Rivers and Landscapes of the Texas Gulf Coastal Plain

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The Texas Gulf Coastal Plain is a large region with a complex landscape that drains into the Northwestern Gulf of Mexico. Over the past five decades there have been numerous studies pertaining to various aspects of the physical geography of the Texas coastal plain. Unfortunately there has been little attempt to provide a comprehensive summary of this information to professionals, or students of physical geography. This paper is intended to represent an essential reference to specialists interested in Texas coastal plain river systems, while being a key resource to students interested in the physical geography of Texas.

This study reviews fundamental concepts in physical geography that pertain to Texas coastal plain river systems, and summarizes the geomorphic and hydrologic characteristics of Texas rivers. Specifically, this paper characterizes the geomorphic divisions within the coastal plain, reviews the hydroclimatology of Texas river basins, and examines linkages between flooding and floodplain processes using a variety of hydrologic and geomorphic indices. The major data sources included U.S. Geological Survey streamflow data and digital topographic data in a GIS format. Texas coastal plain rivers were placed within three scale-dependent categories, including extrabasinal, basin-fringe, and intrabasinal systems. The data reveals substantial differences in flood intensity and floodplain complexity between extrabasinal, basin-fringe, and intrabasinal rivers. The framework utilized in this study represents a promising approach for river managers examining differences in flooding and environmental change along the lower reaches of Texas coastal plain rivers.
Key Words: Texas geography, Gulf Coastal Plain, rivers and floodplains, flooding.

Introduction

Texas is drained by an extensive network of large rivers that flow into the northwestern Gulf of Mexico (Figure 1). As the largest state in the continental U.S., the physical geography of Texas is diverse and includes an array of landscapes which vary according to climate, physiography, and land-use. The rivers that drain Texas reflect this diversity and vary tremendously in size, morphology, and hydrology. However, coastal plain rivers are often erroneously

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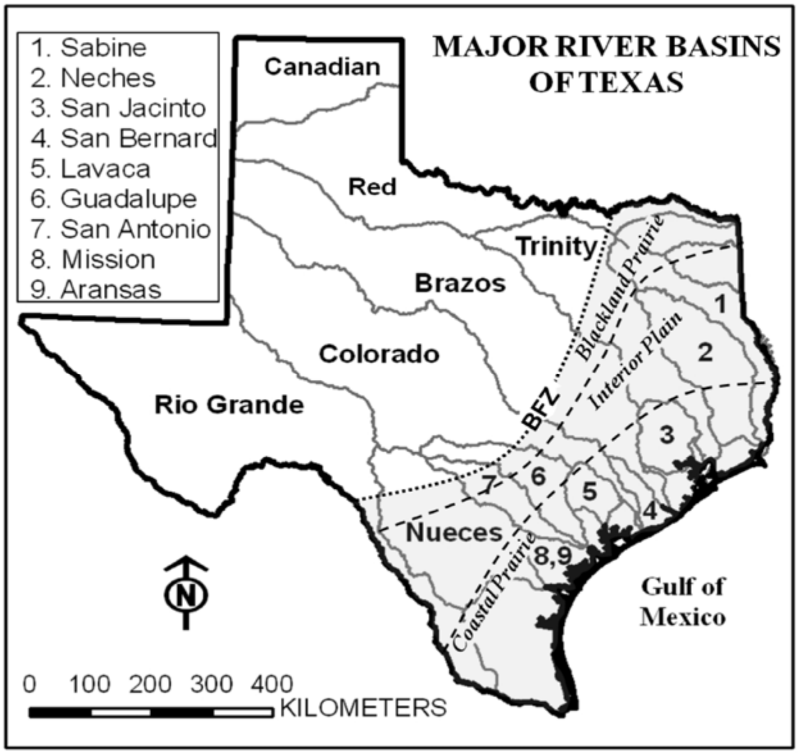

Figure 1. The major river basins of Texas draining into the Gulf of Mexico. Note that the Canadian and Red Rivers flow into the Gulf of Mexico after joining the Arkansas and Mississippi Rivers, respectively, and are not reviewed in this manuscript. The Gulf Coastal Plain is shown as shaded (grey), with the Balcones Fault Zone as the border between the coastal plain and the Edwards Plateau (not labeled). The coastal plain is further segmented into the Blackland Prairie, Interior Plain, and Coastal Prairie.

portrayed as being more similar than unique, which has implications to the development of appropriate management and planning strategies. Unfortunately there is no single resource that provides a comprehensive characterization of Texas' coastal plain river systems.

The coastal plain rivers of Texas have long served as a natural "laboratory" for researchers interested in the evolution and dynamics of fluvial systems, and numerous case studies of individual rivers have been published in the scientific literature. Unfortunately, Texas geography students are significantly disadvantaged because existing physical geography teaching materials rarely provide examples from Texas. Indeed, many text book examples do not apply to Texas because of being developed in other regions. Texas affords many opportunities to teach fundamental principles and concepts in physical geography, particularly as related to the hydrology and geomorphology of coastal plain environments.

The primary goal of this paper is to provide students of Texas geography with an overview and characterization of the Texas Gulf Coastal Plain (Figure 1), by far the largest region in Texas in terms of area and population. This is approached by reviewing the physical characteristics of the Texas coastal plain, emphasizing the climate and geology as the framework for coastal plain rivers. Specific aspects of Texas coastal plain rivers are also examined, with an emphasis on illustrating linkages between climate and hydrology, and flooding and floodplain processes. In covering these themes students are introduced to a number of topics and fundamental concepts in physical geography, but provided examples from Texas. These subjects are very important to the ways in which students interact with the physical environment of Texas. Indeed, the existing lack of materials creates a "disconnect" between what is leaned in the classroom and how many Texas students experience their landscape.

Readers who have had an "introductory" course in physical geography (or geology) should have sufficient background to work through the text. For students without this background, most scientific terms are defined within this manuscript. The definitions for terms may also be found in one of several online dictionaries of physical geography, such as "*PhysicalGeography.net*" (http://www.physicalgeography.net/home.html).

A secondary goal of this paper is to provide specialists with a resource that can be used to characterize Texas coastal plain rivers, the state's largest and most important category of rivers because of their extent and linkages to riparian and coastal ecosystems. Texas coastal plain rivers have been subjected to decades of neglect and mismanagement associated with flood control, navigation, and land use change. Recent and future projections of sea level rise and climate change create additional uncertainty. There is tremendous interest and passion about these issues across Texas. Government agencies are working to develop effective management strategies that simultaneously reduce flood risk and enhance the environmental integrity of Texas rivers. Unfortunately, specialist cannot consult a single comprehensive resource that provides an overview of Texas river systems. This has greatly hindered Texas' ability to develop effective management plans for coping with these various environmental change issues. Thus, this paper is also intended to be of interest to specialists in government agencies and academia by providing a substantial compilation of indices derived from secondary data sources that pertain to the hydrology and geomorphology of Texas rivers.

The Physical Framework

Location and Context

Located at the margins of major North American physiographic, vegetation, and climatic provinces, Texas is a true border state. Texas' landscape is defined by a strong east to west precipitation gradient and a north to south temperature gradient superimposed over the southern limits of the American Great Plains, the eastern margins of the Basin and Range Province and North American Deserts, and the western edges of the eastern temperate forests (coniferous and deciduous). Thus, Texas' landscape is a rich composite of diverse elements, and is distinct because of its union rather than its singularity. Texas rivers are complex, which is in part because of their drainage basins receiving inputs of streamflow and sediment from a variety of landscape types (Hudson and Mossa, 1997a). Indeed, because of the large drainage areas that generally characterize coastal plain river systems, even a single watershed is commonly influenced by very different rock types, land use, and precipitation regimes.

Physical Divisions

Texas is conventionally subdivided into seven physiographic provinces associated with distinctive landscape types (Hill, 1900; Wermund, 1996). The seven physiographic provinces of Texas include the Basin and Range, High Plains (also known as the Llano Estacado), North Central Plains, Grand Prairie, Central Texas Uplift (also known as the Llano Uplift), Edwards Plateau (which includes the Stockton Plateau), and the Gulf Coastal Plains. These seven physiographic provinces strongly correlate with differences in lithology, relief, geomorphology, soils, vegetation assemblages, and more loosely with precipitation (Wermund, 1996; Griffith et al., 2004). Thus, these various physiographic divisions may be considered surrogates for ecoregions, a term widely adapted by biologists and planners at state and federal agencies for defining areas with similar ecological qualities (Linman et al., 2002; Griffith et al., 2004). The correlative quality of physiographic provinces is important, as it strongly influences the hydrologic regime and sediment load of rivers, both of which are critical controls on the geomorphic and ecological dynamics of rivers and floodplains.

Hydroclimatology

One of the most defining elements of Texas' physical geography is its precipitation pattern. Spatially, precipitation varies along a pronounced east to west gradient, but varies little from north to south (Jones, 1989; Hudson and Mossa, 1997a). The annual precipitation along the middle Rio Grande Valley at El Paso averages 15 cm, while near the lower reaches of the Trinity and Sabine Rivers in east Texas there is an average of 140 cm of precipitation (Jones, 1989). Seasonally, late fall and late spring are the wettest periods, and in most parts of the state April and May receive the highest precipitation. The source of moisture is predominately from the Gulf of Mexico, and to a lesser extent from the Pacific Ocean.

River basins in Texas may be impacted by four major precipitation mechanisms; westerly migrating cyclones (fronts), tropical cyclones, convectional thunderstorms (Bomar, 1983; Jones, 1989), and anomalous positions of the subtropical jet stream. The rainfall mechanisms range in scale from regional to local, and are very much influenced by the pattern of the polar jet stream in the winter and the subtropical jet stream in the fall and spring. Subtle changes in the jet stream from "average" positions can result in a shift in the dominant rainfall mechanism that influences a watershed. Such changes can occur due to El Nino - La Nina cycles, and are important to Texas as it concerns water management, flood control, and river and estuarine environments (Longly, 1994; Tolan et al., 2004; Tolan, 2007). Snow melt is important only to the Rio Grande drainage system, primarily from the Rocky Mountains in Colorado and New Mexico during the spring, and is not further considered.

Westerly migrating cyclones have moisture sources from the Gulf of Mexico and Pacific and deliver widespread precipitation along frontal boundaries. This is the dominant precipitation mechanism from the late fall though spring as cooler air masses from Canada or the Pacific come in contact with warm moist air from the Gulf of Mexico. Frontal precipitation is the most dependable source of precipitation to Texas and is important to watersheds of all sizes draining northern, central, eastern, south-central, and southeastern portions of the state, but tends to be less important to watersheds draining west or southwestern Texas.

Tropical cyclones originating in the Atlantic, Caribbean, or Gulf of Mexico are important during the late summer and early fall. Although their timing and location is highly variable, tropical cyclones can produce rainfall events of high intensity and duration, which can generate flooding in smaller watersheds (Jones, 1989; Slade and Abbott, 2002). Tropical cyclones need not be at hurricane status to be hydrologically important. Some of the most substantial floods in recent Texas history have occurred because of smaller tropical cyclones stalling and becoming stationary over land as they continue to draw in moisture from the Gulf of Mexico. Recent examples include the devastating flooding of Houston in June 2001 from Tropical Storm Allison, and the Guadalupe River flooding of July 2002. Both cases involved a relatively disorganized tropical wave that reformed and strengthened in the Gulf of Mexico, with the flooding caused more by duration than storm severity. The July 2002 flood event in the Guadalupe basin had a flood recurrence interval of about 10 yrs (Hudson, unpublished data) and caused extensive flooding along the Guadalupe valley between the Edwards Plateau and the coastal plain (Figure 2).

A. B.

Figure 2. Example of flooding along the Guadalupe River valley in July 2002. A. Flooding on July 3 shortly before the flood wave crested. The flooding is within the narrow incised valley upstream of New Braunfels, within the Balcones Fault Zone. Note inundation within the canopy of mature pecan trees, located near the submerged river bank. At low stage the top of the bridge is ~12 m above the Guadalupe River. Photo source: P.F. Hudson. B. Flooding of the broad river valley downstream of Cuero on July 7, one day after the crest of the flood wave. Note the high suspended sediment load. The river is located in background, ~75 m beyond tree line. Photo source: P.F. Hudson.

Convectional precipitation tends to occur in the late spring and early summer, and draws moisture from the Gulf of Mexico or from evaporation of local soil moisture (Bomar, 1983). Convectional precipitation can result in intense rainfall events, but generally occurs over a small area and for a limited duration (hours). For this reason convectional precipitation is important to small and intermediate sized basins, particularly within humid eastern and central Texas, but is much less important to the stream hydrology and geomorphology of large watersheds.

Finally, anomalous positions of the subtropical jet stream over the eastern United States, especially during the summer months, can result in persistent troughs that effectively route Gulf of Mexico moisture over Texas, as opposed to the eastern half of the country. Low-pressure systems act as the convergent mechanism to produce appreciable rainfall totals over Texas. For example, the summer of 2007 was characterized by a persistent trough in the jet stream over the eastern half of the U.S., drawing in moisture from the Gulf of Mexico and generating persistent precipitation, as well as flooding along small and intermediate sized rivers. Interestingly, these low-pressure systems were not associated with frontal boundaries or tropical cyclones.

Large portions of the Texas landscape are often classified as dry or *parched*, according to regional drought indices. This is largely the result of high rates of evapotranspiration and the timing of precipitation events, rather than the actual rainfall totals (Jones, 1989). Indeed, much of Texas receives moderate annual rainfall, although it is often associated with infrequent intense events. The average annual precipitation of Austin, in Central Texas, is 79 cm. By comparison, the average annual precipitation of London, England, generally considered to be wet and humid, is only 58 cm. The higher temperatures in Texas result in much greater rates of evapotranspiration, the process by which soil moisture is transferred from soil and plants to the atmosphere. Additionally, rather than infiltrating into the ground and replenishing soil moisture and recharging aquifers, much of the precipitation generated by intense rainfall events in Texas quickly produces runoff and flows overland into stream channels. Indeed, Texas has recorded some of the highest rainfall intensities in the world, which is responsible for portions of the state being referred to as "flash flood alley" (Beard, 1975; Baker, 1977; Slade and Abbott, 2002). However, flooding is a complex process and requires consideration of specific precipitation mechanisms and the location and geomorphology of river basins.

Rainfall events produced by the four precipitation mechanisms outlined above are often influenced by topography, particularly the abrupt rise in elevation along the Balcones Fault Zone (Slade and Abbott, 2002; Earl and Dixon, 2005; Nielsen-Gammon, 2005). Additionally, the most severe floods in Texas tend to occur when there is a confluence of precipitation mechanisms and landscapes, and are typically preceded by wet conditions. Such was the case for the great Guadalupe River flood of October 1998, which occurred when a trough of low pressure aligned west of the Balcones Escarpment and drew in moisture from the Gulf of Mexico and from hurricanes in the eastern Pacific (Slade and Persky, 1999; Slade and Abbott, 2002). In terms of Texas hydroclimatology, this represented the proverbial "perfect storm". The event generated 48 hr rainfall totals exceeding 25 cm for an area covering 12 counties in the San Antonio and Guadalupe headwaters, with most of the rainfall delivered in a 12-hour period. Record flood peaks were established for all lower-basin gauging stations along the main-stem Guadalupe. At the downstream-most station, Victoria, the streamflow (discharge) peaked at 13,200 cubic meters per second (m^3/s). This greatly exceeded the previous peak event of 5,068 m^3/s, a record that had stood since 1936. To put it in perspective, the discharge at bankfull stage (slightly below flood stage) for the Guadalupe River at Victoria is 258 m^3/s.

The seasonal and spatial pattern of Texas precipitation is well illustrated by examining the annual streamflow regime for large coastal plain rivers, which by virtue of their size reflect regional precipitation and landscape characteristics. Daily discharge values (m^3/s) for the Nueces, Colorado, and Sabine Rivers for hydrologic year 2002 are displayed in Figure 3. A hydrologic year, or water year, begins with the onset of soil moisture recharge and is defined so that a seasonal period of runoff occurs within a single year. In the northern hemisphere a water year begins October 1 and ends September 30, which gen-

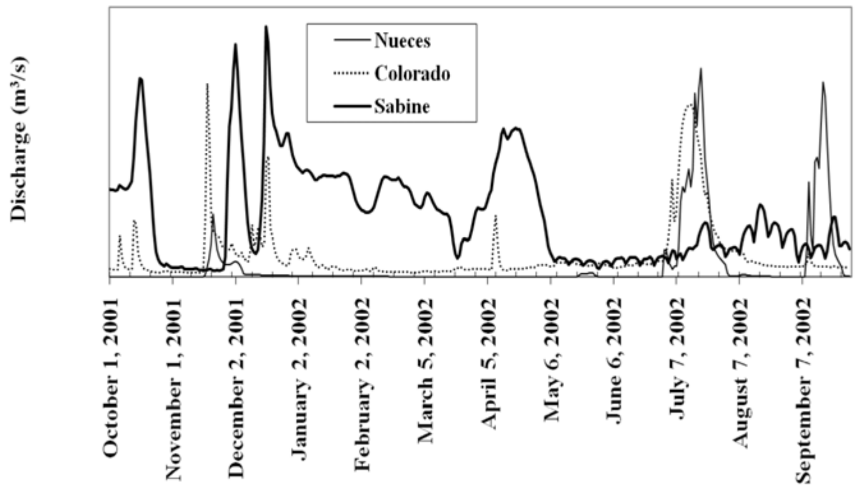

Figure 3. Daily streamflow (discharge) (m^3/s) values of the 2002 hydrologic year for the Nueces, Colorado, and Sabine Rivers. The pattern of each river illustrates typical temporal (seasonal) variability over a hydrologic year, which is related to the mechanism of precipitation. The flow variability between rivers illustrate the spatial (west to east) precipitation gradient across Texas. The stations are located near at the lower reaches near the outlet to the Gulf of Mexico. Data source: US Geological Survey for the Nueces River near Three Rivers (08210000), Colorado River at Columbus (08161000), and the Sabine River near Ruliff (08030500).

erally coincides with a decrease in tropical cyclone activity and an increase in the frequency of westerly migrating cyclones in the middle latitudes. The streamflow pattern of all three rivers illustrates the distinctive seasonality of Texas precipitation, while the streamflow variability between rivers is explained by the distinctive west to east precipitation gradient across Texas. The influence of fall, winter, and spring middle latitude cyclones is well illustrated by the discharge peaks for the Sabine and Colorado Rivers, but much less so for the Nueces. The headwaters for the Nueces basin are located near the southern limits of major frontal advance. Further, unlike the Sabine and Colorado Rivers, the Nueces streamflow pattern does not exhibit substantial base flow (streamflow derived from groundwater), suggesting that the alluvial aquifer contributes very little streamflow between individual rainfall events. Interestingly, the Sabine River displays a “sawtooth” streamflow pattern from May through September. This is due to the release of discharge from the large Toledo Bend Reservoir located upstream of the gauging station (Phillips, 2003). The data also illustrate the influence of tropical cyclone derived precipitation on streamflow in July. The cyclone migrated from the Gulf of Mexico and stalled above the Edwards Plateau, and was therefore important to the streamflow of the Colorado and Nueces Rivers, but was less of an influence on east Texas rivers such as the Sabine. This same event generated large scale flooding along the Guadalupe River (Curran et al., 2005; Earl and Dixon, 2005) and is discussed further below.

The Texas Coastal Plain

The Texas Coastal Plain is an extensive low-relief landscape that trends northeasterly across Texas from the Rio Grande to the Red River (Figure 1). The province is part of the larger Gulf of Mexico structural basin, which extends below sea level as a broad continental shelf. The Gulf Coastal Plain is by far the largest physiographic province within Texas, dominating Texas' landscape east of Ft. Worth, Austin, and Del Rio. The width of the Gulf Coastal Plain ranges from 450 km along the Rio Grande valley, to 225 km along the Guadalupe River valley. The southern and central Gulf Coastal Plain slopes easterly and southeasterly towards the Gulf of Mexico, while a small segment of the coastal plain north of Dallas slopes easterly into the Red River basin, which eventually flows into the extensive Mississippi River system. Within the coastal plain there are regional scale “structural” controls, such as the northwesterly aligned San Marcos Arch in south-central Texas and the Houston embayment of east Texas. These features influence the orientation of rivers as they flow across the coastal plain towards the Gulf of Mexico.

From the Rio Grande to the Brazos River at Waco the coastal plain borders the Edwards Plateau, an extensive uplifted plateau of predominantly thick horizontally-bedded Cretaceous limestone. Flanking the eastern margins of the Edwards Plateau is the normal-faulted Balcones Fault Zone (also referred to as the Balcones Escarpment). While the Balcones Fault Zone is a distinct geologic and geomorphic division (Abbott and Woodruff, 1986), it is generally considered together with the deeply incised eastern Edwards Plateau as the Texas Hill Country, and is influential to the hydrology of coastal plain rivers draining the region. The steep slopes and thin clayey soils of the Texas Hill Country, combined with intense rainfall events, has resulted in this region being referred to as "flash flood alley" (Baker, 1977; Jones, 1989). Additionally, the highly productive Edwards aquifer (Ryder, 1996) represents a dependable supply of base flow (ground water) between rainfall events, critical sustenance to aquatic ecology during drought, and a buffer to rapid urbanization along the Austin-San Antonio corridor (Bowles et al., 2006). The region also represents the source for several artesian spring-fed rivers which flow into coastal plain watersheds, including Barton Creek (Colorado watershed), Comal River (Guadalupe watershed), Frio River (Nueces watershed), San Marcos River

(Guadalupe watershed), and Salado Creek (Brazos watershed). North of the Brazos River the Gulf Coastal Plain borders the Grand Prairie province, composed of Cretaceous sandstone and limestone, the headwaters for the Trinity River.

Although the Gulf Coastal Plain is generally characterized as one of the least complicated physiographic and geomorphic provinces of North America (Walker and Coleman, 1987), it is incorrect to characterize the Texas coastal plain as featureless (e.g., Jones, 1989). The Texas coastal plain is quite complex and heterogeneous, contributing to the variability of Texas coastal plain river systems, and has undergone different land-use histories. Conventionally the Texas coastal plain is further subdivided into three belts (Table 1, Figure 1), corresponding with distinctive changes in the age of rocks, relief, and elevation (Hill, 1900; Wermund, 1996).

The upper portion of the Texas coastal plain is the Blackland Prairie, a belt of marl, shale, and limestone ranging in age from late-Cretaceous to early-Tertiary (Figure 4-A). Elevations of the Blackland Prairie range from 350 to 150 m, with the highest elevations along the Austin-San Antonio corridor. The Blackland Prairie ranges in width from 25 km near San Antonio, to 225 km north of Dallas. The topography consists of low gently rolling hills. The soils are thick, fertile, and black. The dominant soil orders are mollisols and vertisols, of which the Houston Black (State Soil of Texas) dominates. The region is considered the southern extension of the U.S. Great Plains. As such, it is intensively utilized for agriculture and less than 1% of the native prairie grasslands remain. Improper land management, particularly associated with intensive cotton farming in the late 1800s and early 1900s following waves of nineteenth-century European immigration, was associated with high rates of soil erosion and gullying (Strong, 1938; Jordan, 1996). More recent studies have shown that, while overall soil erosion rates are lower, soil erosion continues to be a concern for land managers (Harmel et al., 2006). Proper land management of the Blackland Prairie is important because eroded soils flushed into rivers often initiates a geomorphic cycle of erosion and sedimentation which degrades channel and riparian habitats. The Sabine River is the only coastal draining river with its headwaters in the Blackland Prairie. Primarily the province represents the headwaters for important (> 2,500 sq. km) tributaries for large coastal draining watersheds, such as Plum Creek (Guadalupe watershed), Chambers Creek (Trinity watershed), the Sulphur River (Red River), and the Atascosa River (Nueces watershed).

The Interior Coastal Plain is the largest division of the Texas Gulf Coastal Plain, and consists of a broad belt of Tertiary sedimentary strata (Figure 4-B) with moderate structural control. This section consists of alternating resistant and soft strata, predominantly sandstone and shale, which become progressively less steeply dipping towards the coast. Elevations range from 250 m to

Table 1. Major Geomorphic Divisions of the Texas Gulf Coastal Plain.

Division	[1] Age (Geologic units)	[2]Lithology (order of dominance)	Elevation (m)	Width: max. - min. (km)
Blackland Prairie	Late-Cretaceous to Paleocene (Navarro and Taylor; Wilcox and Midway groups)	Shale, limestone, marl, and sandstone	350 - 150	225 - 35
Interior Coastal Plain	Eocene, Oligocene, Miocene, and Pliocene (Claiborne Groups, Jackson Groups, Catahoula Fmn., Flemming and Oakdale Fmn., Goliad Fmn, Ogallala Fmn., and Willis Fmn.)	Sandstone, shale, limestone	250 – 90	400 - 125
Coastal Prairie	Pliocene to late-Holocene (Lissie, Beaumont, and Deweyville Fmn.)	Unconsolidated deposits: silty/clays, sands and gravels	90 - 0	140 - 75

Source: [1]Barnes, 1992; [2]Wermund, 1996.

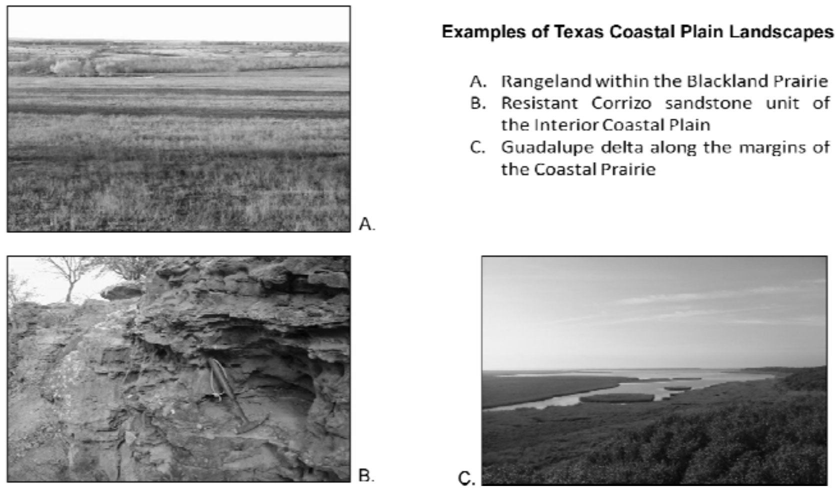

Figure 4. Images of Texas Coastal Plain, illustrating the diversity in landscapes between the three major divisions of the coastal plain. A. Blackland Prairie. Typical agricultural landscape east of the Edwards Plateau. Photo source: National Resource Conservation Service for Texas. B. Interior Coastal Plain. The resistant and very oxidized Carrizo sandstone (lower Tertiary), a dominant unit forming elongated ridges that serve as regional drainage divides and the headwaters for tributaries to coastal plain watersheds. Photo source: P.F. Hudson. C. Coastal Prairie. The Aransas National Wildlife Refuge at the Guadalupe delta. Photo source: VisitUSA.com

90 m. Several of the more resistant sandstone units form gentle cuestas, elongated hills dipping towards the Gulf, while the softer shale units generally form low and flat plains and valleys (Hill, 1900; Doering, 1935; Walker and Coleman, 1987). A variety of Miocene-aged formations represent the headwaters for several smaller coastal draining watersheds that form in the Interior Coastal Plain, including the Lavaca, Mission, San Bernard, and Aransas Rivers (Figure 1, Table 1). While these watersheds are two orders of magnitude smaller in size than larger coastal plain watersheds, they are important for water resources, irrigation for agriculture (Texas Water Development Board, 2005), and perform ecological functions vital to Texas coastal zone environments (National Research Council, 2005). Other first order streams draining cuesta dip slopes and rolling hills represent important headwaters for small basins that contribute sediment and runoff to the lower reaches of intermediate sized coastal plain rivers, such as Coleto Creek (Guadalupe watershed) and Big Cow Creek (Sabine watershed). These streams are supplied base flow (ground wa-

ter) from the major Coastal Lowlands aquifer system (Ryder, 1996). The larger river valleys which traverse the Interior Coastal Plain display changes in width and orientation as they come in contact with faults and resistant strata, such as along the Guadalupe River where it cross the resistant Carrizo sandstone unit (lower Tertiary) (Figure 4-B).

The lowest and youngest belt of the Texas coastal plain is known as the Coastal Prairie. The Coastal Prairie appears almost perfectly flat, but actually consists of a sequence of very gently dipping Pliocene to Holocene surfaces of fluvial, deltaic, and marine origin (Winker 1982, Bartek et al., 1991). From the higher Lissie (Pliocene) surface (90 m) the landscape grades from extensive grasslands and farmland to coastal marsh and bays (Figure 4-C), a landscape assemblage that extends along an arc from Corpus Christi to southwestern Louisiana (Griffith et al., 2004). The dominant formative process on the evolution of the Coastal Prairie landscape has been Quaternary sea level fluctuation, which resulted in repeated phases of fluvial incision and deposition and coastline advance and retreat.

A major problem near the coast is ground subsidence. This occurs naturally due to sediment loading and faulting, but greatly accelerated during the 20th century due to human intervention for fluid extraction (petroleum and ground water). Ground subsidence is of great concern in southeastern Texas, particularly between the featureless Katy Prairie and the Sabine River. At the coast, subsidence is associated with an increase in the loss of wetlands and erosion of the coastline. However, subsidence within large urban areas, such as Houston, is associated with increasing flood risk. Indeed, the costliest flood event in Texas history occurred when Tropical Storm Allison stalled over Houston for five days, resulting in more than 80 cm of precipitation (NWS, 2001). The runoff quickly overwhelmed local bayous and drainage pumps and resulted in widespread flooding (Figure 5).

Because of the poor drainage and low relief, the Coastal Prairie is very sensitive to climate change and sea level rise. While this point was made forcefully clear with the recent landfall and associated storm surge of Hurricane Rita in 2005, geomorphic and sedimentologic evidence from the Colorado River delta suggest that sea level was 2 m higher during the middle-late Holocene (Blum et al., 2001). Such geomorphic evidence represents a vital and exploitable historical database for understanding coastal response to predicted sea level and climate change scenarios (e.g., Titus and Richman, 2001). A distinctive element of the Coastal Prairie landscape is the broad low-gradient mainstem river valleys, which include low Holocene terraces and multiple channel belts (Galloway, 1981; Blum and Valastro, 1994; Aslan and Blum, 1999). The alluvial valleys are dominated by meandering rivers with complex floodplains. Closer to the coast the rivers form deltas which have anastomosing (anabranching, having multiple channels) patterns. During the late Quaternary

Figure 5. Urban flooding in Houston from Tropical Storm Allison. Substantial ground subsidence (surface lowering) due to fluid withdrawal is considered to increase flood risk and flood vulnerability. Photo source: National Weather Service Houston / Galveston Flood Forecast Office.

each river system has displayed a unique history of adjustment to climate change and sea level rise, resulting in distinctive floodplain landscapes characterized by variable rates of channel erosion and multiple abandoned channels (Aslan and Blum, 1999) and lakes.

Basins, Rivers, and Flooding

Watershed Characterization

Frequently depicted as low-energy river systems prone to flooding, Texas' coastal plain rivers are usually portrayed as being more similar than unique. This is appropriate when comparing rivers of the coastal plain with other physiographic settings. However, along the Texas Gulf Coastal Plain, rivers display considerable geomorphic and hydrologic diversity. Previous authors (e.g., Winker, 1979; Blum and Valastro, 1994) have suggested that Texas river may be placed into three scale-dependent categories (Table 2), depending on their source of drainage. These three categories include extrabasinal, basin-fringe, and intrabasinal systems.

The largest (10^{-5} km^2) coastal plain rivers, extrabasinal watersheds, primarily derive their drainage from distant hinterland sources above the coastal

Table 2. Hydrologic and geomorphic characteristics of Texas coastal plain river systems draining into the Gulf of Mexico.

River (USGS ID) (1)	Drainage area (km^2)	Length (km)	Median daily. Q (2) (cms)	Avg. annual max Q (cms)
Extrabasinal Rivers				
Rio Grande near Brownsville (08475000)	557,722[1]	2,895[1]	7.22	421[9]
Colorado River at Wharton (08162000)	109,472	1,387[4]	37.1	977
Brazos River at Richmond (08114000)	118,230	2,060[4]	83.0	1,600
Basin Fringe Rivers				
Nueces River near Mathis (08211000)	43,502	752.7	3.68	482
San Antonio River at Goliad (08188500)	10,844	622.7	9.97	411
Guadalupe River at Victoria (08176500)	15,539	739.1	28.9	991
San Jacinto River (08068090) [5]	10,230[2]	191.2	9.60[5]	614[7]
Trinity River at Romayor (08066500)	46,572	1,147	76.7	1,360
Neches River at Evadale (08041000)	25,780	681.8	92.9	864
Sabine River near Ruliff (08030500)	25,511	907.9	127.7	1,210
Intrabasinal Rivers				
Aransas River near Skidmore (08189700)	2,210	146.8	0.12	258
Mission River at Refugio (08189500)	2,665	168.2	0.34	296
Lavaca River near Edna (08164000)	5,925[3]	189.6	4.17[6]	544[8]
San Bernard River near Boling (08117500)	2,721	233.8	3.51	265

(1) Hydrologic data obtained from lowermost US Geological Survey stream gauging stations, except where noted (see footnotes below). All geomorphic data obtained from measurements of US Geological Survey 1:24,000 topographic maps and DEMs in a GIS. The data was sampled along river reaches adjacent to lowermost US Geological Survey gauging station.
(2) Q = discharge (streamflow) in cubic meters per second (cms)
(3) Qbf = bankfull discharge
(4) Sinuosity: ratio of channel length to valley length
(5) Floodplain relief (m): difference in elevation between meander belt ridge and backswamp or floodplain bottoms

Table 2, continued. Hydrologic and geomorphic characteristics of Texas coastal plain river systems draining into the Gulf of Mexico.

River (USGS ID) (1)	Q_bf (3) (cms)	Peak Q (cms)	Flood intensity (Peak Q / Q_bf)	Holocene Valley width (km)
Extrabasinal Rivers				
Rio Grande near Brownsville (08475000)	335[10]	898	2.68	~125
Colorado River at Wharton (08162000)	1,280	4,500	3.52	8.0
Brazos River at Richmond (08114000)	2,480	3,480	1.40	8.0
Basin Fringe Rivers				
Nueces River near Mathis (08211000)	173	3,910	22.6	1.5
San Antonio River at Goliad (08188500)	230	3,910	17.0	0.7
Guadalupe River at Victoria (08176500)	258	13,200	51.2	3.5
San Jacinto River (08068090) [5]	283[7]	3,680[7]	13.0	3.0
Trinity River at Romayor (08066500)	2,310	3,450	1.49	11.0
Neches River at Evadale (08041000)	841	3,540	4.21	7.5
Sabine River near Ruliff (08030500)	402	3,430	8.53	10.0
Intrabasinal Rivers				
Aransas River near Skidmore (08189700)	30.3	2,340	78.0	0.5
Mission River at Refugio (08189500)	140	2,240	16.0	1.0
Lavaca River near Edna (08164000)	192[8]	4,250[8]	22.1	1.5
San Bernard River near Boling (08117500)	88.3	903	10.2	10.0

1. Rio Grande drainage area and channel length from GIS computations available as an online report published by University of Texas at Austin Center for Research in Water Resources. Note, these values differ from US Geological Survey estimates.
2. San Jacinto drainage area includes Buffalo Bayou.
3. Includes Navidad River basin.
4. From Kammerer (US Geological Survey Open File Report 87-242).
5. Composite of 7 individual gaging stations (08071280, 08071000, 08070500, 08070200, 08069000, 08068500, and 08068090).
6. Composite of 5 individual gaging stations (08164000, 08164390, 08164450, 08164503, and 08164504).
7. Computed only for 08068090.
8. Computed only for 08164000.
9. Computed only for the period of record: WY1935 to WY1977; peak flows show dramatic reduction since WY1977.
10. Only approximately; no stage-discharge relation available from IBWC; determined by regression line through four available flows near NWS flood stage of 8.23 meters.
11. Does not include Deweyville Terrace.

Table 2, continued. Hydrologic and geomorphic characteristics of Texas coastal plain river systems draining into the Gulf of Mexico.

River (USGS ID) (1)	Sinuosity (4)	Channel width (Q_bf)	Floodplain relief (m) (5)
Extrabasinal Rivers			
Rio Grande near Brownsville (08475000)	2.36	50	7.00
Colorado River at Wharton (08162000)	1.53	100	1.85
Brazos River at Richmond (08114000)	1.71	125	2.30
Basin Fringe Rivers			
Nueces River near Mathis (08211000)	1.32	35	2.75
San Antonio River at Goliad (08188500)	1.68	35	3.90
Guadalupe River at Victoria (08176500)	2.48	60	4.75
San Jacinto River (08068090) [5]	1.11	100	0.40[11]
Trinity River at Romayor (08066500)	1.55	150	5.80[11]
Neches River at Evadale (08041000)	1.78	75	0.70[11]
Sabine River near Ruliff (08030500)	2.27	65	2.10
Intrabasinal Rivers			
Aransas River near Skidmore (08189700)	1.33	35	1.5
Mission River at Refugio (08189500)	1.48	25	0.55
Lavaca River near Edna (08164000)	1.31	30	5.90
San Bernard River near Boling (08117500)	1.25	20	4.20

plain, and include the Rio Grande, Colorado, Brazos, and Red Rivers. The Brazos, Rio Grande, and Red Rivers are amongst the longest rivers in the U.S., while the Colorado ranks 16^{th} (Kammerer, 1990). These systems essentially flow across the coastal plain as narrow entrenched valleys and receive little drainage from the coastal plain, particularly the Rio Grande and Colorado Rivers (Figure 1). The Rio Grande obtains most of its drainage from outside the state, while only distant tributaries of the Colorado and Brazos Rivers are located outside of Texas. Large portions of the upper Colorado and Brazos watersheds internally drain to playa lakes in the High Plains, and only small tributaries intermittently transmit water and sediment from the High Plains to the river systems. Of the three extrabasinal rivers the Rio Grande has a much larger watershed (Table 2) and longer history, draining large parts of northern Mexico, most of New Mexico, and portions of southern Colorado. Like other deltas along the Gulf of Mexico the main channel of the Rio Grande splits into multiple channels (distributary channels) before discharging into the coast. The Arroyo Colorado is an excellent example of an old (abandoned) Rio Grande distributary channel. The Rio Grande discharge is heavily regulated by large reservoirs along the main-stem channel in Texas and New Mexico, and along major Mexican tributaries. Because of the extremely contentious nature of Texas – Mexico water politics, very little Rio Grande water is allowed to be diverted to adjacent floodplain riparian environments. Thus, hydrologic “connectivity” between the channel and floodplain is severely limited due to an extensive infrastructure of flood control levees located along the entire length of the Rio Grande.

The drainage of the coastal plain land surface is dominated by basin-fringe and intrabasinal systems (Figure 1). Basin-fringe watersheds are intermediate (10^{-4} km^2) sized systems with headwaters formed near the updip margins of the coastal plain, and include the Nueces, San Antonio, Guadalupe, Trinity, Neches, and Sabine Rivers. Basin-fringe rivers that drain the Edwards Plateau and flow into the low gradient coastal plain, such as the Guadalupe, are interesting because of the abrupt change in floodplain geomorphology that occurs as they cross the Balcones Fault Zone. Commonly this is associated with a change from a narrow valley with limited floodplain development, to a broad floodplain that includes a complex variety of floodplain surfaces and riparian environments (Figure 6).

The smallest (10^{-3} km^2) coastal draining systems are intrabasinal watersheds, which include the Lavaca, Mission, San Bernard, San Jacinto, and Aransas Rivers. The headwaters of these rivers are formed on the Willis and Lissie formations along the margins of the Coastal Prairie with the Interior Coastal Plain (Figure 1).

Drainage Basin Scale, Slope, and Flooding

There are a variety of ways to examine and compare the geomorphology of river systems. A common geomorphic perspective useful for comparing different watersheds is the longitudinal profile (Knighton, 1998). A longitudinal profile is a plot of river channel distance (“X” axis) by channel elevation (“Y” axis). Longitudinal profiles reveal meso-scale spatial differences in the slope (energy gradient) of a river channel. Over long distances the slope of a river channel is generally related to the evolution of the drainage system over long time periods (10^{-4} to 10^{-5} years). Reach-scale changes, over shorter distances, in river gradient are often associated with changes in the dominance of specific depositional and erosional processes, resulting in changes in hydrology, river channel pattern, and floodplain geomorphology (Leopold and Wolman, 1957; Nanson and Croke, 1992; Hudson, 2004; Phillips et al., 2004). The longitudinal profiles for the coastal plain rivers of Texas are shown in Figure 7.

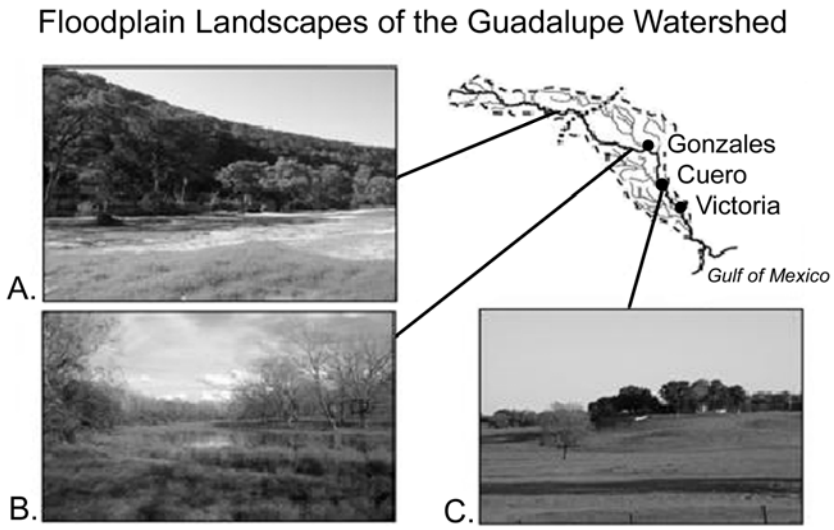

Figure 6. Floodplain landscapes of the Guadalupe watershed. The Guadalupe basin crosses the Balcones Fault Zone (dotted line) and undergoes an abrupt change in geomorphology, associated with a distinct change in floodplain environments. A. Upstream of the Balcones Fault Zone, within the canyon incised into Cretaceous limestone. Note that river flows along high bluff. Photo source: P.F. Hudson. B. Infilled oxbow lake upstream of Gonzales. Such lakes are hydrologically connected to the Guadalupe River through old river channels. Photo source: P.F. Hudson. C. Broad floodplain and adjacent Tertiary surface, downstream of Cuero. Photo source: P.F. Hudson.

When comparing extrabasinal rivers, the Brazos and Rio Grande flow great distances across the coastal plain and have appreciably low slope profiles (Figure 7). The Colorado has a steeper gradient because it flows off of the elevated Edwards Plateau closer to the coast than the Brazos or Rio Grande. Within basin-fringe rivers the Nueces, San Antonio, and Guadalupe have the steepest slope profiles because of the narrower coastal plain. The Trinity, Neches, and Sabine river systems flow a greater distance over the coastal plain and have much lower gradients. The steepest channel gradients are associated with intrabasinal rivers, which have the shortest channel distances within the coastal plain. Thus, the gradient of smaller intrabasinal rivers originating on the low coastal plain surface (Coastal Prairie) is appreciably greater than much larger rivers that flow from higher coastal plain surfaces.

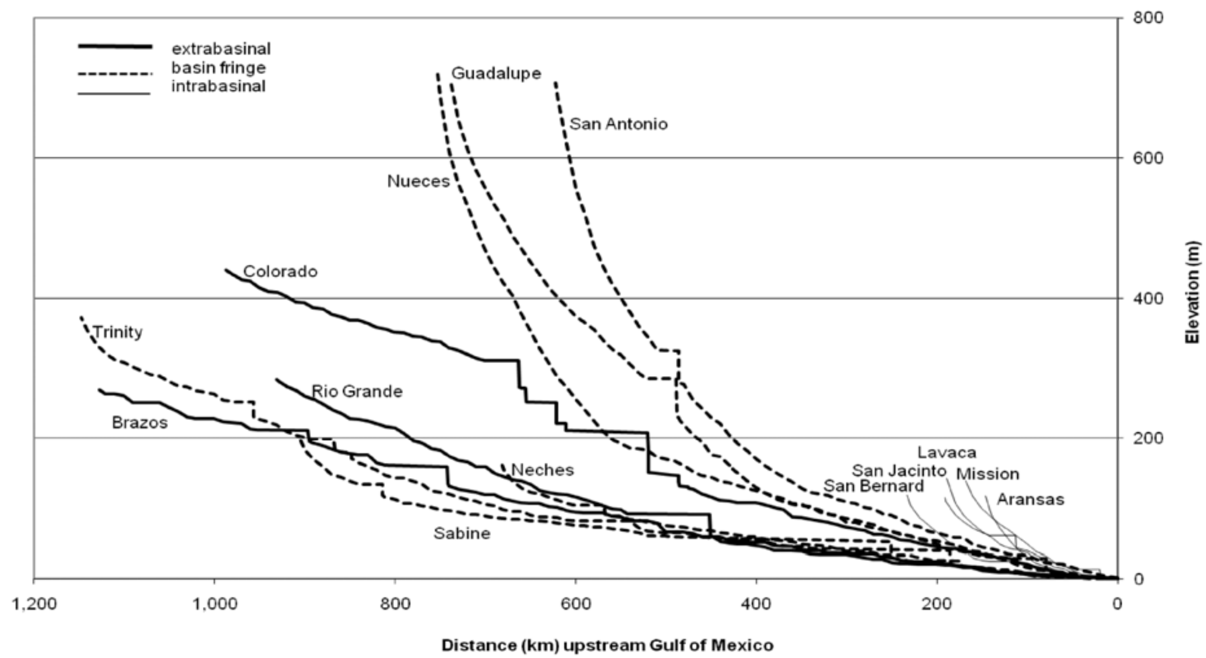

Figure 7. Longitudinal profiles of Texas coastal plain river channels, plotted as channel distance ("X" axis) and elevation ("Y" axis). Solid lines are extrabasinal systems, dashed lines are basin-fringe rivers, and shorter lines are intrabasinal rivers. The presence of dams and reservoirs on the longitudinal profiles can be seen by the "stair step" pattern. The profiles represent the entire channel length for intrabasinal rivers. Longitudinal profiles of extrabasinal and basin-fringe rivers are extended to above the Balcones Fault Zone.

The slope of a watershed influences the intensity of flood events. The low slopes and large size of extrabasinal rivers results in flood peaks being attenuated (flattened) as they flow downstream. Indeed, considering the large size of these basins, the magnitude of the annual maximum discharge and the peak-flood of record is not particularly impressive (Table 2). For example, the Rio Grande is Texas' largest drainage basin, but of the fourteen coastal draining watersheds it has the smallest peak discharge (898 m^3/s). In comparison, the much smaller Guadalupe, Colorado, and Lavaca watersheds have had peak discharges of 13,200, 4,500, and 4,250 m^3/s (Table 2), respectively. An obvious factor that should be considered is the influence of dams, which are ubiquitous across Texas (Graf, 1999). However, it should be noted that the peak flood event on the Guadalupe River in 1998 occurred well downstream of Canyon Lake in the Texas Hill Country, which was developed explicitly for flood control.

The magnitude (size) of a flood peak is not necessarily equivalent to the *intensity* of the flood event. Flood intensity is important because it relates to the degree of erosion and damage to structures (engineering, housing) during a flood event. An index of flood intensity should be considered with respect to the discharge at or near flood stage, the point at which the river overtops its banks. Such an index is geomorphically significant because it explicitly relates to river channel dimensions and is referenced to the point at which overbank flow occurs. A simple index of flood intensity is the ratio of a peak flood event to the bankfull discharge. This index is independent of scale, enabling comparison between large and small basins. The data show that the flood intensity of smaller basins is appreciably greater than large extrabasinal watersheds (Table 2). The average flood intensity of extrabasinal, basin-fringe, and intrabasinal systems was 2.53, 16.86, and 31.58, respectively. That each of these categories includes rivers draining humid and arid landscapes and have mainstem dams suggests that scale (drainage area) is more influential than climate (average annual precipitation) to flood intensity.

Coastal plain rivers are essential to the coastal zone due to their discharge of fresh water and fluvial sediments into brackish and shallow marine environments. Upon entering the coastal zone fluvial sediments are further transported by waves and currents to various coastal settings. These sediments are transported to coastal wetlands and beaches for protection against storm surges associated with tropical cyclones. However, although flooding is more intense along basin-fringe and intrabasinal river systems, the potential for fluvial sediments to be dispersed to the coastal zone by intense events is greater for extrabasinal systems. This is because the magnitude of discharge and sediment loads transported by extrabasinal systems, as well as their geomorphic setting. A distinguishing characteristic of extrabasinal rivers along the Texas coast is that the Brazos, Colorado, and Rio Grande have essentially infilled the lower reaches of their Pleistocene incised valleys. These systems are the only Texas rivers with large modern deltas which prograde into the Gulf of Mexico, enabling fluvial sediments and waters to be directly debauched into the coastal zone (Hudson and Mossa, 1997b). The sediment from smaller basin-fringe and intrabasinal systems is largely trapped in coastal bays or stored upstream at the transition from the alluvial valley into the delta zone (Phillips, 2003). The supply of fluvial sediment to the coastal zone is an important issue to Texas (Longley, 1994; Tolan, 2007), and there is currently disagreement as to whether or not main-stem dams are responsible for a reported decline in sediment delivery (Phillips et al., 2004; White et al., 2002).

Floodplains: Environment and Process

Large coastal plain river valleys, such as Texas', include a diversity of floodplain environments. A general model of a large coastal plain river valley showing various floodplain environments can be seen in Figure 8. The figure shows a plan (overhead) perspective with various floodplain environments depicted, and a cross-sectional profile that illustrates the topography of associated floodplain environments. The floodplain topography is a critical control on flooding, with low floodplain surfaces being flooded more frequently and for a longer duration than higher surfaces. Within a river valley the meander belt is generally perched above the lower lying floodplain bottoms or backswamps, with the natural levees representing the highest form of topography. Natural levees are elongated landforms created by sediments deposited from numerous individual flood events, and slope towards lower lying floodplain environments. Because they flood less frequently, natural levees are often utilized for agriculture and settlement.

Flooding is a fundamental control on depositional processes that create floodplains, and on erosional processes that modify river channels and floodplains. Flooding of large river valleys occurs due to several processes and is intricately related to the type of floodplain environment. The most significant type of floodplain inundation is associated with overbank flooding, which occurs when channel banks and natural levees are overtopped by streamflow fed from the upper reaches of the watershed. Overbank flooding commonly inundates an extensive portion of a river valley, and characterized the 2002 flood along the Guadalupe River (Figure 2). Although it generally takes long periods of time (10^{-2} – 10^{-3} yrs), the sediments deposited by large overbank flood events result in floodplain aggradation, the vertical "construction" of floodplain surfaces. The thickness of flood deposits varies greatly within a river valley from a single flood event, generally from several millimetres to hundreds of millimetres, and for different flood events at the same location. However, within a river valley flood sedimentation is generally greatest (~10s to 100s mm) along natural levees. The thickness of flood deposits is very

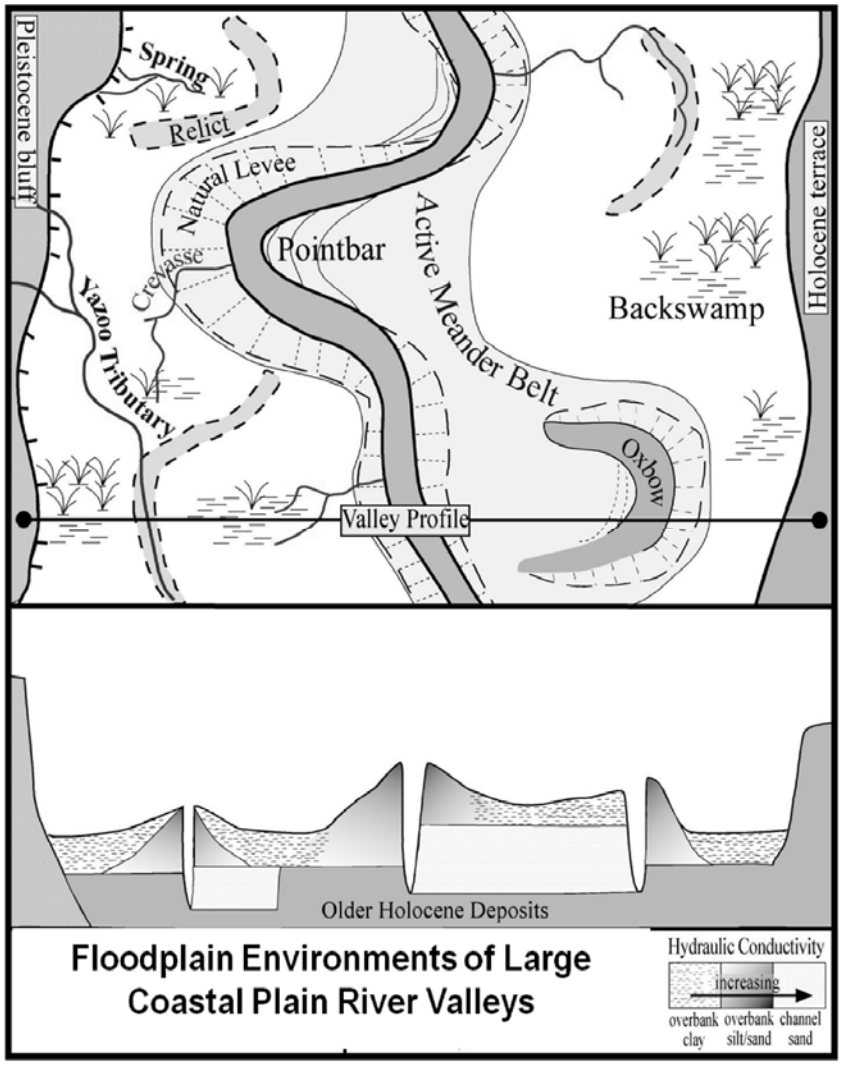

Figure 8. Model of floodplain environments and associated topography for large alluvial coastal plain river valleys, which is appropriate for large rivers along the Texas Gulf Coastal Plain. The hydraulic conductivity influences groundwater flow and floodplain drainage, and increases from clay to sand. Modified from Hudson and Colditz, 2003.

Figure 9. Recent flood deposits from the July 2002 flood along the Guadalupe River floodplain upstream of Gonzales (taken November 2002), illustrating the process of vertical floodplain accretion. The flood sediments are primarily sand and silt, and average ~20 mm in thickness. Photo source: P.F. Hudson.

low (~ 1-5 mm) towards floodplain bottoms and backswamps (Hudson, field observations). Figure 9 shows sedimentation from the July 2002 flood event along the lower Guadalupe River near Gonzales. The flood deposits primarily consisted of fine sand and silt, and averaged about 20 mm in thickness.

Other types of local (minor) flooding occurs more frequently, but are associated with much less geomorphic change (depositional or erosional). Such events do not usually overtop channel banks (natural levees), but do result in inundation of specific floodplain reaches. “Local” mechanisms for floodplain inundation include groundwater seepage associated a rise in the water table of the alluvial aquifer, direct precipitation onto the floodplain surface, and streamflow discharged into the floodplain through small channels connected to the river. The latter category often involves old river courses and crevasse channels. Additionally, small streams draining the adjacent terrace flow onto the floodplain and terminate, or flow within floodplain bottoms as a “yazoo” style stream (Figure 8). It is important to note that in many instances flooding occurs by a combination of the above reviewed processes. For example, overbank flooding is often preceded by localized floodplain inundation caused by an increase in groundwater or conduit flow through old crevasse channels. Moreover, the floodplain topography is important because it represents a topographic control on flood flow paths, and can segregate (trap) flood waters within a specific floodplain section. After recession of the discharge event the floodplain topography may effectively block the drainage of flood waters, resulting in portions of the floodplain remaining flooded for weeks or months.

It should be noted the model shown in Figure 8 does not apply to all reaches of a river valley because large river basins in Texas exhibit downstream changes in floodplain complexity. Thus, Figure 8 is appropriate for the lower coastal plain, but is less appropriate upstream of the coastal plain. The Balcones Fault Zone, in particular, represents a major physiographic divide that has significant implications to understanding floodplain geomorphology. This is well represented along the Guadalupe watershed (Figure 6A-C). Upstream of the Balcones Fault Zone the floodplain is narrow and incised into resistant limestone (Figure 6-A). However, downstream of the Balcones Fault Zone the river flows within softer coastal plain strata. The increase in valley width provides the space for older floodplain deposits to be preserved. Thus, floodplain complexity increases downstream of the Balcones Fault Zone, and is associated with the preservation of older channels, oxbow lakes, and the associated floodplain topography (Figure 6B-C).

Cross-sectional profiles of the lower reaches of Texas coastal plain rivers reveals differences in the complexity of floodplain environments between extrabasinal, basin-fringe, and intrabasinal watersheds (Figure 10A-C) as illustrated by the Brazos, Guadalupe, and Lavaca basins, respectively. The Brazos valley displays the greatest width, due to having a greater drainage area and discharge (Table 2). However, the Brazos also illustrates the presence of the variety of floodplain environments associated with such a large river valley (Figure 10A). The topography of natural levees is discerned along the fringes of the active channel. Other topographic features within the floodplain include older channels, including yazoo style streams, and point bar deposits associated with a partially buried meander belt. The Guadalupe River valley represents a basin-fringe system. Although displaying less floodplain complexity than the Brazos, the Guadalupe is large enough to exhibit considerable topography across the valley (Figure 10-B) which includes a second meander belt, clearly visible in the profile data. Flooding along the Guadalupe valley and delta region, downstream of the confluence with the San Antonio River, has been a persistent problem for over a decade. However, the major problem is that the floodplain remains inundated for months after the river flood crest has receded. This represents a serious constraint on grazing and agricultural activities. Finally, an example of an intrabasinal river valley is shown by the Lavaca (Figure 10-C). The Lavaca valley displays much less complexity than the Brazos or the Guadalupe, and is dominated by the presence of a single channel belt adjacent to a terrace.

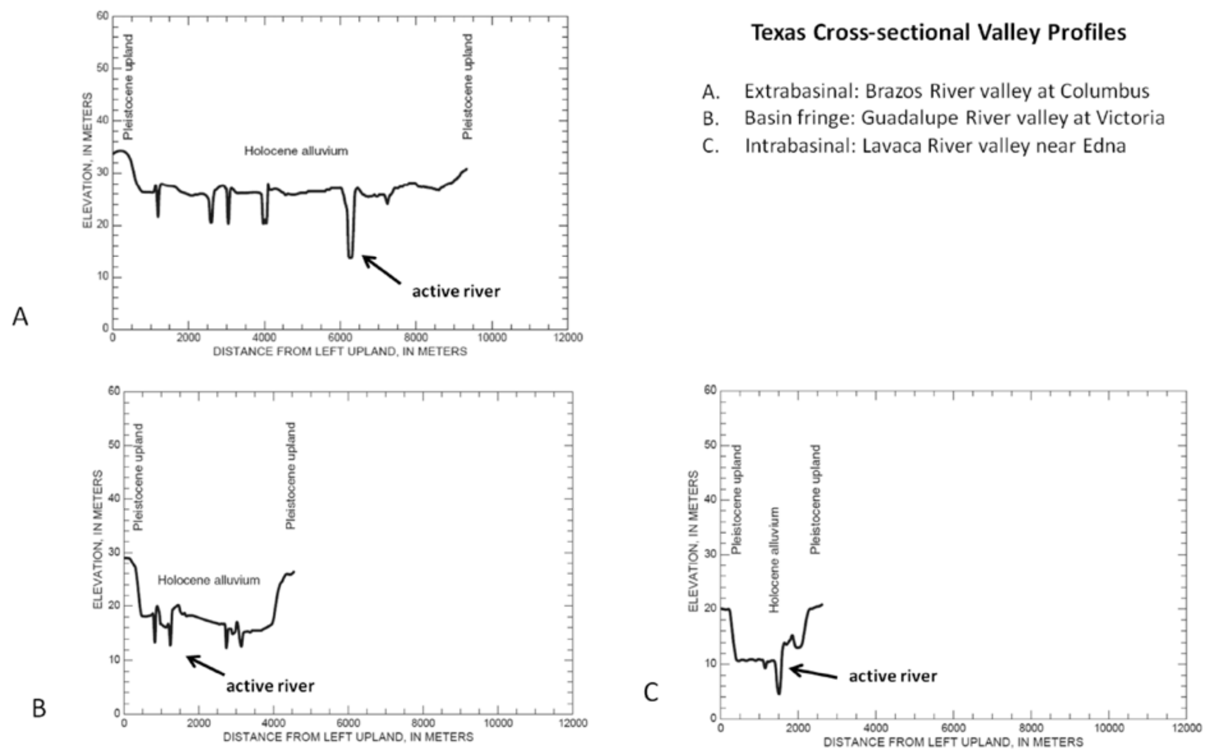

Figure 10. Cross-sectional profiles of the Brazos, Guadalupe, and Lavaca River valleys, displaying the complexity in topography across the floodplain.

Although floodplains are depositional landforms, in some instances erosion caused by flooding can initiate abrupt modifications to river channels, which significantly alters floodplain structure and topography. Avulsion is the process by which a river channel switches course and creates a new channel (Aslan and Blum, 1999; Stouthamer and Berendsen, 2007). An example of an ongoing avulsion is shown in Figure 11, which shows the exact point of avulsion and channel switching along the lower Guadalupe River valley downstream of Victoria. The process of avulsion is triggered by flooding, whereby a new channel is "cut" (eroded) into the floodplain, and thereby "captures" the streamflow of the former channel. Thus, as the new channel is created the old channel is abandoned and commonly forms a lake or slow moving river, such as a yazoo style channel (Figure 8). In some instances an avulsion results in an old channel being "reoccupied" by a later avulsion, which is particularly common along the lower reaches of large coastal plain valleys and deltas in Texas (Aslan and Blum, 1999). The formation of new channel belts by avulsions is a major reason for Texas' large floodplains exhibiting complexity in environment, topography, and flooding.

An additional significant way in which flooding can alter the structure and function of the floodplain is by initiating channel "cutoffs". Along the lower Guadalupe River between Cuero and Victoria, large floods in 1998 and 2002 caused three meander bends to cutoff, forming three new oxbow lakes. A meander bend refers to the river channel that flows along point bars (sedimentary deposits). Meander bend cutoffs occur due to persistent channel bank erosion along the outside of adjacent meander bends, on either side of a point bar. When the channel erodes through the point bar, the meander bend is cutoff, forming a new oxbow lake in the old channel (Figure 8). Along meandering rivers the oxbow lakes have a distinctive curved pattern, which enables them to be easily identified and mapped by using topographic maps, air photos, or satellite imagery.

Floodplain lakes, such as oxbows, represent important floodplain environments within Texas river valleys. Because of significant alteration to most floodplains for agriculture, floodplain lakes represent one of the only viable aquatic floodplain environment. The ecological significance of floodplain lakes is enhanced due to the hydrologic connectivity with river channels, which represents important pathways for migration and dispersal of fishes and other aquatic organisms (Zeug and Winemiller, 2008). After formation of an oxbow lake, sedimentation becomes the dominant process influencing oxbow lake environments. An example of an oxbow lake formed in 1998 along the Guadalupe River downstream of Cuero is well illustrated by Figure 12, which includes a digital air photo from 2004 and field photos from 2007. While relatively recent, this oxbow lake is already experiencing a rapid influx of sediments due to large flow events flushing sediment into the lake. The associated

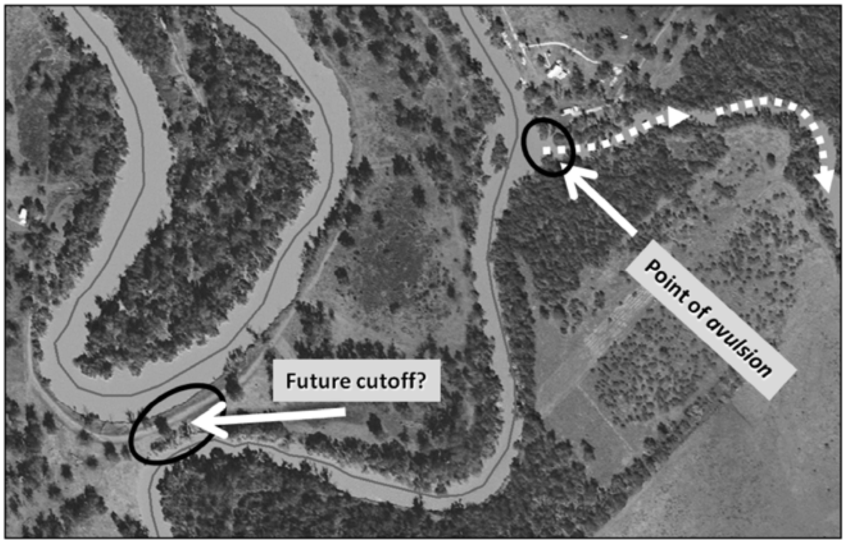

Figure 11. An example of a river channel avulsion and bifurcation along the lower Guadalupe River, downstream of Victoria. The bifurcation occurs at the nodal point of an avulsion, the process by which a river switches course and creates a new channel belt. The photo also shows the possible location of a future cutoff, which would result in a shortening of the river. For scale, the channel width is ~60 m (see Table 2). The source of the image is a 2004 Digital Ortho Quarter Quadrangle (1-m resolution) available from the Texas Water Development Board.

sedimentation transforms the lake environment into a wetland that is only "connected" with the Guadalupe River during large events. Eventually the oxbow lake will completely infill and exist only as an arcuate shaped wetland. This is shown in Figure 6-B along the Guadalupe River upstream of Gonzales. While the Guadalupe River provides many excellent examples of oxbow lakes, all of Texas' coastal plain rivers contain oxbow lakes that are undergoing sedimentation and an associated sequence of environmental change. Along the Rio Grande delta channel cutoffs are called "resacas" instead of oxbow lakes, and are also experiencing sedimentation and infilling (Cantu-Graves et al., 2007). Understanding the controls on floodplain lake sedimentation is a major area of research to fluvial geomorphologists, the scientists who examine the formation and dynamics of rivers and floodplains. Additionally, the infilling and associated transformation of channel cutoffs from oxbow lakes (Figure 12) into infilled arcuate wetlands (e.g., Figure 6-B) is an important issue to government agencies in charge of floodplain management and the conservation of riparian environments.

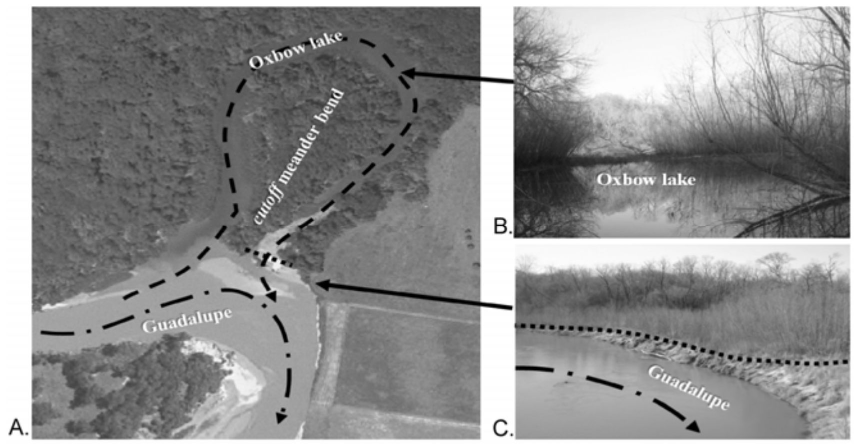

Figure 12. Example of oxbow lake along the Guadalupe River downstream of Cuero. A. A 2004 image showing a meander bend cutoff and oxbow lake formed during the extreme flood event of October 1998, the largest flood on record for the Guadalupe River. The image shows a rising river stage and hydrologic connectivity between the oxbow lake and Guadalupe River. The dashed line shows the former Guadalupe River channel. Sedimentation and growth of vegetation at the downstream end of the oxbow lake, while the lake is being infilled at the upstream end of the cutoff. Image source: Digital Ortho Quarter Quadrangle (1-m resolution) available from the Texas Water Development Board. B. Recent photo (February 2007) from inside the oxbow lake, showing rapidly growing vegetation following accretion of fine grained sediments (silt and clay). Photo source: P.F. Hudson. C. Accretion of sediment in the cutoff channel (February 2007). The dotted line shows the top of the sedimentary surface that has formed since the 1998 cutoff, and is referenced on A. Photo source: P.F. Hudson.

Conclusions and Summary

Texas has a broad coastal plain drained by an extensive network of large rivers that flow southeasterly into the Gulf of Mexico. These rivers represent one of the state's most valuable "natural" resources and are critical to Texas' future.

This paper has presented a variety of hydrologic and geomorphic indices to characterize the physical diversity of Texas rivers. The tremendous interest in Texas river systems by a diverse array of specialist and government agencies concerned with engineering, hydrology, ecology, and management suggests that it is critical to have adequate information that pertains to Texas rivers.

Thus, a contribution of this paper is that it puts forth a variety of geomorphic and hydrologic indices that can be further utilized in future studies.

The diversity of Texas fluvial systems represents many excellent opportunities to teach students about physical geography. Thus, this paper has also provided a review of fundamental concepts in physical geography as they pertain to the Texas Gulf Coastal Plain. The major concepts and topics reviewed in this paper include the following:

1) Texas hydroclimatology (Figure 2, 3, 5; Table 2). The spatial variability in Texas precipitation and the major precipitation mechanisms were reviewed, including conventional, tropical cyclone, and westerly migrating fronts. The importance of the spatial and seasonal variability in precipitation to streamflow was illustrated by showing discharge data for the Nueces, Brazos, and Sabine Rivers.

2) Coastal plain geomorphology (Table 1, Figure 1 and 4). Data pertaining to the geology and topography of the coastal plain was compiled from secondary sources to provide an overview of coastal plain landscapes, as segmented into the Blackland Prairie, Interior Plain, and Coastal Prairie.

3) Drainage basin characterization (Table 2, Figures 7 and 10). All Texas coastal draining watersheds were placed into categories depending on their source of drainage. The largest coastal draining river basins are large extrabasinal systems that include the Rio Grande, Colorado, and Brazos Rivers. These systems primarily drain distant interior hinterlands, while the coastal plain is primarily drained by much smaller basin-fringe and intrabasinal watersheds. The geomorphic and hydrologic distinction between these stems was emphasized, with particular attention to differences in floodplain complexity, longitudinal (slope) profiles, and flood intensity. Within the coastal plain, longitudinal (slope) profiles are primarily dependent upon distance rather than the elevation of the coastal plain surface. At the lower reaches of large basins this categorization is suggested to be important to the index of flood intensity, which represents a scale-independent index to characterize flood severity.

4) Flooding and floodplain complexity (Figures 6, 8, and 10). A comparison of valley profiles between the three categories of river basins shows that floodplains are not flat, and larger rivers tend to have more complex floodplains than smaller rivers. The complexity of a floodplain influences flooding, which occurs as large overbank events or as smaller localized events that do not require overbank conditions.

5) Floodplain processes (Figure 9, 11, and 12). Flooding is a major control on the development of floodplains. Large flood events that overtop natural levees are important because they distribute sediment across the floodplain, resulting in floodplain aggradation. However, flooding can also initiate erosion of river channels, which can significantly influence the structure and complexity of the floodplain. This was illustrated by providing examples from the Gua-

dalupe River floodplain concerning channel avulsion (switching) and in the formation and dynamics of meander bend cutoffs and oxbow lake formation.

For the past fifty years coastal plain rivers have been heavily modified by humans to support water-resource development, navigation, and flood control. All of the large coastal plain rivers in Texas are regulated by main-stem dams and reservoirs. However, flooding is persistent along coastal plain rivers and represents a serious and significant risk to humans residing along river valleys. Flooding is also a fundamental environmental process that is critical to the vitality of aquatic and floodplain ecosystems (National Research Council, 2005). Indeed, because of their significance to riparian and coastal environments, as well as the dependence of human activities on these rivers, Texas' coastal plain rivers represent the state's most important category of rivers. In the face of climate change and sea level rise there is uncertainty as to the response of Texas' rivers to different environmental change scenarios. A greater understanding of the fundamental processes that govern these diverse fluvial systems will help to assure that appropriate management plans are pursued.

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