Miocene Uplands

Representative reach: Reach 11, from Big Creek to Brazos River.

Valley setting: Unconfined.

Channel planform: Continuous floodplain on both margins. Meandering single-thread channel.

Bed material: Sand, mud, sandstone

Geomorphic units:

- Cutbanks.
- Tributary occupying Brazos River paleochannel
- Stable, vegetated point bars
- Paleochannel trough
- Alluvial terraces
- Bedrock outcrops

Part 4
Trajectories of Change

HYDROLOGY

As indicated in the phase 1 report (Phillips, 2006) some evidence exists of discharge changes before and after roughly 1940, but there are no detectable recent or ongoing trends of change in the discharge regime. Future changes in flow regimes will depend on changes or variations in climate, water withdrawals, water transfers into or out of the Brazos River watershed, and land use changes which influence hydrologic response. The lower Brazos River does contain one priority reservoir preservation site (Allens Creek), which could be developed in the future. Potential impacts of development at this site on instream flow have been studied by Oosting et al. (2004).

Like other rivers in the region, the Brazos is responding to the contemporary trend of rising Holocene sea levels. The Lower Coastal Plain river styles are currently influenced by tidal and coastal backwater effects. The locus of change related to sea level will be at the upstream end of the Lower Coastal Plain style reaches. Changes may include channel and floodplain aggradation (which could increase the likelihood of future avulsions), increased sinuousity accomplished by lateral migration involving the growth of meander amplitudes, and an upstream translation of the locus of sediment deposition and of the turbidity maximum in the Brazos estuary.

CHANNEL INCISION/AGGRADATION

Lower Brazos River

The existence, rate, and controls of channel incision were identified in phase 1 (Phillips 2006) as key research issues. The Brazos River is an incised system, and apparently has been for the past 7.5 to 8.5 ka (Waters and Nordt, 1995; Taha, 2007). The steep banks, coupled with the infrequent overbank flow in much of the study area, and exposed bedrock in the channel in much of the upper study area, suggests that incision may have occurred recently and may still be occurring. Taha's (2007) work suggests that maximum banktop-to-channel separation was achieved about 1,500 years ago, but recent and contemporary scour of the channel bed is evident at some locations.

Dunn and Raines (2001) analyzed stage-discharge relationships for the Hempstead, Richmond, and Rosharon stations to determine changes in water surface altitude at specific discharges. For a discharge of 5,000 ft^3 sec^{-1} (142 m^3 sec^1) the long term decline in water surface elevation has been about 0.0085 m yr^{-1} at the Hempstead station, 0.017 at Richmond, and 0.020 m yr^{-1} at Rosharon, with statistically significant slopes for the trend lines (Dunn and Raines, 2001). This trend indicates net bed degradation or channel incision on the order of a meter (2 to 4 feet) over the period of record. The FM2004 bridge crossing near Lake

Jackson has experienced scour (Mueller, 2002), and repeated cross-section surveys at several bridge crossings obtained from the Texas Department of Transformation also show scour, on average.

Local field evidence of recent incision is also evident. Most of the tributaries in all the Brazos river styles except the Lower Coastal Plain are incised, at least in their lower reaches, in response to Brazos River downcutting. Butler Bayou, for example, occupies a Brazos River paleochannel. However, the longitutudinal profile in figure (13) shows how a steep convex reach has been incised in the lower ~ 3 km as the stream has adjusted to the lower base level. Such features are common in Brazos tributaries.

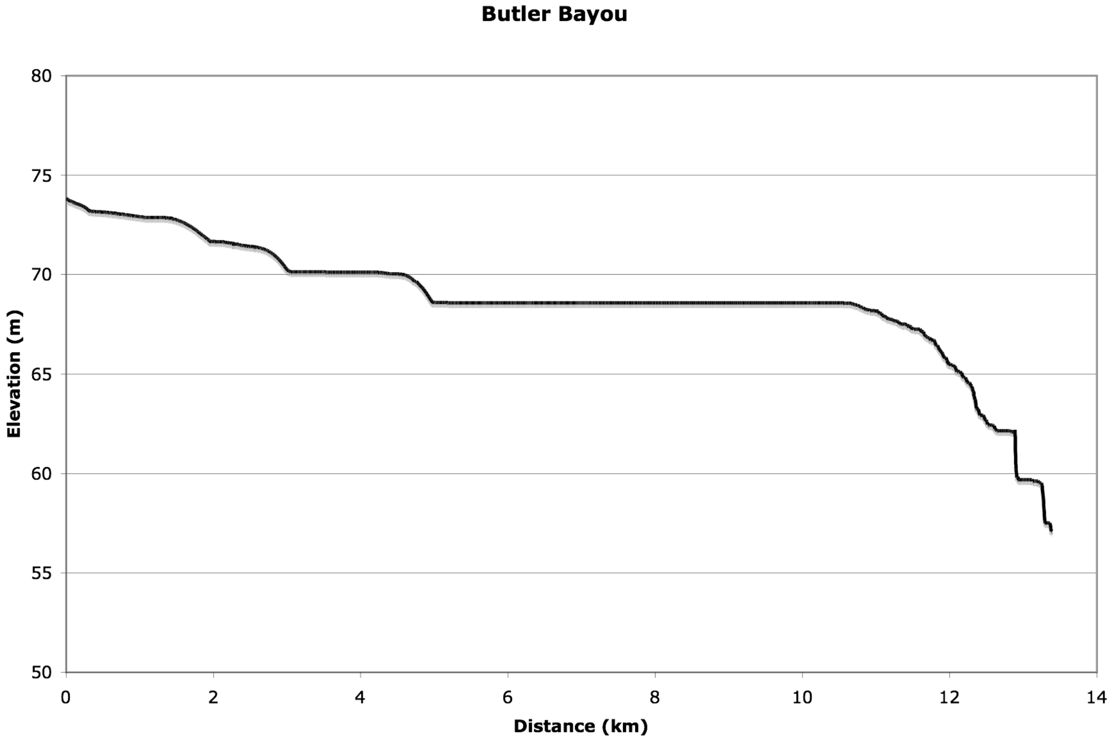


Figure 13. Longtitudinal profile of Butler Bayou.

Other field evidence of incision is also evident. For example, at the FM1093 bridge crossing near Simonton, concrete pads originally built flush with the stream bed were 1.75 m above the water level (on 11 November, 2006; Figure 14).

Figure 14. Concrete pads originally flush with the channel bed now exposed at FM1093 near Simonton.

Figure 15. Exposed sandstone bedrock in the Brazos River channel near Wellborn.

The Brazos has been downcutting into valley fills in the recent geologic past, but in many cases is at or near bedrock (figure 15). The bedrock is generally much more resistant than the alluvial fills. The combination of exposure of bedrock in the channel bed, and rising base level due to sea level rise, will not likely cause a cessation in incision, but will cause a decline in the rate. Localized rapid incision is still possible, but is most likely upstream of the Lower Coastal Plain river styles, and where there is still a significantly thick alluvial layer in the channel. Even where the substrate underlying channel alluvium is clay rather than bedrock *per se*, this more resistant material appears to retard vertical erosion (Mueller, 2002; Phillips, et al. 2005).

Lower Navasota River

Localized channel scour is certainly evident in the Navasota River, but all the various anabranching river styles, encompassing essentially all reaches upstream of Navasota, are aggradational. The frequent avulsions necessary to create the anabranching pattern are generally consistent with an aggrading system, as is the high frequency of overbank flow.

Field evidence of aggradation is also abundant. Buried soil profiles were observed in floodplain alluvium at several locations (Figure 16). The lack of pedogenic development and preservation of stratification in deposits overlying the buried soils indicates recent (historic to contemporary) deposition. Burial of the bases of trees and other vegetation, and of recent litter layers, was also observed (Figure 17), as was the presence of obviously historic or contemporary human-made items in alluvial deposits (Figure 18).

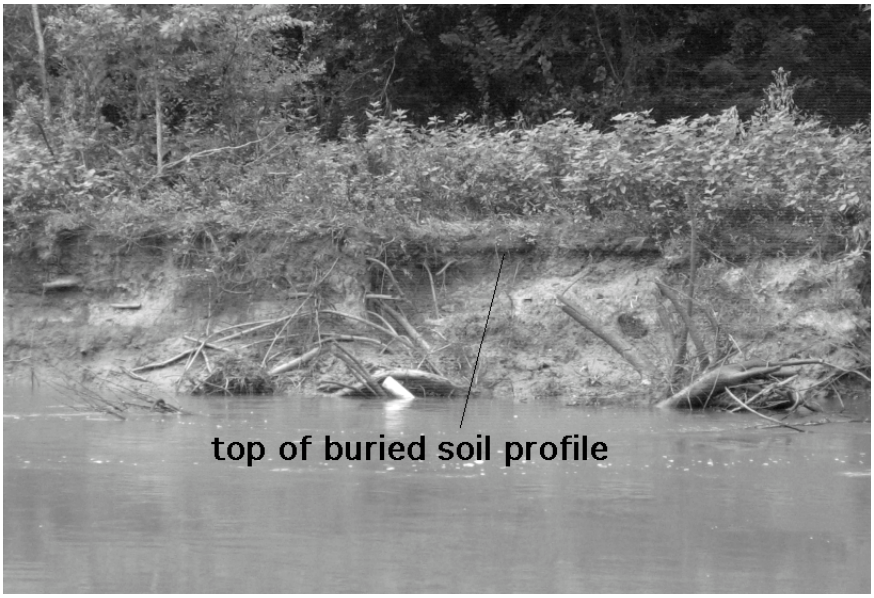


Figure 16. Cutbank at Bundic Road landing on the Navasota River showing typical section of soil profile buried by floodplain alluvium.

Figure 17. Small trees and shrubs along the Navasota River with bases buried by recent floodplain alluvium.

Figure 18. Example of recent or historic item (glass bottle) deposited in Navasota River alluvium.

Buried soil profiles suggest accelerated historic erosion on the uplands, which in turn results in accelerated sedimentation on formerly relatively stable or slowly accreting floodplains. Buried soil profiles—sometimes including multiple paleosols—can also be observed in Brazos River alluvium (Figure 19). However, Waters and Nordt (1995) have shown that burial of these paleosols occurred before the most recent episode of Quaternary incision. The pedogenic development evident in the surficial materials (compared to the minimally altered material typically found in the material overlying buried profiles in the Navasota system) is consistent with prehistoric rather than historic or contemporary burial.

Figure 19. Buried soil profile in Brazos River alluvium exposed in the banks of Thompson's Creek.

With the abundance of evidence of recent sedimentation, including fresh deposits following high flows observed in March and August, 2007, aggradation in the Navasota valley can be expected to continue unless major changes in land use or soil conservation and sediment control occur.

LATERAL MIGRATION

Bank erosion and cutbanks are common in both rivers of the study area. However, they are typically associated with point bars or infilling on the opposite bank. Further, in any given reach channel widths are comparable, in the ~1960, 1980s, 1990s, and 2004-2006 channels shown on maps and aerial photographs. Thus there is no evidence of general channel widening (or narrowing), though widening or narrowing may occur locally.

Brazos River

The lower Brazos River migrates laterally in almost every reach and river style. In confined and the confined portions of partly confined river styles, future migration will be limited mainly to the floodplain-bounded side of the river, though some local erosion into valley sides may occur. The artificial reach of river near Freeport is the only reach of any considerable length which does not show evidence of lateral migration in recent decades. This evidence includes photorevised topographic maps, aerial photography, and field evidence.

At each site visited in the field, a sample point was established, and bank condition assessments were made for four areas—left and right bank, and upstream and downstream of the sample point. With the exception of anthropically modified sections (rip-rap, bridge abutments, etc.), the river banks fell into three general categories:

1. Active cutbanks, characterized by steep, near-vertical slopes, erosion scarps and/or slump scars, exposed soil/sediment, and (in some cases) recently toppled trees.

2. Inactive or recovering cutbanks, characterized also by characterized by steep, near-vertical slopes, erosion scarps and/or slump scars, but with little exposure of bare soil and significant vegetation cover.

3. Stable, vegetated banks, with generally dense vegetation cover, and limited bare soil exposure.

Active and inactive cutbanks all exhibited an overall concave profile shape, or a concave section near the base. Stable banks had convex (or occasionally straight) profile shapes.

Most sections evaluated had at least one active cutbank, indicating active bank erosion. In addition, a related study of the unexpectedly high occurrence of non-acute tributary junction angles on the lower Brazos (Phillips, 2007c) found that lateral river channel migration which encroaches on meandering tributaries is responsible for most of the non-acute confluences.

The classified bank sections, believed to be representative of the lower Brazos River as a whole, break down as shown in Table 20. This indicates that lateral migration is a local, shifting phenomenon. Thus prediction is necessarily local, based on assessments of bank conditions, and the geometry and recent movement trends of meander bends.

Table 20. Classification of the condition of Brazos River bank sections assessed in the field. The eroding-upland category indicates banks where gully erosion on the upland/floodplain surface and/or mass wasting of the upper banks, rather than river flow, is the primary erosional agent. Paleobanks are apparent former bank positions above the current active bank tops due to channel incision.

Bank Condition	*N*	*Percent*
Stable, vegetated, convex banks or point bars	36	50.0%
Active cutbanks	14	19.4
Recovered / recovering cutbanks	11	15.3
Active point bars	4	5.6
Eroding-upland	3	4.2
Stable-engineered (rip-rap)	2	2.8
Paleobanks	2	2.8

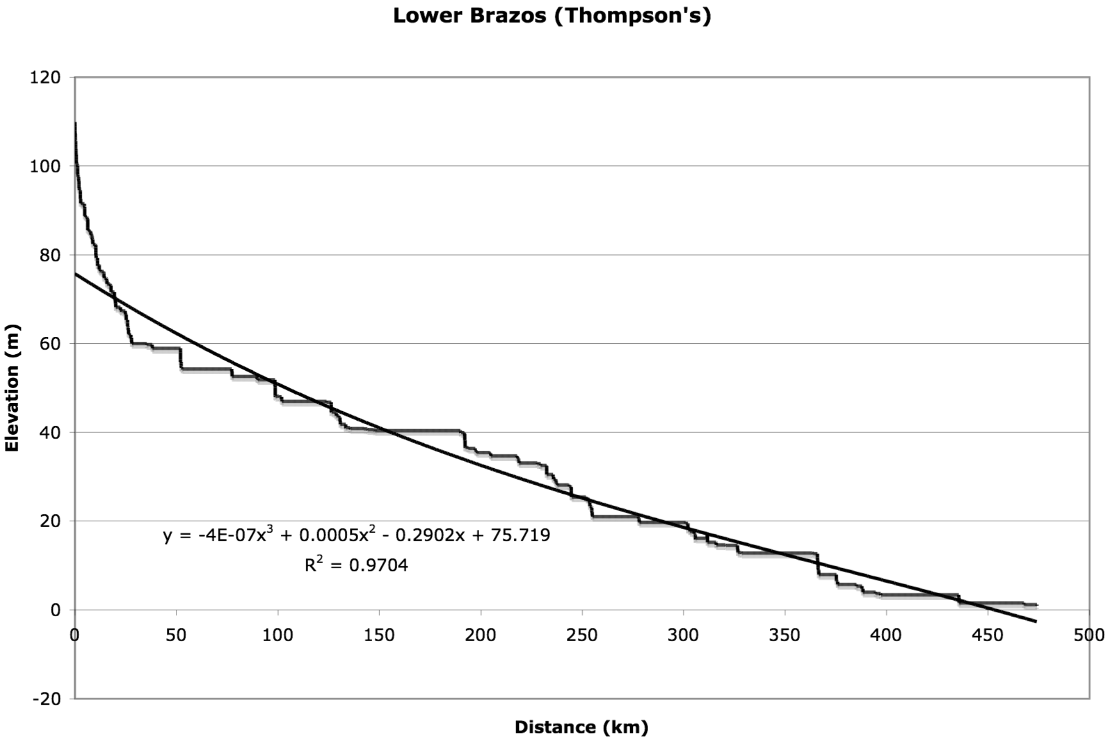
There is no reason to expect any acceleration or deceleration in the active lateral migration regime of the lower Brazos River. In specific locations, continuation of existing migration trends will depend on proximity to the valley side, and on the propensity of larger meanders to experience cutoffs.

Navasota River

Navasota channels are also active, though stable banks and inactive cutbanks are more common, and active cutbanks less common, than in the Brazos. Lateral migration of individual channels is less evident in most of the Navasota River due numerous avulsions. Thus, the lateral shifts of water and sediment occur primarily due to avulsions rather than channel migration.

SLOPE

While energy grade slope is critical from a hydraulic perspective, general changes in reach slope are associated with channel gradients. The longitudinal profiles of the lower Brazos and Navasota Rivers are shown in figure 20, from the drainage divide of a tributary within the study area, to the river mouth. Best-fit trend lines are shown to smooth out the step-like appearance resulting from deriving the profiles from digital elevation models. The Brazos profile exhibits the expected steeper headwater reach and flatter lower reach. In between the profile is more convex than would be theoretically expected, suggesting the possibility of further downcutting in this area. However, the resistant bedrock exposed in these reaches may be responsible for the convexities and will inhibit the rate of vertical erosion in the future. The Navasota profile shows a concave upper and convex lower portion. This, to varying extents, is representative of many Brazos River tributaries, with steepened lower portions where downcutting has occurred in response to the lower base level of the incising Brazos.



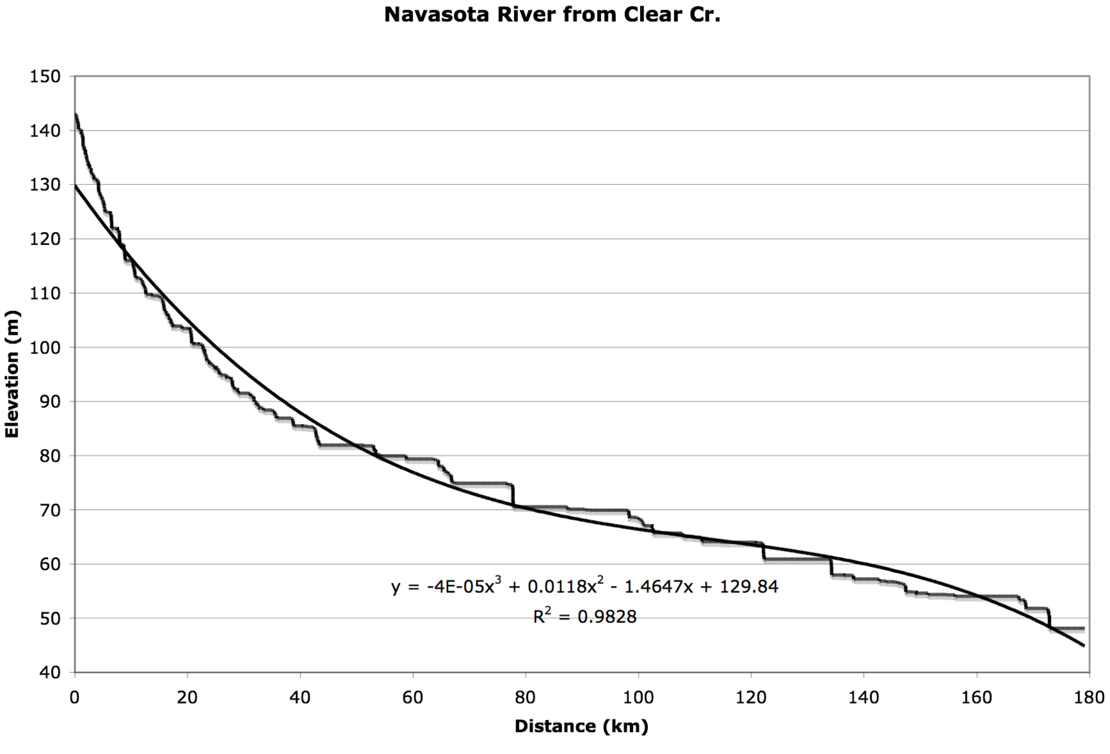


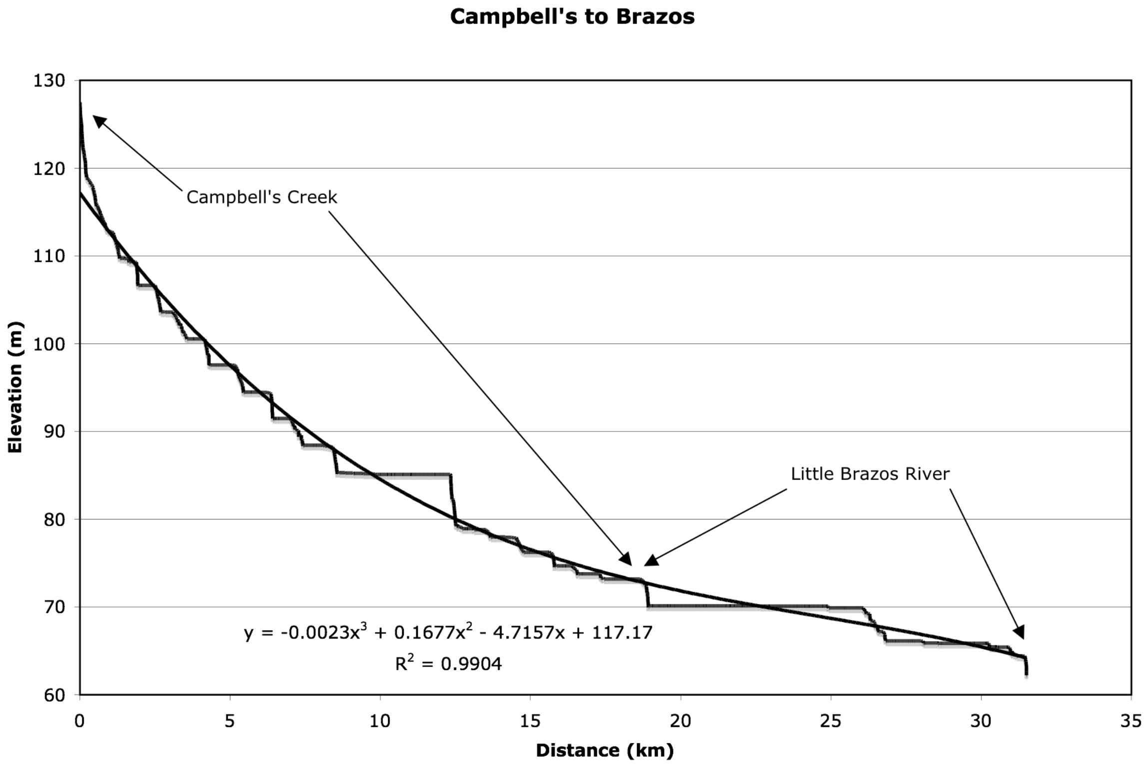
Figure 20. Longitudinal profiles of the Brazos River, beginning at the headwaters of Thompson's Creek, and the Navasota, from upper Clear Creek.

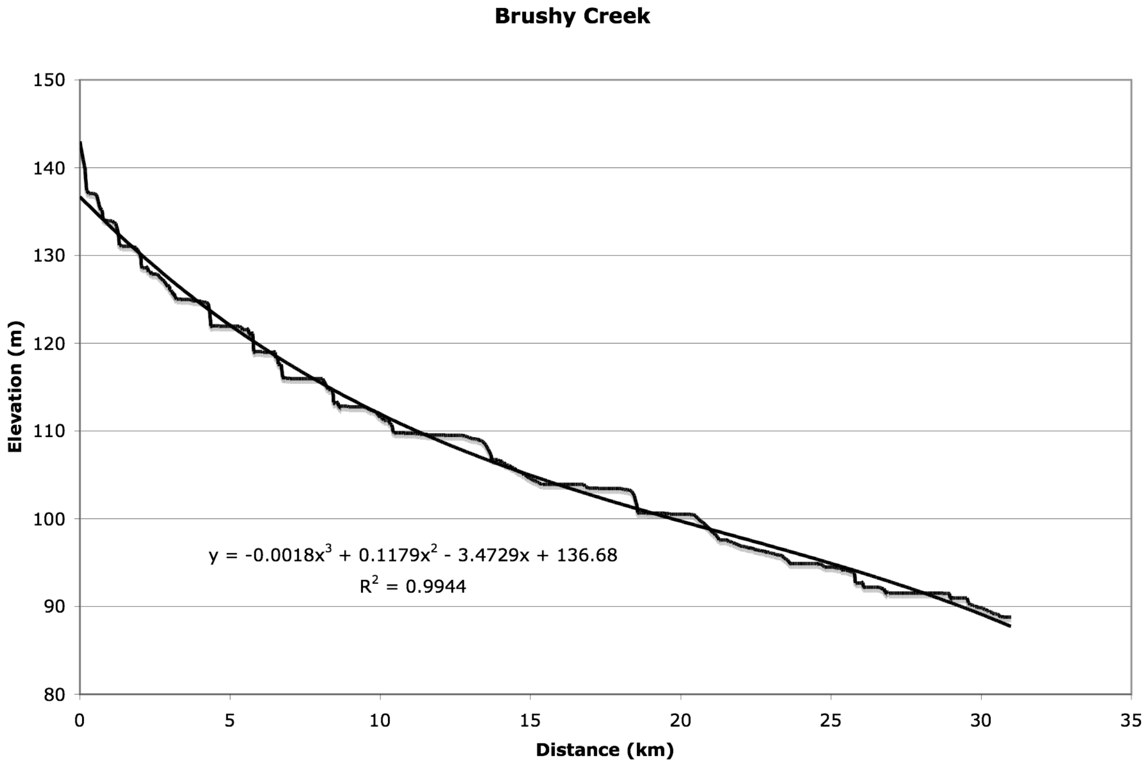
Several tributary profiles of both the lower Brazos and Navasota River were examined (figures 21, 22). Linear, power, exponential, logarithmic, and second- and third-order polynomial functions were applied to each, with the best-fit line shown in each case. In some cases several different functions provide good fits. This is not unusual, as several different nonlinear functions can often provide good approximations to longitudinal profiles.

A concave-up longtinudinal profile shape has traditionally been considered the normative, graded, or steady-state dynamic equilibrium form. This interpretation is increasingly challenged in fluvial geomorphology, due to the frequent deviations observed, and to the fact that a number of different processes and controls—some of which clearly do not result in any sort of graded or equilibrium condition—can lead to the same shape (e.g., Snow and Slingerland, 1987; Ohmori, 1991; Harmar and Clifford, 2007).

However, while the general concave-up shape does not, by itself, reveal much about geomorphic processes, controls, or history, deviations from this general pattern are often informative. Thus it is noteworthy that the best-fit function for most of the Brazos tributaries is a third-order polynomial describing a generally concave upper and convex lower profile (fig. 21). The steeper slope in the lower reaches can be interpreted, as described earlier, as a response to changing base level as the Brazos has incised. The lower convexity is in some cases quite pronounced (Butler Bayou, Turkey Creek, Big Creek) and in others more subtle (Thompson's Creek, Brookshire & Bessie Creeks, and Campbell's Creek/Little Brazos River). The only example not to exhibit this pattern, Reason Creek, is contained entirely within the alluvial valley and may not predate the Brazos incision.

The Navasota River tributaries shown in figure 22 also have a third-order polynomial as the best fit trend line, but in only one case (Cedar Creek) is the lower convexity pronounced. The low concavity and relatively steep lower slopes suggest that these tributaries may have also been adjusting to incision in the Brazos River and in the Navasota trunk stream, which would indicate that the aggradation in the Navasota valley is recent.





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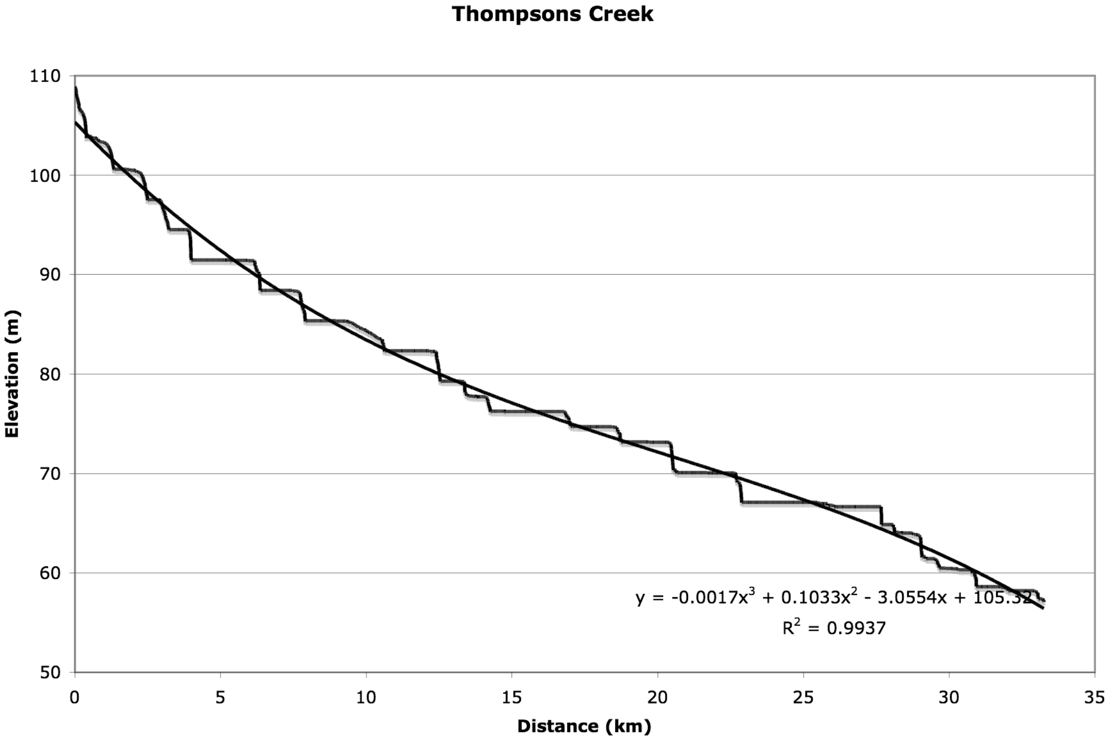

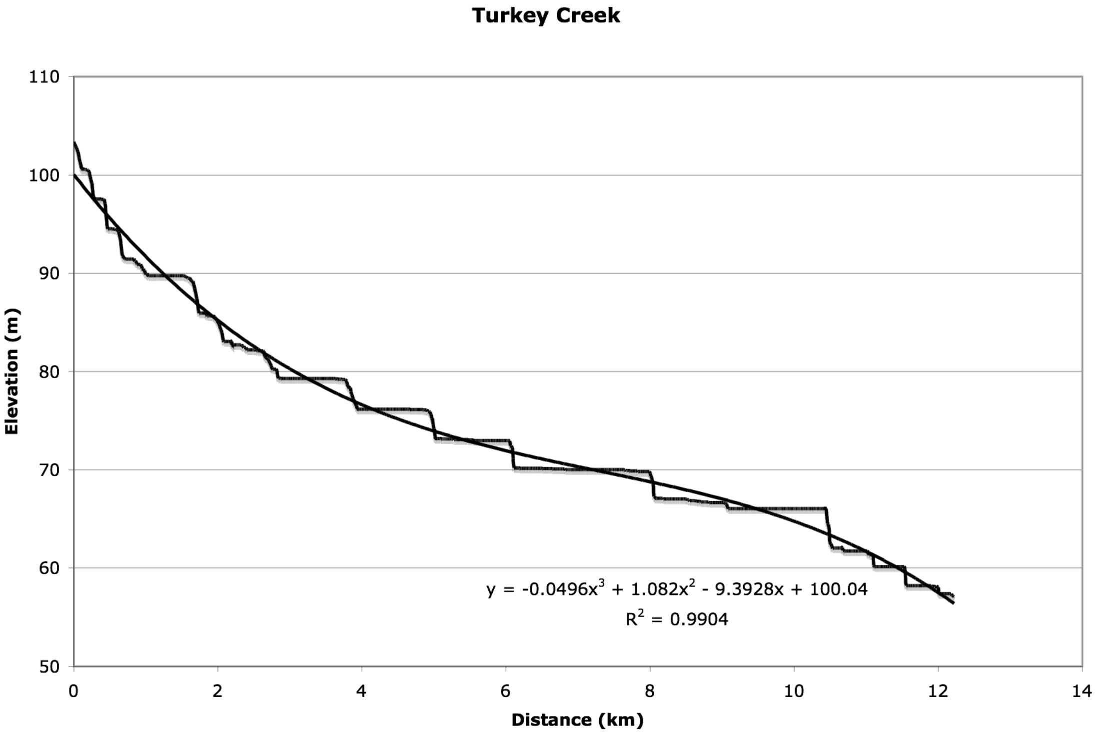

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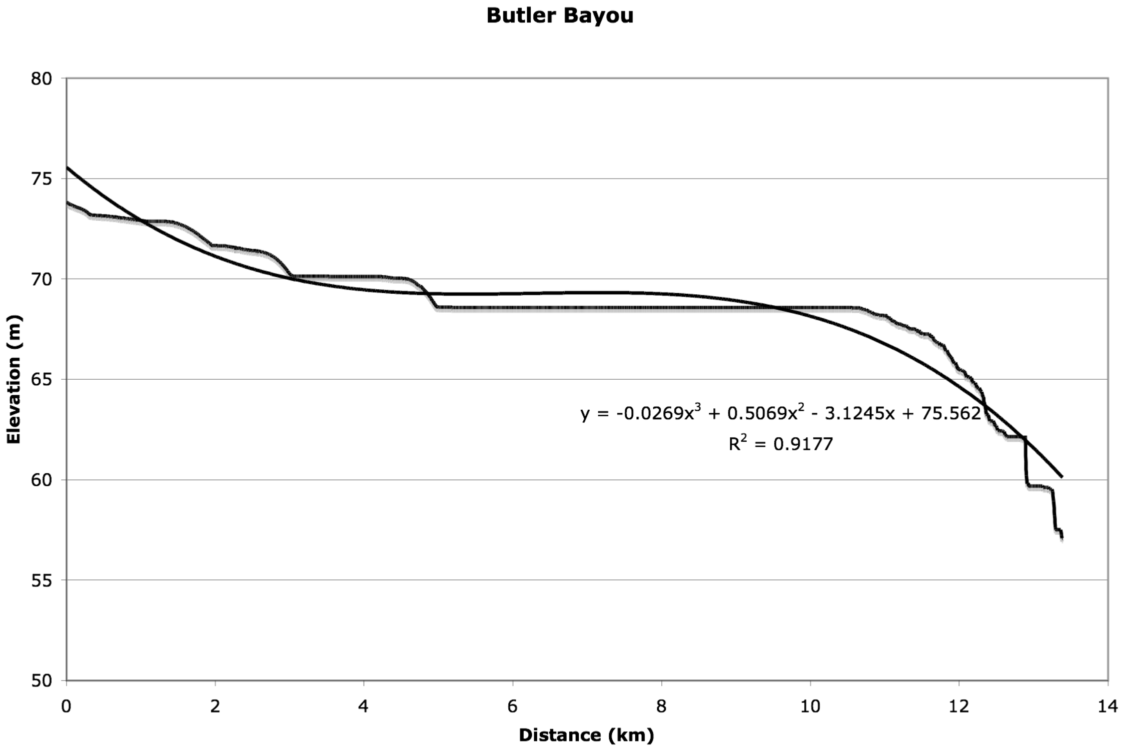

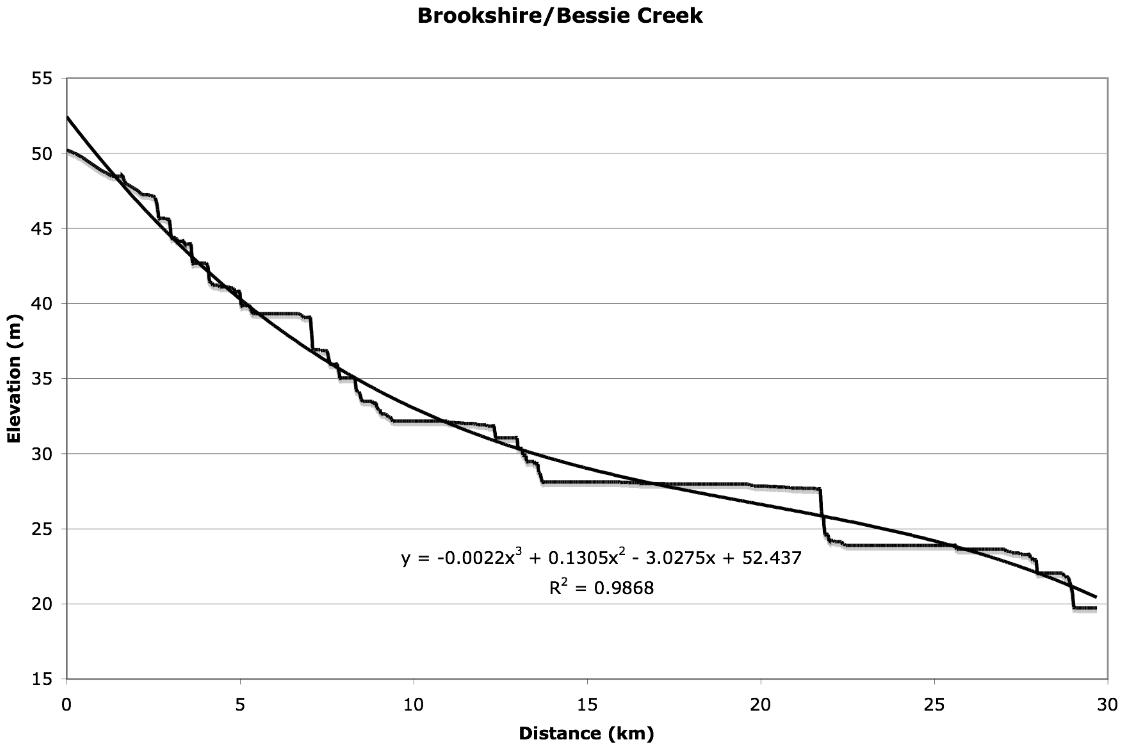

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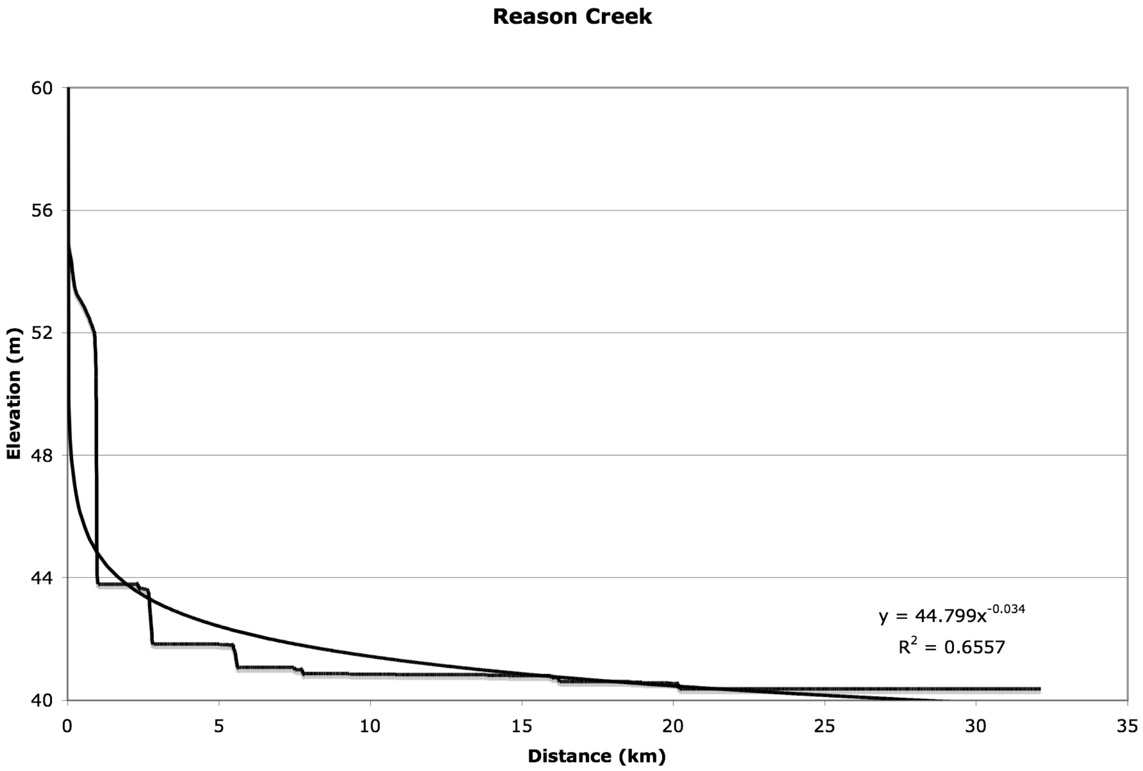


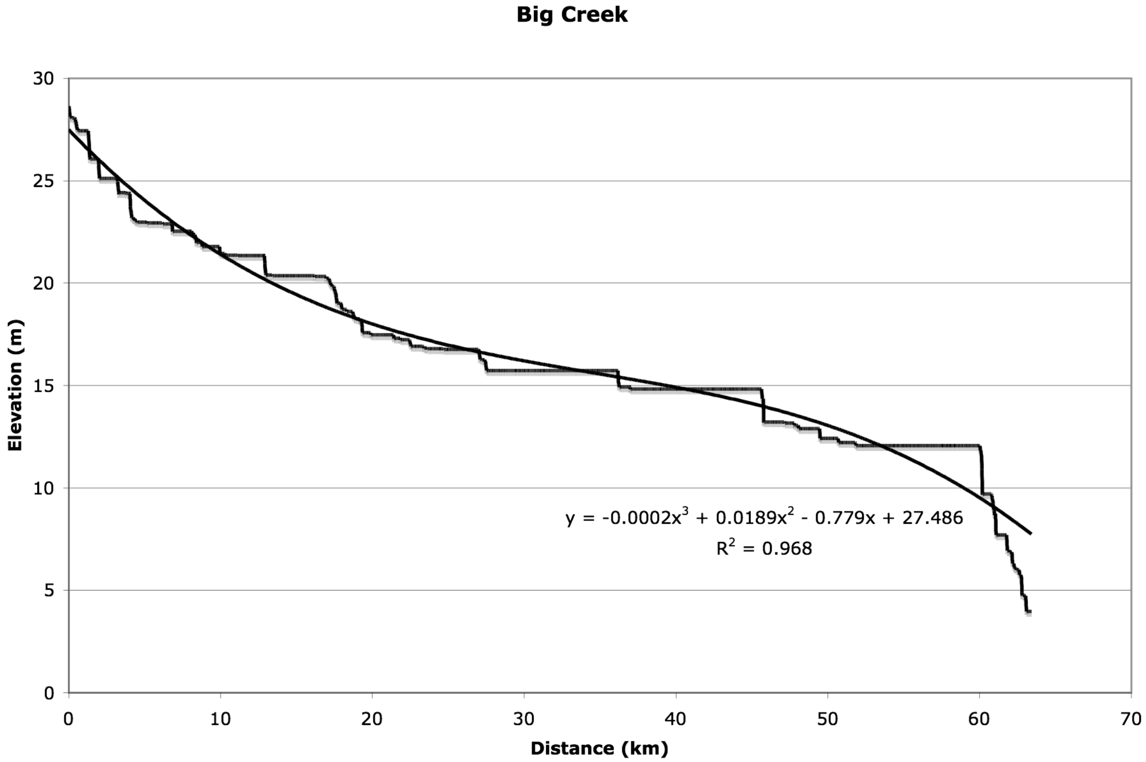
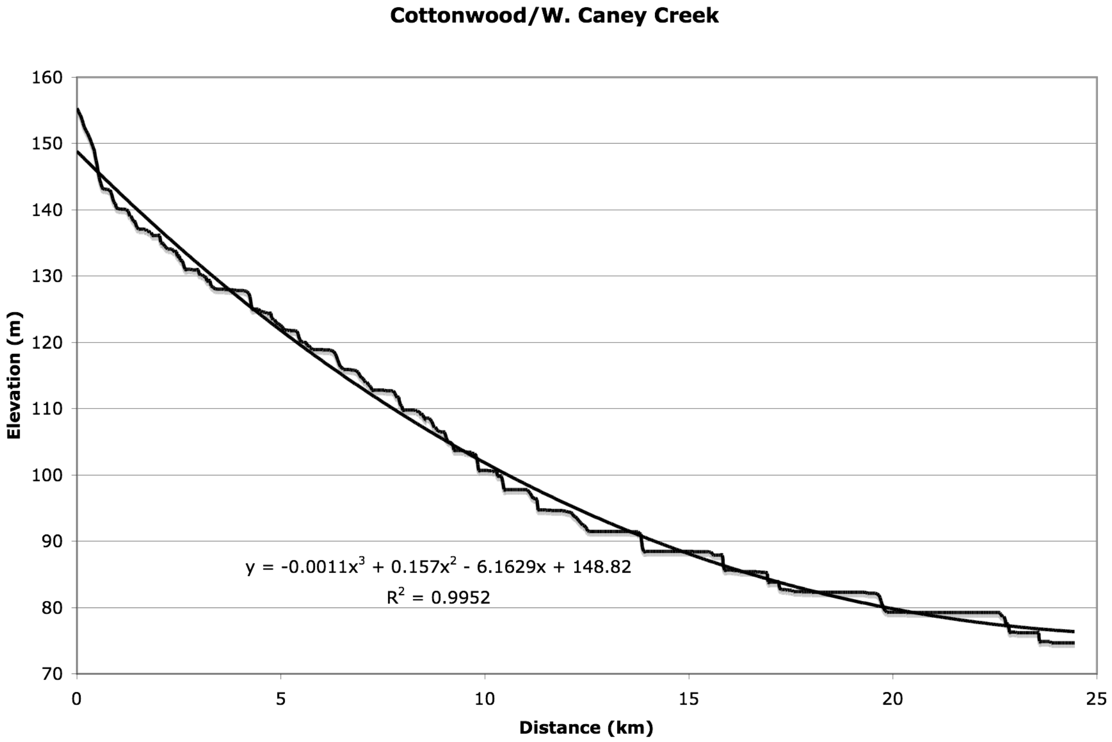
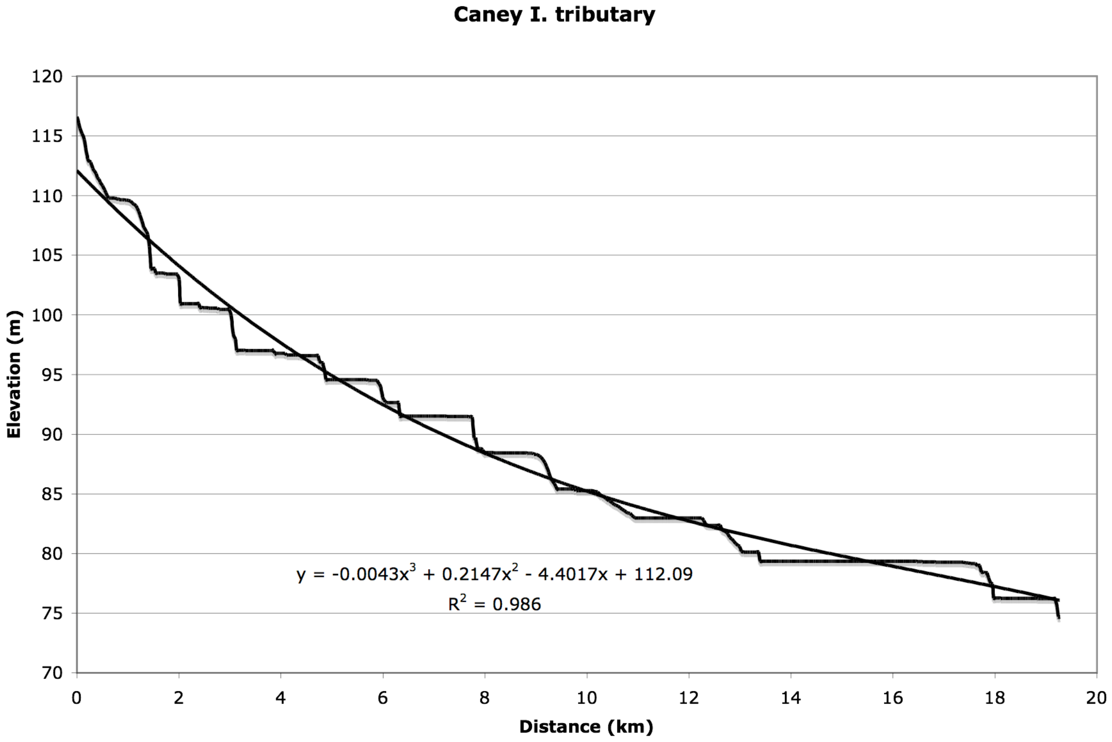


Figure 21. Longitudinal profiles of several tributaries of the lower Brazos River.





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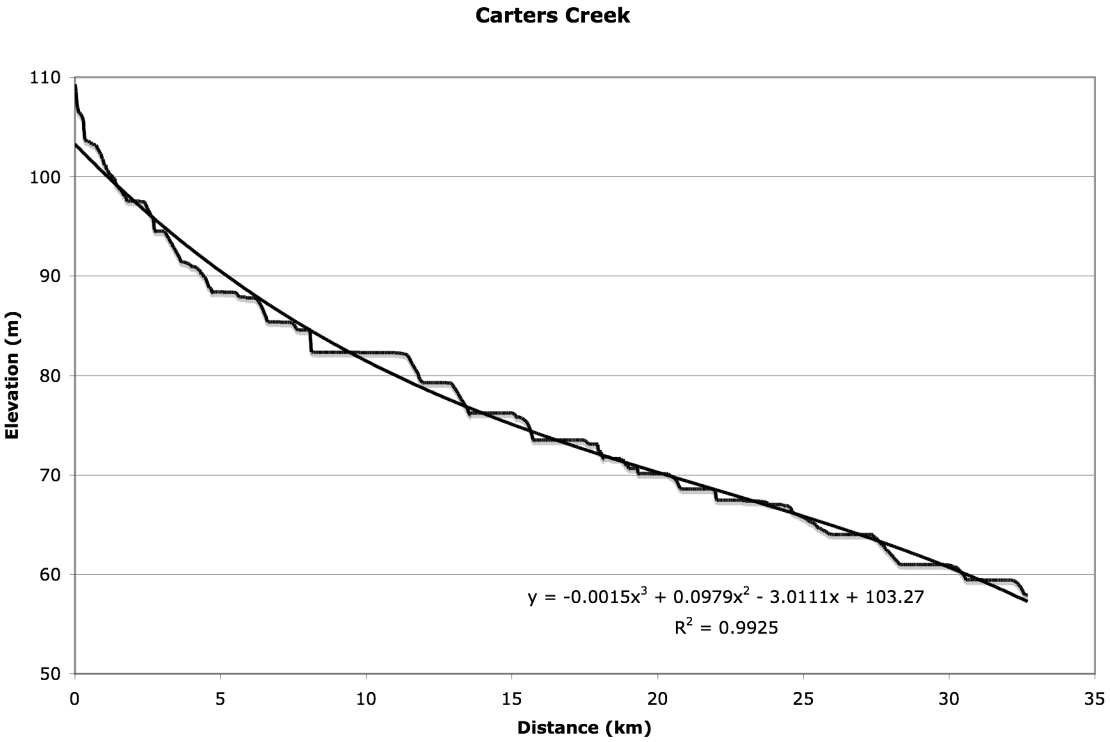

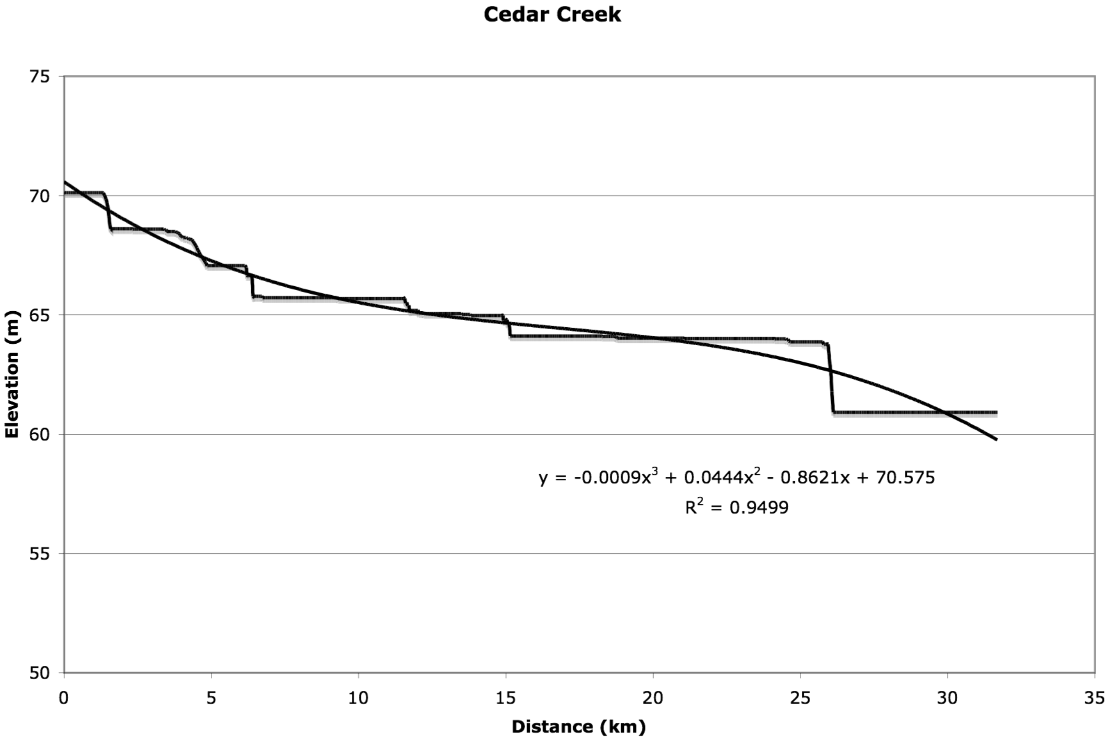

Figure 22. Longitudinal profiles of some tributatries of the lower Navasota River.

Cutting and filling within the channel is only one mechanism by which slopes can change. Avulsions generally occur along gradients of slope advantage and thus tend to increase mean channel slopes. The former Brazos River channel now occupied by Oyster, Jones, and Bessie's Creeks, for example, is significantly more sinuous than the modern channel. Whereas the modern river length from the avulsion point to the Gulf of Mexico is 253 km, the length along the paleochannel is about 325 km. This channel shift represents an increase in average slope from the avulsion point to the Gulf from 0.0001168 to 0.00015 (28 percent).

The growth and cutoff of meanders increases or decreases the distance between upstream and downstream points, thus changing slope gradients between those points. The pre- and post-cutoff distances between points immediately up- and downstream of the cutoffs was measured from aerial photographs. In the Brazos, the ratio of pre- to post-cutoff distances averaged 10.2 (i.e., the distance was reduced by a factor of 10.2) for neck cutoffs, with a range of 2.8 to 24.8. As expected, the ratio for chute cutoffs was smaller (1.98 to 2.5, mean 2.3). The ratios for the Navasota were similar—10.1 for neck cutoffs (3.6 to 15.5) and 2.0 for chutes (1.3 to 3.6).

Slope changes associated with lateral migration (meander growth) and channel changes (cutoffs and avulsions) are expected to dominate any changes in slope in the near future.

SEDIMENT TRANSPORT

Three periods, with distinctly different sediment transport regimes in the lower Brazos River were identified by Seelig and Sorenson (1973). From 1922-40, suspended sediment concentrations averaged about 5,000 parts per million (ppm), and from 1941-50, concentrations generally declined to about 2,000 ppm. In the 1951-65 period, concentrations declined slightly, but remained in the 1,000 to 3,000 ppm range. Seelig and Sorenson (1973) ascribed the decline to a combination of sediment trapping in upstream dams, improved soil conservation, and land use change.

Mathewson and Minter (1976) found that suspended sediment concentrations and total sediment loads at Richmond decreased over the 1924-70 period. They attributed the reduction to a combination of sediment storage in bars between Waco and the lower reaches of the river, and reduced frequency of high flows.

The sediment transport record for Richmond was divided into pre- and post-dam periods (before and after 1939) by Gillespie and Giardino (1997). Their statistical analysis showed that pre-dam discharge and sediment concentrations were significantly greater than after 1939. Dunn and Raines (2001) found that the percentage of sand at a given discharge declined at the Richmond station over the 1982-95 period compared to 1969-81, possibly related to a change in typical velocities. However, they also found no statistically significant change in the median annual load.

The Brazos River at Richmond transports most sediment during moderate discharge events, with 90 percent of the load transported in 17 percent of cumulative time (Hudson and Mossa, 1997). Thus, the changes in discharge, which have primarily influenced higher and lower flows, likely have had limited influence on sediment transport capacity.

Dunn and Raines (2001) approached the sediment transport problem from the perspective of shear stress necessary to mobilize the coarsest bed material, concluding that the lower Brazos has sufficient capacity to entrain these clasts at least 11 percent of the time. At least 82 percent of the time, the Brazos River can mobilize its typical bed material (Dunn and Raines ,2001).

A significant decrease in cropland area (from 32 to about 8 percent in the lower Brazos basin from 1924-92) has substantially reduced erosion potential and thus, potentially, sediment delivery (Dunn and Raines, 2001). However, the prevalence of bars in both the Navasota and Brazos Rivers, the apparently active alluvial sedimentation, and the ready availability of transportable channel and floodplain alluvium, suggests that both rivers are transport-limited rather than supply-limited. To the extent any changes in sediment transport occur, they are likely to be attributable to changes in transport capacity rather than supplies from upland erosion. This may be addressed during sediment budget studies, which should be coupled with assessment of evidence of changes in sediment transport throughout the study reaches, as the records from the Richmond station are the basis for almost all previous work.

Depending on the source, time period of record, data set, and figure used for drainage area, mean annual specific sediment yield for the Brazos River at Richmond ranges from 79 to 386 t km^{-2} yr^{-1} (SCS, 1959; Hudson and Mossa, 1997; Coonrod, et al., 1998; Oosting et al., 2004).

Repeat surveys of Lake Limestone (Austin et al., 2003) show changes in lake storage capacities from 1979 (impoundment began in late 1978) to 1993, when the reservoir was surveyed, and 2002, when the lake was resurveyed. The original capacity was 278,026,806 m^3 (225,400 ac-ft; at conservation pool level), with surveyed capacities of 264,985,202 m^3 (214,827 ac-ft) in 1993 and 256,696,204 m^3 (208,017 ac-ft) in 2002. The loss in capacity is likely due to sediment accumulation, which has been documented in Lake Limestone via acoustic profiling and coring (Dunbar and Allen, 2003), though differences in lake survey methods may introduce some error (Austin et al., 2003). Assuming a density of lake sediments of 1 t m^e (consistent with other studies; e.g. Smith et al. 2002.), this implies a mean annual sediment yield of about 530 t km^{-2} yr^{-1} for the 1748 km^2 watershed upstream of Lake Limestone Dam. Dellapena et al. (2004) report evidence of steady-state accumulation in analysis of lake bottom cores, which is consistent with the lake surveys, which indicate a nearly constant yield (531 t km^{-2} yr^{-1} over the entire 1979-2002 period; with rates of 533 for 1979-93 and 527 for 1993-2002).

The specific sediment yield for the lower Navasota River, as indicated by the Lake Limestone data, is systematically higher than any measurements for the Brazos, notwithstanding the variation in yields reported for the station at Richmond. Resurveys of Somerville Lake on Yegua Creek (Sullivan et al. 2003) suggest (using the same assumptions as above) a yield of 85 t km^{-2} yr^{-1} over the 1967-95 period in that 2,608 km^{2} watershed.

Coonrod et al. (1998) adjusted sediment yield data from SCS (1959), reporting values of 295 and 376 t km^{-2} yr^{-1} for the Brazos River at Waco and Richmond, respectively, and 176 t km^{-2} yr^{-1} for the Navasota River at Easterly. However, Coonrod et al.'s (1998) analysis of daily suspended sediment data collected in the 1960s-late 1980s gave lower values; 228 t km^{-2} yr^{-1} for the Brazos at Richmond and 51 for the Navasota at Easterly. TWDB lake resurvey data was used by Phillips et al. (2004) to compute a mean specific sediment yield for 27 east Texas reservoirs of 375 t km^{-2} yr^{-1}.

AVULSIONS AND CHANNEL CHANGE

Between Bryan and the Navasota River, Waters and Nordt (1995) found stratigraphic evidence of four avulsions between about 8.1 ka and 0.3 ka. In the lower 160 km, Taha and Anderson (2007) dated three major avulsions at about 7.5, 4.0, and 1.5 ka. This is generally consistent with analyses in this project, which found evidence of nine avulsions, four of which occur upstream of the Navasota confluence, three in the area considered by Taha and Anderson (2007), and two others in between. No previous work on channel changes has been conducted in the Navasota River.

In this study potential avulsions were identified where paleochannel alignments intersected the modern river. These location of these intersections was recorded, though in some cases the river course changes occurred away from the modern channel.

In both the lower Brazos and Navasota channel changes, including meander cutoffs and avulsions, were cataloged from aerial photographs and satellite images. All Brazos and seven Navasota River potential avulsion sites were field-checked to determine whether paleochannels identified from imagery had dimensions (discernible from paleobanks and the surveyed size of depressions) consistent with former river channels. This was not the case in all locations surveyed. For example, in Brazoria and Fort Bend counties former barge canals connecting former plantations that parallel the river give the appearance of paleochannels.

Meander cutoffs were characterized as neck or chute cutoffs, depending on whether the new channels cut across the base or neck of the bend, or across a point bar. Avulsions were characterized as relocations, where a new channel was established and the old channel either infilled or was occupied by a tributary; or anastamoses, where both channels persisted and rejoined downstream. Results are shown in Table 21.

Table 21. Cutoffs and avulsions.

	Cutoffs		*Avulsions*		*Crevasse*
	Neck	*Cutoff*	*Relocation*	*Anastamosing*	*splays*
Brazos	14	3	9	0	46
Navasota	6	8	9	18	not assessed

Cutoffs and avulsions both begin as breaches of natural levees, but not all such breaches result in channel change. In some instances flow through crevasses spreads and decelerates; in other cases the flow may be more channelized, but the channels do not persist. Evidence of these events are often preserved as crevasse splays on the floodplain surface. Apparent evidence of 46 separate crevasse splays was evident along the lower Brazos, from aerial photographs. While a few such features were observed in the field along the Navasota, they were not evident from imagery. This may be due to fewer such features on the Navasota, but is probably at least partly attributable to a generally finer load in the Navasota River, such that easily-recognizable sand splays are less common. Also, much of the Brazos alluvial valley is in row crops and pasture, compared to the highly forested Navasota valley, making splay features more difficult to find in the latter.

Avulsions generally fall into three categories. Progradational avulsions occur in strongly aggrading systems, where they may be forced by general or local aggradation and serve as a mechanism for distributing sediment. Incision avulsions result when flow through a levee breach incises a channel into the floodplain. Annexation avulsions occur when existing paleochannels or tributary channels are annexed or occupied by the river. According to Aslan and Blum (1999), Texas Gulf coastal plain rivers undergo two distinct styles of avulsion—reoccupation of former channels (annexation), and diversion into flood basins (progradation). The Nueces and Trinity Rivers are believed to represent early stages of sedimentary infilling in response to Holocene sea level rise, and avulse by reoccupying late Pleistocene channels cut during falling and lower-stand sea levels. The Colorado River is characterized as representing a later stage of infilling where most of the accommodation space is filled. Avulsions here occur as repeated diversions into floodplain depressions. The Brazos is considered similar to the Colorado in this regard.

Blum and Aslan (2006) linked floodplain formation and alluvial sedimentology in the Texas coastal plain region to avulsions. Transgressive to highstand facies-scale architecture reflects changes through time in the dominant styles of avulsion, and follows a predictable succession through different stages of valley filling. During the early stages of valley filling, avulsion occurs by reoccupation of abandoned falling stage and lowstand channels, with erosion and reworking of older channelbelt sands. This produces channel-in-channel stacking patterns, or multilateral and multistory channelbelts. As rates of valley filling increase, channelbelts aggrade rapidly and avulsion occurs by repeated diversion into floodplain depressions. This creates ribbon-like channelbelts, ribbon-like crevasse channel sands, and thin (<5 m) multilateral and multistory crevasse–splay sheet sands that are encased in thick successions of massive to laminated floodbasin muds.

When rates of aggradation are relatively low, avulsion by channel reoccupation again becomes the dominant process. The Sabine/Neches and Trinity incised valleys are unfilled, in the early stages of filling as described above, and avulsion has so far taken place by reoccupation of Deweyville falling stage to lowstand channelbelts. By contrast, the Brazos and Colorado valleys are filled, and has progressed through the entire sequence described above (Blum and Aslan, 2006). In the lower Brazos valley Taha and Anderson (2007) show a series of progradation avulsions progressing upstream as the locus of sediment accumulation migrates during sea level rise.

Oyster and Bessie's Creeks occupy the former Brazos River channel in the lowermost basin. An avulsion node near Brazoria is believed by Taha and Anderson (2007) to be associated with a previously unrecognized listric fault in the vicinity, and experienced an avulsion about 7 ka. Another avulsion from the Oyster Creek channel occurred about 4 ka near Rosharon. The avulsion causing the Brazos to divert from what is now the Bessie's Creek/Oyster Creek channel occurred near Garrett Lake about 1.5 ka (Taha and Anderson, 2007).

Stratigraphic evidence from the Bryan-Navasota section shows that avulsions occurred at about 9 to 9.4 and 2.5 ka, and about 500 and 300 years BP (Waters and Nordt, 1995). The location of these shifts was not specified, but all occurred after the system began incising into valley fills deposited before 9.4 ka.

Much of the lower Navasota is an anabranching or anastamosing system. Avulsions are necessary to create and maintain such patterns, and the Navasota is no exception, as indicated by the 27 apparent avulsions identified (Table 20)—an average of about one every 6 km over the 160 km of anabranching river styles.

The cumulative evidence suggests that:

•While avulsions are more common in rapidly aggrading situations (e.g., the lower Navasota), they appear to occur readily throughout the study area. Incision does not preclude avulsion, as at least seven occurred during periods of general downcutting in the lower Brazos (Waters and Nordt, 1995; Taha and Anderson, 2007).

•Avulsion has occurred within 300 years in the lower Brazos. Given the large number of crevasse splays observed, the availability of old channels for potential reoccupation (14 of the 19 river styles include prominent river paleochannels), high channel-floodplain connectivity (12 river styles are characterized by high connectivity), and cross-floodplain flow to former channels such as Oyster Creek, there is a high likelihood of future avulsions. These are most likely in the river styles characterized by high channel-floodplain connectivity and by paleochannels.

•Avulsion is an ongoing process in the lower Navasota. Evidence of channel changes in the recent past includes a now-abandoned gaging station at the SH21/US190 bridge where the dominant channel is not the one which was monitored. Local residents also recalled shifts among available subchannels. Though the specific dates and nature of these events could not be confirmed, the field evidence was generally consistent with their recollections. The various anabranching river styles in the lower Navasota are likely to continue to experience channel shifts.

SYNTHESIS

The objectives of this project included refining the river styles-based geomorphic assessment to characterize the character, behavior, and current geomorphic condition of the rivers; and determine trends of river evolution and future trajectories of change, as outlined in part 3 and the preceding portions of part 4. An additional objective, development of guidelines and protocols for applying a river styles-based geomorphic assessment in Texas, is presented in part 5 below. This section is intended to tie the results and interpretations above to some specific geomorphic questions laid out in the objectives.

Critical Transition Points and Zones

Critical process-form transition points and zones are characterized by boundaries or transitions in multiple geomorphic criteria as identified in the BCA. These are:

(1) Boggy Creek confluence with the Brazos River (Brazos reaches 3-4). The changes here are directly or indirectly related to valley confinement, as the river leaves a confined reach, pinned to the left valley wall, and crosses the alluvial plain. This is also associated with an increase in sinuousity.

(2) Yegua Creek confluence with the Brazos River (Brazos reaches 4-5). Besides joining with a large tributary, a major avulsion occurred near this location. There is also a transition from Eocene to Miocene geology and associated changes in valley width and confinement. Channel floodplain connectivity declines, and fewer active point bars are found downstream.

(3) Hidalgo Falls (Brazos reaches 5-6) is a key feature in its own right, and is also associated with significant changes in channel slope, valley width, channel pattern, and connectivity. The confluence with the Navasota river is also a short distance downstream.

(4) The bedrock confined valley river styles (Brazos reaches 9, 10) are associated with transitions in valley width and confinement and channel-floodplain connectivity, controlled by geology, on both the upstream (reaches 8-9) and downstream (10-11) ends.

(5) Allens Creek (Brazos reaches 16-17) is associated with changes in valley width and confinement, channel pattern, and sinuousity. These effects are largely controlled by the influence of antecedent valley features associated with a Pleistocene meander scar, as described by Sylvia and Galloway (2007).

(6) The reach from Rosenberg to Richmond (Brazos reach 19) is bounded by significant changes in valley width and sinuousity on the upstream end (18-19), controlled by a

geological transition into the middle coastal plain and a significant avulsion site. At the downstream end (19-20), changes occur in valley confinement, channel pattern, channel-floodplain connectivity, and sinuousity.

(7) In the general vicinity of Harris Reservoir (Brazos reaches 24, 25, 26) a series of transitions occur in valley width, sinuousity, channel pattern, slope, and point bars. The limit of tributary incision and the point at which the channel is cut to below sea level occur within this zone. This transition is associated with coastal backwater effects and very low slopes associated with the outermost coastal plain.

(8) Holland Creek (Navasota reaches 9-10) marks transitions in valley width and confinement, channel pattern, and channel-floodplain connectivity. This transition is associated with the Navasota exiting its own valley and crossing the Brazos alluvial valley.

(9) The Navasota River confluence with Big Creek (Navasota reaches 10-11) is the point at which the Navasota begins occupying a Brazos River paleochannel.

Critical points or zones 1, 2, and 8 are associated with internal morphology and dynamics of the river system, while 2, 3, 4, and 6 are either wholly or partly controlled by geological constraints. Antecedent fluvial/alluvial morphology plays a key role in transitions 5, 6, 7, and 9, and the Quaternary sea level history in transitions 5 and 7.

Relationships Between Modern and Paleochannels

The paleochannels representing former Brazos and Navasota River courses which can still be observed (some are presumably buried or otherwise obliterated) fall into several categories.

Infilled paleochannels are depressions indicating former channel positions which may be inundated during wet periods and convey flow during floods. The degree of infilling varies both within and between paleochannel courses. They are often discontinuous, and may contain reaches where the former channel position is barely evident, reaches perennially occupied by sloughs, and various intermediary states (figure 23). Both their surface topography and relatively easily-erodible fills make infilled paleochannels candidates to be reactivated by avulsions.

Figure 23. Brazos River floodplain near Millican. The former Brazos channel is evident on the upper left, including completely infilled segments and reaches holding water.

Semi-active subchannels are often inundated at normal water levels, but convey little or no flow, and are activated at high flows. Active subchannels are those which convey at least some downstream flow at normal water levels.

Some former river channels are occupied by tributaries or distributaries. Butler Bayou near College Station, Big Creek near Millican, and the lowermost Navasota River occupy former Brazos paleochannels, for example. Oyster Creek is a special class of distributary channel which might be called watershed fragmentation, since there is no hydraulic connection from the Brazos except during floods.

In the Navasota River connections beween the current dominant channel and the anabranches or paleochannels are quite strong. During high flows interdistributary channelized and cross-floodplain flow between subchannels was observed. Old channels are also apparently reactivated frequently in this system, and the merger of subchannels is common during large floods.

Connections are not as strong in the Brazos. However, backwater flooding into tributary-occupied paleochannels is common in the steeply incised valley fill, meandering incised valley fill, meandering confined incised valley fill, and strongly meandering valley fill river styles. Cross-floodplain flow into distributary-occupied paleochannels is common in the unconfined low-sinuousity, avulsed alluvial valley II, partly-confined low sinuousity, partly-confined low-sinuousity II, lower coastal plain, and low-sinuousity lower coastal plain river styles.

Controls of Channel Incision

The local controls of channel downcutting are substrate and slope adjustments. Where bedrock (or, to a lesser extent, resistant pre-Holocene clays) are exposed the rate of channel bed scour is greatly reduced. Because slope changes associated with lateral migration (meander growth) and channel changes (cutoffs and avulsions) are expected to dominate any changes in slope in the near future, slope adjustments are not a major control of channel incision in the Brazos River.

Brazos vs. Navasota

A key question emerging from this work is the fundamentally different morphologies, behaviors, and river styles in the lower Brazos and lower Navasota rivers. Why is the Navasota experiencing more aggradation, limited incision, and the anabranching character not found in the lower Brazos? A detailed investigation is beyond the scope of this study, but some preliminary suggestions can be made. First, the anabranching is consistent with the aggradational nature of the valley. The aggradation may be partly attributable to the apparently higher rates of sediment production in the Navasota area referred to earlier. In a study of a Brazos River tributary upstream of the study are for this project, Nordt (2004) showed that the depositional and erosional phases of Cowhouse Creek are out of phase with trends in the Brazos. Thus it could be that the Navasota River is still in a pre-incisional phase. However, other lower Brazos tributaries are typically incised and do not exhibit the strongly aggradational, anabranching characteristics of the Navasota.

Nordt (2004) identified an apparent increase in soil erosion on Cowhouse Creek in response to warmer climate conditions, which resulted in widespread valley filling. This may have also occurred in the Navasota system. However, in the latter case either this fill was not strongly incised, or any incision has subsequently been buried by historical and recent sediment.

At this point the latter interpretation is favored, based on the shape of tributary long profiles, and the recent/historical nature of much of the Navasota valley alluvium. In addition to the possibility of higher erosion and sediment yield rates than the Brazos, the narrower, bedrock-controlled valley of the Navasota may limit sedimentary accommodation space such that even if per-unit-area erosion and sediment yield rates were similar, more aggradation would result in the Navasota system. This is still speculative, however, and further research is needed.

Part 5
Guidelines and Protocols for River Styles Applications in Texas

The Boundary Coincidence Analysis (BCA) approach for river styles characterizations is recommended for the Texas Instrream Flow Program. The advantages of a BCA approach are that it:

- Provides a systematic framework for identifying key geomorphic chacteristics along a river corridor.

- Results in the identification of key transition zones and hinge points.

- Is consistent with the general RS-based approach (Phillips, 2007b).

BOUNDARY COINCIDENCE ANALYSIS

The general procedures in applying BCA are as follows:

1. Identify Potential Boundary Criteria

Potential boundary criteria are factors that potentially control, or reflect, major changes in the environmental framework of the river, or in the environment of the river and its valley. Some factors should be considered in essentially any river system. These include:

- Geologic framework. This is primarily the surficial geology, but may also include tectonic or other structures.

- Valley width.

- Valley confinement.

- Sinuousity.

- Channel and valley slope.

- Channel and network morphology and geometry; e.g., single-thread vs. anabranching patterns, convergent vs. divergent flow networks; dendritic vs. structurally-controlled drainage patterns, etc.

Potential boundary criteria also include factors which are important in particular river systems or environmental settings. For example, the following factors should be considered in the southeast Texas Coastal Plain, but my not be relevant elsewhere in Texas:

- Tidal and coastal backwater effects.

- Point at which thalweg is cut to below sea level.

- Presence and size of sandy point bars.

- Pleistocene paleomeanders.

Anthropic factors should not be ignored. In some cases impounded reaches, backwater effects from impoundments, and scour zones downstream of dams may represent important boundaries. Potential boundaries may also be associated with zones affected by flow regulation, withdrawals, or returns. Channelized, hardened, and other engineering features and activities should also be considered.

Finally, some pontential boundary controls may vary with scale. For instance, within the lower Trinity or Brazos Rivers climate variability is limited and there are no significant climate-related boundaries. If one were considering the entire Brazos or Trinity Watershed, however, encompassing several climate zones, then climate should be considered as a significant potential boundary criterion.

2. Identify Individual Boundaries; Eliminate Ineffective Criteria

Preliminary identification of boundaries associated with individual criteria allows identification of criteria which can be excluded in subsequent analyses. Two legitimate rationales for exclusion are lack of variation, and lack of geomorphic relevance. If an entire study reach appears to have similar sinuousity, for example, and if subdividing yields sinuousity values within a relatively small range (say, 1.5 to 1.7), then this criterion is not useful in identifying geomorphically significant variations in the study reach. This is not to imply that (say) sinuousity is unimportant in characterizing the study area; just that it is not useful in subdividing it.

An example of limited geomorphic relevance is the ratio of valley to channel width in southeast Texas. This ratio is quite significant in many situations, and is used in many classification systems. However, in the study area, though this ratio varies quantitatively quite a bit, it is uniformly large. That is, even the smallest ratio indicates valley widths much larger than channel widths, and a lack of valley width control on fluvial behavior.

3. Check and Refine Individual Boundaries

Many criteria may require field checking to determine the proper location and nature of the boundary. For example, anabranching channels and avulsions in the lower Sabine River are evident from maps, digital elevation data, and aerial photographs. However, the nature and relative importance of these features in determining the flow patterns in the lower Sabine are evident only in the field.

For another example, an apparent linear ridge in the digital elevation model could be real, or an artifact of the data. In some cases cross-checking with aerial photographs and topographic maps might be sufficient to confirm without field work. The origin of the ridge (fault trace? Pleistocene barrier island trend? old railroad grade?) might be determined from GIS data, or might require field investigation.

4. Boundary Coincidence Assessment

If boundaries are within about 0.25 percent of the river length (e.g., about 0.5 km over a 200 km reach), they may be considered coincident. If individual boundaries are nearby, an assessment should be made as to whether their locations are within the potential error or uncertainty associated with the boundary designations. In some cases, boundaries may be both accurately and precisely defined—for example, the apex of the bayhead delta in the Trinity River, or Hidalgo Falls on the Brazos. In other cases, the boundary may be accurate—e.g., between two zones of high and low sinuousity—but imprecise in the sense of exactly where the separation is marked. Finally, a boundary may be precisely specified but uncertain in terms of accuracy. For example, slope breaks may be precisely identified in digital elevation model-derived profiles, but the inherent uncertainty in such data, particularly as it relates to channels, limit one's confidence in the exact location of the break in slope.

If boundaries are in proximity, if the differences could be accounted for by error and uncertainty in boundary demarcation, and if there is a plausible geomorphic relationship between the criteria (e.g., slope and sinuousity, or geologic setting and valley width), the boundaries should be considered coincident.

5. Identify Key Hinge Points

A location with multiple coincident boundaries is a potential hinge or transition pont (or zone). Reaches with several nearby but not coincident boundaries may be considered transition zones in some cases--that is, a single reach identified by a river style characterized by systematic changes over short distances. In other cases such reaches may be divided up into individual reaches, each characterized by its own river style.

How such reaches should be treated depends on the specific geomorphic situation, the scale or analysis (or of final products), and the management relevance of the changes and boundaries. For instance, boundaries related to, e.g., slope, sinuousity, and bed material may be highly significant with respect to aquatic habitats, and thus to the IFP. Boundaries within a tidally-dominated section, conversely, which are not greatly influenced by upstream flow, may be of limited relevance to the IFP.

6. Apply River Styles

Relatively long river reaches between boundaries should be assigned to a single river style, and sections characterized by relatively close but not coincident boundaries treated as outlined above. Minor or single boundaries between key hinge points or transition zones may be used to subdivide or separate river styles, depending on the magnitude, geomorphic significance, and management relevance of the changes they reflect.

References Cited

Alford, J.J., Holmes, J.C., 1985. Meander scars as evidence of major climate change in southwest Louisiana. Annals of the Association of American Geographers 75, 395-403.

Austin, B., Thomas, D., Burns, R., Sansom, M., Moltz, H. 2003. Volumetric Survey Report of Lake Limestone. April 2002 Survey. Austin: Texas Water Development Board.

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

Blum, M.D., Price, D.M., 1998. Quaternary alluvial plain construction in response to glacio-eustatic and climatic controls, Texas Gulf Coastal Plain. In Shanley, K., McCabe, P., eds., Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks. Tulsa, OK, Society for Sedimentary Geology, SEPM spec. publ. 59, 31-48.

Brierly, G.J., Fryirs, K., 2000. River styles, a geomorphic approach to catchment characterization: Implications for river rehabilitation in Bega catchment, New South Wales, Australia. Environmental Management 6, 661-679.

Brierly, G.J., Fryirs, K., 2005. Geomorphology and River Management. Applications of the River Styles Framework. Oxford, Blackwell.

Brierley G, Fryirs K, Outhet D, Massey C., 2002. Application of the River Styles framework as a basis for river management in New South Wales, Australia. Applied Geography 22, 91-122.

Chin, A., Bowman, J.A., 2005. Changes in flow regime following dam construction, Yegua Creek, south-central Texas. In Norwine, J., Giardino, J.R., Krishnamurthy, S., eds., Water for Texas. College Station: Texas A&M University Press, p. 166-177.

Chin, A., Harris, D.L., Trice, T.H., Given, J.L., 2002. Adjustment of stream channel capacity following dam closure, Yegua Creek, Texas. Journal of the American Water Resources Association 38, 1521-1531.

Coonrod, J.E.A., Holley, E.R., Maidment, D.R., Ward, G.H. 1998. Suspended Sediment Yield in Texas Watersheds. Austin: Texas Water Development Board.

Dellapena, T.M., Bronikowski, J., Majzlik, E., Manuel, J., Noll, C. 2004. Brazos River Authority May 2003 CHIRP Sub-bottom Profilers Survey and Sediment

Core Analyses of Aquilla Lake, Granger Lake, Limestone Lake, Lake Proctor. Austin: Texas Water Development Board.

Dunbar, J.A., Allen, P.M. 2003. Sediment Thickness from Coring and Acoustics Within Lakes Aquilla, Granger, Limeston, and Proctor: Brazos River Watershed, TX. Austin: Texas Water Development Board.

Dunn, D.D., Raines, T.H., 2001. Indications and Potential Sources of Change in Sand Transport in the Brazos River, Texas. U.S. Geological Survey Water-Resources Investigations Report 01-4057.

Ewing, T.E., Budnik, R.T., Ames, J.T., Ridner, D.M., Dillon, R.L., 1991. *Tectonic Map of Texas. Austin: Texas Bureau of Economic Geology.*

Gillespie, B.M., Giardino, J.R., 1997. The nature of channel planform change—Brazos River, Texas. Texas Journal of Science 49, 108-142.

Harmar, O.P., Clifford, N.J. 2007. Geomorphological explanation of the long profile of the lower Mississippi River. Geomorphology 84, 222-240.

Heinrich, P., Snead, J., McCulloh, R., 2002. Lake Charles 30 X 60 Minute Geologic Quadrangle. Baton Rouge: Louisiana Geological Survey.

Hudson, PF, J. Mossa. 1997. Suspended sediment transport effectiveness of three large impounded rivers, U.S. Gulf Coastal Plain. Environmental Geology 32 (4): 263-273.

Mathewson, C.C., Minter, L.L., 1976. Impact of Water Resource Development on Coastal Erosion, Brazos River, Texas. College Station: Texas Water Resources Institute, Technical Rept. 77.

Mueller, D. 2002. BSDMS Summary Report. Brazos River at FM2004 Near Lake Jackson, TX. U.S. Geological Survey, National Bridge Scour Database. URL: http://water.usgs.gov/osw/techniques/bs/BSDMS/BSDMS_1.htm

Morton, R.A., Blum, M.D., White, W.A. 1996. Valley fills of incised coastal plain rivers, southeastern Texas. Transactions of the Gulf Coast Association of Geological Societies 46, 321-331.

NAS Committee on Review of Methods for Establishing Instream Flows for Texas Rivers, 2005. The Science of Instream Flows: A Review of the Texas Instream Flow Program. Washington: National Academy of Science report, National Academies Press.

Nordt, L. 2004. Late Quaternary alluvial stratigraphy of a low-order tributary in central Texas, USA and its response to climate and sediment supply. Quaternary Research 62, 289-300.

Nordt, L.C., Boutton, T.W., Hallmark, C.T., Waters, M.R. 1994. Late Quaternary vegetation and climate changes in central Texas based on the isotopic composition of organic carbon. Quaternary Research 41, 109-120.

Ohmori, H. 1991. Change in the mathematical function type describing the longitudinal profile of a river through an evolutionary process. Journal of Geology 99, 97-110.

Oosting, T., Mathews, R., Austin, B., 2004. Analysis of Instream Flows for the Lower Brazos River—Hydrology, Hydraulics, and Fish Habitat Utilization. Final Report to the U.S. Army Corps of Engineers. Austin: Texas Water Development Board.

Otvos, E.G., 2005. Numerical chronology of Pleistocene coastal plain and valley development; extensive aggradation during glacial low sea-levels. Quaternary International 135, 91-113.

Parsons, M., Thoms, M. and Norris, R. 2002. Australian River Assessment System: Review of Physical River Assessment Methods — A Biological Perspective. Cooperative Research Centre for Freshwater Ecology Monitoring River Health Initiative Technical Report 21. Canberra: Environment Australia.

Phillips, J.D., 2007b. Geomorphic controls and transition zones in the lower Sabine River. *Hydrological Processes* (in press).

Phillips, J.D., 2007c. Perfection and complexity in the lower Brazos River. *Geomorphology* 91: 364-377

Phillips, J.D., Slattery, M.C. 2006. Sediment storage, sea level, and sediment delivery to the ocean by coastal plain rivers. *Progress in Physical Geography* 30: 513-530.

Phillips, J.D., Slattery, M.C., 2007a. Downstream trends in discharge, slope, and stream power in a coastal plain river. *Journal of Hydrology* 334: 290-303.

Phillips, J.D., Slattery, M.C., 2007b. Antecedent alluvial morphology and sea level controls on form-process transition zones in the lower Trinity River, Texas. *River Research and Applications* (in press).

Phillips, J.D., Slattery, M.C., Musselman, Z.A. 2005. Channel adjustments of the lower Trinity River, Texas, downstream of Livingston Dam. Earth Surface Processes and Landforms

Phillips, J.D., Slattery, M.C., Musselman, Z.A. 2004. Dam-to-delta sediment inputs and storage in the lower Trinity River, Texas. Geomorphology 62: 17-34.

Rodriguez, A.B., Anderson, J.B., Simms, A.R., 2005. Terrace inundation as an autocyclic mechanism for parasequence formation: Galveston estuary, Texas, U.S.A. Journal of Sedimentary Research 75, 608-620.

Rodriguez, A.B., Hamilton, M.D., Anderson, J.B., 2000. Facies and evolution of the modern Brazos delta, Texas: wave versus flood dominance. Journal of Sedimentary Research 70, 283-295.

Seelig, W.N., Sorenson, R.M., 1973. Investigation of Shoreline Changes at Sargent Beach, Texas. College Station: Texas A&M University/U.S. Army Corps of Engineers rept. 169.

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

Snow, R.S., Slingerland, R.L. 1987. Mathematical modeling of graded river profiles. Journal of Geology 95, 15-33.

Soil Conservation Service, U.S. Department of Agriculture. 1959. Inventory and Use of Sedimentation Data in Texas. Austin: Texas Board of Water Engineers Bull. 5912.

Sullivan, S., Thomas, D., Elliott, W., Segura, S., Robichaud, M. 2003. Volumetric Survey of Somerville Lake. Austin: Texas Water Development Board.

Taha, Z.P., 2007. Fluvial response to base level change: A case study of the Brazos River, East Texas, U.S.A.: Ph.D. Dissertation, Rice University, Houston, TX, 156 pp.

Taha, Z.P., Anderson, J.B. 2007. The influence of valley aggradation and listric normal fauling on styles of river avulsion: A case study of the Brazos River, Texas, USA. Geomorphology (in press): doi: 10.1016/j.geomorph.2007.07.014

Thomas, M.A., Anderson, J.B., 1994. Sea-level controls on the facies architecture of the Trinity/Sabine incised-valley system, Texas continental schelf. In R.W. Dalrymple, R. Boyd, B.Z. Zaitline, eds., Incised-Valley Systems: Origin and Sedimentary Sequences. SEPM (Society for Sedimentary Geology), 63-82.

Thomson, J.R., Taylor, M.P., Brierly, G.J., 2004. Are River Styles ecologically meaningful? A test of the ecological significance of a geomorphic river characterization scheme. Aquatic Conservation—Marine and Freshwater Ecosystems 14, 25-48.

Waters, M.R., Nordt, L.C. 1995. Late Quaternary floodplain history of the Brazos River in east-central Texas. Quaternary Research 43, 311-319.

Yancey, T.E., Davidoff, A.J. 1994. Paleogene Sequence Stratigraphy of the Brazos River Section, Texas. Field Trip Guide, Gulf Coast Association of Geological Societies, Austin, TX, 104 p.

Appendix

SCOPE OF WORK PLAN

Field Data Collection in Support of Geomorphic Classification in the lower Brazos and Navasota Rivers, Texas: Phase Two

Jonathan D. Phillips

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Overview

This work plan addresses a continuation of a cooperative research study of the geomorphology of the Navasota and lower Brazos Rivers. The study is designed to determine the geomorphic context and constraints for management of instream flows and aquatic and riparian habitats by addressing the physical framework of the river channel. In the first year an appropriate geomorphic classification scheme was identified and applied to the study area at a broad scale, based on maps, imagery, geographical information systems databases, and other data sources. This continuation is intended to introduce more detail (finer spatial resolution), to incorporate field data and observations, and to resolve issues regarding the geomorphic conditions and trajectories of change.

The specific objectives are to:

(1) Apply the river styles-based geomorphic assessment identified in year one to:
    (1a) develop a baseline characterization of the character and behavior of the lower Brazos (downstream of Bryan, TX) and Navasota Rivers,
    (1b) assess current geomorphic condition of the river, in the context of ecological functions and instream flows,
    (1c) determine trends of Holocene, historical, and recent river evolution,
    (1d) estimate the future trajectory of geomorphic change, and
    (1e) determine recovery potential of degraded or suboptimal reaches.

(2) Identify critical process/form transition points along the study rivers.

(3) Resolve geomorphic questions arising from the first year of work, specifically:
    •The cause and timing of avulsion events.

•Hydrologic and geomorphic relationships between the Brazos River and tributaries (including portions of the Navasota) current occupying former Brazos channels.

•Potential bedrock (loosely defined here as any relatively cohesive pre-Quaternary material) controls on (further) channel incision.

•Causes of and future potential for bed degradation and lateral channel migration.

(4) Develop guidelines and protocols for applying a river styles-based geomorphic assessment approach in alluvial rivers in Texas.

Objective (1) duplicates one set of objectives for year 1. The difference is that the first phase focused on the broad scale of river reaches and features discernible from aerial photographs, imagery, and maps, and covered the entire Brazos River downstream of SH 21 near Bryan, and Navasota River below Lake Limestone. This phase will focus on selected representative and problematic reaches and sites to be examined in the field.

Methods

Field studies will focus on sites or reaches that:

•Appear to be critical boundaries or transition zones—for example, the apparent site of a major avulsion away from the channel now occupied by Bessie and Oyster Creeks, and the Hidalgo Falls area.

•Are representative of the most prevalent river styles identified in phase 1.

•Present key geomorphic questions, such as areas of the Navasota River that appear to behave as anabranching sreams at high flows.

Baseline Characterization at these local river scales will confirm and modify if necessary earlier determinations of the environmental framework of the river in terms of geology, topography, hydrology, soils, and land use.

Current Geomorphic Condition assessments will be made based on field indicators of factors such as the degradational or aggradational state of the channel, frequency of overbank flooding, lateral migratory stability, presence or absence of diagnostic geomorphic features (for example knickpoints, cut banks, point bars, tributary-mouth bars or deltas, oxbows, and meander scars), and morphometric properties (for example valley vs. channel width ratio, channel sinuosity, valley slope).

River Evolution Trends can be assessed in part from the characterizations and assessments above. Trends in lateral channel migration, for instance, can be deduced from channel and floodplain morphological features.

Trajectories of Change for the near future will be developed from a combination of historical extrapolation, consideration of factors that may slow, accelerate, or prevent ongoing changes in the future, and incorporation of the effects of possible, proposed, or expected changes in environmental factors (for example, continued sea level rise, or future water withdrawals).

Recovery Potential assessment will be derived from coupling the evaluation of the current geomorphic condition with the likely trajectories of change. A matrix will be constructed for reaches considered degraded or problematic, and the extent to which ongoing and future change is likely to maintain, enhance (worsen), mitigate (improve) the current state, or move the reach to a different condition.

The geomorphic indicators include topographic, morphology, sedimentary, stratigraphic, pedologic, and cultural features, as utilized in previous work for the TWDB by the principal investigator on the Trinity and Sabne Rivers and Loco Bayou.

Personnel and Responsibilities

TWDB will oversee the activities and serve as contract manager. Dr. Jonathan Phillips of the University of Kentucky (but acting as an independent contractor) is responsible for all objectives and tasks in the scope of work, assisted as needed by research assistants arranged for and compensated by Phillips.