Channel Change Caused by Water and Sediment Distribution in the San Antonio River Deltaic Plain

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Prepared for the Guadalupe-Blanco River Authority
Texas Water Development Board Contract Number 1004831024
Via subcontract

FINAL REPORT
MARCH 2011

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PROJECT OBJECTIVES

The purpose of this project is to understand historical changes in channel patterns and water and sediment distribution in the lowermost San Antonio River associated with major channel changes (avulsions). The project also seeks to identify areas of high risk or probability for future avulsions, and to develop recommendations for incorporating channel change and avulsion regimes into water resource management. The study area corresponds with the deltaic plain of the river. The San Antonio delta merges with the delta of the Guadalupe River, which the San Antonio River joins near Tivoli.

The specific objectives from the project scope of work are to:
(1) Determine the historic and late Holocene avulsion regime of the San Antonio River between U S Highway 77, near McFaddin, TX and the Guadalupe River, in the context of the Holocene geomorphic evolution of the river and the Guadalupe Delta plain.
(2) Identify actual and potential human impacts on avulsions, and other channel change processes.
(3) Identify locations of high probability or risk of future avulsions, stability of any channel breaches, and assess the developmental stage and stability ("equilibrium" condition) of existing flow bifurcations.
(4) Determine the impact of avulsions on the dynamics of water and sediment distribution.
(5) Develop recommendations for integrating avulsions into water resource management in the study area.

At least two major avulsions—one ongoing—have occurred in historic times. The San Antonio River shifted from what is now called the Old River channel sometime after 1930 near McFaddin. The boundaries between Refugio and Victoria Counties were fixed at this time, and older maps show the Old River channel as the San Antonio River and as the county boundary. Sometime between 1930 and 1948 the San Antonio River established a connection with Elm Bayou near Tivoli. The latter has captured an increasing proportion of the flow since. Major logjams have persistently developed near the San Antonio/Elm Bayou split, raising the question of the relationship between the channel shift and the effects of the woody debris.

BACKGROUND
Avulsions

Avulsions are relatively abrupt changes in the course of river channels, or the establishment of new anabranches. Avulsions are related to cutoffs (which involve single channel bends or meanders), but encompass longer channel reaches and are distinct from cutoffs. Channel changes are of obvious concern for river users and managers and riparian landowners, and many even have political implications, as channels are sometimes political boundaries. Avulsions may also play an important, sometimes dominant, role in the construction of floodplains and alluvial deposits. Geomorphologists and sedimentologists increasingly see avulsions, rather than lateral migration and overbank deposition, as the major mechanism of floodplain construction in many river systems (Slingerland and Smith, 2004; Blum and Aslan, 2006; Gouw, 2007). While external factors may trigger channel shifts, modern and historical studies and interpretations of ancient alluvial sequences indicate that internal (within the fluvial system) processes are the dominant controls in many cases (McCarthy et al., 1992; Mohrig et al., 2000; Gouw, 2007; Stouthamer and Berendsen, 2007; Phillips, 2009; 2011).

The comprehensive review by Slingerland and Smith (2004) found that the causes of river avulsions remained relatively unknown: "At present, we simply don't know the necessary and sufficient conditions causing a river avulsion" (258). Beyond the hydrologic, geomorphic, ecological, and engineering implications of avulsions, Texas coastal plain rivers have historically been profoundly influenced by avulsions (Blum and Aslan, 2006). Much of the research on river avulsions in general, and in the Gulf Coast region in particular, has focused on the sedimentary record, due to the critical role of avulsions in floodplain construction and the major influences on alluvial architecture. Relatively little work, by contrast, focuses on the types of channel shifts, the fate of abandoned channels, and potential geomorphic controls of avulsion regimes, though such studies have increased in recent years (e.g., Makaske et al., 2002; Aslan et al., 2005; Gouw, 2007; Stouthamer and Berendsen, 2007; Taha and Anderson, 2008; Phillips, 2009; 2011).

Avulsions are unquestionably strongly associated with aggrading systems (Slingerland and Smith, 2004; Gouw, 2007). They are not randomly distributed within aggrading systems, and both internal (autogenic) or external (allogenic) conditions or forcings that may promote or inhibit avulsions are known (see, e.g.,Taha and Anderson, 2008; Stouthamer and Berendsen, 2007). However, the specific location and timing of avulsions is not predictable, and is highly contingent on localized conditions and histories, and the timing of flood and other hydrogeomorphic events (Jones and Schumm, 1999; Makaske, 2001; Slingerland and Smith, 2004; Gouw, 2007; Phillips, 2009; 2011).

Avulsions are best understood in a setup-and-trigger context. Setup factors make channel changes possible or likely, and include aggradation of channels and floodplains, low downvalley gradients, potential slope gradient advantages within the alluvial valley, and the presence of paleochannels and/or floodbasins which may be reoccupied (Aslan and Blum, 1999; Makaske, 2001; Slingerland and Smith, 2004; Aslan et al., 2005; Gouw, 2007; Phillips, 2009; 2011). Though extreme events such as earthquakes, landslides, and rare hydrometeorological events can cause channel shifts, in most cases an aggrading valley and the availability of potentially steeper flowpaths outside the existing channel can be thought of as the necessary setup conditions for an avulsion. While aggradation of the channel bed above the backswamp areas or low points of the nearby floodplain is not necessary for avulsions to occur (see Tornqvist 1993; Hood, 2010; Phillips, 2011), such a condition seems to make an eventual avulsion inevitable (Jerolmack and Mohrig, 2007;

Jerolmack and Paola, 2007). This is the major reason avulsions are common in deltaic settings.

Trigger factors are conditions or events that divert flow from the main channel. These may be flow obstructions such as log or ice jams, landslide or other slope failures along valley sides, or even bar/bedform evolution within the channel. Triggers also include factors that create low or weak spots in natural levees, such as erosion or mass wasting along banks or levees, tree uprooting, and trampling by wildlife or livestock. Avulsions are triggered during high flows—if not floods, at least in-bank flows high enough to impinge on natural levees.

Avulsions thus require the setup factors of aggradation and potentially steeper flow paths, high flow events, and triggers to divert flow. Avulsions begin as crevasses or flow diversions, some of which result in splay or fan deposits rather than channels. Even when crevasse channels form they may not persist. Those that persist may result in channel relocations, or the development of anabranching or distributary patterns. These may also be associated with meander cutoffs, which may be further categorized as neck cutoffs (occurring at or near the base of the bend) or chute cutoffs (across a point bar). The possible outcomes following a crevasse are illustrated in figure 1.

Aslan and Blum (1999) identified two distinct avulsion styles in Texas Gulf of Mexico coastal plain rivers—reoccupation of former channels, and diversion into flood basins. The Nueces and Trinity Rivers are examples of the former. They 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 an example of the latter, characterized as representing a later stage of infilling where most of the accommodation space is filled. Avulsions there occur as repeated diversions into floodplain depressions. In a study of five Texas Rivers, Phillips (2009) confirmed the stage of valley filling as a first-order control of avulsion styles, with a variety of local factors, many involving the specific geomorphic history of the river, determining avulsion regimes within the unfilled valleys. As shown in figure 2, distinct avulsion styles are found in a rapidly aggrading valley (Navasota River), an infilled incised valley (Brazos River, similar to the Colorado River in this regard), and the unfilled incised valleys of the Sabine, Neches, and Trinity River. Among the latter, various aspects of inherited topography and geomorphic history result in distinct avulsion regimes. The San Antonio and Guadalupe Rivers are unfilled incised valleys, and would thus be expected to avulse chiefly by reoccupation of former channels, similar to the Nueces, Trinity, Neches, and Sabine Rivers. However, the specific controls over the San Antonio avulsion regime are yet to be identified.

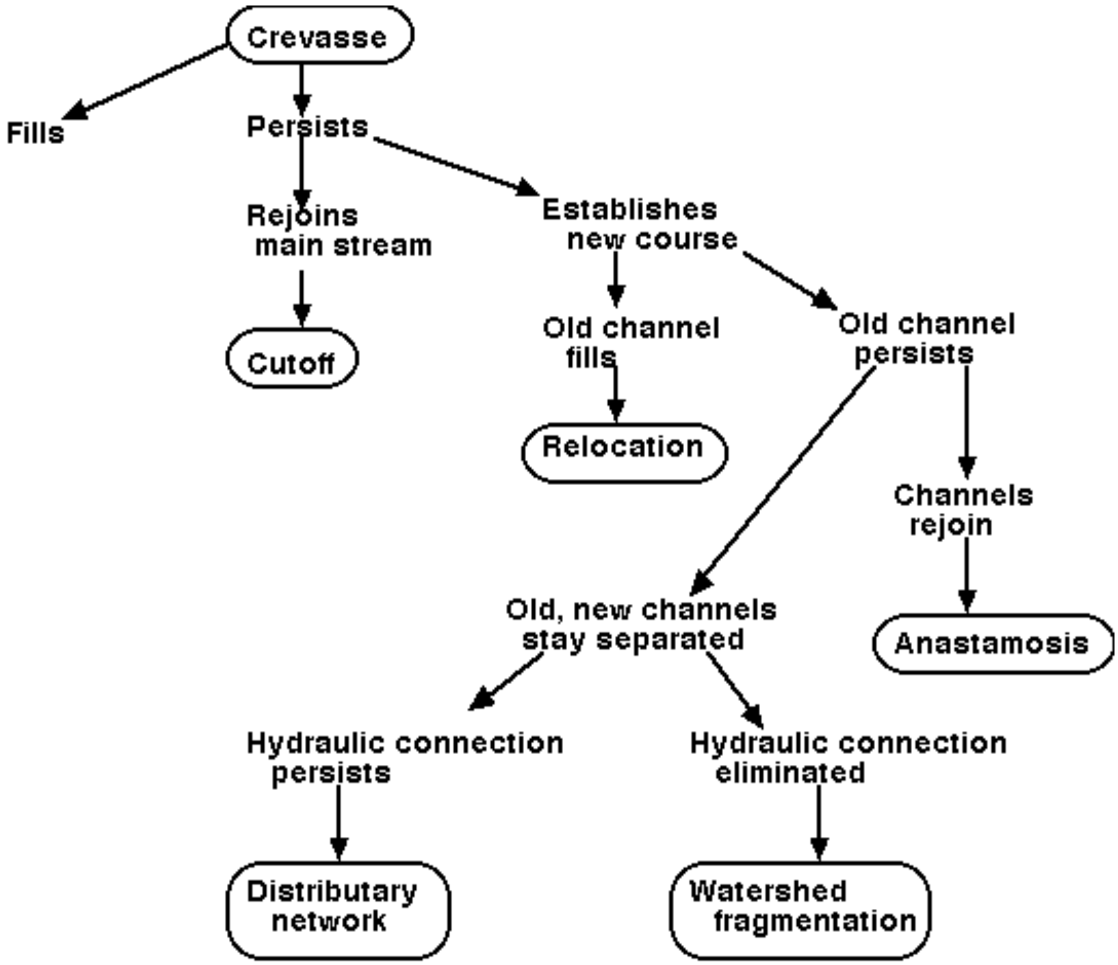


Figure 1. Possible outcomes of a crevasse that cuts a channel (as opposed to a splay or fan deposit).

In unfilled incised valleys, channels may be short-lived due to the abundance of paleochannels and erodible channel deposits, which lead to frequent avulsions (Aslan and Blum, 1999). Reoccupation of paleochannels is often discontinuous downstream, with Holocene channels typically occupying the paleochannels for only 5 to 10 km.

Avulsions still occur regularly in the Texas coastal plain region. Waters and Nordt (1995) found evidence of Brazos River avulsions as recently as 300 and 500 years BP. Radiocarbon dates from tree stumps in growth position indicate that the Colorado River avulsed 200 to 400 BP from the main post-Beaumont alluvial valley near Wharton, TX (Aslan and Blum, 1999). Evidence of avulsions within recent decades exists in the lower Navasota, Neches, and Sabine Rivers (Phillips, 2009). At least one historical avulsion has occurred on the lower Guadalupe River (from the old river channel which now lies east of the Victoria barge canal). The lower San Antonio River has experienced at least two previously known historical avulsions, as well as the ongoing shift into the Elm Bayou route.

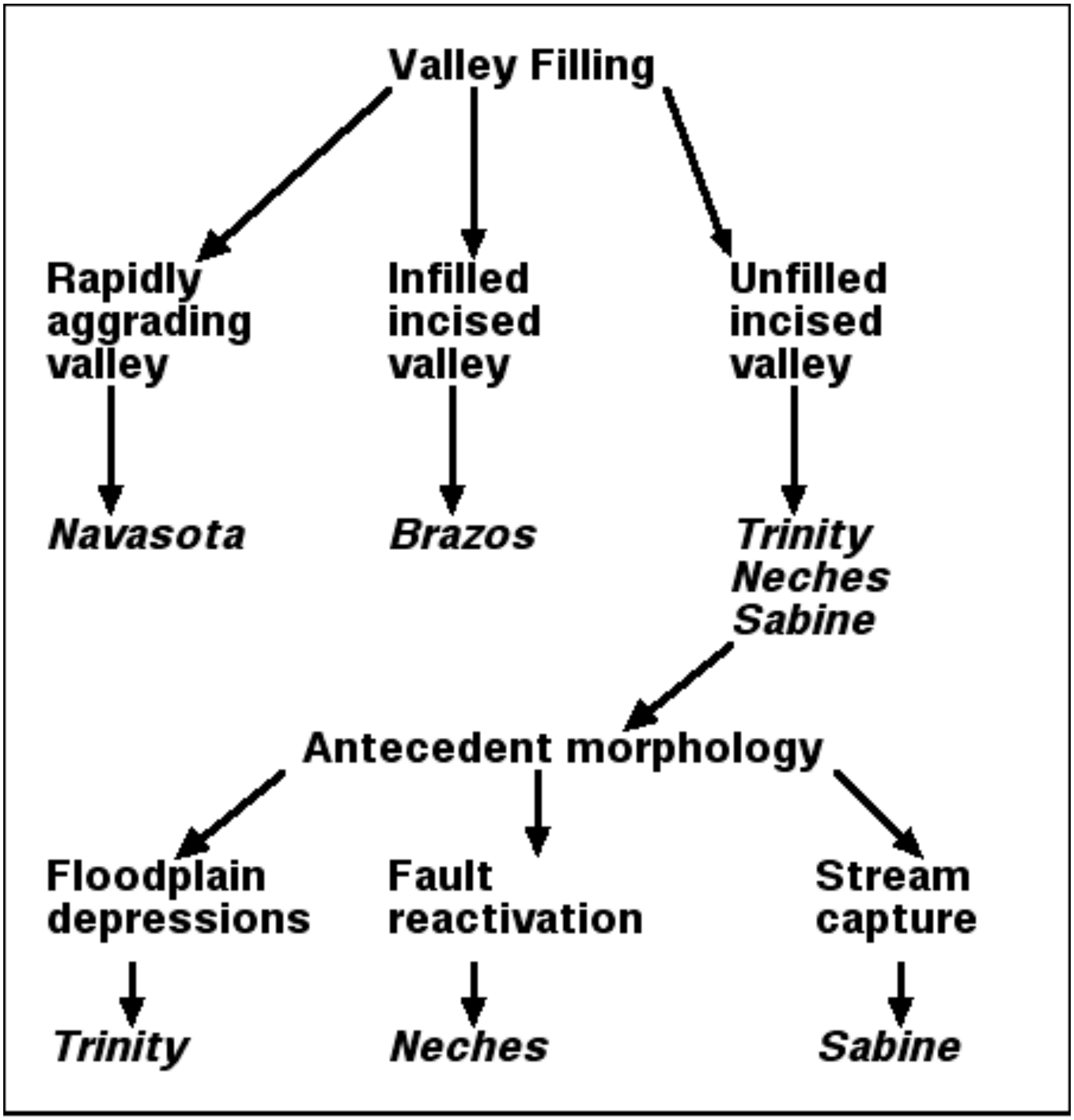


Figure 2. Major controls over avulsion regimes in five Texas rivers studied by Phillips (2009), from which this figure in taken. The San Antonio River occupies an unfilled incised valley.

Jerolmack and Mohrig (2007) argue that branching and anastamosis (formation of multiple channels) in depositional rivers derives from instabilities that result in avulsions. The existence of multiple stable channel branches seems to arise from conditions conducive to net deposition of sediment and a degree of bank resistance to erosion and lateral channel migration. They derived the mobility number

$$M = (d\, v_c)/(w\, v_a) \qquad (1)$$

where d is mean channel depth relative to the bank top, w is channel width, and v_c, v_d are the rates of lateral bank erosion and of channel aggradation. $M >> 1$ signifies a single channel dominated by lateral migration and reworking of floodplain sediments, while $M << 1$ indicates channels that aggrade rapidly relative to lateral migration, with avulsions likely to be frequent and multiple channel patterns likely (Jerolmack and Mohrig, 2007).

Most analyses of avulsion conditions focus on upstream mechanisms that influence aggradation and overbank flow frequency, but Kleinhaus et al. (2010) argued that downstream factors may profoundly affect avulsion potential. Based on studies of a river diversion in the Netherlands, Kleinhaus et al. (2010) found that the downstream potential for flood conveyance or downstream flow attraction by (ebb) tides greatly enhance the potential for rapid and full avulsions due to the energy gradient increase. Such conditions are common in lower portions of deltas.

STUDY AREA

The study area (figures 3, 4) is the San Antonio River from the U.S. Highway 77 crossing near McFaddin in Victoria County to the river mouth, as well as the river valley and adjacent areas of the combined San Antonio/Guadalupe River delta. The San Antonio River has its headwaters as a fluviokarst system near the city of San Antonio in Bexar County. The main channel is about 386 km (240 mi) long, with a drainage area of 2419 km^2 (934 mi^2). The San Antonio River joins the Guadalupe River in the tidally-influenced delta area, just upstream of the Guadalupe-Blanco River Authority Saltwater Barrier near Tivoli, about 6.5 miles (11 km) upstream of the Guadalupe/San Antonio Bay.

Climate in the study area is humid subtropical, with hot summers and mild winters. Mean annual temperature at Victoria is 70^o F (21.1^o C). The hottest month is August, with an average high of 94^o F, and average low of 74^{o}F (33.4 and 23.4^o C). The coldest month is January, when the average high is 63 and low is 42.5^{o}F (17.1 and 5.8^o C). Mean annual precipitation is 37 inches (950 mm) in Victoria and 39 in (980 mm) in Goliad. Precipitation falls throughout the year, with March the driest and September the wettest months, on average. Summer droughts are not uncommon.

The geologic framework is entirely Quaternary (McGowen et al., 1976). The valley-bounding formation is the Pleistocene Beaumont formation. Alluvial, deltaic, and coastal deposits within the valley consist primarily of Holocene fills, but some Pleistocene terrace remnants occur within the valley.

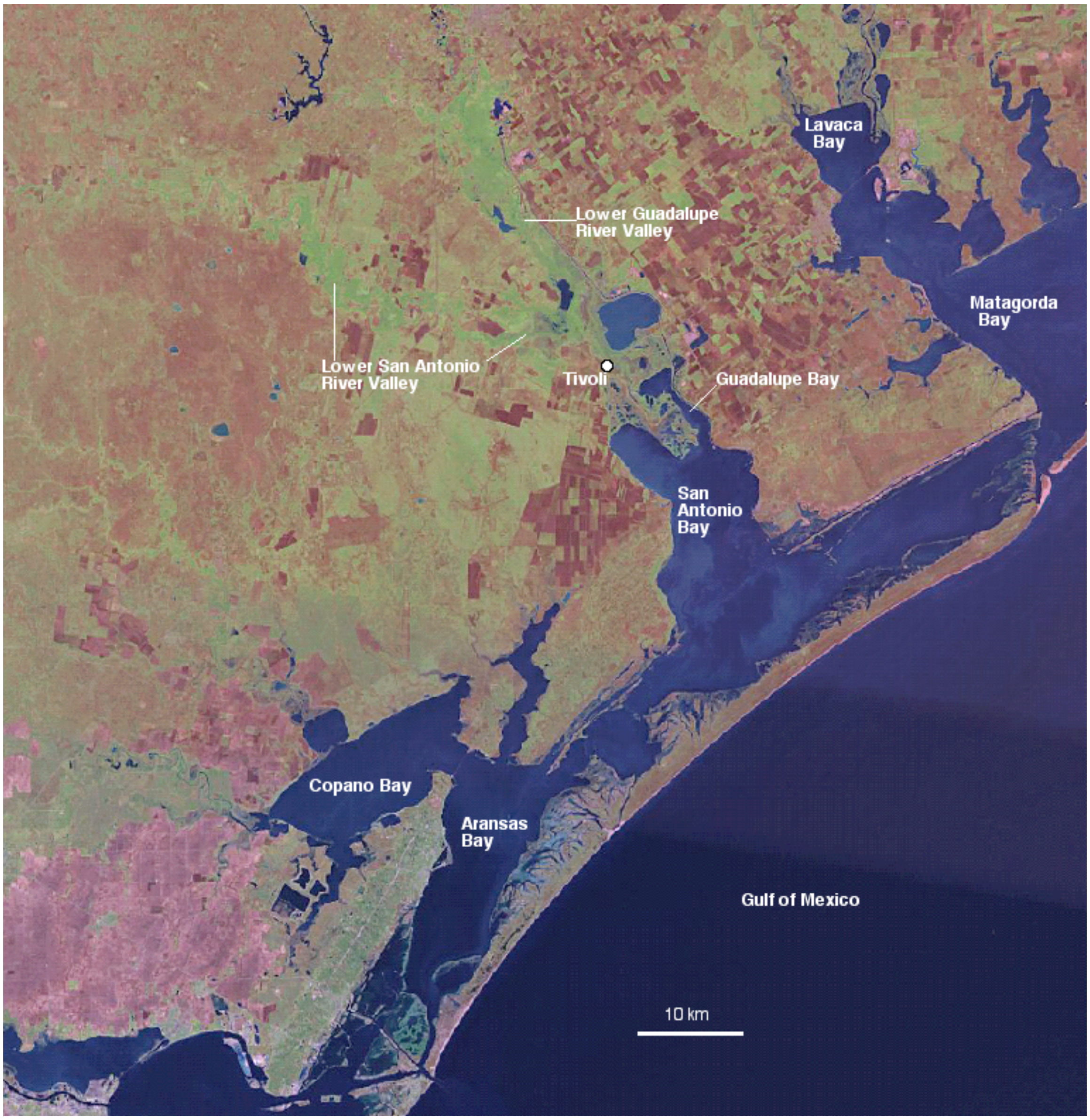


Figure 3. San Antonio and Guadalupe Bays and lower San Antonio and Guadalupe Rivers and nearby estuaries in the Texas Coastal Bend area. Base map is a LANDSAT satellite image. The town of Tivoli is at 28.455^{o} N, -96.888^{o} W.

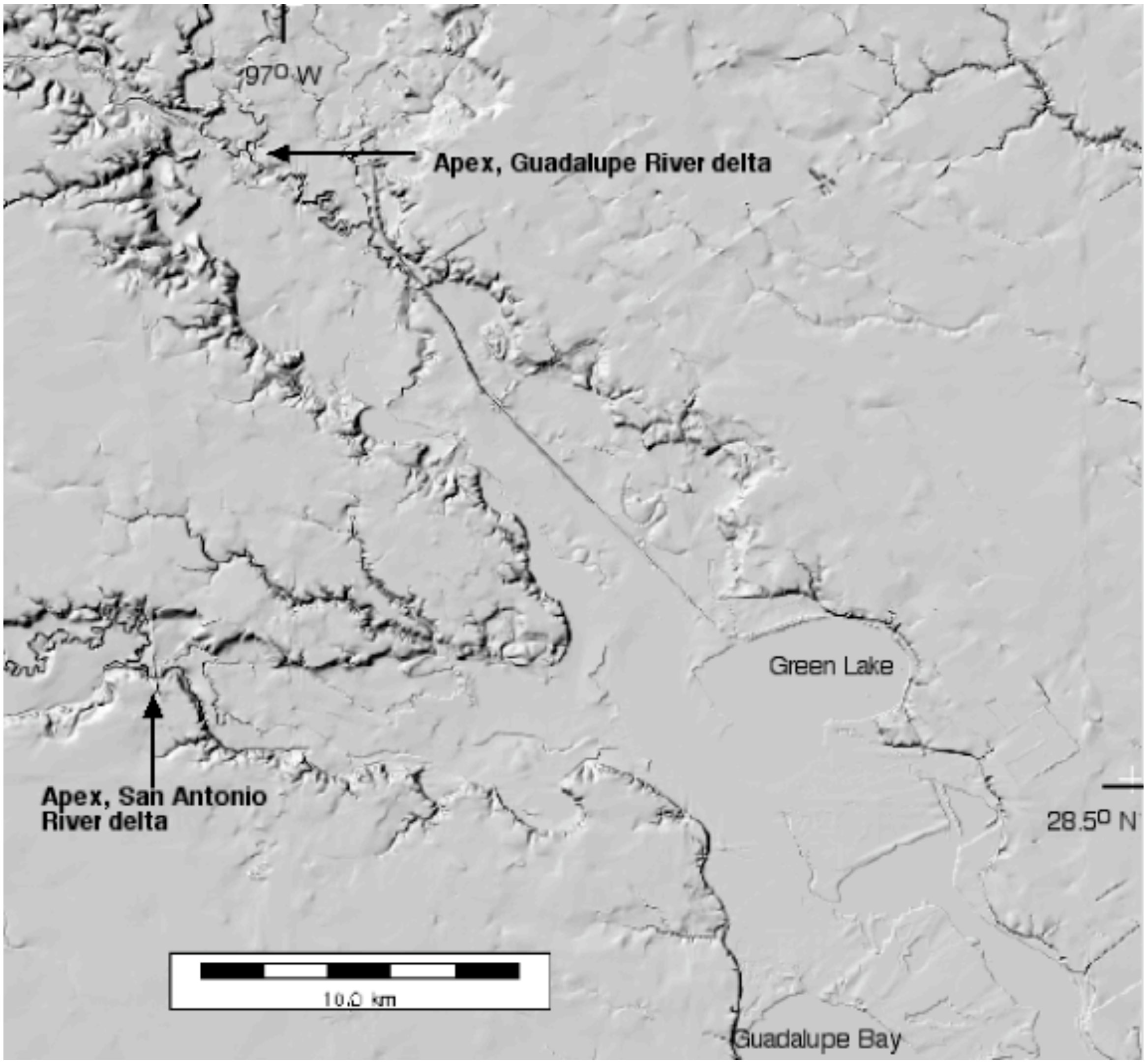


Figure 4. Shaded relief map showing the Guadalupe/San Antonio River delta area.

Delta Evolution

Development of the Guadalupe delta over the Holocene was reconstructed by Donaldson et al. (1970). The delta is part of a complex of lagoonal and deltaic deposits, slowly prograding into San Antonio Bay. Alluvium is deposited in a shallow, low-energy water body, and as the delta prograded into shallower water, distributary channels cut below the level of the modern bay floor. Donaldson et al. (1970) argued that the Guadalupe delta has a distinctive style, characterized by: (1) fluvial water and sediment discharge that dominate weaker waves and currents of the bay; (2) shallow-water deposition such that waves can rework the deposits; (3) river channels incised below the bay floor; (4) progressive shallowing of the bay due to delta progradation; and (5) growth by development of a series of subdeltas, with most of the inactive subdeltas presently deteriorating.

The origins of the delta can be traced to about 9000 BP, when the incised valleys of the Texas coastal Bend area from Matagorda Bay to Baffin Bay began infilling (Ricklis and Blum, 1997). By about 7500 BP, bay sedimentation had created shallows and habitats suitable for species exploited by humans. Ricklis and Blum (1997) show, based on analysis of a number of archaeological sites (including one on Guadalupe Bay and another near the San Antonio/Guadalupe River confluence), a pattern whereby human occupance corresponds with periods of stable or slowly rising sea-level. These occurred between about 7500-6800, 5900-4200, and after 3000 BP. In between were periods of rapid sea-level rise, with little or no evidence of human occupance of the delta or estuarine shores (Ricklis and Blum, 1997). Sea-level approached modern levels (though continuing to rise slowly) about 3000 BP, with the modern barrier island systems established by 2500-2000 BP (Ricklis and Blum, 1997). As discussed in chapter 2, the modern San Antonio River Delta was established in its approximate modern position after 3000 BP.

Contemporary and recent historical rates of bayhead delta sedimentation were estimated by White et al. (2002) for the Trinity, Lavaca-Navidad, and Nueces systems, Texas, using ^{210}Pb inventories. They found a general decrease in accretion rates from the northeast (Trinity) to southwest (Nueces). This trend would imply Guadalupe delta rates between the 0.328 ± 0.022 cm yr^{-1} mean rate found for the Lavaca-Navidad and the Nueces mean or 0.262 ± 0.034. However, both the Lavaca and Nueces Rivers have major reservoirs on the lower river that likely influence sediment fluxes in the deltas (White et al., 2002). As this is not the case for the San Antonio and Guadalupe Rivers, these rates cannot confidently be applied to the Guadalupe/San Antonio delta.

A reconstruction of Guadalupe/San Antonio delta development over the past ca. 2000 years is presented by Weinstein and Black (2009), reproduced in figures 5 and 6.

Like other Gulf of Mexico rivers, the lower San Antonio and Guadalupe Rivers have been profoundly influenced by sea level change. Throughout the Quaternary a series of valley incision episodes during colder climates and lower sea-levels have alternated with aggradation during rising sea-level, creating a system of alluvial terraces within the river valleys, which are themselves cut into the older, Pleistocene Beaumont terrace. Sea-level has generally been rising throughout the Holocene, though the pace of change and the possibility of a highstand up to 2 m higher than present earlier in the Holocene remain uncertain and controversial topics (c.f., Morton et al., 2000; Blum et al., 2001; McBride et al., 2007; Milliken et al., 2008; Simms et al., 2009).

The upper end of the delta corresponds approximately with a tectonic feature, known as the post-Vicksburg uplift (among other names). The high sinuosity upstream of highway 77 and lower sinuosity downstream reflects the influence of the uplift (Ouchi, 1985).

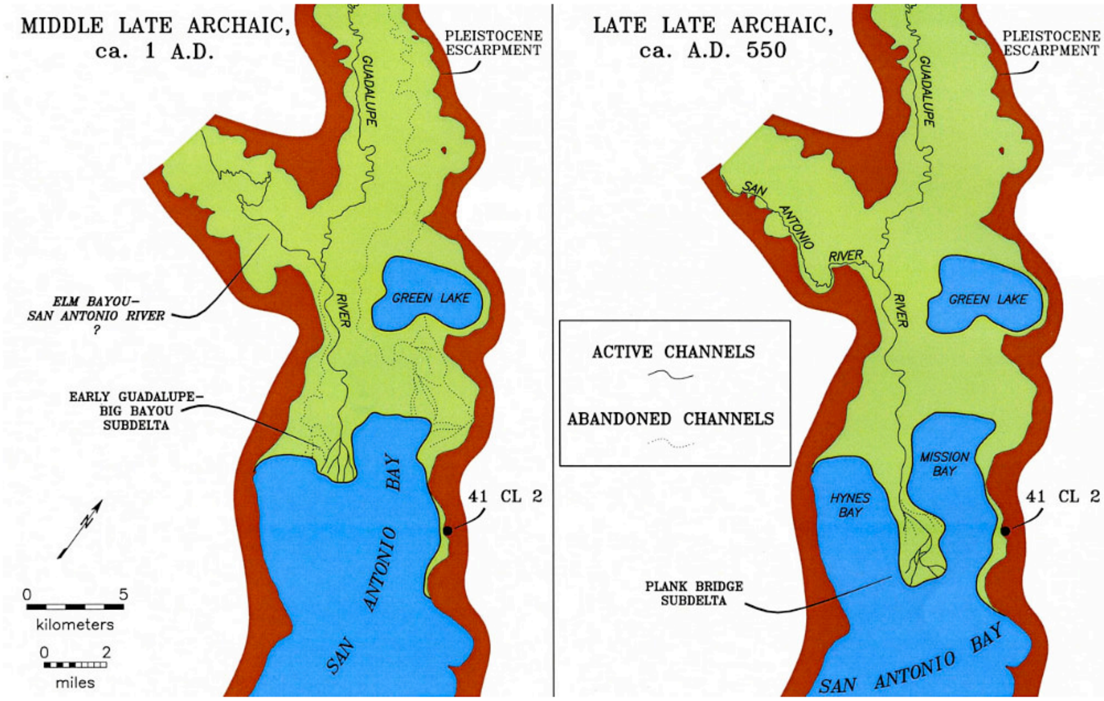


Figure 5. Inferred development of the Guadalupe/San Antonico delta and upper San Antonio Bay ca. 1 and 550 A.D. Source: Weinstein and Black, 2009; http://www.texasbeyondhistory.net/guadbay/images/Guadalupe-Delta-Aransas.html, from an original by Coastal Environments, Inc.

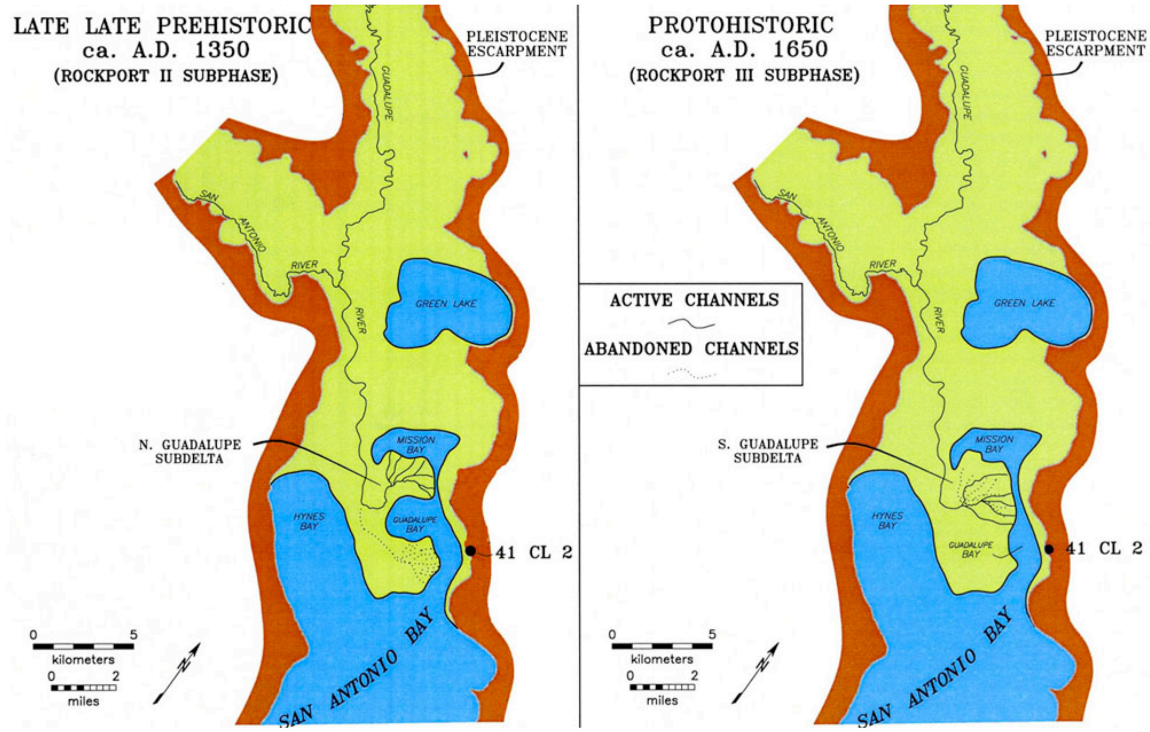


Figure 6. Inferred development of the Guadalupe delta and upper San Antonio Bay area from about the late part of the Late Prehistoric period 650 years ago (A.D. 1350; Rockport II) to the Protohistoric period (A.D. 1650; Rockport III). Source: Weinstein and Black, 2009, http://www.texasbeyondhistory.net/guadbay/images/Guadalupe-Delta-Aransas.html, from an original by Coastal Environments, Inc.

METHODS

Channels in the San Antonio delta area—whether active, infilled, or somewhere in between, were identified and cross-checked based on field observations and a number of map, imagery, and geographical information system (GIS) data sources described below.

Initial field reconnaissance of the Guadalupe and San Antonio River deltas was undertaken in January, 2010. More detailed field observations were conducted in June, 2010, by a combination of vehicle, foot, and kayak access. The delta channels are generally not accessible by motorized craft.

U.S. Geological Survey 1:24,000 scale topographic maps were obtained in digital form from the Texas Natural Resources Information System (TNRIS; http://www.tnris.state.tx.us/datadownload/download.jsp). Aerial photography in the form of digital orthophoto quarter quads (DOQQ) was also obtained from TNRIS, including 1996 images at 1-m resolution, and 2006 images at 2-m resolution. Aerial photography at 1-m resolution flown in early 2009 was accessed through *Google Earth.*

Topographic data in digital elevation model (DEM) form was obtained from the U.S. Geological Survey via the national data distribution center (http://seamless.usgs.gov/). These are LiDAR data at a 3-m horizontal resolution. Soil maps (1:24,000 scale) were downloaded from the U.S. Department of Agriculture's *Web Soil Survey* (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm) site. 1:250,000 scale geologic maps (*Geologic Atlas of Texas)* were obtained from TNRIS.

Various software was used to view and analyze the maps and GIS data, including ARCGIS (ESRI, Inc.), RiverTools (Rivix, Inc.), Graphic Converter, and ExpressView. In addition, oblique aerial photographs taken from a helicopter in February, 2008 were obtained from Walter C. Womack of McFaddin, and various historical maps in hardcopy form were also utilized.

Identification of active channels, or abandoned channels which still hold or convey water, is straightforward. In other cases potential paleochannels were identified on the basis of linear or sinuous depressions visible on the delta or alluvial valley floor. Apparent abandoned (or partially abandoned) channels or anabranches were considered possible former courses of the San Antonio River (as opposed to tributary or distributary channels which were never dominant channels) if their course was generally downvalley, the width of the trough, depression, or channel was consistent with the width of the modern river channel in the vicinity, and if the size and wavelength of any meanders was consistent with an abandoned river channel. Some of the features so identified are anabranches, distributaries or sloughs of the modern river, some are occupied by underfit tributaries, and some are wholly or partially infilled. Channel segments were classified as indicated in Table 1, based on channel morphology, sediment infills, vegetation, and field observations. Examples are shown in figures 7-13.

Table 1. Classification of San Antonio River Delta channels and paleochannels.

Category	*Description/Criteria*
Dominant	Active channel conveying more than 50% of non-flood flows
Active Anabranch	Anabranch that conveys flow in most flow conditions, but carries <50% of non-flood flows
Active Distributary	Distributary that conveys flow in most flow conditions; but carries <50% of non-flood flows
Semi-Active	Conveys flow during high flows, but is dry or characterized by discontinuous flow during low or normal flows
Billabong (slough)	Holds standing water at all times except extreme droughts, but does not convey downvalley flow except during floods
Tributary-occupied	Formerly dominant river channel now occupied by underfit tributary
Infilled	Trough-like depression. May contain water during wet periods or convey flow during floods, but is otherwise not inundated.

Figure 7. Dominant channel. San Antonio River downstream of the confluence with Old River, which is a semi-active distributary in this vicinity.

Figure 8. An artificially-straightened section of Cross Bayou, which currently functions as an active anabranch.

Figure 9. The CushKuy Connector, a man-made channel which now functions as part of an active distributary route connecting Cushman Bayou and Kuy Creek.

Figure 10. Old River at its junction with the San Antonio River, looking downstream. Old River in this area is a semi-active channel.

Figure 11. A billabong (slough) in a portion of the Old River paleochannel.

Figure 12. A portion of the Cushman Bayou paleochannel occupied by an underfit tributary stream.


Figure 13. This slight depression is an infilled portion of the Cushman Bayou paleochannel.

The setup factor of aggradation (more specifically, channel aggradation which exceeds the rate of floodplain surface accretion) was assessed on the basis of historic bridge cross-sections for the U.S. 77 crossing near McFaddin, obtained from the Texas Department of Transportation. Other bridges in the study area are private, and no similar records are available. Field survey of the dominant channels was based on geomorphic indicators. Key indicators of channel aggradation (or incision) include exposure or burial of bedrock or basal materials; topographic changes relative to cultural features such as pilings, boat ramps, etc.; bank failures; vegetation; and soil/sediment stratigraphy. DEM data was used to identify locations where potential slope advantages exist, as well as aggradation status on a regional (delta-wide) scale.

Trigger factors were assessed based on the field survey and aerial photography, with an emphasis on logjams and large woody debris.

Stability of Flow Splits

Asymmetric channel bifurcations with unequal divisions of water and sediment appear to be more stable than 50-50 splits, with the latter tending to evolve toward dominance of one channel or another following (even relatively minor) disturbances (Edmonds and Slingerland, 2008).

The stability of an initial flow split depends on whether sediment is proportioned between the two branches in the same proportion as water (Slingerland and Smith 1998; Letter et al., 2008; Hood, 2010). If one branch or the other is receiving disproportionately high sediment loads (Q_s) relative to discharge (Q), it will eventually clog up, with the other branch becoming dominant. Denoting the two branches with subscripts 1, 2, the stability condition is

$$Q_1/Q_2 \approx Q_{s,1}/Q_{s,2} \qquad (2)$$

In a transport-limited system with erodible bed and banks (such as the San Antonio River Delta), a reasonable assumption is that sediment load is partitioned in direct proportion to stream power per unit weight of water (P_u), which is related to cross-sectional stream power (Ω):

$$\Omega = \gamma\ Q\ S \qquad (3)$$

where γ, the specific gravity of the water, is a constant, and *S* is the energy grade slope. Because discharge is the product of cross-sectional area (*A*) and velocity (*V*),

$$P_u = \Omega/\gamma A = VS \qquad (4)$$

If sediment load is proportional to P_u, then the stability condition is

$$Q_{s1}/Q_{s2} \approx P_{u1}/P_{u2} = (V_1S_1)/(V_2S_2). \qquad (5)$$

As Q = AV, this reduces to

$$A_1/A_2 = S_1/S_2. \qquad (6)$$

This stability criterion was specifically addressed for the San Antonio/Elm Bayou split based on field surveys.

Chapter 2
Paleochannels and Avulsions

CHANNELS OF THE SAN ANTONIO DELTA

A number of active, semi-active, and infilled channels exist in the lower San Antonio River delta area. Some of these are identified in figure 14. These are channels whose size and situation indicate that they may have been at one time the dominant river channel. These are described below in terms of major channel segments or reaches.

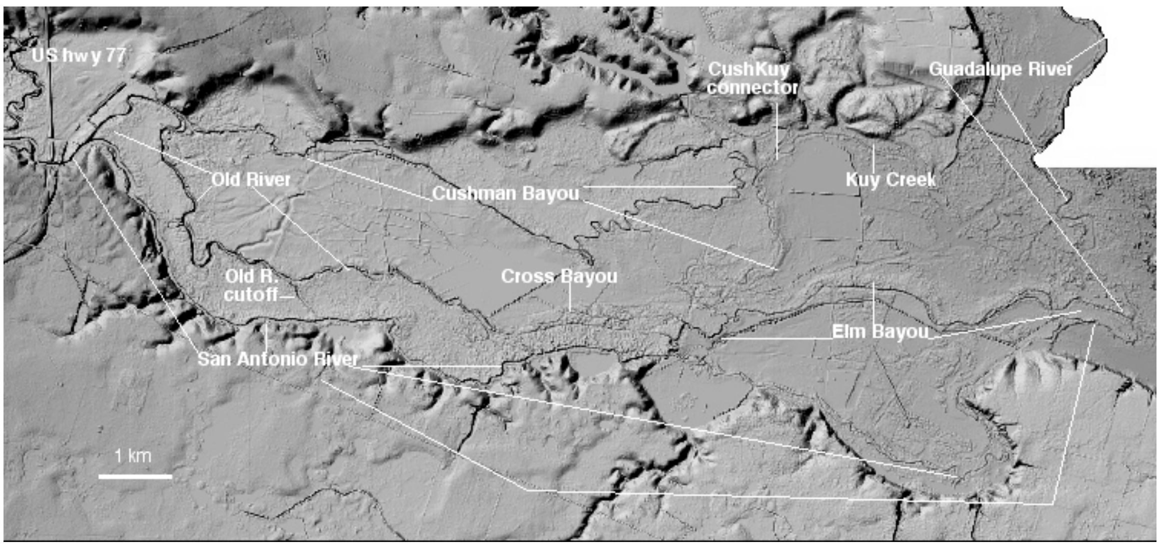


Figure 14. Shaded relief map of the San Antonio River delta area, showing channels referred to in the text. In all cases contemporary names are used.

San Antonio River

The San Antonio River from Highway 77 to Elm Bayou is the dominant channel, carrying flow in all conditions and conveying more than 50 percent of the discharge, at least in non-overbank flows. The river avulsed to its current position about 2 km downstream of the highway bridge sometime between 1847 and about 1930. The modern boundaries of Victoria and Refugio Counties were established in 1847, with the boundary between them based on the San Antonio River. This boundary follows the Old River and Old River Cutoff channel. However, the contemporary main channel was apparently dominant by the time the McFaddin Oil and Gas Field in the delta began to be exploited around 1930-31.

The reach from Old River Cutoff to Elm Bayou has apparently been dominant since before 1847. Downstream of Elm Bayou, the San Antonio channel is an active distributary, but this 11 km reach is not the dominant channel.

Elm Bayou

Elm Bayou is the dominant channel from the junction or split with the San Antonio, for 8.5 km to the Guadalupe River. The bayou has very little drainage area upstream of the confluence with the San Antonio. Elm Bayou was previously the dominant channel for at least one, and possibly two previous configurations of the lower San Antonio River (to be discussed later), and the avulsion from the San Antonio therefore represents reoccupation of a former channel.

Old River

The Old River channel joins the San Antonio River about 2 km downstream of highway 77. From here to and through the Old River Cutoff, this was the dominant channel at one time, and was at the time county boundaries were established in 1847. At the confluence with the San Antonio, the channel has infilled and aggraded, such that its width is on the order of 10 m (vs. about 40 m for the San Antonio at their confluence)(Fig. 15). The bed has aggraded at least 2 m above the river bed, and there is no hydraulic connection at normal or low flows. Water from the San Antonio River does enter the old River channel at high sub-banktop flows.

About 2 km downstream of the San Antonio is the confluence with Cushman Bayou, discussed below. Further downstream, Old River is a slough or billabong which conveys flow during high flow events. The Old River Cutoff is currently infilled, partly as a result of the upstream avulsion to the newer course, but also because a constructed drainage canal between levees, just upstream of the cutoff and parallel to it, captures whatever channelized flow there is that moves from this vicinity to the San Antonio River.

Further downstream, the Old River course is older. Because of levees, artificial channels, and other topographic and hydrographic modifications, it is difficult to tell whether this channel connected with Elm Bayou or the San Antonio channel (or both).

The Flat Bayou paleochannel extends northeast from Old River, at a point upstream of Old River Cutoff. This older paleochannel apparently connected to the Cushman Creek Channel. Various portions of it are infilled, tributary occupied, or billabong.

Figure 15. Old River channel at the confluence with the San Antonio.

Cushman Bayou

From its confluence with Old River described above, Cushman Bayou flows nearly 17 km to a connector canal cut between Cushman and Kuy Creek. Cushman is occupied by an underfit tributary in most of this zone, though the uppermost reaches are semi-active or infilled.

The artificial channel connecting Kuy and Cushman (termed here the CushKuy Connector) was apparently intended to direct Kuy Creek flow into lower Cushman Bayou. Whatever its original intent, the connector now directs flow from lower Cushman Bayou up to Kuy Creek. This phenomenon was observed in the field, and the landowner confirmed that Cushman-to-Kuy flow through the connector is typical.

When Cushman Bayou was the dominant channel, Elm Bayou formed its outlet to the Guadalupe River. The Cushman watershed has been fragmented, however. Flow from upper Cushman Bayou is mainly diverted through the connector, while lower Cushman drains into Elm Bayou. Field evidence suggests that the lower Cushman channel was infilled until relatively recently (<5 years ago), and has been reopened, apparently due to avulsion from another Elm Bayou tributary into the Cushman channel.

The planform of Cushman Bayou is unusual (see figure 14). After a long straight reach, the channel makes a general turn toward the northeast, and begins intense meandering. Near the connector, the channel turns to follow a meander path south toward Elm Bayou. Just east of the latter channel segment is a small escarpment, very subtle but clearly visible from the LiDAR-derived maps. This is apparently a tectonic feature. The high sinuosity upstream and lower sinuosity downstream is characteristic of alluvial rivers up- and downstream of an axis of flexure, analagous to the San Antonio River at the upper end of the study area (see chapter 1; Ouchi, 1985; Schumm et al., 2000). Tectonic influences could also explain the general northeast to south change in the channel trend. An extensive system of levees and ditches east of the escarpment has eliminated or obscured the natural drainage patterns, making interpretations difficult. However, the *Tectonic Map of Texas* (Ewing et al., 1991) does show a fault in this vicinity.

Kuy Creek

Kuy Creek has its origins as an upland tributary. However, where this incised stream enters the San Antonio River valley, near the confluence with Rotten Kuy Creek, it occupies a former river channel. The lower end of Kuy Creek joins the Guadalupe about a kilometer upstream of Elm Bayou. However, much of the intervening area has been extensively modified by wetland and wildlife habitat creation and enhancement, levees, and artificial drainage. Based on a flow routing algorithm applied to the LiDAR-derived DEM, the inferred Kuy Creek flowpath is shown in figure 16.

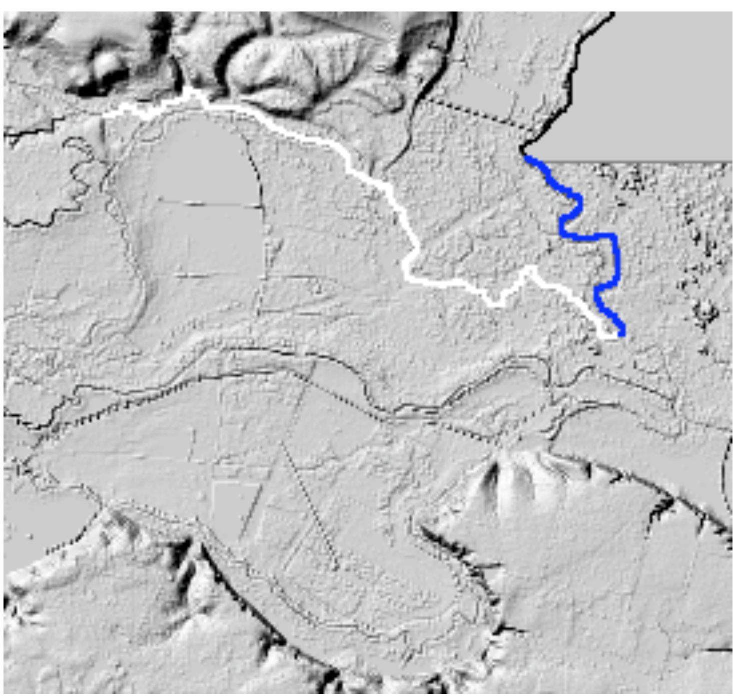


Figure 16. Path of Kuy Creek (white) to the Guadalupe River (blue) in its lower reaches. The channel in a portion of this reach has been obscured by modifications described in the text; the path is based on a flow routing algorithm for those sections.

The upper deltaic, paleochannel portion of Kuy is tributary occupied, but from the CushKuy Connector downstream the major source of flow is distributary flow from the CushKuy connector as described above.

The Kuy Creek former river channel extended to the west along Rotten Cuy Creek, toward the upper reaches of Cushman Bayou. This route is termed here the CushKuy Paleochannel. The upper reaches of this nearly 6 km path are infilled, and the lower portion is tributary-occupied (Rotten Kuy Creek).

Summary

The channel and paleochannel segments discussed above are shown in Table 2. The upstream and downstream elevations are derived from DEM data, and are thus subject to some imprecision and uncertainty. However, field observations confirm that the relative elevations shown are mostly correct, with the lower portion of Cushman Bayou being an exception. As the table shows, abandoned river channels are in some cases infilled, but mostly now function as active or semiactive distributaries, semi-active anabranches, or billabongs. Previous river courses are discussed in the next section.

Table 2. Channel and paleochannel sections in the San Antonio River delta. US, DS refer to elevations at the upstream and downstream ends of the segment (masl); O.R. = Old River.

Channel Segment	*US Elev.*	*DS Elev.*	*Length (km)*	*Slope*	*Width (m)*	*State*
San Antonio: 77 to Elm Bayou	7.15	5.54	11.06	0.0001459	35-50	Dominant channel
San Antonio: Elm to Guadalupe R.	5.54	1.65	11.24	0.0003461	11-13	Active distributary
Elm Bayou: San Antonio R. to Cushman Bayou	5.54	3.46	0.76	0.0036751	20	Dominant channel
Elm Bayou: Cushman to Guadalupe R.	3.46	1.65	7.74	0.0002571	18-20	Dominant channel
Old River: San Antonio to Cushman	9.24	8.48	2.12	0.0003602	10-13	Semi-active anabranch
Old River: Cushman to O.R. cutoff	8.48	6.13	5.00	0.0004685	8-10	Billabong
Old River Cutoff: Old River to San Antonio River	6.13	7.15	0.85	-.0014118	<10	Infilled
Old River: O.R. cutoff to Cushman Bayou	6.13	3.89	7.78	0.0002946	8-13	Infilled
Cushman Bayou: Old River to Kuy Connector	8.48	3.39	16.64	0.0003059	9-13	Tributary-occupied
Cushman Bayou: Kuy Connector to Old River	4.77	3.89	2.19	0.0004018	7-10	Distributary
CushKuy Paleochannel: Cushman to Kuy Cr. via Rotten Kuy Cr.	7.38	2.89	5.74	0.0007816	9-15	Infilled; tributary-occupied
Kuy Creek: Rotten Kuy Cr. to Kuy Connector	4.47	2.89	1.09	0.0017222	5-13	Tributary-occupied
Kuy Creek: Kuy connector to Guadalupe	3.05	1.65	8.04[1]	0.0001744	8-12	Active distributary
Flat Bayou Paleochannel	9.07	5.44	>4.00[2]	0.0008893	9-20	Infilled; tributary occupied; billabong

RIVER PATHS

The channel segments described in the previous section together describe at least seven fundamentally different dominant flow paths through the delta. These are shown in figure 14 and discussed below. It should be recognized, however, that (like the contemporary situation) various distributaries and anabranches were likely active at any given time in addition to the dominant channel.

San Antonio River

The channel currently labelled on maps and identified as the San Antonio River all the way to the Guadalupe defines this route. This became the dominant channel sometime after county boundaries were established in 1847 and before exploitation of the McFaddin Oil and Gas Fields about 1930. This continued to be the chief flow path until the mid to late 20th century, when Elm Bayou began capturing most of the flow.

San Antonio River-Elm Bayou

The San Antonio-Elm Bayou route is currently dominant. The crevasse or avulsion connecting the San Antonio and Elm Bayou at or near the current split is not evident on 1930 aerial photography. According to several local residents, a channel from the San Antonio to Elm Bayou had been established due to a crevasse during a flood by the late 1940s. However, local residents and landowners are unanimous in their opinion that the San Antonio channel still carried most of the flow through the mid and well into the late 20th century. At present, Elm Bayou carries about 75 percent of the discharge at the split.

Old River-San Antonio River

This path, with Old River connecting to the San Antonio channel via Old River Cutoff, became dominant sometime before 1847 and was the dominant path when county boundaries were established.

Old River

The Old River route is the same as above as far as Old River Cutoff. An older Old River paleochannel continues east from here, and connected most likely to the Elm Bayou channel. An artificial channel between levees roughly parallels part of this path, between the Old and San Antonio Rivers.

Cushman-Elm Bayou

This path starts on Old River, and follows the Cushman Bayou channel to Elm Bayou, and thence to the Guadalupe.

Kuy Creek

The route is the same as above, but proceeds through the CushKuy Paleochannel via Rotten Kuy Creek to the Kuy channel, and via the latter to the Guadalupe.

Flat Bayou Paleochannel

This route follows Old River to the Flat Bayou Paleochannel (FBC). A cursory look at the map suggests the latter continues north to connect with the Cushman channel, following this via Elm Bayou to the Guadalupe. However, detailed topography suggests the possibility of a bend to the east, and to Elm Bayou via Cross Bayou. The latter is leveed and the presumed original channel path is obscured. However, distance from the upper end of Old River along the FBC to the Guadalupe via the Cushman route is more than 30 km, while distance via the Cross Bayou route is less than 23 km. All other pathways from the same starting point to the Guadalupe have distances of 19 to 26 km (table 3), suggesting the Cross Bayou pathway is more likely.

Relative Ages

Contemporary observations and historical information show that the San Antonio-Elm route is the youngest, followed by the San Antonio route, and the Old River-San Antonio path. Because Cushman Bayou occupies an alluvial ridge (figure 14), channel shifts more likely occurred from rather than to this channel in most instances. Thus this pathway is considered to be older than the San Antonio and Old River channelways. The infilling of the Flat Bayou and CushKuy Paleochannels indicates that these are older than the Old River and Cushman Bayou channels, respectively. A more northerly path preceding the more southerly routes is also inferred by the reconstructions of Weinstein and Black (2009; see figures 5, 6). The relative chronology is shown in Table 3.

The timing for paths 1 and 2 in Table 3 is constrained by historical information. Path 3 must have been initiated significantly before 1847, and the Weinstein and Black (2009) maps suggest that a more southerly path had occurred by 550 AD. The same source speculates a more northerly path between 1 and 550 AD.

Paleochannels evident in the contemporary delta must have been established no earlier than when the delta estuary complex reached is approximate contemporary position. Geoarchaeological evidence from the Guadalupe-San Antonio estuary and delta area and nearby areas suggests areas of stable or slowly rising sea between about 7500-6800, 5900-4200, and after 3000 BP. In between were periods of rapid sea-level rise (Ricklis and Blum, 1997). Sea-level approached modern levels (though continuing to rise slowly) about 3000 BP, with the modern barrier island systems established by 2500-2000 BP (Ricklis and Blum, 1997). Detailed reconstructions of the Holocene history of Corpus Christi Bay to the southwest of the Guadalupe-San Antonio Bay, and of the Matagorda-Lavaca estuary to the northeast are available (Maddox et al., 2008; Simms et al., 2008). Both estuarine systems reached their approximate contemporary positions after about 7300 and by 6700 BP. In the Corpus Christi Bay-Nueces River system a major bayhead delta backstepping event occurred about 2600 BP (Simms et al., 2008), which is at least approximately coincident with establishment of the modern bayhead delta in the Galveston-Trinity Bay system (Anderson et al., 2008). The approximate modern location of the deltas in the Matagorda-Lavaca estuary system was reached sometime after 2800 to 3000 BP. McGowen et al. (1976) also estimated establishment of the Guadalupe bayhead delta at about 3000 BP. Based on this, the Guadalupe-San Antonio River deltaic system likely also reached its approximate contemporary geography after 3000 BP, so that the earliest paleochannels now evident must be younger than this.

Mean channel slope gradients for the various pathways are shown in Table 4.

Table 3. Relative chronology of San Antonio River channel paths through the delta. Distance is the measured or estimated distance from the San Antonio/Old River confluence to the Guadalupe River. Time is when the path apparently became dominant.

Channel Path	Distance (km)	Time
1. San Antonio River-Elm Bayou	18.86	late 20th century
2. San Antonio River	21.60	1847-1930
3. Old River-San Antonio River	23.95	550? – pre-1847
4. O.R.-Flat Bayou Paleochannel-Cushman-Elm Bayou	22.73	1 – 550 AD?
6. Old River-Cushman-Elm Bayou	26.50	After 3000 BP to 2000 BP?
7. Kuy Creek	21.80	After 3000 BP

Table 4. Distances of Major Flow Paths From San Antonio River/Old River Split Near Highway 77, to Guadalupe River.

Path	Distance (km)	Mean Slope ($X 10^{-4}$)
San Antonio River (SAR) – Elm Bayou (EB)	18.86	2.92
SAR-EB-Cushkuy Connector Kuy	22.26	2.47
SAR	21.60	2.55
Old River (O.R.) – O.R. Cutoff - SAR	23.95	2.30
O.R. – Flat Bayou paleochannel (FBC) – CB – EB	30.47*	1.80
O.R. – FBC – Cross Bayou – EB	22.73*	2.42
O.R. – Cushman Bayou (CB) – EB	26.50	2.08
O.R. – CB – CushKuy Paleochannel – Kuy Creek	21.80	2.52

The sites of major channel shifts are shown in figure 17. Site 1 is the Old River to San Antonio avulsion, and location 2 is the site of the Cushman Bayou avulsion to Old River. Site 3 is at the junction of Old River and the Flat Bayou paleochannel, and 4 at Old River Cutoff. Site 5 is uncertain, but is the location of a possible shift from a route along the northern boundary of the delta into the Cushman Bayou channel. Sites 6 and 9 are associated with artificial channels connected to Old River, and between Kuy Creek and Cushman Bayou, respectively. The San Antonio-Elm Bayou split is at location 7, and the diversion from Elm Bayou to the Cushman channel is at 8.

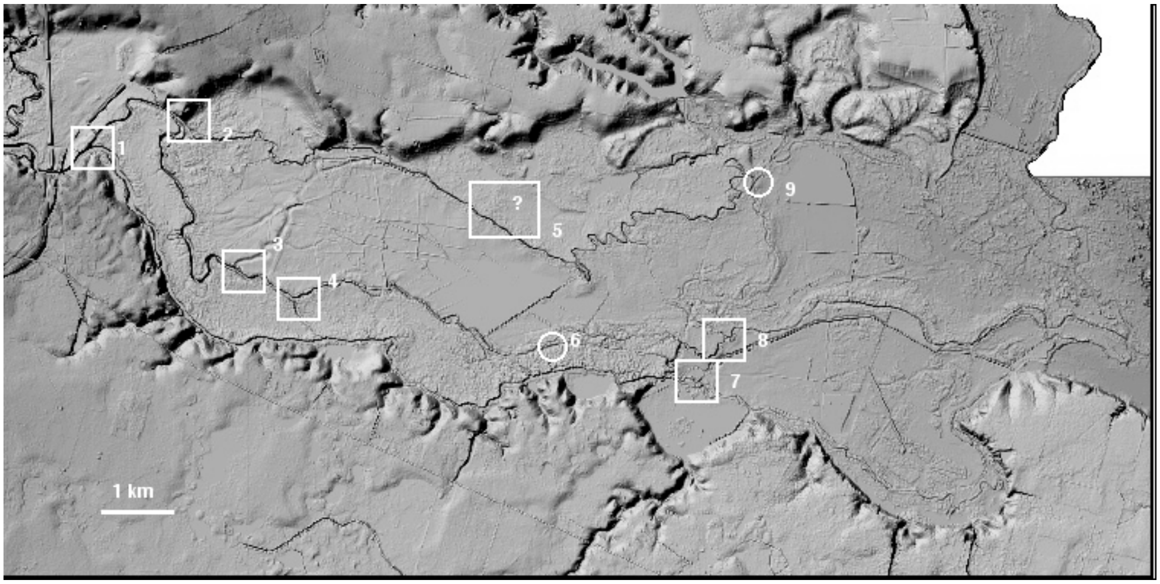


Figure 17. Avulsion sites in the San Antonio River Delta. Circles indicate sites where avulsions occurred along or due to artificial channels.

WHY SO MANY AVULSIONS?

Avulsions are a common feature of Texas Gulf Coastal Plain rivers (Aslan and Blum, 1999; Blum and Aslan, 2006; Phillips, 2009; 2011), and in deltas worldwide (Makaske, 2001; Makaske et al., 2002; Gouw, 2007; Stouthamer and Berendson, 2007). Even in this context, however, the lower San Antonio River seems particularly prone to channel shifts, though in a global context the avulsion frequency implied by the evidence outlined above is by no means unusually high (Makaske et al., 2002 Stouthamer and Berendson, 2007).

The mobility number discussed earlier (eq. 1, ch. 1) suggests frequent avulsions when $M = (d\ v_c)/(w\ v_a) << 1$. Quantitative data for this expression are not available in the study area, but abundant field evidence exists to show that the rate of lateral bank erosion (v_c) is negligible. Few cutbanks exist in the study area, and there is little other field evidence of bank erosion or channel migration. Abundant field evidence also indicates that the rate of channel aggradation (v_d) is relatively rapid. This includes channel insets, buried riparian vegetation, construction of channel shelves, and channel bed elevations higher than surrounding backswamp areas. High v_d and low v_c values indicate a very low mobility number.

The muddy, fine-grained cohesive sediments dominating the study area may also contribute to high avulsion frequency. In general, this tends to inhibit lateral channel migration, leading to lower mobility numbers. In the lower Macquarie River, Australia, Ralph and Hesse (2010) found that cohesive bank sediments limit laterial migration, leading to a dominance of vertical accretion and channel aggradation, and to a "predisposition for periodic avulsion to be the main form of lateral adjustment" (63).

Tornqvist (1993) also found that cohesive soils are the principal condition promoting anastamosis in the Rhine-Meuse delta.

Soil survey data (extracted from http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm) shows that soil series with surface textures in the clay textural class (such as Aransas Clay) comprise about half of the surface area of the San Antonio delta, and soils in the silty clay surface textural class comprise most of the other half (table 5). However, table 5 shows that the lower San Antonio River is not unique in this regard.

The difference appears to be related to the sediment transported by the rivers rather than the texture of the mapped deltaic and alluvial soils. In contrast to the southeast Texas Rivers (San Jacinto, Trinity, Neches, Sabine), the San Antonio and Guadalupe Rivers have significant proportions of their drainage areas within the Texas Blackland Prairie region, characterized by clayey, vertic soils. The Colorado and Brazos Rivers also drain the blackland prairie areas, but the size of their drainage basins is such that the areas of clayey soil are proportionally less important than in the Guadalupe and San Antonio Rivers. Limestone-dominated areas, which tend to produce clayey sediments, are also proportionally more important in the San Antonio and Guadalupe Rivers, which both have headwaters in fluviokarst areas of the Edwards Plateau.

Based on U.S. Geological Survey data collected at Victoria on the Guadalupe River and Goliad on the San Antonio, Holley (1992) found that both rivers transport a high proportion of fine sediment in suspension. The mean value of the percent finer than 0.0625 mm (silt and clay fractions) was 92% for the San Antonio and 83% for the Guadalupe. This is consistent with Morton and Donaldson (1978) who noted a higher sand content in the Guadalupe compared to the San Antonio River portion of the delta. Holley (1992) also found that suspended sediment concentrations for a given flow rate was about five times higher for the San Antonio River at Goliad than for the Guadalupe station. Thus, despite the fact that flows of the Guadalupe River at Victoria are about twice those of the San Antonio River at Goliad, the total sediment load of the Guadalupe is only slightly larger (Holley, 1992).

Welborn (1967) collected data on sediment transported by major rivers predating many of the major dam impacts. His work shows finer sediments being transported by the San Antonio, Guadalupe, Nueces, and Lavaca Rivers (70 to 73 percent clay; 1 to 2 percent sand) as opposed to the Colorado, Trinity, and Sabine Rivers to the northeast (38 to 62 percent clay; 9 to 39 percent sand). This suggests that rivers such as the Lavaca and Nueces may also experience high avulsion frequency, but this has not been investigated.

Table 5. Surface texture class of soils in deltas of Texas rivers. The San Antonio delta data is based on an inventory of the entire delta; data for other rivers are based on sample areas along the axis of the dominant channel within the delta. The percent clay column represents the range of clay content in the textural class.

San Antonio

Soil texture class	*Percent clay*	*Dominant Series*	*Percent land cover*
Clay	40 - 100	Aransas	49
Silty clay	40 - 60	Rydolph	47
Clay loam	28 - 40	Sinton	4

Guadalupe

Soil texture class	*Percent clay*	*Dominant Series*	*Percent land cover*
Clay	40 - 100	Aransas	73
Silty clay	40 - 60	Rydolph	27
Sand	0 - 10	Zalco	<1

Colorado

Soil texture class	*Percent clay*	*Dominant Series*	*Percent land cover*
Clay	40 - 100	Brazoria	55
Silty clay	40 - 60	Placedo	<1
Silty clay loam	28 - 40	Clemville, Norwood	40
Sand	0 - 10	Riolomas	4

Nueces

Soil texture class	*Percent clay*	*Dominant Series*	*Percent land cover*
Clay	40 - 100	Aransas	84
Clay loam	28 - 40	Sinton	11
Loam	8 - 28	Sinton	2
Sandy loam	0 - 20	Odem	3

Brazos

Soil texture class	*Percent clay*	*Dominant Series*	*Percent land cover*
Clay	40 - 100	Pledger	59
Silty clay loam	28 - 40	Asa	26
Silt loam	0 - 28	Norwood	15

Trinity

Soil texture class	*Percent clay*	*Dominant Series*	*Percent land cover*
Clay	40 - 100	Estes, Kaman	68
Loam	8 - 28	Mantachie	11
Sandy loam	0 - 20	Owentown	4
Sand	0 - 10	Voss	16

The setup conditions for avulsions include channel aggradation, which is clearly present in the lower San Antonio River, and slope advantages, which are also common. The San Antonio, Elm Bayou, Old River, and Cushman Bayou channels all occupy alluvial ridges, with channel bed elevations in many cases higher than those of backswamp areas and flood basins behind the natural or artificial levees. A potential trigger factor—large woody debris jams—is also common. This is discussed in the next chapter.

Chapter 3
Logjams and Large Woody Debris

The lower San Antonio and (to a lesser extent) Guadalupe Rivers have been profoundly affected by large woody debris (LWD) and logjams in recent decades. The San Antonio River currently (2010) features a major logjam in the delta near Tivoli, extending at least 1.55 mi (2.5 km) upstream from the Elm Bayou, and down both branches. The debris was more or less continuous in this reach in June, 2010. Further downstream on both channels are numerous smaller logjams, spanning the entire channel and dense enough to be impassable by canoe or kayak even in near-bankfull flows. Logjams are also common further upstream on the San Antonio River and on the Guadalupe River downstream of Victoria. In addition to the aesthetic problems, inconvenience, navigation blockage, and potential adverse water quality and habitat impacts (due to trash and anthropic debris accumulating in the logjams), the features cause localized bank erosion and channel shifts. These effects, along with the possible role of logjams in avulsions, are the focus here.

News media reports, conversations with local residents, and comments from agencies such as the Guadalupe-Blanco River Authority and the Texas Water Development Board indicate strong public perceptions in the lower San Antonio and Guadalupe River areas that logjams play a major role in flooding, channel bank erosion, and possible channel shifts or avulsions. This is not unique to south Texas; Chin et al. (2008) show that there are in general strong public opinions or suspicions that woody debris in channels impedes flow and increases flooding. LWD certainly has significant local impacts on flow hydraulics in the immediate vicinity, producing both flow accelerations and ponding, and both erosion and deposition in various circumstances (see review by Montgomery et al., 2003). Logjams are also known as an avulsion trigger (Schumm and Jones, 1999; Makaske et al., 2002). Changes in the wood regime of rivers can have effects as great as those of changes in discharge or sediment inputs (Montgomery et al., 2003).

LWD is defined as woody pieces at least 10 cm (4 in) in diameter; essentially trees, logs, and larger limbs and branches. Following conventional usages, a LWD snag is a log or tree, or local wood accumulation, large enough to be a hazard to navigation (and a significant riverine habitat element). A logjam is an accumulation that occupies the entire channel width, effectively preventing navigation. The term log raft has been used historically in reference to major logjams kilometers or more in length.

Early European explorers and settlers to the lower Mississippi Valley and Gulf Coast region sometimes encountered log rafts that completely blocked channels for tens to hundreds of kilometers, prohibiting navigation and playing a major role in avulsions. The most famous of these occurred on the Red and Atchafalaya Rivers, Louisiana, and the Colorado River, Texas. The source of the woody debris for these blockages is unknown, but Phillips and Park (2009) showed (based on effects of Hurricane Rita in 2005) that a category 3 hurricane can deliver enough wood directly to a river channel to initiate a major channel blockage.

WOODY DEBRIS EFFECTS ON STREAM FLOW

Perceived increases in flooding are commonly attributed to in-stream wood, resulting in efforts to remove it. Removals are increasingly controversial, however, because of the recognition of the important ecological and habitat functions of LWD, as well as the potential geomorphic destabilizing effects of wood removal (e.g., Montgomery et al., 2003; Chin et al., 2008). Expense is also a major issue.

While very high densities of wood, or LWD at channel constrictions, may cause increased flooding, flume experiments conducted by Young (1991) showed that levels of LWD commonly occurring in lowland rivers of southeastern Australia have no significant effect on flood levels. Lester and Wright (2008) specifically tested the notion of increased flooding as a result of LWD by experimentally adding wood to eight Australian streams, and compared stages, velocities, and bed and bank erosion rates with unmodified reaches. While the (expected) local effects were found, no clear evidence was obtained of increased flooding or erosion over the 18-month study period (Lester and Wright, 2008). Phillips and Park (2009) examined hydraulic geometry at several gaging stations in southeast Texas affected by Hurricane Rita at similar cross-sectional areas before and after the storm. They found no evidence of flow impedance and increased flooding or flood risk due to LWD, despite widespread public perception of such.

If LWD forms dams or occupies enough of the channel to significantly reduce cross-sectional area, and if the debris is not mobilized at high flows, flooding may be increased due to displacement of water from the channel. Otherwise effects of LWD are manifested via roughness and frictional resistance. Manga and Kirchner (2000) found that LWD on the channel bed provides a disproportionately high proportion of total flow resistance, relative to its surface area. As debris accumulates in a channel, total shear stress increases due to depth increases, but an increasing proportion of total shear stress is borne by the debris rather than the bed itself. Measurements before and after woody debris removal in a field experiment by Dudley at al. (1998) showed that the mean Manning's roughness coefficient (*n*) was increased 39 percent by LWD. The *n* value increased nearly proportional to the area of debris and/or vegetation facing flow. The effects of LWD on roughness and flow resistance decreased as water depth increased, a result consistent with the general tendency for roughness elements to become less significant as they are drowned. These results indicate that roughness effects of LWD are likely to be inversely related to flow.

The friction factor *f* in the D'Arcy-Weisbach flow resistance equation is

$$f = 8g \;\; V^2 R S \qquad (7)$$

where V is velocity, R is hydraulic radius (cross-sectional area/wetted perimeter), S is the energy grade slope, and g the gravity constant. Shields and Gippel (1995), In their study of LWD effects on flow resistance, considered resistance to derive from grain roughness, bars and bedforms, bends (channel curvature), and debris:

$$f = f_{grain} + f_{bedforms} + f_{bends} + f_{debris} \quad (8)$$

Form drag (D) of a solid object in fluid is

$$D = (C_d \, g \, V^2 \, A_d)/2\gamma \quad (9)$$

C_d is a drag cofficient for the debris, γ the specific weight of water, and A_i the projected area of the debris on a plane normal to the flow. V is here the velocity approaching the obstruction. Treating D as a sum of the debris drag of multiple pieces of debris (i.e., D = $\sum D_i$),

$$\frac{D}{g\,A\,L} = \frac{f_d \, a \, V^2}{8g\,R} \quad (10)$$

with cross-sectional area (A), V and R treated as reach averages. L is the reach length and a kinetic energy correction factor, assumed by Shields and Gippel (1995) to be 1.15.

Assuming channel roughness to be uniformly distributed in a reach, and R = A/w, where w is mean reach surface width (a reasonable approximation where w >> depth), Shields and Gippel (1995) derived

$$f_{debris} = f_d = (4/a)\,(C_d \, A_d)/(w\,L) \quad (11)$$

with $C_d = \sum C_{d,I}$ and $A_d = \sum A_{d,i}$.

The general relationship

$$C_d = C'_d/\{a[1-A_d/(wR)]^b\} \quad (12)$$

was parameterised based on flume experiments by Shields and Gippel (1995):

$$C_d = 0.6/\{0.997[1-A_d/(wR)]^{2.06}\} \quad (13)$$

where C'_d is the drag coefficient for a vertical cylinder of diameter d in a flow of infinite exent (i.e., no boundary effects), and the a, b values shown are empirically derived.

Shield’s and Gippel’s (1995) results can be generalized to examine the effects of debris on the friction factor. With $A \approx wR$, $a \approx 1$ and $b \approx 2$, eq. (5) can be written

$$f_d \approx [(1-A_d/A)^2 \, A_d]/(w\,L) \quad (14)$$

Eq. (14) reveals the strong dependence of f_d on the concentration of the debris relative to the size of the channel. Given the decline of f_d as A and w increase with larger flows, it is open to question as to whether LWD has significant impacts on channel conveyance and flooding potential at higher flows. Eq. (14) suggests that impacts of LWD on channel conveyance capacity are likely to be most pronounced at lower flow levels.

Theory and previous work thus suggests that LWD snags, and logjams which do not occupy a large proportion of the channel volume, are likely to have minimal impacts on flooding. However, larger logjams where a large proportion of the cross-sectional area is blocked by wood could have such impacts. This suggests that in the study area small jams have little or no effect on flooding, but that channel-blocking LWD accumulations do.

Wallerstein and Thorne (2004) identified four woody debris jam types in the Yazoo Basin, Mississippi, on the basis of their net influence on flow and the local impacts on channel geometry. Underflow jams result in scour underneath a log with some deposition just downstream. Dam jams block the entire cross section, with sediment accumulation behind the debris dam and flow overtopping the jam. A deflector jam blocks the entire channel, diverting flow around the side less strongly anchored to the bank, to initiate bank erosion. Flow parallel/bar head jams occur where channel width is significantly greater than debris element width and the debris is aligned roughly parallel to flow or deposited against incipient bars.

LWD jams observed in the lower San Antonio/Elm Bayou include deflector and flow parallel bars. The other jam types likely exist on smaller tributaries and subchannels, but were not observed on the main channel. The major logjams up- and downstream of the split do not fit neatly into the Wallerstein and Thorne (2004) classification, which was developed for sand-bed streams. These jams apparently occur as floating debris begins to accumulate upstream of a cross-channel anchor log. They are porous enough to allow flow to pass through. Living trees tipped across the channel by bank erosion or slumping, and low-hanging branches from riparian trees play a key role in initiating LWD blockages in Elm Bayou and the San Antonio River downstream of the split.

SAN ANTONIO RIVER-ELM BAYOU LOGJAM

As of June 2010 a more-or-less continuous logjam began about 1.55 mi (2.5 km) upstream of the San Antonio River-Elm Bayou confluence, and continued to Fagan Bridge on the San Antonio River (figure 18), and past the confluence on Elm Bayou. Other, smaller jams existed on Elm Bayou further downstream, and were also reported on the San Antonio by local residents. The main logjam appeared to have undergone no obvious changes in extent between a reconnaissance visit in January, 2010, and June.

In a 1996 DOQQ, LWD jams are visible in the vicinity, but no logjam comparable in extent to the 2010 case. The 1996 image shows a 90 m long jam just upstream of the bend shown in figure 19, as well as another full-channel logjam further upstream. A 1995 aerial photograph seems to show generally similar trends, but the image quality is poor. A DOQQ from 2004 (figure 20) shows a smaller, discontinuous logjam, though the San Antonio from Elm Bayou to Fagan Bridge was jammed. The obstruction extended about 350 m upstream from the bridge. Full-channel logjams are also visible in Elm Bayou 65 to 70 downstream of the split, and small jams in two locations further upstream. An image from October, 2005 shows the channel from the split to Fagan bridge fully jammed, but otherwise the channel in the vicinity of the split is relatively clear. Small logjams are visible further downstream on Elm Bayou.

February, 2008, helicopter photography by local landowner Walter Womack showed the upstream limits of the jam in approximately the same place as in 2010 (figure 19), as is the downstream end on Elm Bayou. However, the logjam did not extend into the San Antonio River, and a significant stretch of LWD-free open water existed, comprising in essence two smaller logjams that coalesced between early 2008 and 2010. An aerial image from late October, 2008 shows a 760 m long jam beginning at the bend shown in figure 19, several smaller jams between there and the split, and full blockage beginning about 130 m upstream of the split and extending about 230 m down Elm Bayou.

LWD has been consistently been noted as a major feature of the area. Holley (1992) noted overhanging trees and floating LWD as hazards that prevented water and sediment sampling via small boat, and as far upstream as Goliad, floating logs inhibited sampling. In December 1998 a newspaper reported that a dam created by log debris had blocked the river, reducing flow by 90 percent (*Corpus Christi Caller-Times,* 12/11/98). The article suggested that this blockage was the main cause of the diversion to Elm Bayou, and also quoted a GBRA official as saying that LWD blockages have caused the lower Guadalupe River to change course. According to the newspaper, the blockage caused unprecedented flooding at the US 77 crossing. A river-blocking logjam occurred at the US 77 and Union Pacific railroad crossing in the upper delta in October, 2009. This was cleared by loosening the debris, allowing it to be transported downstream.

Figure 18. Logjam upstream of Fagan Bridge, June 2010.

Figure 19. Oblique aerial view of the upstream end of the logjam near the San Antonio/Elm Bayou confluence in February, 2008 (photo by Walter Womack). The bend in the photo is about 2.6 km or 1.6 mi upstream of the Elm Bayou split.

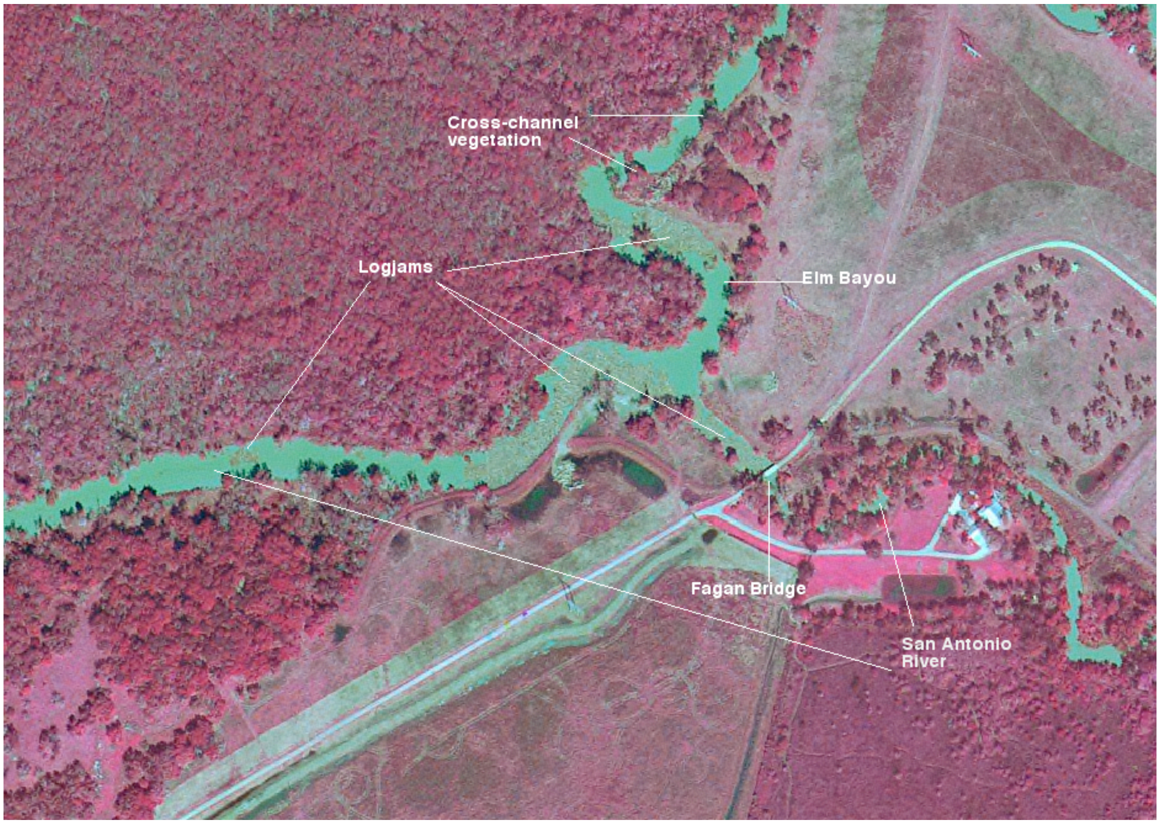


Figure 20. Section of digital ortho quarter quad taken in 2004 showing the San Antonio River/Elm Bayou split. Vegetation shows up as reddish in this false-color image. As compared to this image, the logjam in 2010 was continuous through the first meander of Elm Bayou and along the San Antonio to Fagan Bridge. The jam also extended further upstream in 2010. Note the cross-channel vegetation in Elm Bayou, which could be bank or in-channel vegetation, or plants growing on LWD jams (or a combination). Finally, note the disparity in channel widths up- and downstream of Fagan Bridge.

HYDROLOGIC AND GEOMORPHIC IMPACTS

According to local residents and landowners the logjam has increased local flooding of the valley bottom. While these reports are highly plausible and credible, they are impossible to verify from stage or discharge records, as there are no gaging stations or other hydrologic measurements available in the vicinity. However, in some cases water levels within the logjam are very near channel capacity when stages are well below banktop in unjammed areas, and when discharge is not unusually high (figure 21). The impression of local observers of increased bottomland inundation due to the logjam is correct.

Figure 21. San Antonio River logjam near Tivoli in January, 2010, with the water level very near banktop. Discharge at the McFaddin gaging station on this day ranged from 881 to 906 cfs, which is well within the normal flow range.

The logjam clearly causes local channel widening. Field measurements in the confluence vicinity show typical channel widths of 30 to 32 m in the logjam portions of the San Antonio River, and 18 to 24 m in unjammed portions in the vicinity.

The channel widening occurs by at least two mechanisms. The first is by simple bank erosion on one or both banks (figure 22). Water moving along the margin of the LWD simply scours the bank, resulting in channel widening. Active cutbanks were observed along several sections of the jam in 2010. The second mechanism is lateral displacement of flow over the natural levee, which appears to require a significant growth of trees along the levee. In this case the bank is more resistant to erosion, but any minor levee weakness or low point may allow high flows to cross the natural levee and move downstream parallel to the main flow. This is also illustrated in figure 22.

Figure 22. Bank erosion caused by flow deflection at the margin of the logjam (top). Channel widening by lateral flow displacement over a forested levee (bottom). The boxed area shows the forested leveee top and former channel bank, with the new channel area established outside (left). The main, wood-jammed channel is to the right of the box. Note the new wood accumulations in the displaced channel. (Flow is toward the top of the photograph; photo by Walter Womack, February 2008).

The San Antonio River channel becomes noticeably wider at the upstream limit of the logjam in 2010, and the river/Elm Bayou channel is consistently wider through the major logjam reach. The pronounced widening at this point is evident on the 2004 DOQQ, though LWD is not evident in the image at that point (figure 20). This widening is not evident in the 1996 DOQQ. This indicates that the development of a major, persistent logjam in the split area occurred sometime after 1996 and significantly before 2004. It also suggests that there may be some controlling factor at this upstream point that either facilitates LWD accumulation downstream or inhibits it upstream. The latter seems more likely, given the observed downstream channel narrowing.

The LWD jams are dynamic, and despite the recent year-to-year persistence of LWD obstructions in the split area, local removal by natural fluvial processes does occur. This is consistent with studies further upstream on the San Antonio River, which shows that even some very large jams are mobile (Curran, 2010). However, in that reach Curran (2010) found that jams often reform in the same location.

In the delta area, removal of LWD by natural transport processes from a widened channel may lead to recovery in terms of channel width. Cutbanks become stabilized and vegetated, and inset bars develop within the channel. The latter become vegetated and stabilized, resulting in channel widths similar to unjammed reaches. This sequence is shown in figures 23-27.

Figure 23. Initial stages of logjam effects, with no significant channel width changes yet. This is the upper end of the San Antonio River logjam upstream of Elm Bayou in January, 2010.

Figure 24. Stage 1 of channel widening. Flow deflection causes bank erosion on one or both sides of the logjam, resulting in channel widening. These photos are near the San Antonio River/Elm Bayou split.

Figure 25. When a logjam in a widened channel is removed (in this case by natural fluvial processes), the overwidened channel may experience rapid bar formation. This is occurring on the right bank of Elm Bayou (foreground, above), but has not occurred on the left bank (background).

Figure 26. Recovering over-widened channel after logjam removal, Elm Bayou. An inset bar on the left bank is evident, while the formerly active cutbank on the right has become stabilized and vegetated.

Figure 27. Inset channel bars in early (top) and late (bottom) stages of formation in Elm Bayou channel formerly over-widened by peripheral erosion around a logjam.

It also appears that channel widening is finite. This is based on three observations—first, jammed channels in the split vicinity, regardless of the longevity and density of wood, appear to only widen to about 30 m. Second, lateral channel shifts may become stabilized (figure 28). Third, the San Antonio River from the split to Fagan bridge has widened sigificantly, but the banks have stabilized despite the entire width of the channel being completely filled (figure 29).

Figure 28. A semi-permanent or persistent lateral channel shift. The log jam at left has stabilized, and bank erosion on left bank in the right of the photo (flow is toward the camera) has displaced the channel (Elm Bayou).

Figure 29. Logjam on the San Antonio River between the Elm Bayou Split and Fagan Bridge in June, 2010. Flow is toward the camera. The channel here has widened relative to unjammed nearby reaches, and apparently stabilized with no active cutbanks observed.

Wood Source

Forest cover within the delta is relatively limited. Thus floating of downed woody debris from floodplain areas during overbank flows is limited within the study area. Bank erosion, the primary mechanism for wood delivery to coastal plain rivers, is also limited. The major source of wood, then, is fluvial transport from upstream.

WOODY DEBRIS AND THE ELM BAYOU AVULSION

The San Antonio River's shift to the Elm Bayou channel is an example of an avulsion. LWD may indirectly promote local aggradation by reducing flow velociites and thus transport capacity, and thus help create the setup factors for avulsion. However, logjams are primarily important as a trigger effect.

In the study area, such flow deflections can result in channel widening (see fig. 22), but may also result in local channel shifts. Depending on the length, these could be considered as either local island-braiding, or an avulsion. This has occurred recently within the San Antonio River Delta logjam, creating an island (fig. 30).


Figure 30. If a weakness in the bank or natural levee is present, lateral flow deflection around the logjam may divert flow out of the main channel. This has occurred on this section of Elm Bayou a short distance downstream of the split. Note the flow on the left side of the picture around the island separating this new channel from the jam. Depending on the length of the diversion this could be considered either an avulsion or creation of an island due to channel widening. The fate of the new side-channel after jam removal depends on the relative slope and conveyance capacity of the new channel vs. the jammed channel.

Despite these observations, however, *the logjam is not responsible for the avulsion into the Elm Bayou channel.* This conclusion is based on several observations. First, flow diversion into the Elm Bayou channel predates formation of large logjams in the vicinity. Second, the strong slope advantage of the Elm Bayou path and the channeling of Cross Bayou flow into the bayou favor this channel, regardless of any debris effects. Third, removal of debris by the GBRA in 2008 upstream of Fagan Bridge—but not from Elm Bayou—had no effect on the dominance of the Elm Bayou channel. Fourth, and most convincingly, there is far more LWD, and channel-blocking logjams, in Elm Bayou downstream of the split than in the San Antonio channel. If the logjam were damming flow to a significant extent, this would not be the case.

WHY THE FREQUENT LOGJAMS?

There is no reason that the San Antonio River should have a greater supply of woody debris than other rivers in the region, though in rivers such as the Nueces and Lavaca-Navidad, with impoundments a short distance upstream of the deltaic areas, debris input may be limited by the upstream dams. As described above, wood input within the San Antonio delta is minor. The primary reason for the frequent jams involves channel width.

In all types of streams, large LWD accumulations are least likely to occur where channel width is large relative to the length of logs or debris pieces. Channels in the deltaic areas of larger, sandier rivers such as the Sabine, Neches, Trinity, Brazos, and Colorado are significantly wider than those in the lower Guadalupe and San Antonio Rivers. Figure 31 shows the relationship between channel width and upstream drainage area for gaging station locations on the lower portions of 11 Texas rivers (Sabine, Neches, Trinity, San Jacinto, Navasota, Brazos, Colorado, Lavaca, Guadalupe, San Antonio, and Nueces). Widths were measured from 2008 aerial images, and drainage areas taken from U.S. Geological Survey gaging station data. This shows that widths in the lower San Antonio and Guadalupe Rivers are in the lower range of channel widths. Their location below the best-fit trend line also indicates that they are proportionally narrower relative to their drainage area. The other unlabelled data points in the lower left area of figure 31, below the trend line, are also fine-grained areas such as the Nueces, Navasota, and Lavaca Rivers.

Figure 32 shows the downstream trend of channel widths within the San Antonio River delta (widths measured from DOQQs). Width—as expected—is locally variable, but rather than the general downstream increase in width as drainage area and discharge increases, there is a clear decreasing trend. From the upper delta to Elm Bayou width decrases from around 40 m to about 20 m. A short distance further downstream, width declines to a model value of about 10 m. The channel narrowing in the vicinity of the split and further downstream likely accounts for the tendency of logjams to recur in this area. Curran (2010) found, in a study further upstream on the San Antonio River, that it is common for logjams to reform at certain locations.

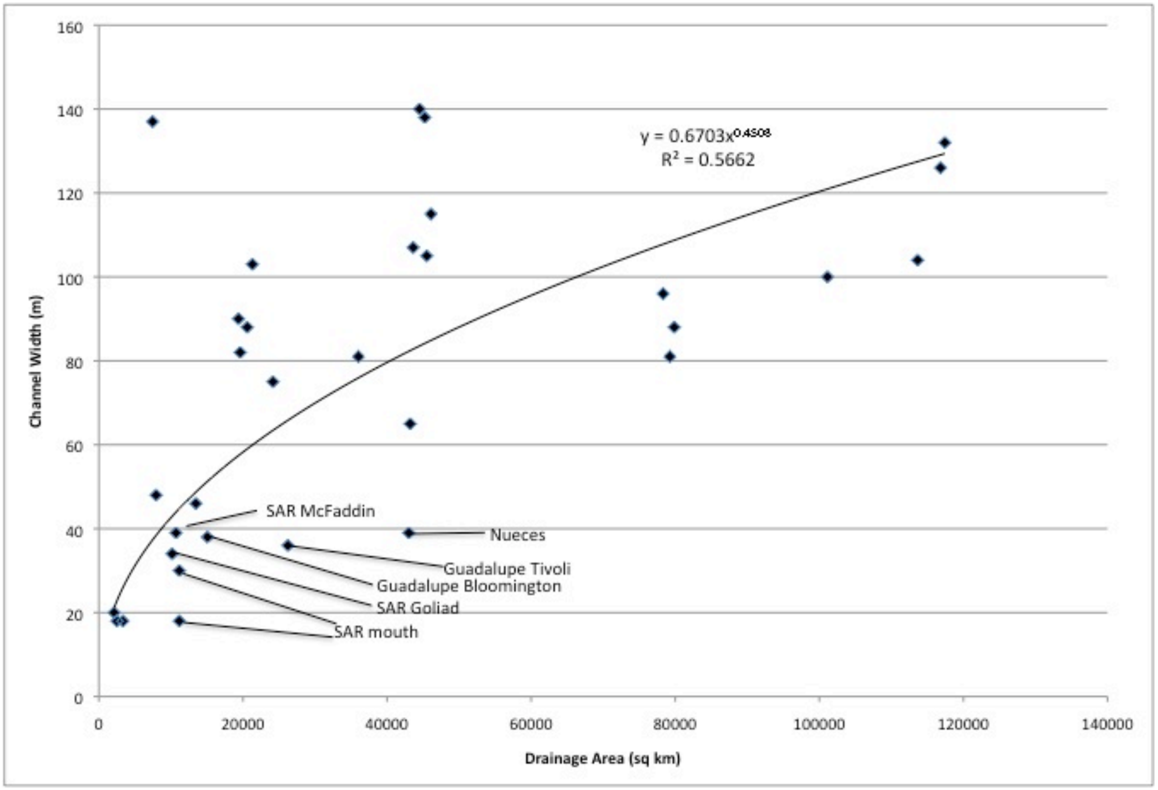
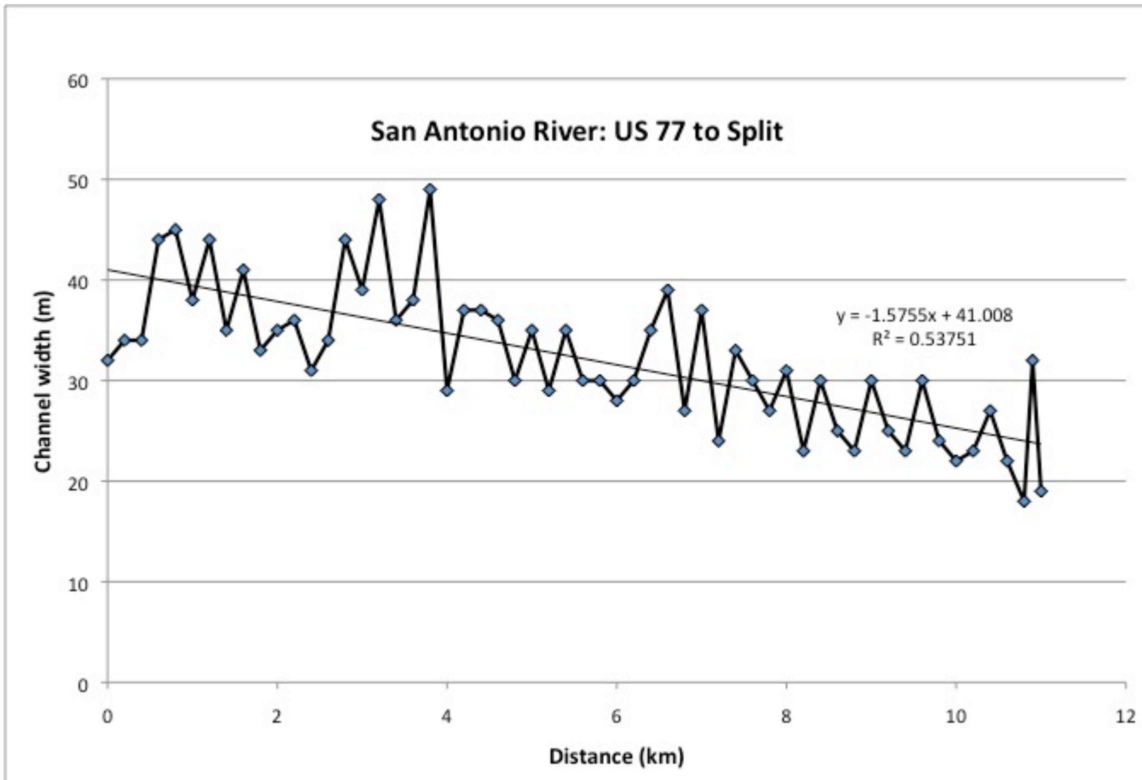


Figure 31. Relationship between channel width and drainage area for gaging stations on the lower reaches of 11 Texas rivers (see text). SAR = San Antonio River. The SAR mouth data points include Elm Bayou and the SAR. The best-fit regression is also shown.

Why the unusual narrowing trend? First, the fine-grained cohesive soils in the delta create high levels of bank stability and allow for narrower channels with smaller width/depth ratios than are possible in sandier environments. Second, the channel width measurements are only for the main, dominant channel. Further downstream, multiple channels, particularly at higher flows, are available to help convey discharge. The break in figure 32 (from widths generally >40 m to <40 m) about 4 km downstream from the San Antonio-Old River confluence is near the headwaters zone of Cross Bayou, which apparently conveys significant amounts of down-valley flow during wet periods.



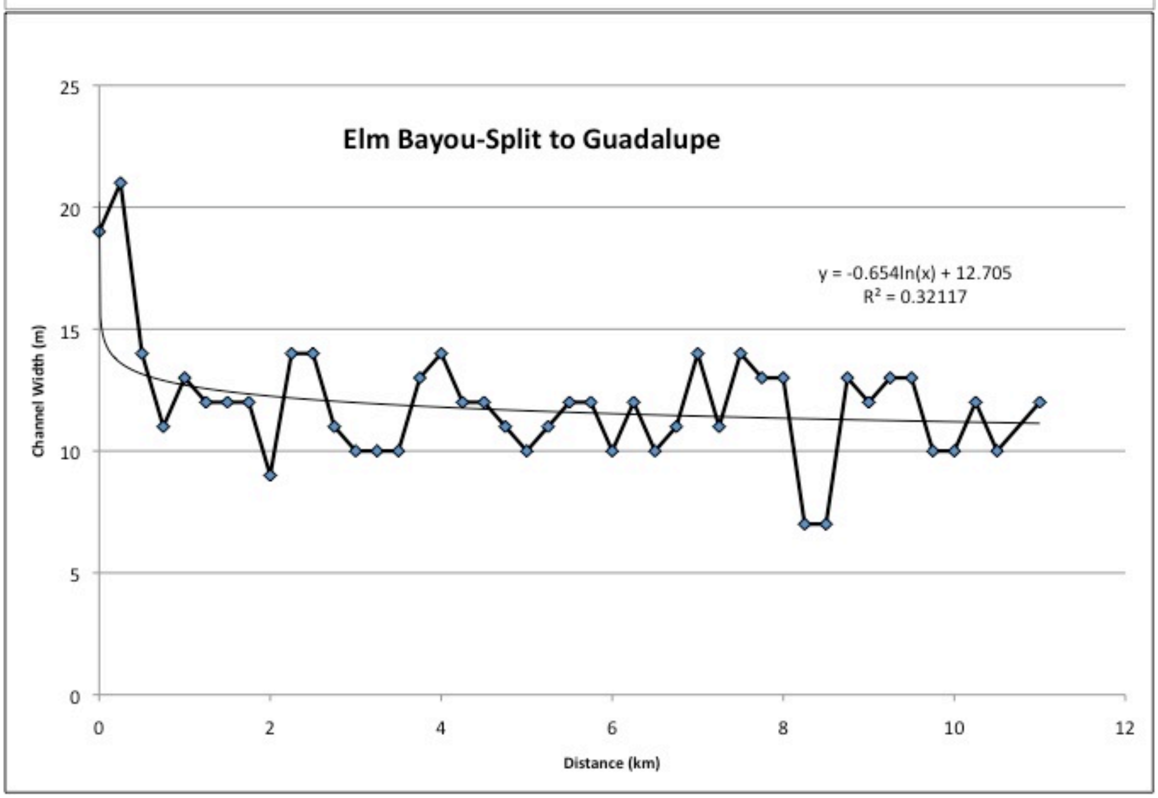


Figure 32. Downstream variations in banktop channel width in the San Antonio River Delta.

Chapter 4
Summary and Conclusions

AVULSION REGIME

One objective of this study was to determine the historic and late Holocene avulsion regime of the study area. At least nine major avulsions have occurred within the last 3000 years or less, and at least four in historic times. This is a minimum estimate of avulsion frequency, as some previous avulsions may not have been discovered in this study. In addition, short sections of paleochannels exist which represent either relatively minor local channel shifts, or fragments of larger shifts. Figures 33 and 34, for instance, show examples of such abandoned channels.

Avulsions are common in deltas, and in other Gulf of Mexico Coastal Plain Rivers. Thus the shifting channels in the study area are not unexpected. One setup condition for avulsions is channel aggradation, which is clearly present in the lower San Antonio River, and slope advantages, which are also common (see figures 33 and 34). Cohesive soils, narrow channels, and large woody debris jams also contribute to the tendency toward avulsion.

Avulsions are a natural and relatively frequent feature of the late Holocene and modern San Antonio River Delta, and will continue to occur in the future.

Large woody debris and logjams play a role as avulsion triggers in alluvial rivers and deltas, and this is no doubt the case for the San Antonio River. However, the large logjams in the vicinity of the Elm Bayou split are not responsible for that particular channel shift.

Figure 33. Shaded relief map of the upper San Antonio River Delta, showing a low-lying flood basin between the San Antonio and Old River alluvial ridges, and an avulsion node (box) at the Old River-Cushman Bayou junction. Note the paleochannels in the lower right area of the box, and paralleling the main channels.

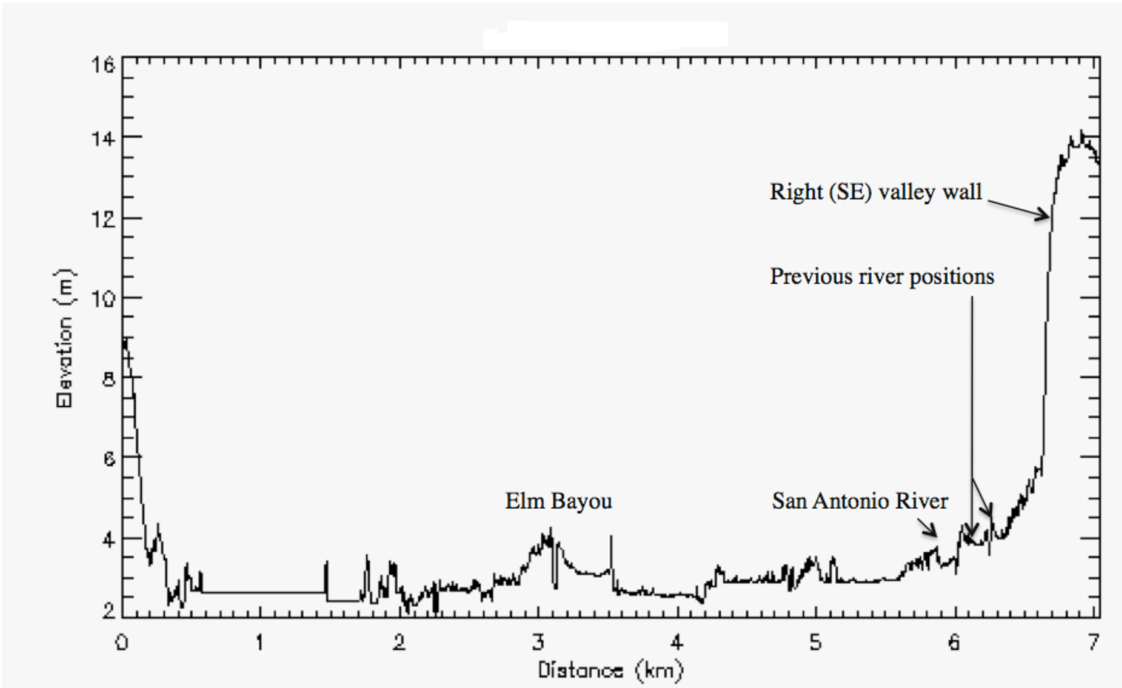


Figure 34. Topographic cross-section across the delta downstream of the San Antonio-Elm Bayou split. Note the former channel positions, and the backswamp and flood basin areas below the elevation of the channel beds.

Human Impacts

A second study objective was to identify actual and potential human impacts on avulsions and other channel change processes. At least one case exists where anthropic modifications have enabled establishment of a channel pathway that would not otherwise exist. This is the current distributary path from Cushman Bayou into the Kuy Creek channel and wildlife impoundments via the man-made CushKuy Connector channel. There is also evidence that topographic modifications near the San Antonio-Elm Bayou split may have helped enable that shift, though it would have eventually occurred anyway. Levee construction (and possibly some artificial straightening) of portions of Cross Bayou, a natural paleochannel or anabranch, seem to be maintaining this path as a semiactive anabranch.

In a broader sense, urbanization, construction, agriculture, mining, and forestry since the mid 1800s has generally increased erosion and sediment loads of Texas rivers, and the San Antonio is no exception. These increased loads may contribute to the channel aggradation in the lower delta. However, given the nature of deltas, and evidence from other Texas rivers that the lower coastal plain reaches were transport-limited even before human-accelerated erosion, this is likely a minor contributing factor at best (Phillips and Slattery, 2006; 2007; Slattery et al., 2010), though the potential geomorphic and ecological impacts upstream may well be significant.

The delta area has experienced a number of hydrologic modifications, including artificial ditches and canals, construction of levees and road causeways, wildlife impoundments, and pumping of oil, natural gas, and water. Water diversions from the lower Guadalupe River also influence the lowermost San Antonio River. Resources for a detailed analysis of the history and impacts of these modifications were not available in this study. However, it is clear that they do impact the overall pattern of water flux and distributions in the delta (and of course, in some cases this is precisely what they are intended to do). These modifications in some cases probably, and in other cases certainly, influence the specific location and timing of flow shifts. However, as their influences are likely to inhibit as often as they facilitate channel change, the cumulative impacts on the avulsion regime are minimal.

Dynamics of Water and Sediment Distribution

How do avulsions impact the dynamics of water and sediment distribution? This question reflects another of the project objectives. Actually, it is more accurate to state that avulsions reflect, or are an outcome of, the dynamics of water and sediment distribution.

Where sediment supply is greatly in excess of sediment transport capacity—as is the case in most deltas and many other lower coastal plain alluvial settings—channel aggradation is common and eventually triggers crevasses. Some of these crevasses become established channels and create distributaries, anabranches, or new channels. This means that any given moment there exist relatively water and sediment-rich zones, and relatively poor areas, though an absolute shortage of either water or sediment is rare. The concentration of water fluxes and sediment accumulation in particular areas of the delta—and periodic shifts in these areas—are to be expected and are exactly what is observed in the San Antonio River Delta.

In the broader context of the Guadalupe River delta, its associated tidal wetlands, and the Guadalupe/San Antonio Bay complex, the most recent avulsions have had minimal impacts. The Elm Bayou outlet at the Guadalupe is very close to the San Antonio/Guadaupe confluence, and the Kuy Creek distributary pathway is a short distance upstream of Elm Bayou.

STATUS AND STABILITY OF FLOW BIFURCATIONS

Another key project objective was to determine the developmental stage and stability of existing flow bifurcations. The San Antonio/Old River split has progressed to the point that the Old River channel conveys flow only at high water levels. The Elm Bayou/Cushman Bayou bifurcation could not be observed in the field. This flow split is relatively recent and apparently quite active at present. However, the Elm Bayou path is steeper and more efficient than the Cushman-Cushkuy Connector-Kuy pathway. Thus the latter is unlikely to become a dominant channel, though its persistence as an active distributary is possible.

Primary attention was given to the San Antonio-Elm Bayou split, discussed below.

Stability of the Flow Split

Equation (6) from Chapter 1 shows that the stability condition for a flow split is $A_1/A_2 \approx S_1/S_2$. Stability would imply that both channels will be maintained, with Elm Bayou dominant and the San Antonio persisting as a distributary, with approximately the same proportion of flow. Instability indicates that Elm Bayou would eventually capture all non-flood flow, or that the flow proportion would shift one way or the other. The slope gradient from the split to the Guadalupe River down Elm Bayou is 0.0007612, while slope down the San Antonio branch is 0.0003461. This implies that the cross-sectional area of the steeper path (Elm Bayou) should be about 2.2 times greater than the San Antonio channel if the split is stable.

Cross-sections were measured in both channels at unjammed sections just downstream of the split in June, 2010. The banktop-to-banktop cross-sectional area for Elm Bayou was 52.4 m^2, while the cross-sectional area of flow at the time of measurement was 17.1 m^2. On the San Antonio branch, the banktop cross-section was 41.8 m^2, while the flow cross-sectional area was 6.3 m^2. These ratios are 1.24 and 2.71, respectively. For the banktop case, this implies that some combination of scour of the Elm Bayou channel or infill of the San Antonio channel would be necessary to achieve a stable split. The ratio >2.2 for the measured flow case suggests this is already occurring. This is supported by the fact that the San Antonio sample site bankfull cross-sectional area is decreasing. The upper banks are fully stabilized with dense, relatively mature woody vegetation, and an inset bar is developing that was not submerged during cross-section measurement. As this trend continues, the ratio of banktop cross-section areas is likely to get closer to the 2.2 ratio necessary for maintenance of the split.

The banktop width/mean depth ratio is about 6.9 for the Elm Bayou cross-section and 15.7 for the San Antonio River. This suggests that the Elm Bayou channel is likely to have greater tractive force or shear stress, giving it a greater ability to maintain or increase channel capacity. Basal shear stress is given by

$$\tau = \gamma\, d\, S \qquad (15)$$

where γ is specific gravity of water ($\approx$ 9.8 N m^{-3}), d is depth in m, and S is slope. Mean boundary shear stress is obtained by substituting hydraulic radius (= cross-sectional area/wetted perimeter) for *d.*

Maximum (based on maximum depth) and mean boundary shear stresses were computed for both channels, using the slope gradients given above. Mean boundary shear stress was 2.6 times higher for banktop conditions in the Elm Bayou channel, and nearly 4.5 times higher for measured flow conditions (11.04 vs. 4.22 and 8.86 vs. 1.98 N m^{-2}, respectively). Maximum bed shear stress was more than 4.1 times higher in Elm Bayou for banktop flow, and nearly 5.4 times greater for measured flow conditions (41.55 vs. 10.07 and 21.78 vs. 4.04 N m^{-2}, respectively). These differences are shown graphically in figure 35.

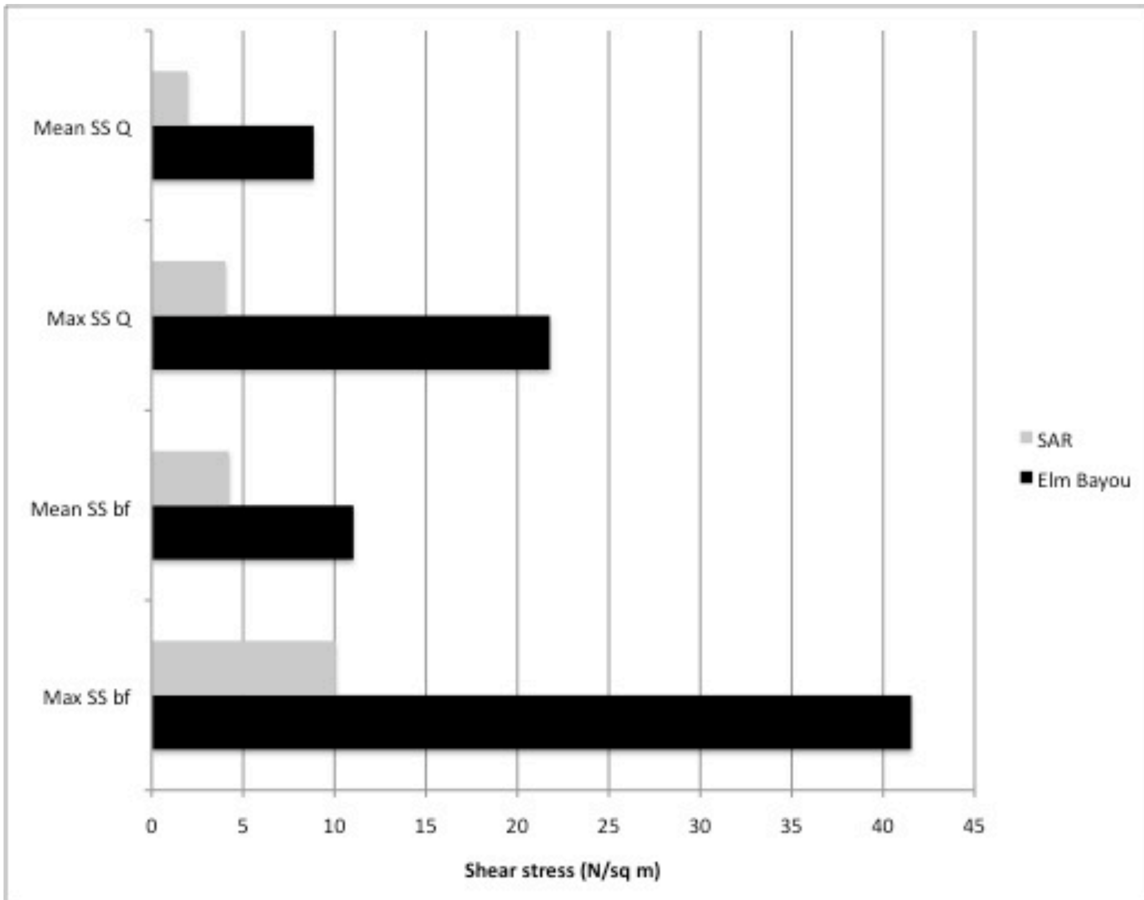


Figure 35. Differences in mean boundary and maximum bed shear stress (SS) for bankfull or banktop conditions (bf) and flow conditions at the time of measurement (Q) for Elm Bayou and the San Antonio River (SAR) downstream of the flow split.

The Elm Bayou channel has a significant slope advantage and a shear stress advantage as well. There is no reason to believe that it will not continue to be the dominant channel in the near future, or that the San Antonio channel in this vicinity will regain dominance. The San Antonio channel is likely to persist as an active distributary, with a somewhat smaller share of flow than at present.

FUTURE AVULSIONS

Identification of locations of high probability or risk of future avulsions was another task of this project. Channel shifts have been a feature of the San Antonio River delta throughout recorded history and the Holocene. This is not unexpected, as avulsions are common in deltaic settings. There is no reason to expect any change in this behavior. While the channel-shifting of the lower San Antiono River may seem unusually frequent to laypersons accustomed to thinking of river channels as relatively stable and semipermanent, the frequency of avulsion in the study area is not unusual. The nine known avulsions within 3000 years or less (see chapter 2) amounts to one, on average, every 333 years, or about 0.3 per century. Even if this figure is tripled to account for undercounting of avulsions and/or overestimation of the time frame, it is in the same range as the low avulsion frequency periods identified for the Rhine-Meuse delta by Stouthamer and Berendson (2001).

The setup conditions for avulsion continue to be present in the lower San Antonio River. The system is actively aggrading, and in many cases channel beds are near or above the elevation of surrounding flood basins. Thus potential slope advantages if crevasses occur abound. The avulsion history also provides numerous paleochannels that can potentially be reoccupied, as is now occurring on Elm Bayou and lower Cushman Bayou. Trigger factors such as LWD are also present.

Because avulsions are contingent on trigger factors and high flows, the timing and exact location of avulsions is unpredictable. In the San Antonio River delta, two areas in particular, however, have a high probability of avulsions in the near future—the latter being rather vaguely defined as anytime between today and a couple of decades from now.

One of these zones is the San Antonio River from the Old River confluence a short distance downstream of highway 77 to about Flat Bayou. There are at least three reasons for this. First, the current main channel is actively aggrading, as described in Chapter 3 and shown in figure 36. Second, both the San Antonio and Old River courses occupy alluvial ridges, with a lower-elevation flood basin in between. This provides local slope advantages should a flood crevasse breach the natural levee (figure 33). Finally, this general area, as illustrated by the Old River/Cushman Bayou confluence, has been a hotspot for avulsions. This may be related to listric fault movements associated with the post-Vicksburg uplift, analagous to the Brazos River avulsion node identifed by Taha and Anderson (2008).

The second high-probability zone is from the current San Antonio-Elm Bayou split downstream to approximately Cushman Bayou. This is also an area of a number of past avulsions, and is also characterized by flood basins with elevations similar to or lower than the active channel beds (figure 34). In addition, the narrow channels and propensity for logjams to form increases the likelihood of flow deflection. Tectonic forcing is also a potential factor here.

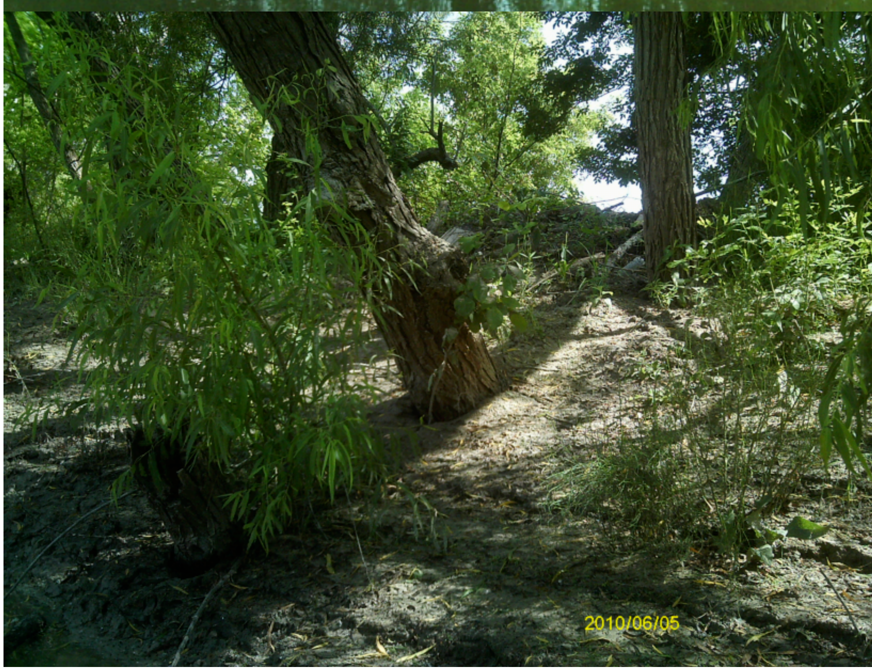


Figure 36. Examples of channel aggradation indicators. Accreting and prograding bank (top); burial of riparian vegetation (bottom).

MANAGEMENT RECOMMENDATIONS

The final objective of the project was to develop recommendations for integrating avulsions into water resource management.

First, this study shows that land and water resource managers and stakeholders should *recognize that avulsions are a natural and expected occurrence.* These channel shifts should not be viewed as abnormal or harmful in any hydrologic, geomorphic, or ecological sense. Second, because avulsions are normal and expected in this environment, any *attempts to prevent avulsions or confiine flow to any particular channel indefinitely are ill-advised.* Such efforts would be expensive, would present numerous engineering challenges, and would require constant, or at least chronic and reoccurring, maintenance and repair. In addition, such efforts would disrupt the natural hydrogeomorphic behavior of the delta and likely have adverse ecological impacts. Given the recommendations above, it is further advised that *land use and development in the deltaic paleochannel areas, flood basins and backswamps be limited* in terms of permanent infrastructure that cannot be readily relocated. These areas are likely to experience avulsions in the future.

Logjams and LWD contribute to channel change and flooding in the area. Wood contribution within the delta is limited by a relatively small proportion of forest cover, and limited bank erosion and lateral channel migration. Given the circumstances described in chapter 3, LWD jams are likely in the lower delta, and will most likely continue to recur following removal. One strategy to limit the occurrence and extent of these jams would thus be to intercept large floating debris in the vicinity of the highway 77 and rail crossings, where removal of accumulated debris might be simpler than in more remote areas of the delta (analagous to periodic GBRA removal at the Tivoli barrier on the Guadalupe River). However, the engineering feasibility of debris removal at this point has not been determined, and may be affected by pipeline crossings and other factors. Another potential approach would be periodic patrols by small boat to identify incipient logjams and potential jam-forming snags or obstructions. These could be manually removed to prevent or inhibit formation of major jams.

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References Cited

Anderson, J.B., Rodriguez, A.B., Milliken, K.T., Taviani, M., 2008. The Holocene evolution of the Galveston estuary complex, Texas: evidence for rapid change in estuarine environments. In: Anderson, J.B., Rodriguez, A.B. (eds), Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise. Boulder, CO: Geological Society of America special paper 443, 89-104.

Aslan, A., Autin, W.J., Blum, M.D. 2005. Causes of river avulsion: insights from the late Holocene avulsion history of the Mississippi River, USA. Journal of Sedimentary Research 75, 650-664.

Aslan, A., Blum, M.D., 1999. Contrasting styles of Holocene avulsion, Texas Gulf Coastal Plain, USA. In Smith, N.D., Rogers, J., eds., Fluvial Sedimentology VI. Special Publication, International Association of Sedimentology. Oxford, Blackwell, pp. 193-209.

Blum, M.D., Aslan, A. 2006. Signatures of climate vs. sea-level change within incised valley-fill successions: Quaternary examples from the Texas Coastal Plain. Sedimentary Geology 190, 177-211.

Blum, M.D., Misner, T.J., Collins, E.S., Scott, D.B., Morton, R.A., and Aslan, A. Middle Holocene sea-level rise and highstand at +2m, central Texas coast, 2001, Journal of Sedimentary Research, v. 71, p. 581-588.

Chin A, Daniels MD, Urban MA, Piegay H, Gregory KJ, Bigler W, Butt AZ, Grable JL, Gregory SV, Lafrenz M, Laurencio LR, Wohl E. 2008. Perceptions of wood in rivers and challenges for stream restoration in the United States. Environmental Management 41: 893-903.

Curran, J.C. 2010. Mobility of large woody debris (LWD) jams in a low gradient channel. Geomorphology 116, 320-329.

Donaldson, A.C., Martin, R.H., Kanes, W.H., 1970. Holocene Guadalupe Delta of the Texas Gulf coast. In Deltaic Sedimentation, Modern and Ancient. Society of Economic Paleontologists and and Mineralogists special publication 15, Tulsa, OK, pp. 107-137.

Dudley SJ, Flischenich JC, Abt SR. 1998. Effect of woody debris entrapment on flow resistance. Journal of the American Water Resources Association 34: 1189-1197.

Edmonds, D.A., Slingerland, R.L., 2008. Stability of delta distributary networks and their bifurcations. Water Resources Research 44, doi:10.1029/2008WR006992.

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.

Gouw, M.J.P., 2007. Alluvial architecture of fluvio-deltaic successions: a review with special reference to Holocene settings. Netherlands Journal of Geosciences 86, 211-227.

Holley, E.R., 1992. Sediment transport in the lower Guadalupe and San Antonio Rivers. Tech. Rept. No. 154, Texas Water Resources Institute, College Station, 114 p.

Hood, W.G., 2010. Delta distributary dynamics in the Skagit River Delta (Washington, USA): extending, testing, and applying avulsion theory in a tidal system. Geomorphology 123, 154-164.

Jerolmack, D.J., Mohrig, D., 2007. Conditions for branching in depositional rivers. Geology 35, 463-466.

Jerolmack, D.J., Paola, C., 2007. Complexity in a cellular model of river avulsion. Geomorphology 91, 259-270.

Jones, L.S., Schumm, S.A. 1999. Causes of avulsion: an overview. In Smith, N.D., Rogers, J., eds., Fluvial Sedimentology VI. Special Publication, International Association of Sedimentology. Oxford, Blackwell, p. 171-178.

Kleinhans, M.G., Weerts, H.J.T., Cohen, K.M., 2010. Avulsion in action: reconstruction and modelling sedimentation pace and upstream flood water levels following a Medieval tidal-river diversion catastrophe (Biesboch, The Netherlands, 1421-1750 AD). Geomorphology 118, 63-79.

Lester RE, Wright W. 2009. Reintroducing wood to streams in agricultural landscapes: changes in velocity profile, stage, and erosion rates. River Research and Applications 25, 376-392.

Letter, J. V., Jr., Pinkard, C.F., Jr., Raphelt, N.K. 2008. River diversions and shoaling. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-VII-9. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://chl.erdc.usace.army.mil/chetn.

Maddox, J., Anderson, J.B., Milliken, J.T., Rodriguez, A.B., Dellapena, T.M., Giosan, L., 2008. The Holocene evolution of the Matagorda and Lavaca estuary complex, Texas, USA. In: Anderson, J.B., Rodriguez, A.B. (eds), Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise. Boulder, CO: Geological Society of America special paper 443, 105-120.

Makaske, B. 2001. Anastomosing rivers: a review of their classification, origin, and sedimentary products. Earth-Science Reviews 53, 149-196.

Makaske, B., Smith, D.G., Berendsen, H.J.A., 2002. Avulsions, channel evolution and floodplain sedimentation rates of the anastamosing upper Columbia River, British Columbia, Canada. Sedimentology 49, 1049-1071.

Manga M, Kirchner JW. 2000. Stress partitioning in streams by large woody debris. Water Resources Research 36, 2373-2379.

McBride, R.A., Taylor, M.J., and Byrnes, M.R., 2007, Coastal morphodynamics and Chenier-Plain evolution in southwestern Louisiana, USA: a geomorphic model: Geomorphology 88, 367-422.

McCarthy, T.S., Ellery, W.N., Stanistreet, G. 1992. Avulsion mechanisms on the Okavango fan, Botswana: the control of a fluvial system by vegetation. Sedimentology 39, 779-795.

McGowen, J.H., Proctor, C.V., Brown, L.F., Evans, T.J., Fisher, W.L., Groat, C.G., 1976. Environmental Geologic Atlas of the Texas Coastal Zone. Port Lavaca Area. Austin: Texas Bureau of Economic Geology, 107 p.

Milliken, K.T., Anderson, J.B., Rodriguez, A.B. 2008. A new composite Holocene sea-level curve for the northern Guf of Mexico. In Anderson, J.B., Rodriguez, A.B. (eds)., Response of Upper Gulf Coast Estuarines to Holocene Climate Change and Sea-Level Rise. Boulder, CO: Geological Society of America special paper 443, pp. 1-12.

Mohrig, D., Heller, P.L., Paola, C., Lyons, W.J., 2000. Interpreting avulsion process from ancient alluvial sequences: Guadalope-Matarranya system (northern Spain) and Wasatch Formation (western Colorado). Geological Society of America Bulletin 112, 1787-1803.

Montgomery DR, Collins BD, Buffington JM, Abbe TB. 2003. Geomorphic effects of wood in rivers. In Gregory SV, Boyer KL, Gurnell AM (eds), The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium series 37, pp. 21-47.

Morton, R.A., Donaldson, A.C. 1978. Hydrology, morphology, and sedimentology of the Guadalupe fluvial-deltaic system. Geological Society of America Bulletin 89, 1030-1036.

Morton, R.A., Paine, J.G., Blum, M.D. 2000. Responses of stable bay-margin and barrier-island systems to Holocene sea-level highstands, western Gulf of Mexico. Journal of Sedimentary Research 70, 478-490.

Ouchi, S. 1985. Response of alluvial rivers to slow active tectonic movement. Geological Society of America Bulletin 96, 504-515.

Phillips, J.D. 2009. Avulsion regimes in southeast Texas rivers. Earth Surface Processes and Landforms 34: 75-87.

Phillips, J.D. 2011. Universal and local controls of avulsions in southeast Texas rivers. Geomorphology, doi.org/10.1016/j.geomorph.2010.10.001

Phillips, J.D., Park, L. 2009. Forest blowdown impacts of Hurricane Rita on fluvial systems. Earth Surface Processes and Landforms 34, 1069-1081.

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., 2007. Downstream trends in discharge, slope, and stream power in a coastal plain river. Journal of Hydrology 334, 290-303.

Ralph, T.J., Hesse, P.P., 2010. Downstream hydrogeomorphic changes along the Macquarie River, southeastern Australia, leading to channel breakdown and floodplain wetlands. Geomorphology 118, 48-64.

Ricklis, R.A., Blum, M.D. 1997. The geoarchaeological record of Holocene sea level change and human occupation of the Texas gulf coast. Geoarchaeology 12, 287-314.

Schumm, S.A., Dumont, J.F., Holbrook, J.M. 2000. Active Tectonics and Alluvial Rivers. New York: Cambridge University Press.

Shields FD, Gippel, CJ. 1995. Prediction of effects of woody debris removal on flow resistance. Journal of Hydraulic Engineering 121: 341-354.

Simms, A.R., Anderson, J.B., Rodriguez, A.B., Taviani, M., 2008. Mechanisms controlling environmental change within an estuary: Corpus Christi Bay, Texas, USA. In: Anderson, J.B., Rodriguez, A.B. (eds), Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise. Boulder, CO: Geological Society of America special paper 443, 121-146.

Simms, A.R., Aryal, N., Yokoyama, Y., Matsuzaki, H., DeWittt, R. 2009. Insights on a proposed mid-Holocene highstand along the northwestern Gulf of Mexico from the evolution of small coastal ponds. Journal of Sedimentary Research 79, 757-772.

Slattery, M.C., Todd, L.M., Phillips, J.D., Breyer, J.A. 2010. Holocene sediment accretion in the Trinity River delta, Texas, in relation to modern fluvial input. Journal of Soils and Sediments 10: 640-651.

Slingerland, R., Smith, N.D. 1998. Necessary conditions for a meandering-river avulsion. Geology 26, 435-438.

Slingerland, R., Smith, N.D. 2004. River avulsions and their deposits. Annual Review of Earth and Planetary Sciences 32, 257-285.

Stouthamer, E., Berendsen, H.J.A., 2001. Avulsion frequency, avulsion duration, and interavulsion period of Holcoene channel belts in the Rhine-Meuse delta, the Netherlands. Journal of Sedimentary Research 71, 589-598.

Stouthamer, E., Berendsen, H.J.A. 2007. Avulsion: The relative roles of autogenic and allogenic processes. Sedimentary Geology 198, 309-325.

Taha, Z.P., Anderson, J.B. 2008. The influence of valley aggradation and listric normal fauling on styles of river avulsion: A case study of the Brazos River, Texas, USA. Geomorphology 95, 429-448.

Tornqvist, T.E., 1993. Holocene alteration of meandering and anastamosing fluvial systems in the Rhine-Meuse delta (central Netherlands) controlled by sea-level rise and subsoil erodibility. Journal of Sedimentary Petrology 63, 683-693.

Wallerstein NP, Thorne CR. 2004. Influence of large woody debris on morphological evolution of incised, sand-bed channels. Geomorphology 57, 53-73.

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

Weistein, R.A., Black, S., 2009. Guadalupe Bay. In Texas Beyond History (online publication), College of Liberal Arts, University of Texas at Austin. http://www.texasbeyondhistory.net/guadbay/index.html.

Welborn, C.T., 1967. Comparative results of sediment sampling with the Texas sampler and the depth-integrating sampler and specific weight of fluvial sediment deposits in Texas. Austin: Texas Water Development Board Rept. 36, 109 p.

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

Young WJ. 1991. Flume study of the hydraulic effects of large woody debris in lowland rivers. Regulated Rivers: Research and Management 6: 203-211.

Consultants Scope of Work

Channel Change Caused by Water and Sediment Distribution in the San Antonio River Deltaic Plain

Overview

This work plan addresses a cooperative research study by TWDB and GBRA, of channel changes (particularly avulsions) in the lowermost San Antonio River, Texas, and includes the Guadalupe River delta area that is influencing the river. The goal is to understand historical changes in channel patterns and water and sediment distribution in this area, to identify areas of high risk or probability for future avulsions, and to develop recommendations for incorporating channel change and avulsion regimes into water resource management.

The specific objectives are to:
(1) Determine the historic and late Holocene avulsion regime of the San Antonio River between U S Highway 77, near McFaddin, TX and Guadalupe River in the confluence area, in the context of the Holocene geomorphic evolution of the river and the Guadalupe Delta plain.
(2) Identify actual and potential human impacts on avulsions and collect data on other channel change processes.
(3) Identify locations of high probability or risk of future avulsions, stability of any channel breaches, and assess the developmental stage and stability ("equilibrium" condition) of existing flow bifurcations.
(4) Determine the impact of avulsions on the dynamics of water and sediment distribution.
(5) Develop recommendations for integrating avulsions into water resource management in the study area.

Methods

Previous historic and Holocene channel shifts will be identified from topographic maps, digital elevation models, aerial photographs, and field indicators as described in previous work on avulsion regimes in southeast Texas rivers (Phillips 2009a; 2009b). Where possible, definitive historical evidence (e.g., public records, eyewitness and historical accounts, air photo and map comparisons) will be used. The type of avulsion and condition of the older channel will be classified as described by Phillips (2009a). This assessment will form the basis for determining the avulsion regime (objective 1), and a partial basis for objectives 2 and 3, as reoccupation of former channels is a common form of avulsion in Texas coastal plain rivers (Aslan and Blum 1999; Phillips 2009a).

The setup factor of aggradation (more specifically, channel aggradation which exceeds the rate of floodplain surface accretion) will be assessed on the basis of historic bridge cross-sections obtained from the Texas Department of Transportation, supplemented by weighted-line resurveys if no recent cross-sections are available. However, to get sufficient spatial detail this will need to be supplemented with a survey of the study area based on geomorphic indicators. Key indicators of channel aggradation (or incision) include exposure or burial of bedrock or basal materials; topographic changes relative to cultural features such as pilings, boat ramps, etc.; bank failures; vegetation; and soil/sediment stratigraphy. This will be accomplished via a boat reconnaissance of the entire main channel and selected sub-channels within the study area. The geomorphic indicators approach has been used successfully in several previous projects for the Texas Instream Flow Program (e.g., Phillips 2008a; 2008b; 2007; Phillips and Slattery, 2007).

Identification of locations where potential slope advantages exist will be based on analysis of digital elevation models of floodplain topography using 10-m resolution national elevation dataset (NED) data, or, if available, higher-resolution LIDAR topographic data.

Trigger factors mentioned above will be assessed based on the field survey and high-resolution aerial photography (1 m resolution digital ortho quarter quads, or higher-resolution photography if available).

The stability of a flow split depends on whether sediment is proportioned between the two branches in the same proportion as water (Slingerland and Smith 1998; Letter et al., 2008). If one branch or the other is receiving disproportionately high sediment loads (Q_s) relative to discharge (Q), it will eventually clog up, with the other branch becoming dominant. Denoting the two branches with subscripts 1, 2, the stability condition is

$$Q_1/Q_2 \approx Q_{s,1}/Q_{s,2}$$

In a transport-limited system with erodible bed and banks (such as the Guadalupe River delta), a reasonable to assumption is that sediment load is partitioned in direct proportion to stream power per unit weight of water (P_u), which is related to cross-sectional stream power (Ω):

$$\Omega = g\ Q\ S$$

where g, the specific gravity of the water, is a constant, and S is the energy grade slope. Because discharge is the product of cross-sectional area (A) and velocity (V),

$$P_u = \Omega/gA = VS$$

If sediment load is proportional to P_u, then the stability condition is

$$Q_{s1}/Q_{s2} \approx P_{u1}/P_{u2} = (V_1S_1)/(V_2S_2).$$

As $Q = AV$, this reduces to

$A_1/A_2 = S_1/S_2$.

Thus the stability assessment of flow splits requires the survey of cross-sectional areas and slopes. Survey of cross-sections can be accomplished with standard survey gear in combination with a weighted line, echo sounder, or acoustic Doppler current profiler deployed by boat. The cross-sections will be tied to a common reference point, allowing local channel slope to be determined. Because energy grade slopes may differ from channel bed slope and vary during flow levels, water surface slopes will also be measured during a variety of flow events using pressure transducer, ultrasonic, or other appropriate types of water level sensors.

References

Aslan, A., Blum, M.D., 1999. Contrasting styles of Holocene avulsion, Texas Gulf Coastal Plain, USA. In Smith, N.D., Rogers, J., eds., Fluvial Sedimentology VI. Special Publication, International Association of Sedimentology. Oxford, Blackwell, pp. 193-209.

Letter, J. V., Jr., Pinkard, C.F., Jr., Raphelt, N.K. 2008. River diversions and shoaling. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-VII-9. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://chl.erdc.usace.army.mil/chetn.

Phillips, J.D. 2007. Field Data Collection in Support of Geomorphic Classification of in the lower Brazos and Navasota Rivers. Phase 2 of the Project: Geomorphic Context, Constraints, and Change in the lower Brazos and Navasota Rivers, Texas. Austin: Texas Instream Flow Program: http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp.0604830639.

Phillips, J.D. 2008a. Geomorphic Processes, Controls, and Transition Zones in the Middle and Lower Trinity River. Austin: Texas Instream Flow Program: http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp.0704830781

Phillips, J.D. 2008b. Geomorphic Units of the Lower Sabine River. Austin: Texas Instream Flow Program: http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp.0704830782

Phillips, J.D. 2009a. Avulsion regimes in southeast Texas rivers. Earth Surface Processes and Landforms 34: 75-87.

Phillips, J.D. 2009b. Universal and local controls of avulsions in southeast Texas rivers. Geomorphology (forthcoming).

Phillips, J.D., Slattery, M.C. 2007. Geomorphic Processes, Controls, and Transition Zones in the lower Sabine River. Austin: Texas Instream Flow Program: http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp.0600010595.

Slingerland, R., Smith, N.D. 1998. Necessary conditions for a meandering-river avulsion. Geology 26, 435-438.

Products

The final report will include an assessment and description of the avulsion regime of the lower San Antonio River, in the general style of Phillips (2009a), identification of potential human and other causes or triggers of channel change, and assessments of impacts on water and sediment distribution. The report will also include maps (hardcopy and digital) of recent, in-progress, and potential near future avulsions, along with an inventory including descriptions, geographic coordinates, and inferred causes. A map of the study area will also be produced indicating zones of high, intermediate, and low avulsion probability.

For each existing flow split, a stability analysis will be presented. This will include an assessment of stability at the time of measurement, and of developmental trends toward or away from stability.

Finally, recommendations with respect to water management will be presented, with particular attention to:
•Implications for instream flows.
•Destruction, construction, and maintenance of wetlands.
•Potential engineering measures and infrastructure impacts.

Personnel and Responsibilities
The Guadalupe Blanco River Authority (GBRA) will manage the project, and provide or arrange for logistic support such as land and boat access for fieldwork. The CONSULTANT will be responsible for cross-section and water level surveys and all other data collection, analysis, and interpretation, and production of the report to GBRA.

Tasks
(1) Get land assess for areas to be studied. (GBRA Responsiblity)
(2) Assist in locating local source of air photography, maps, and imagery as needed. (GBRA Responsibility)
(3) Literature review and synthesis, assessment, and analysis of existing data.
(4) Build GIS database of study area.
(5) Field data collection.
(6) Analysis and interpretation of field and GIS data.
(7) Produce report with the assistance of the CONSULTANT.

Response to Comments on Draft Final Report

•All required editorial changes and corrections have been made (items 1-5).

•Suggested changes 6 – 8 have been made.

•Recommendation for prevention of logjams by removal at US 77 crossing has been qualified by acknowledging that engineering feasibility is uncertain, and an additional option has been added.

•Other corrections noted by the author/consultant have been made.