# FLOODPLAIN LAKE FORMATION AND DYNAMICS IN THE LOWER REACHES OF LARGE TEXAS COASTAL PLAIN RIVERS:

## BRAZOS, GUADALUPE, AND SAN ANTONIO RIVERS


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## TABLE OF CONTENTS

List of Figures

List of Tables

## 1. PROJECT SCOPE

The Texas Gulf Coastal Plain is an extensive low-relief landscape that trends northeasterly from the Rio Grande to the Red River (Figure 1.1). The lower reaches of Texas' large coastal draining rivers are complex settings characterized by active channels, dynamic flood processes, and considerable heterogeneity within floodplain environments (Phillips, 2008; Hudson and Heitmuller, 2008). A common feature within large coastal plain river valleys are floodplain lakes (Figure 1.2). Because much of the floodplain surface is humanly altered for agriculture and grazing, floodplain lakes represent important riparian environments and serve as critical habitat for a range of aquatic ecosystems (Amoros and Bornette, 2002).

Floodplain lakes are diverse in terms of the formative processes and morphology while exhibiting considerable variability in hydrology and sedimentation, the major process that drives ecological change within these environments (Figure 1.3) (Roozen et al., 2003). Some floodplain lakes are directly connected to main-stem channels and are therefore supplied sediment and streamflow without the river being over bank (e.g., Rowland et al. 2005). Other floodplain lakes are hydrologically separated from the main-stem channel, receiving streamflow and sediment during flood stage. Floodplain lakes can be formed by a variety of processes, including 1. oxbow lakes formed from meander neck or chute cutoffs, 2. abandoned river courses created by channel avulsion, 3. flood incision resulting in scour troughs (crevasse like features), 4. sedimentary processes, including arcuate swale depressions within meander scroll and valley side lakes adjacent to channel belt ridges, and 5. neotectonic and subsidence influences that result in floodplain warping and a change in floodplain drainage. Thus, the mechanisms responsible for floodpain lake formation are distinct, which suggests a different signature of connectivity.

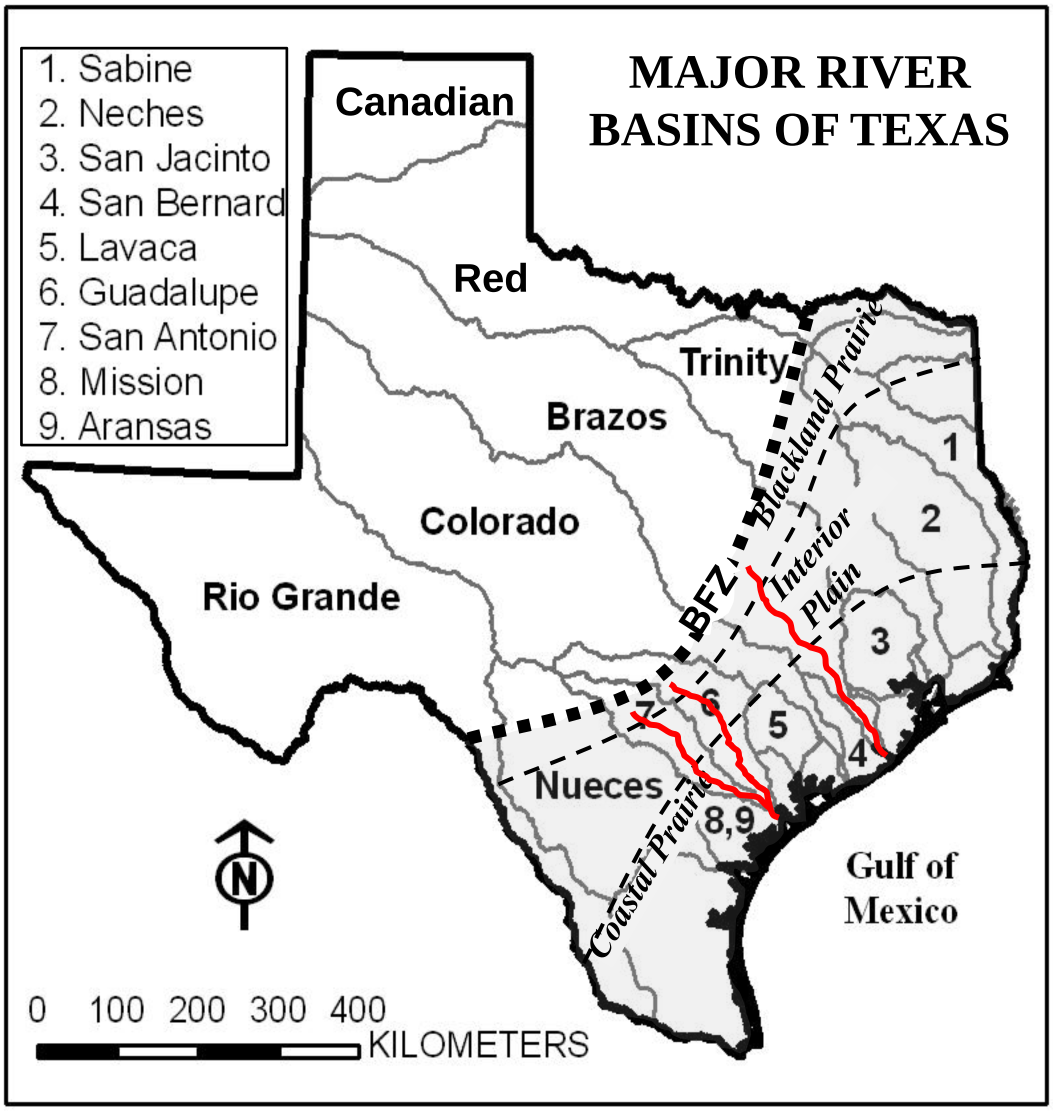



Figure 1.1. The location of the study rivers in the context of the Texas Gulf Coastal Plain.

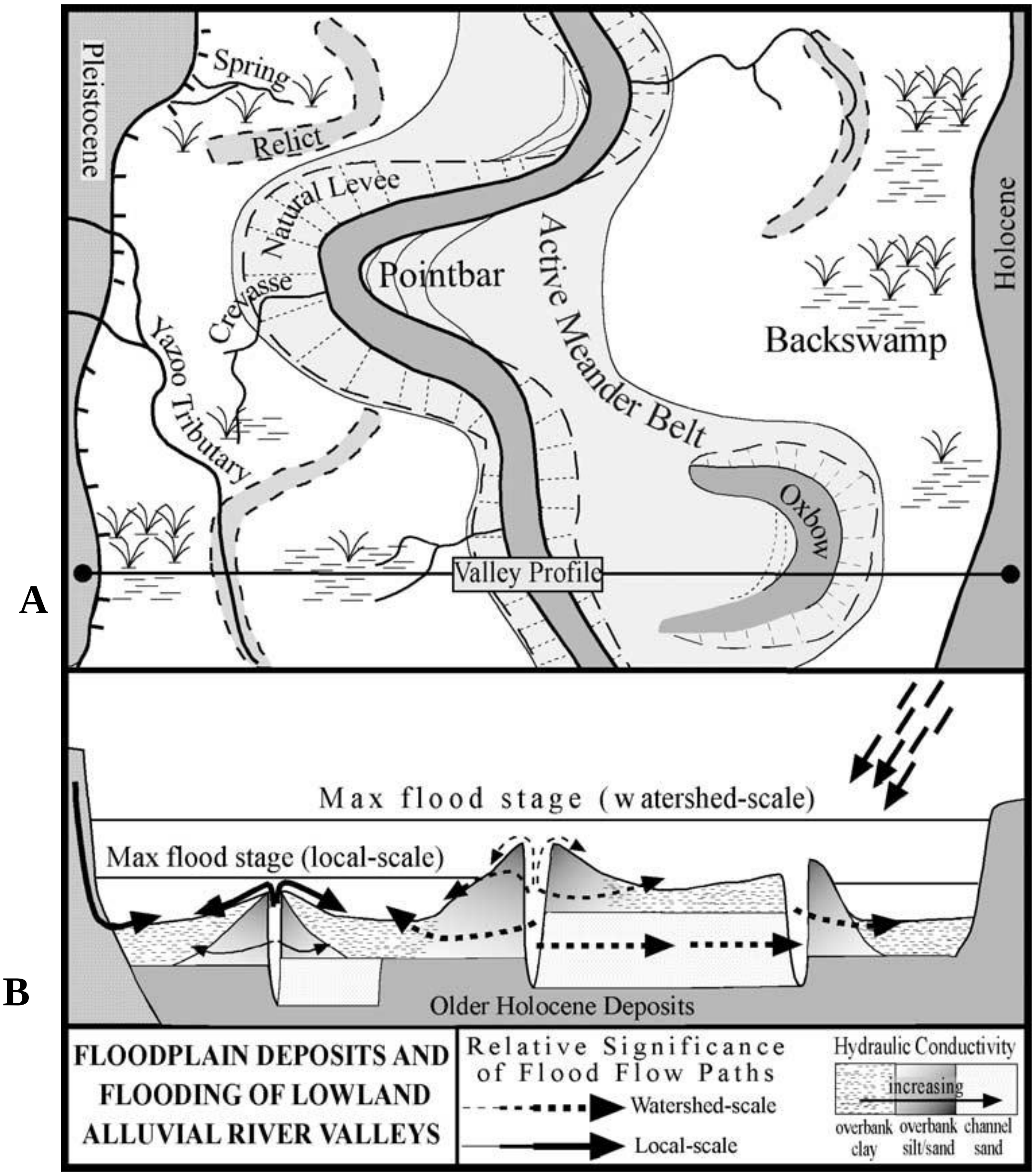



Figure 1.2. Model of floodplain environments and floodplain hydrology of a large lowland alluvial river valley (from Hudson and Colditz, 2003). The figure illustrates the complexity of connectivity associated with floodplain lakes (oxbow and relict channel lakes) attributed to local and main-stem (watershed) sources. A. Plan, B. cross-section. Hydraulic conductivity varies widely within a given valley reach but increases from clay to sand. The model does not represent all scenarios, and in particular the relative significance of flood flow paths varies spatially with flood plain geomorphology and hydrologic regime, and temporally with passage of the flood wave.


Figure 1.3. Some examples of floodplain lake types along the lower reaches of the Texas coastal plain.

Nevertheless, once formed, floodplain lakes evolve over time due to the influence of hydrologic, geomorphic, sedimentologic, and biotic influences (Gagliano and Howard, 1984). Regardless of typology or stage of infilling, however, all types of floodplain lakes and associated wetland environments provide numerous important ecosystem services, such as critical habitat for freshwater aquatic plants and animals, storage of flood waters and flood wave attenuation, and have an important role in biogeochemical cycling.

Gulf Coastal Plain river valleys commonly display systematic downstream spatial changes in fluvial controls, which are manifest in distinctive transition zones in fluvial processes and floodplain environments (Hudson and Kesel, 2000; Hudson and Colditz, 2003; Phillips et al., 2004). Most rivers exhibit longitudinal variation in stream power (gradient and discharge), which is associated with transition zones or hinge points in floodplain processes and in the formation of different types of floodplain water bodies (Hudson and Heitmuller, 2003; Phillips et al., 2004; Phillips, 2008). Specifically, higher gradient zones are associated with lateral activity and oxbow lakes, while low gradient valley segments are associated with lakes formed within abandoned channels (Hudson et al., 2006). Additionally, modern floodplain processes (hydrologic and sedimentologic) that influence these environments are also distinct on either side of the transition zone (Hudson and Heitmuller, 2003; Hudson et al., 2006).

The purpose of this study is to examine the geomorphic and hydrologic characteristics of floodplain lakes in the alluvial valley of three coastal plain rivers in Texas, specifically the Brazos, Guadalupe, and San Antonio Rivers.

## 2. PHYSICAL SETTING

The study sites include the entire reaches of the lower Guadalupe, San Antonio, and Brazos Rivers within the Texas Gulf Coastal Plain, which spans from near the edge of the Balcones Escarpment Zone to the Gulf of Mexico. Thus, the study reaches span the transition from the alluvial valleys and delta plains (Table 2.1).

Floodplain lake dynamics are driven by hydrologic processes under the influence of climatic, geomorphic, and sedimentologic controls. Seasonally, late fall and late spring are the wettest periods in south Central Texas, and April and May receive the highest precipitation. The source of moisture is predominately from the Gulf of Mexico, and to a lesser extent from the Pacific Ocean. Texas has recorded some of the highest rainfall intensities in the world, which is responsible for portions of Guadalupe and San Antonio headwaters commonly to be referred as "flash flood alley" (Beard, 1975; Baker, 1977; Slade and Abbott, 2002). However, flooding is a complex process and requires consideration of specific precipitation mechanisms and the location and geomorphology of the river basins. Texas rivers are impacted by four major precipitation mechanisms; westerly migrating cyclones (fronts), tropical cyclones from the Gulf of Mexico or Pacific, convectional thunderstorms (Bomar, 1983; Jones, 1989; Hudson and Heitmuller, 2008), and anomalous positions of the subtropical jet stream. The rainfall mechanisms range in scale from regional to local, and are very much influenced by the pattern of the polar jet stream in the winter and the subtropical jet stream in the fall and spring. While floodplain lakes are dominated by seasonal discharge pulses, the complexity of lake drainage processes (alluvial and surface) and surface evaporation become important to lake levels after recession of the discharge pulse. Texas evaporation rates are strongly seasonal, with average

Table 2.1. Characteristics of Study Basins

| River Basin | Drainage ($km^2$) | Ch. Length (km) | Valley length (km) | $Q_{50}$ ($m^3/s$) | *$Q_f$ ($m^3/s$) | Peak Q ($m^3/s$) | **Channel width at $Q_{bf}$ (m) |
|---|---|---|---|---|---|---|---|
| Brazos | [1] 117,427 | 2,060 | 353 | [1]257 | [1]1,472 | [1]2,389 | [1]126 |
| Guadalupe | [2] 26,231 | 739 | 257 | [4] 29 | [4] 258 | [4] 13,196 | [2] 48 |
| San Antonio | [3] 10,707 | 623 | 222 | [5] 16 | [5] 249 | [5] 3,681 | [3] 35 |

[1] Brazos (nr Rosharon, 08116650); [2] Guadalupe (nr Tivoli, 08188800); [3] San Antonio (nr McFaddin, 08188570); [4] Guadalupe River at Victoria (because of longer record) [5] San Antonio River at Goliad (because of longer record); *$Q_f$ = discharge at flood stage, based on National Weather Service and US Geological Survey data; ** measured from 2005 DOQQ (1 m)

monthly lake evaporation rates in south-central Texas (Victoria County) being 21 cm for August and 6.7 cm for January (Larkin and Bomar, 1983).

Texas is drained by an extensive network of large rivers that flow southeasterly into the Gulf of Mexico. The three study rivers receive discharge and sediment from the Edwards Plateau and the Texas coastal plain. The Texas coastal plain is an extensive low-relief landscape that trends northeasterly across Texas from the Rio Grande to the Red River, and is part of the larger Gulf of Mexico structural basin. The Gulf Coastal Plain is by far the largest physiographic province within Texas, dominating Texas' landscape east of Ft. Worth, Austin, and Del Rio. The width of the Gulf Coastal Plain ranges from 450 km along the Rio Grande valley, to 225 km along the Guadalupe River valley (Table 2.2). Although the Gulf Coastal Plain is generally characterized as one of the least complicated physiographic and geomorphic provinces of North America (Walker and Coleman, 1987), it is incorrect to characterize the Texas coastal plain as featureless (e.g., Jones, 1989). The Texas coastal plain is quite complex and heterogeneous, contributing to the variability of Texas coastal plain river systems, and has undergone different land-use histories. Conventionally the Texas coastal plain is further subdivided into three belts (Figure 1.1), corresponding with distinctive changes in the age of rocks, relief, and elevation (Hill, 1900; Wermund, 1996). River valleys display changes in width and orientation as they come in contact with faults and resistant strata.

Frequently characterized as low-energy river systems prone to flooding, Texas coastal plain rivers are usually portrayed as being more similar than unique. This is appropriate when comparing rivers of the coastal plain with other physiographic settings. However, along the

Texas Gulf Coastal Plain, rivers display considerable geomorphic and hydrologic diversity and can be placed into three scale-dependent categories depending on their size and source of drainage (Morton and Donaldson, 1978; Winker, 1979; Blum and Valastro, 1994; Hudson and Heitmuller, 2008). The largest (10-$^{5}$ km$^{2}$) coastal plain rivers, extrabasinal watersheds, primarily derive their drainage from distant hinterland sources above the coastal plain, and include the Rio Grande, Colorado, Brazos, and Red Rivers. The Brazos, Rio Grande, and Red Rivers are amongst the 10 longest rivers in the U.S., while the Colorado ranks 16th (Kammerer, 1990). In contrast to the Guadalupe and San Antonio Rivers, the Brazos River receives much less (as a %) drainage from the coastal plain, with considerable drainage coming from the High Plains in northwest Texas and the Edwards Plateau. The drainage of the coastal plain land surface is dominated by basin-fringe and intrabasinal systems. Basin fringe watersheds are intermediate ($10^{-4}$ km$^{2}$) sized systems with headwaters formed near the updip margins of the coastal plain, and include smaller tributaries that drain the sandy coastal plain units. The Guadalupe and San Antonio Rivers are excellent examples of basin fringe rivers.

The longitudinal profiles of the study sites display a nonlinear reduction in channel slope, with the Guadalupe and San Antonio Rivers displaying much higher slopes across the coastal plain than the Brazos (Figure 2.1). Valley profiles for the lower San Antonio, Guadalupe, and Brazos River valleys, constructed from LiDAR data, illustrates the complexity of floodplain settings within the lower reaches of large coastal plain river valleys (Figure 2.2). In particular the river valleys include older Holocene meander belts that appear as raised ridges within the river valley and hydrologically segregate the Holocene floodplain. Additionally, older Holocene

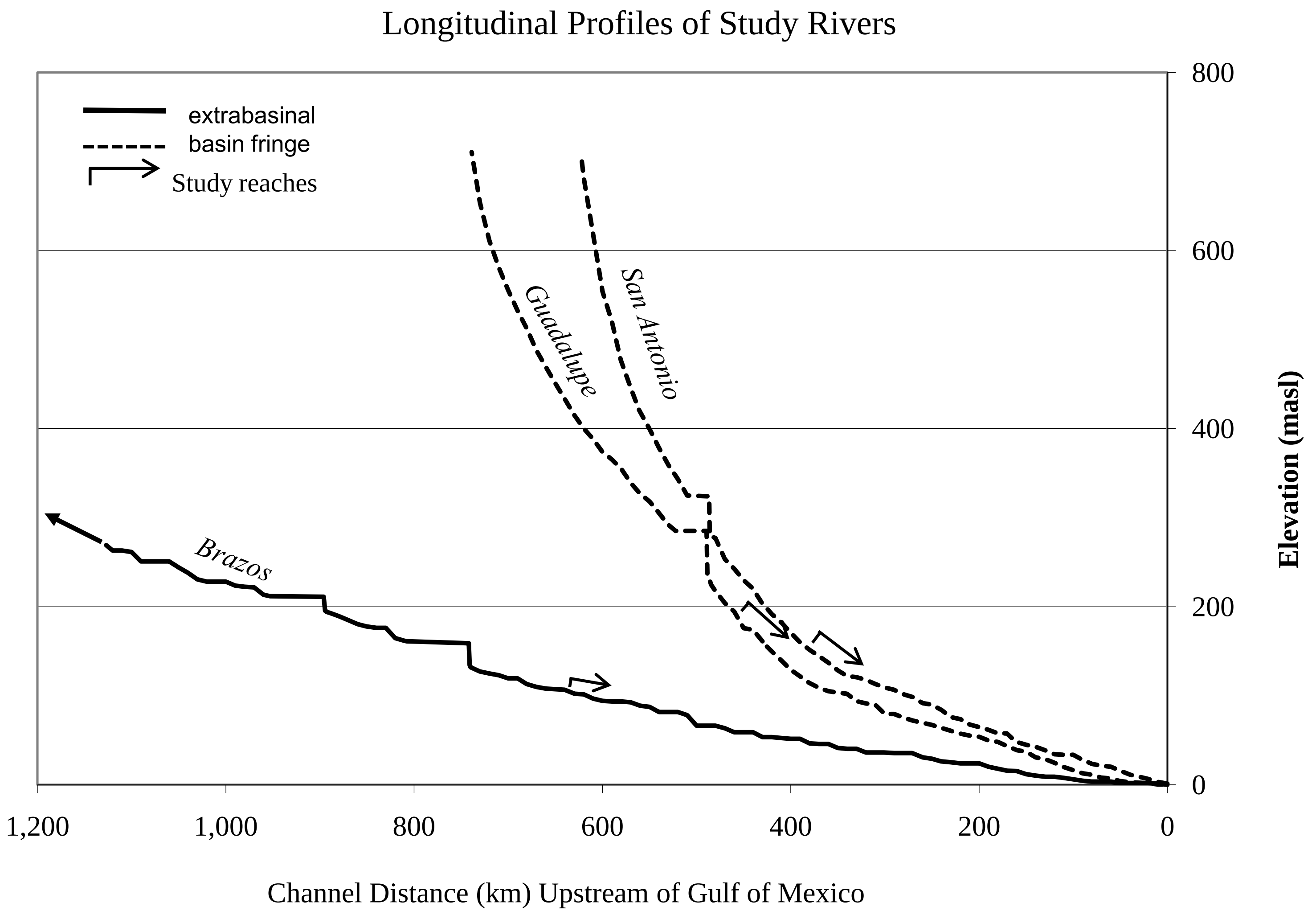
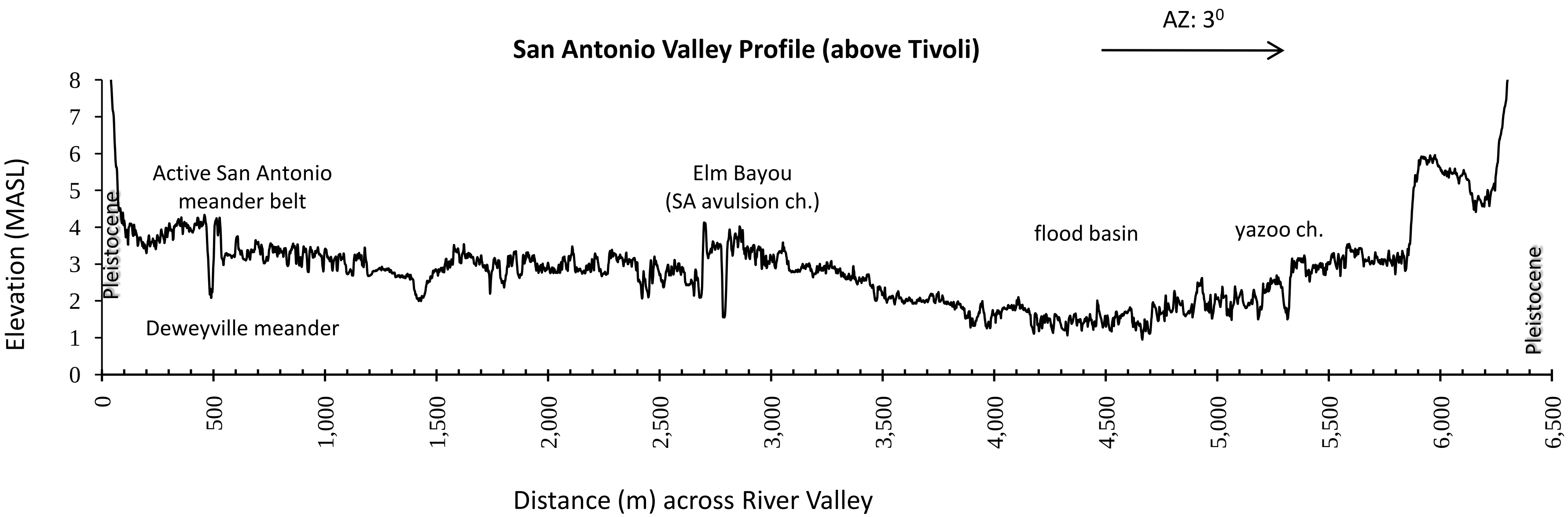



Figure 2.1. Longitudinal profiles of the study rivers. The San Antonio and Guadalupe Rivers are basin-fringe fluvial systems, while the Brazos is an extrabasinal system and crosses a longer swath of the coastal plain.



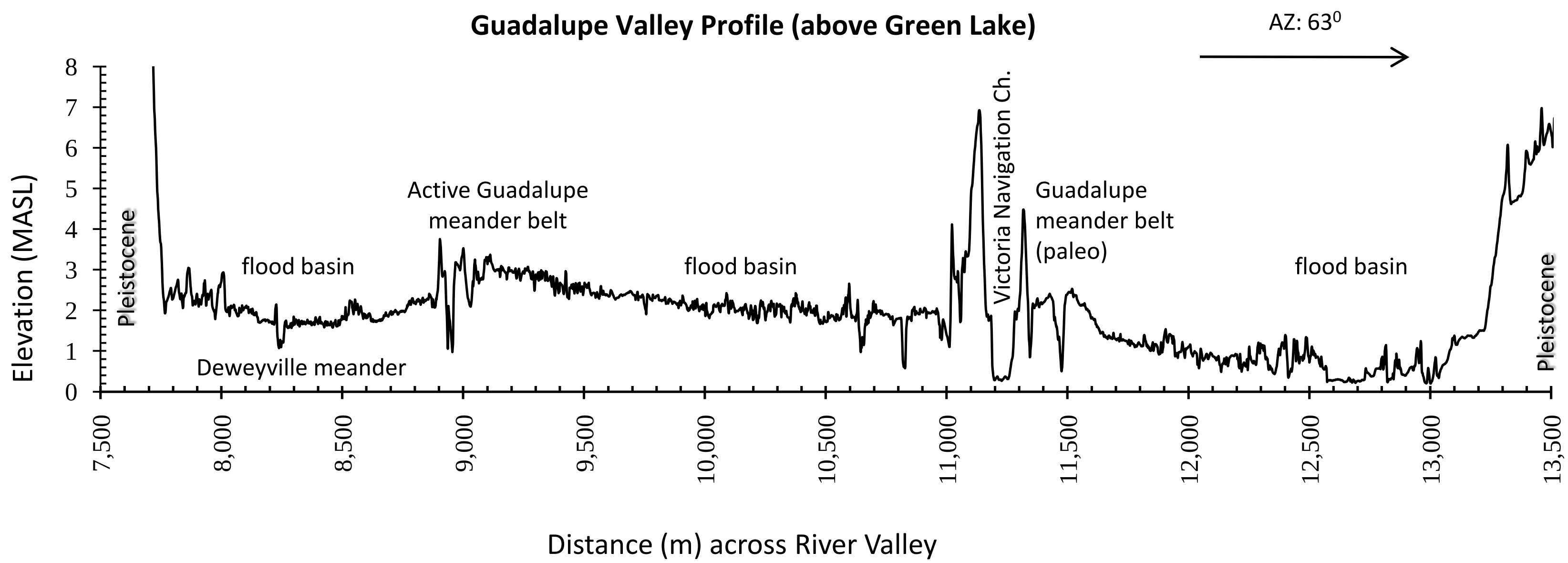




Figure 2.2. A. Topographic profiles of the San Antonio and Guadalupe River valleys, from LiDAR DEM.

LiDAR digital elevation model (DEM) of San Antonio and Guadalupe River valleys, showing location of valley profiles.

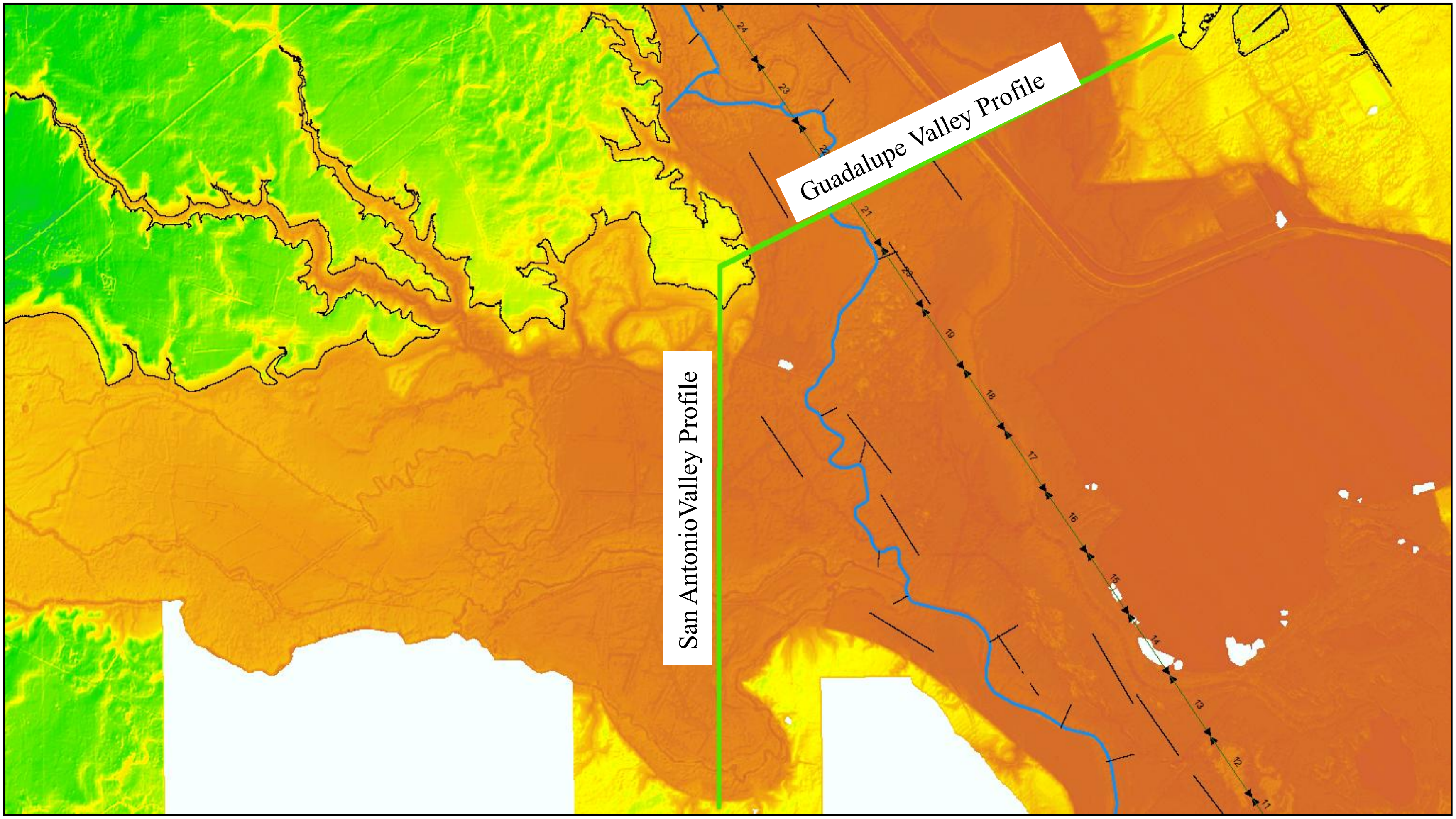



Figure 2.2.A. continued.

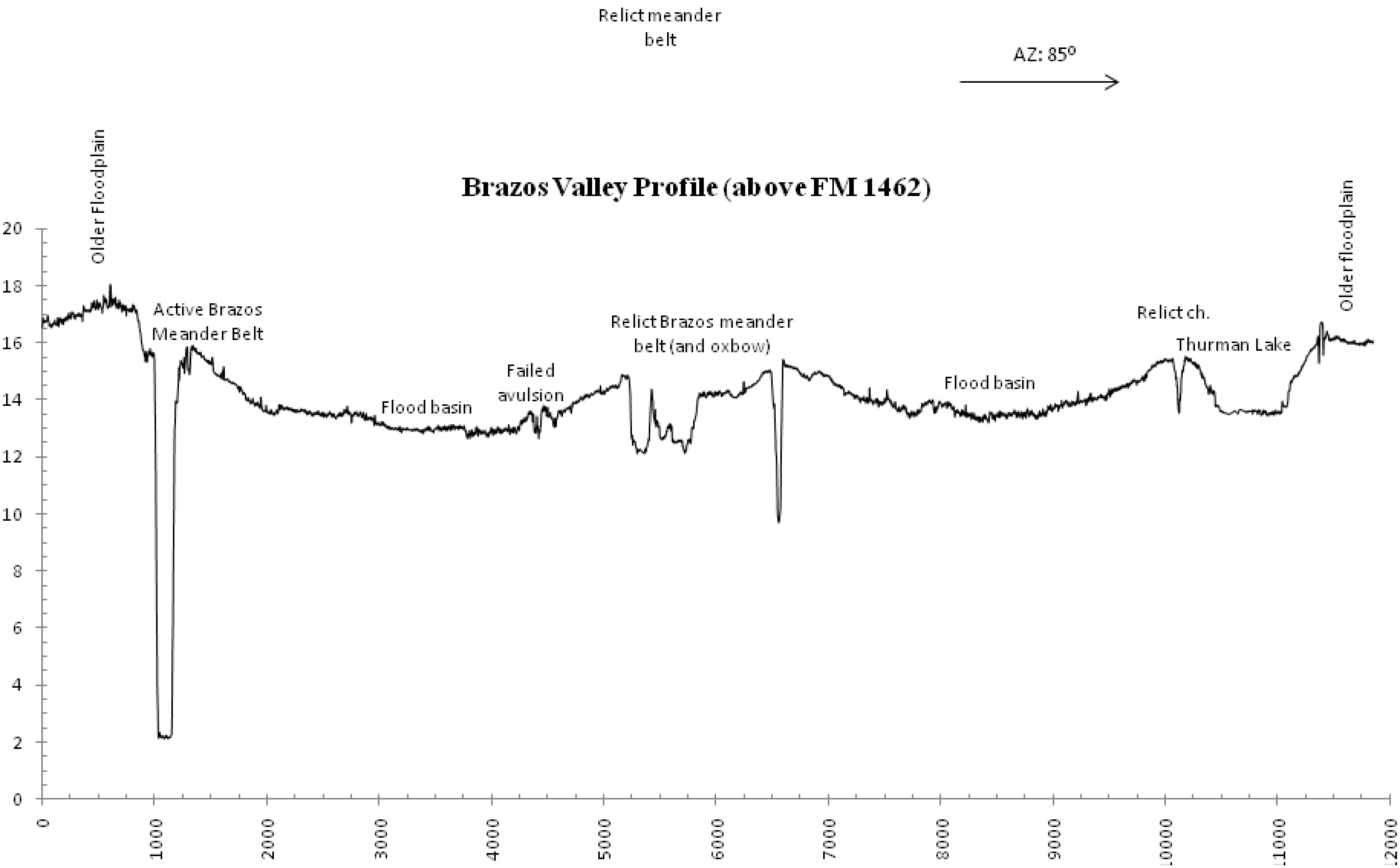



Figure 2.2. B. Topographic profiles of the Brazos River valley, from LiDAR DEM.

LiDAR digital elevation model (DEM) of upper Brazos River Delta, showing location of valley profile.

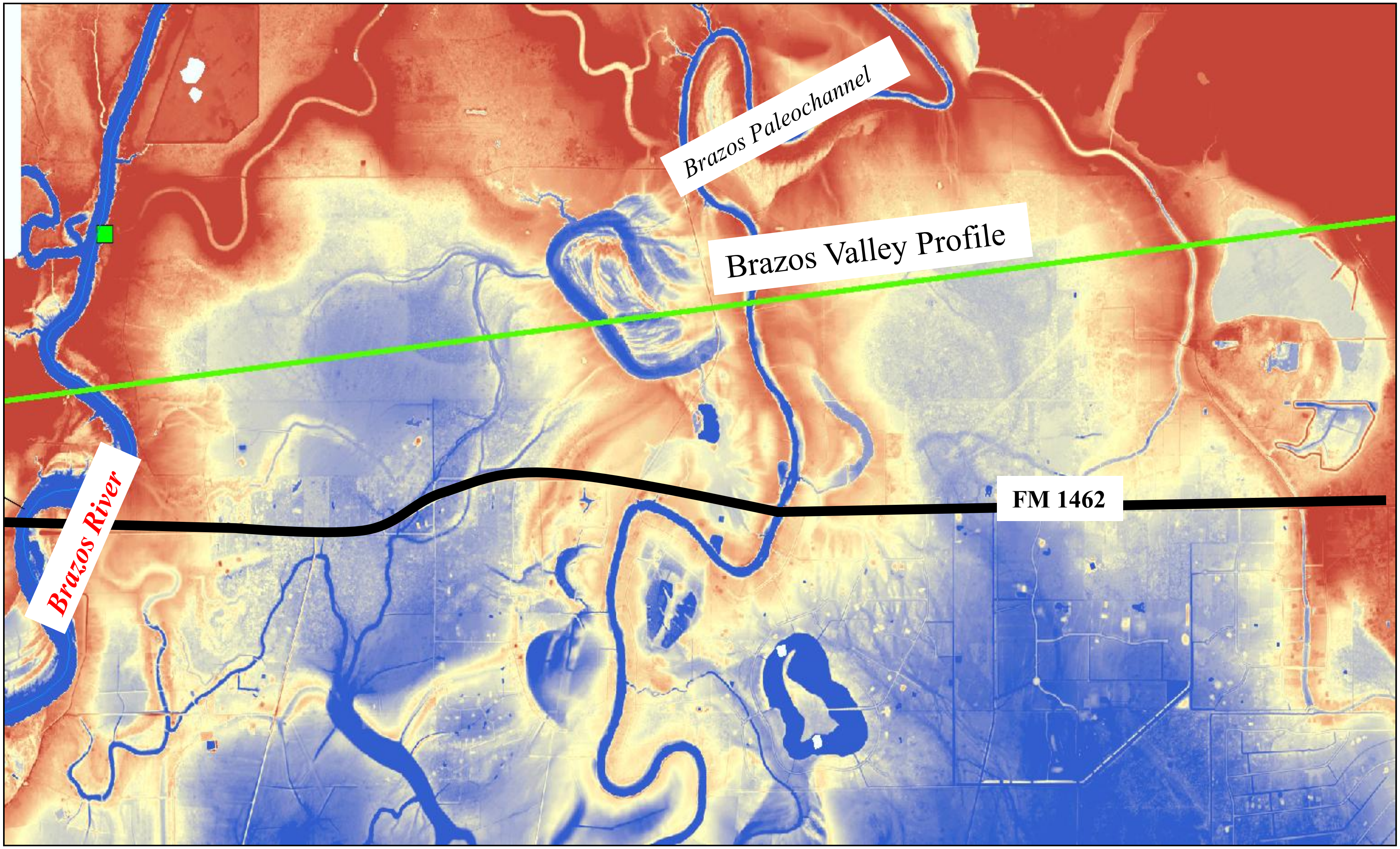



Figure 2.2. B. continued.

surfaces exist as low terraces above the modern floodplain and as lower surfaces associated with flood basins (backswamps) and partially buried channel belts.

Table 2.2. Geologic and geographic divisions within the Texas Coastal Plain (modified from Hudson and Heitmuller, 2008).

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

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

## III. OVERVIEW OF DATA AND METHODS

A variety of approaches were utilized to obtain the data sets analyzed in the study, including field, laboratory, and GIS procedures. These approaches were combined with various data sets to result in an integrated analysis of floodplain lake characterization and hydrologic connectivity along the study reaches. The field and laboratory procedures were utilized for an in-depth study of the Guadalupe, while the GISc approach and the analysis of suspended sediment data was utilized to study the Brazos, Guadalupe, and San Antonio systems.

Field work included installation of pressure transducers and downloading lake stage data, design and installation of sedimentation traps, topographic surveying, manual coring, field characterization of cores and trench profiles, and field reconnaissance to consider field sites and to verify information assessed remotely with aerial photography (DOQQs in GIS) or satellite imagery (Google). Laboratory analysis included in-house particle size determination of sediment samples, pre-treatment of samples for radiocarbon dating, and contract radiocarbon dating by accelerator mass spectrometry (AMS). A Geographic Information System (GIS) was developed in *ArcGIS* to incorporate various secondary data sets for mapping and analyzing floodplain lakes. Finally, a computer spreadsheet (*Excel*) was used for compilation and analysis of various hydrologic, morphologic, and sedimentologic data derived from field, laboratory, and GIS analysis. Further description of data and methods are itemized in the appropriate results section below.

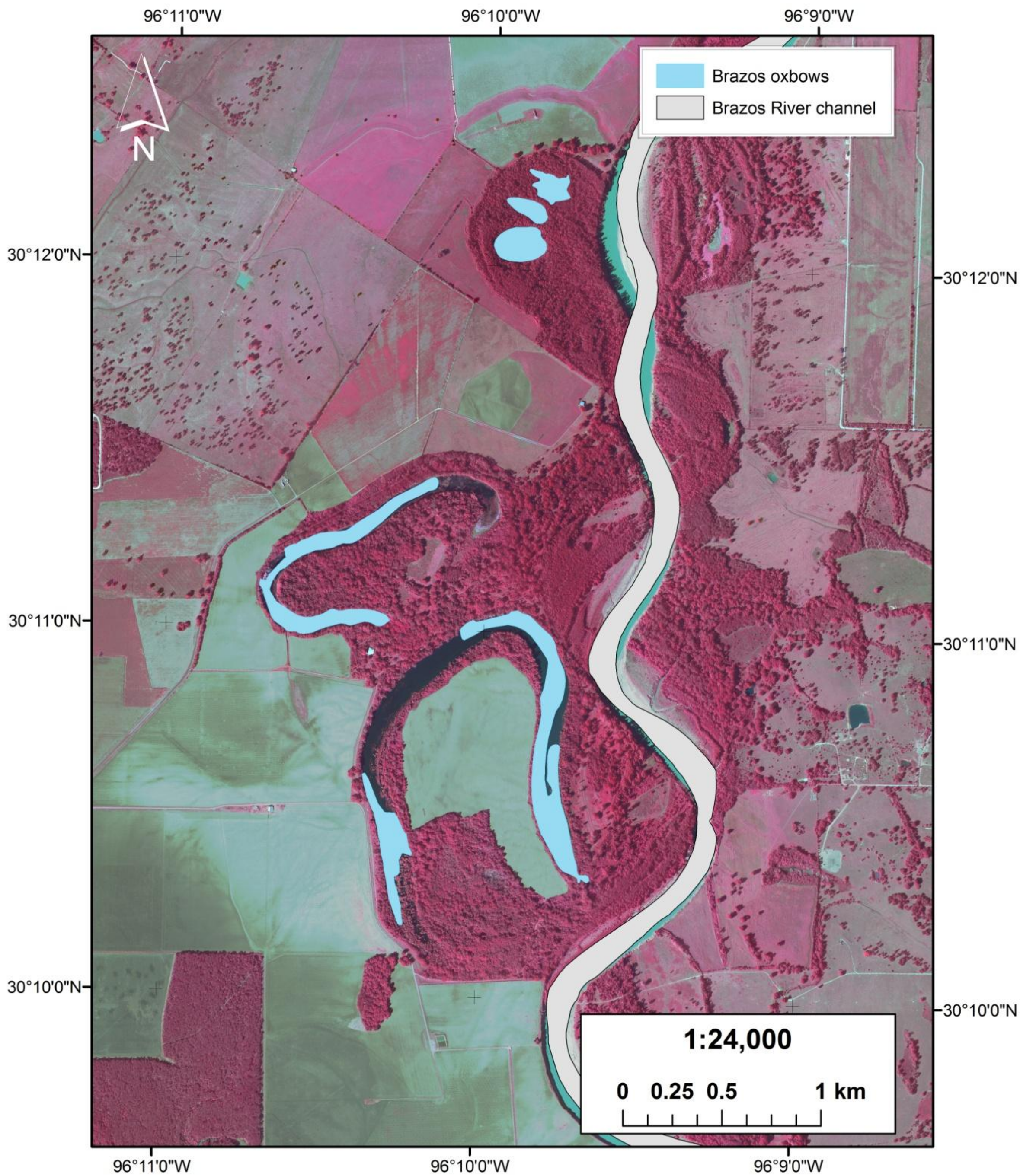
## 4. RESULTS

Although the individual study efforts were somewhat interrelated, the efforts were directed along four major thrusts, including GIS analysis of the river valleys and floodplain lakes (4.1), Hydrologic connectivity of floodplain lakes (4.2), Floodplain lake sedimentation (4.3), and Suspended sediment – discharge dynamics (4.4). Section 4.1 considers floodplain lakes along the entire reaches of the lower alluvial valleys and active deltas for the Brazos, Guadalupe, and San Antonio Rivers. This approach is used to map the location of floodplain lakes, particularly oxbows, along the valley and to consider broader fluvial controls on their spatial distribution. Section 4.2 considers hydrologic connectivity of three floodplain lakes along the lower Guadalupe River, with a particular focus on the relations between stream discharge and lake stage variability from the context of different types of floodplain lakes. Section 4.3 considers sedimentation rates spanning time-scales ranging from thousands of years to individual discharge pulses. Lastly, Section 4.4 considers suspended sediment – discharge dynamics by using secondary data sets available from the US Geological Survey, with the major focus being the Brazos River.

### 4.1 Floodplain Lake and Channel Analysis (Brazos Rivers, Guadalupe, and San Antonio)

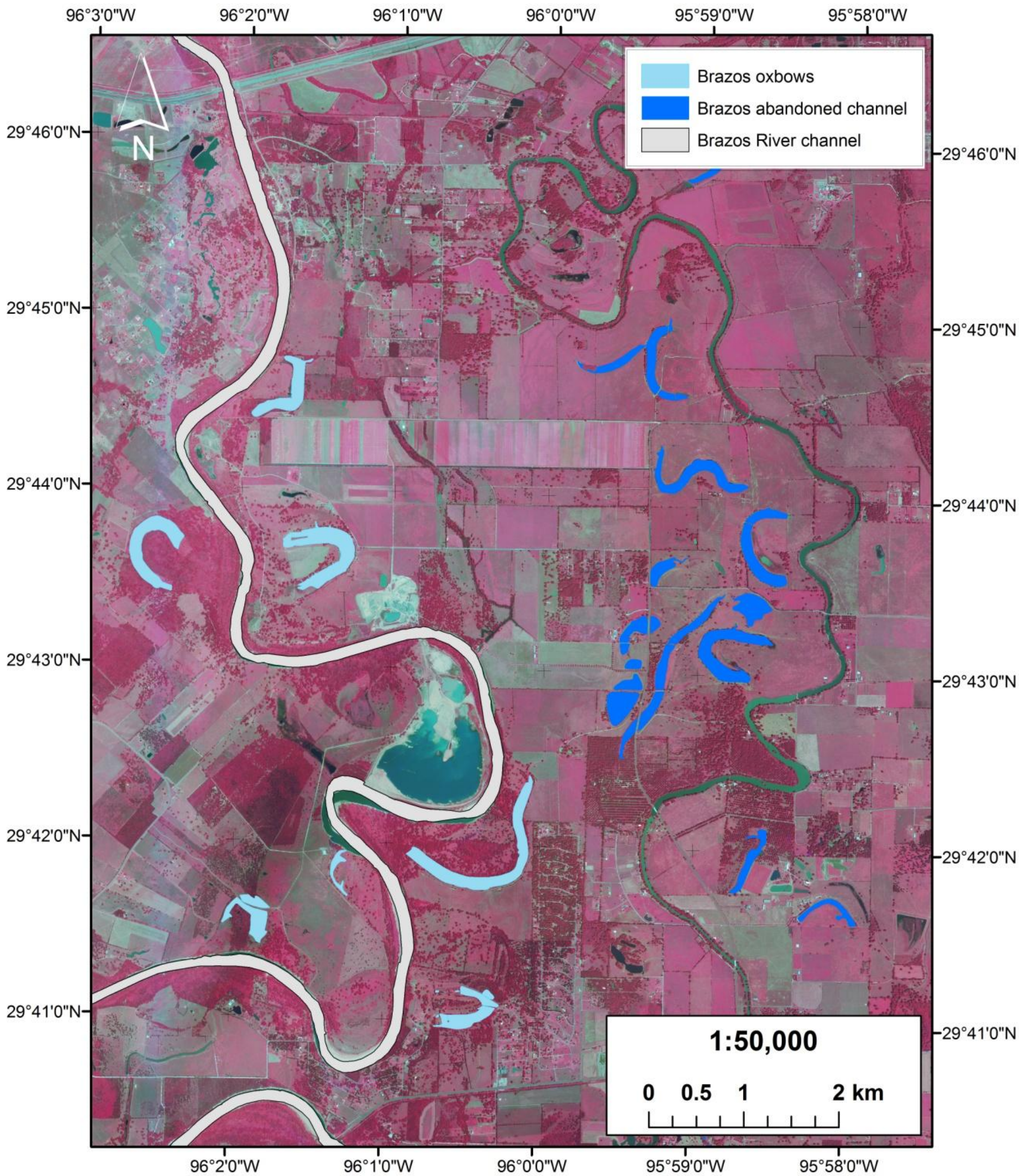
Secondary geospatial data sets were utilized to characterize and examine various fluvial processes that pertain to floodplain lakes along the Brazos, San Antonio, and Guadalupe Rivers. These data are analyzed within a GIS framework, primarily by using ArcGIS and Excel software. The secondary data sets included high resolution (1 m) high altitude infrared aerial photography available as Digital Orthophoto Quarter-Quadrangles (DOQQ), high resolution (=/>1:24,000) water bodies in vector format from the National Hydrographic Dataset (NHD), US Geological Survey (USGS) topographic quadrangle maps (1:24,000) available as digital raster graphics (DRG), and high horizontal (1.5 m) and vertical (< 0.3 m) resolution topography from Light Detection and Ranging (LiDAR) data from the Texas Natural Resource Information Systems (TNRIS). After obtaining the LiDAR data from TNRIS, the data required further processing at the Department of Geography and the Environment's Environmental Information Systems Laboratory. The procedures utilizes in this phase of the analysis were the same for the Brazos, Guadalupe, and San Antonio Rivers.

This phase of the study compares floodplain lakes classified as water bodies in the USGS NHD high resolution "GIS" (vector) "shapefiles" and by USGS 1:24,000 topographic maps. In many instances NHD water bodies were not classified as lakes on topographic maps, and in some cases lakes on topographic maps or clearly visible on aerial photography (DOQQs) were not classified as lakes for the NHD (Figure 4.1.1 A-D). Thus, the inventory is conservative but




Data Sources: High altitude aerial photography from Digital Ortho Quarter Quadrangles (DOQQ), 1 m spatial resolution, 2005, available from the Texas Natural Resource Information System (TNRIS), http://www.tnris.state.tx.us/. Floodplain features from high resolution hydrography from the US Geological Survey's National Hydrographic Dataset (NHD), http://nhd.usgs.gov/index.html.
Department of Geography and the Environment, University of Texas at Austin, 2010

Figure 4.1. A. Oxbow lakes identified from the National Hydrographic Dataset (NHD) and DOQQs along the Brazos Valley, illustrating the occasional underrepresentation of lake size.




Data Sources: High altitude aerial photography from Digital Ortho Quarter Quadrangles (DOQQ), 1 m spatial resolution, 2005, available from the Texas Natural Resource Information System (TNRIS), http://www.tnris.state.tx.us/. Floodplain features from high resolution hydrography from the US Geological Survey's National Hydrographic Dataset (NHD), http://nhd.usgs.gov/index.html.
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Figure 4.1. B. Floodplain lakes from NHD identified as oxbow lakes with the active Brazos channel belt, and oxbow lakes associated with an abandoned channel belt.

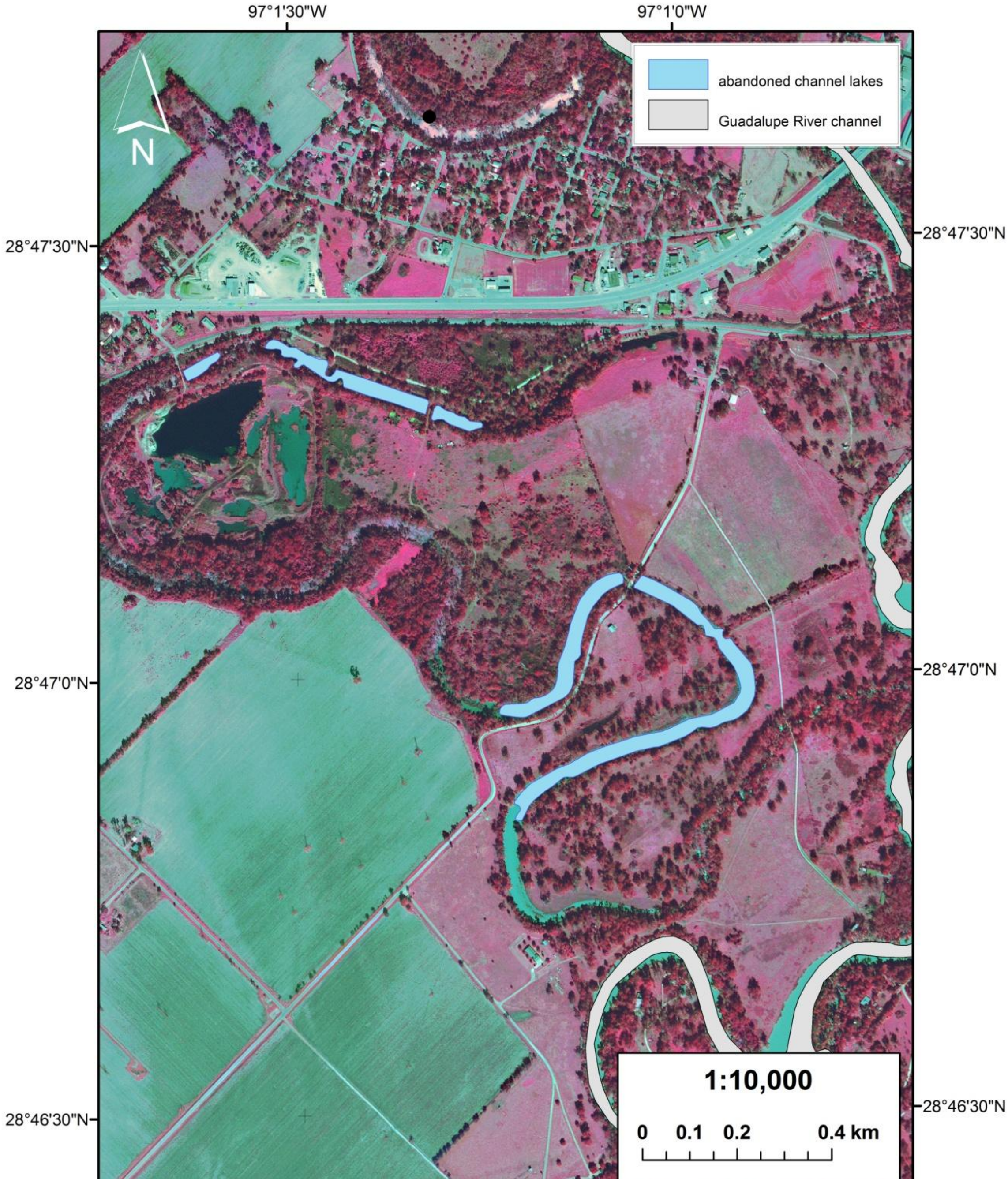


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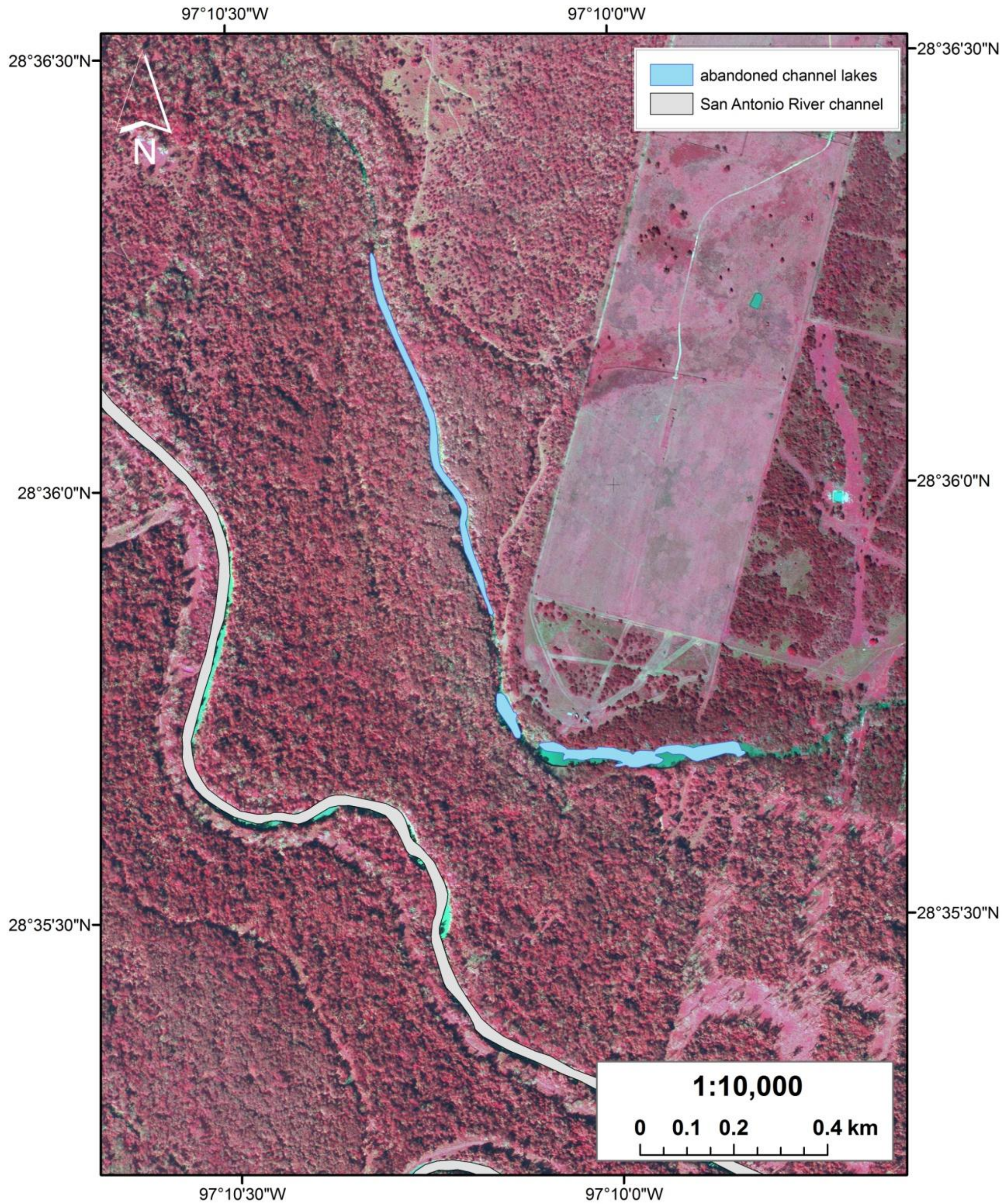
Figure 4.1. C. Floodplain lakes from NHD identified as abandoned channel lakes along the Guadalupe River, adjacent to Victoria. The individual polygons are actually part of the same lake.




Data Sources: High altitude aerial photography from Digital Ortho Quarter Quadrangles (DOQQ), 1 m spatial resolution, 2005, available from the Texas Natural Resource Information System (TNRIS), http://www.tnris.state.tx.us/. Floodplain features from high resolution hydrography from the US Geological Survey's National Hydrographic Dataset (NHD), http://nhd.usgs.gov/index.html. Department of Geography and the Environment, University of Texas at Austin, 2010

Figure 4.1. D. Floodplain lakes from NHD identified as abandoned channel lakes along the San Antonio River. The individual polygons are actually part of the same lake and must be merged in GIS.

provides a reasonable approximation of the relative significance of different floodplain lake types for the three study rivers within the entire coastal plain. Lakes were classified as "oxbow" or "abandoned channel lakes", although other lakes types were recorded (e.g., valley side, swale, etc...). Assignment of floodplain lakes to specific channel belts is straight forward only in the case of channel belts separated by wide flood basins (e.g., Fig. 1.2, 2.2A-B). In the case of highly intertwined channel belts, however, it becomes a sophisticated geomorphic exercise best served by combining soil and stratigraphic mapping (Figure 4.1.2) with field coring. Many "so called" oxbow lakes ("horseshoe" lakes) are not oxbows, but are actually residual meander segments of an abandoned channel belt (local avulsion) that has been partially eroded by the active channel, which leaves the semblance of an oxbow lake. Specifically, this facet of the study:

1. Identified all oxbow lakes and abandoned channel lakes within the three river valleys, from the Gulf of Mexico to (very near) the Balcones Escarpment Zone. Additional oxbow lake attributes that were recorded in the data base included, area ($km^2$), distance from the active channel (km), and whether the lake was on the left or right side of the active channel (downstream). Because most of the floodplain lakes are represented by several individual NHD features (polygons), the various NHD polygons representing a single lake had to be identified (visually) and then "merged" in ArcGIS. Additionally, the NHD data set included thousands of polygon water body features within the floodplain. To judge whether an individual water polygon was part of a floodplain lake required combing through the data set along the entire alluvial valleys, with the assistance of 2005 DOQQs, 1:24,000 topographic maps, and Google. NHD polygons considered not part of a natural floodplain lake were eliminated from the data set. This included cattle tanks, gravel and sand pits, and small reservoirs within the floodplain. This was especially an issue with older (largely infilled)


Figure 4.1.2. Example of stratigraphy and soil horizons along an eroding cutbank within the lower Guadalupe valley. The lower cumulic rich (dark band) buried soil horizon (Ab, paleosol) developed on a sandy point bar surface. The paleosol (old floodplain surface) was subsequently buried by coarser natural levee deposits, in which the active (modern) floodplain soil has developed (note lateral extent of surfaces). The adjacent “oxbow” is likely part of an old channel belt associated with the formation of the old floodplain, which is now being truncated by the modern channel. Alluvial soils and stratigraphy can be used to constrain the ages of different floodplain lakes to elucidate their temporal evolution.

floodplain lakes, particularly abandoned channel lakes. This step in the research was inherently somewhat qualitative, although the procedures followed standard and accepted aerial photo interpretation protocol established for feature recognition (e.g., Avery and Berlin, 1991).

2. Constructed a valley axis from the river mouth at the Gulf of Mexico to a few km below the Balcones Escarpment Zone for spatially referencing geomorphic indices measured within the valley. The valley axis is much shorter than the channel length. Several hinge points along the axis are located where the river shifts orientation, often at resistant strata and structural controls,

3. Measured the "active" valley width at 5 km increments along the valley axis, to the edge of the Balcones Escarpment Zone. This is essentially the floodplain. Floodplains are commonly defined in several ways according to the consideration, which includes geomorphic, hydrologic, and ecological factors. The attempt here is to limit the floodplain to that surface which contains floodplain lakes inundated by the main-stem river. The approach was based on NWS flood stage records at USGS gauging stations, specifically the vertical elevation difference between "flood stage" and "major flood stage". The elevation range was applied locally to valley segments based on the elevation data from digital topographic maps (DRGs) in a GIS. Thus, for the purpose of this study the term "floodplain" refers to a surface that floods historically (active floodplain), but it does not necessarily pertain to low Holocene terraces. Along some valley segments these surfaces have also been recently flooded, such as along the Guadalupe and San Antonio Rivers associated with the great flood of 1998. This approach has been verified in the field by the author for other Gulf Coastal Plain river valleys

(Hudson and Colditz, 2003), as well as for the inundation for the Guadalupe and San Antonio flood of July 2002, which included analysis of a LandSat-7 image of the July 7, 2002 flood,

4. The width of the meander (km) belt was measured perpendicular to the channel belt along the valley axis at 5 km intervals. This index corresponds to the zone of lateral channel activity, and the lateral extent to which flood deposits are topographically significant (i.e., natural levee construction). The meander belt was delineated based on elevation differences between the point bar and natural levee surface relative to the lower floodplain bottoms or backswamp. The zone of lateral activity was defined simply by the meander wavelength (~10 to 14 * channel widths, although frequently with high variability) (Bridge, 2003; Gouw and Berendsen, 2007) and from typical air photo interpretation procedures to identify meander scroll deposits and natural levee deposits from the lower floodplain bottoms. This involved standard air photo interpretation procedures to identify changes in vegetation, as well as the use of cultural features (houses, roads, etc...).

A comparison of oxbow lakes within the three study river valleys is reported in Table 4.1.1. This tabulation reports oxbow lakes along the active channel belt. Applying the same criteria for lake identification, it can be seen that the San Antonio River has far fewer oxbow lakes than either the Guadalupe or the Brazos. This is probably explained by the greater lateral stability of the San Antonio River because of cohesive channel banks (Engel and Curran, 2008). The similarity between the Guadalupe and Brazos valley is somewhat surprising. The Brazos has far more floodplain lakes than the Guadalupe, but many of them are actually old channel lakes rather than true oxbow lakes. Because of its size the total area of oxbow lakes is obviously much higher in the Brazos River valley, with the average oxbow lake area of 0.113 $km^2$. The area of abandoned channel lakes, however, appears to be greater. Without considering valley side lakes, for example, the area of abandoned channel lakes in the Brazos valley is 7.13 $km^2$. The Guadalupe and San Antonio oxbow lakes are about the same size and of similar distance from the active channel.

Table 4.1.1. Oxbow Lakes along the Brazos, Guadalupe, and San Antonio Rivers

| River | # | # left | # right | Avg. dist. (km) between lakes | Total area of oxbow lakes ($km^2$) | Avg. +/- Std. Dev. of oxbow lake area ($km^2$) | Avg. +/- Std. Dev dist. (km) from channel |
|---|---|---|---|---|---|---|---|
| Brazos | 45 | 26 | 19 | 7.8 | 5.075 | 0.113 +/- 0.096 | 0.31 +/- 0.27 |
| Guadalupe | 47 | 25 | 22 | 5.0 | 0.81 | 0.017 +/- 0.015 | 0.29 +/- 0.24 |
| San Antonio | 12 | 3 | 9 | 18.3 | 0.255 | 0.021 +/- 0.024 | 0.29 +/- 0.18 |

The valley width and meander belt width for the three rivers are presented in Figure 4.1.3. The location of oxbow lakes along the river valleys, area of oxbow lakes, and distance from oxbow lakes to river channel is shown in Figure 4.1.4 in relation to the ratio of meander belt width ($W_{MB}$) to valley width ($W_V$), expressed as a percentage (%). The $W_{MB}$ / $W_V$ index is relative to the space available for storage in the valley in excess of the modern meander belt. A value of 100 implies that the entire valley width is occupied by the active meander belt, whereas values < 100 imply that there is space available for residual floodplain deposits and floodplain lakes.

The lower Brazos Valley extends 350 km from the Balcones Fault Zone (just below Waco) to the Gulf of Mexico (Figure 4.1.3). The Brazos valley gradually increases in width from the Balcones Escarpment Zone to the coast, and displays variability associated with older geologic controls and tributaries. At the upper limits of the valley the width is 4.5 km, and there is not a

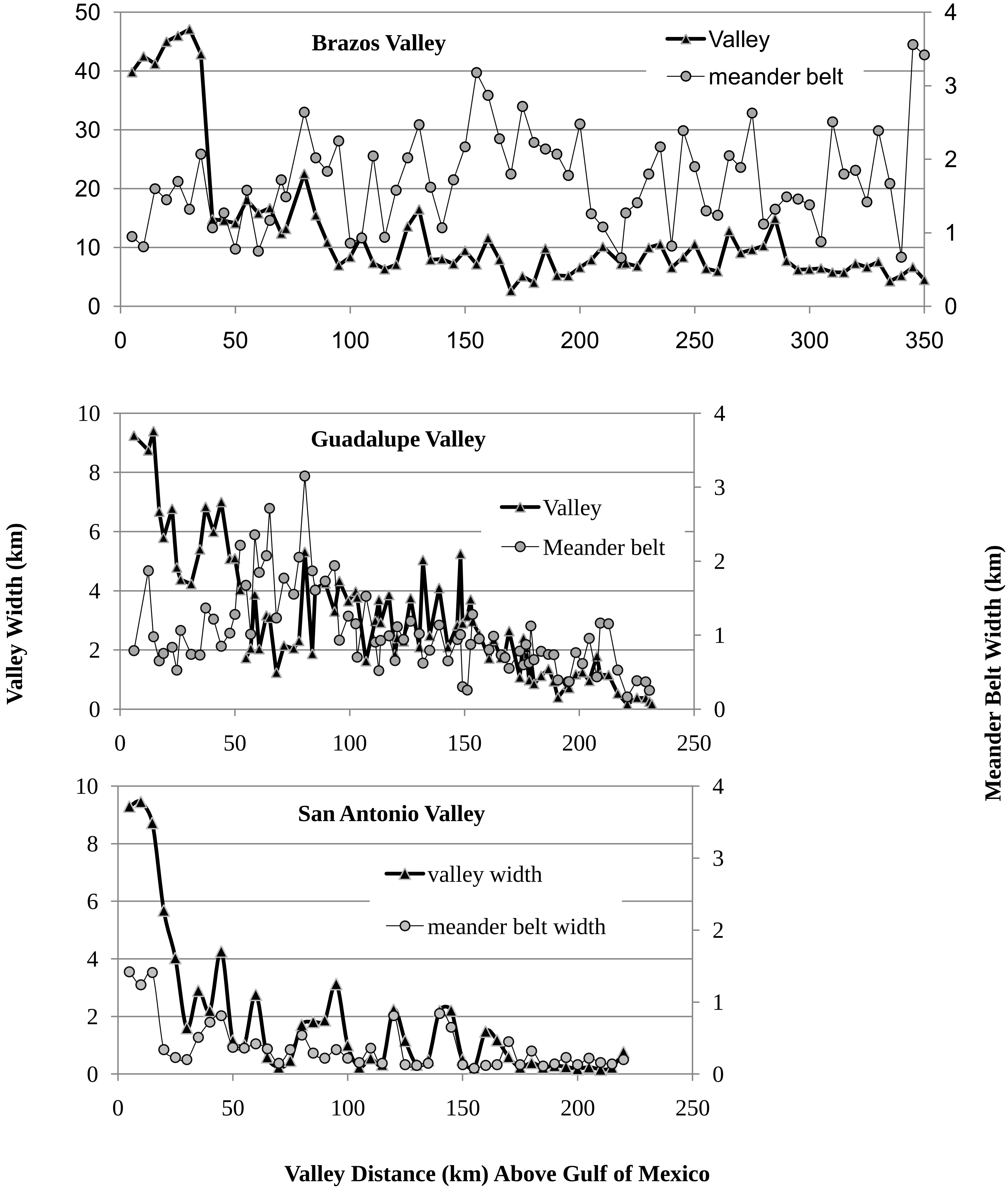



Figure 4.1.3. Valley width and meander belt width along the lower Brazos, Guadalupe, and San Antonio River Valleys. Valley width and meander belt width were measured at 5 km increments along a valley axis. The lowermost reaches are the delta plains. The upper limit of the valley is just below the Balcones Escarpment Zone.

substantial increase until the Little River joins at 280 km, which increases to 14.9 km. There is an increase at 130 km to 16.5 km because of an extensive Deweyville meander bight, and again at 80 km to 22.6 km. The most substantial change occurs at 35 km, when the valley width increases to 42.9 km. This abrupt change is associated with the sharp transition from the alluvial valley to the delta plain. With the data for the delta plain are removed, the relation between valley distance and width exhibits a weak statistically significant trend. The relation of meander belt width to valley distance is more variable, and does not exhibit a statistical trend (does not increase with valley distance). This reflects that the Brazos is an extrabasinal fluvial system, and with only a couple of exceptions, derives the majority of its drainage from distance hinterland sources, above the coastal plain. The absence of an increase in meander belt width then, is partially caused by the absence of significant increases in drainage. Additionally, the variability is caused by the different ages associated with different segments of the channel belt, caused by frequent local avulsions (e.g., Phillips, 2008). For example, the meander belt width between about 305 km to 280 km is considerably low at 1.5 km (Figure 4.1.4). This segment is adjacent to an avulsion node and the modern channel is against the western valley wall. It contains few oxbow lakes (Figure 4.1.4), although there are a number of floodplain lakes within the valley associated with an abandoned channel. A wider meander belt segment occurs from about 205 km to 160 km (below Hempstead). Interestingly, this section has a fairly narrow valley, and at Hempstead (170 km) the valley constricts to just 2.6 km where resistant Pleistocene Lissie deposits impinge the valley. The ratio of meander belt width to valley width is higher within this segment, reflecting less space available for older channel belts. The distance of oxbow lakes from the active channel is also greater in this reach (Figure 4.1.4), which presumably reflects the channel migration after the cutoff. Although this section has a narrow valley, upstream the river

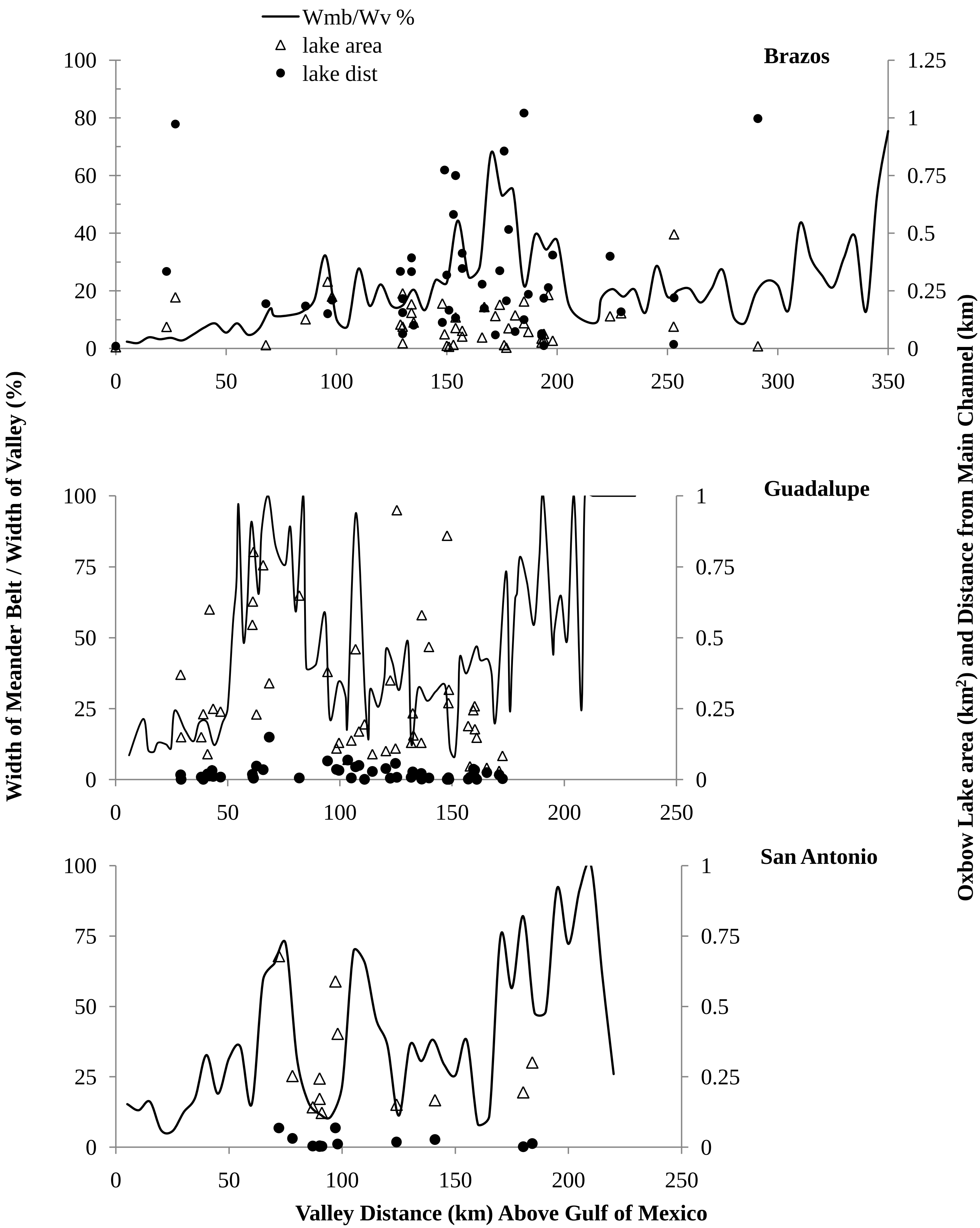



Figure 4.1.4. Location of oxbow lakes along the study rivers, and size and distance from river. The ratio of meander belt width to valley width is a relative index of the space available within the valley.

receives discharge and sediment from the Navasota River (at 206 km) and meanders for about 50 km through a narrow valley that does not contain an additional channel belt. The active scroll deposits and point bar surfaces indicate rapid meander migration (and reworked any older channels). Thus, in the absence of an avulsion along this stretch, the river may have had more time to develop a wider channel belt, accounting for the greater width and the higher frequency of oxbow lakes (Figure 4.1.4). At about 149 km an old channel belt is observed, which in itself includes a number of oxbow lakes (not included in oxbow tally in Table 4.1.1). Downstream of this reach the valley contains at least one additional old meander belt, and at the delta there are a minimum of three older belts. All of the channel belts include various combinations of lakes along a continuum of hydrography expected within large alluvial valleys, such as yazoo streams, curvilinear sloughs, and aligned fragmented lakes. Although there are many oxbow lakes within the lower ~125 km of valley, they tend to be associated with older channel belts and thus the frequency within the modern channel belt is actually quite sparse (Fig. 4.1.4). This also may suggest that the active channel belt has not had the time to generate numerous cutoffs, suggesting that the older channel belts were active for a much greater span of time than the modern channel has been active.

The lower Guadalupe Valley extends 233 km from the Balcones Fault Zone (at New Braunfels) to the Gulf of Mexico (Figure 4.1.3), although oxbow lakes are only located downstream of 175 km (Figure 4.1.4). Between New Braunfels and the delta, at about 20 km (above San Antonio confluence), the width of the valley increases from about 0.5 to 6.75 km. In comparison to the Brazos River this reflects that a larger percentage of the Guadalupe discharge enters lower in the watershed. Valley width displays high variability, particularly in association with larger tributaries and resistant strata. A large increase is noted at about 155 km, where the San Marcos River joins the Guadalupe. At 107 km, just upstream of Cuero, the valley width is only 1.6 km, which is associated with resistant Tertiary strata. Downstream of this constriction the valley widens, in part because of the addition of sizable tributaries, such as Sandies Creek (103 km) and Coleto Creek (39 km), but also large Deweyville meander bights. An abrupt increase in width occurs at 50 km (~Victoria) and at 22.6 km, just upstream of the confluence with the San Antonio Rivers. The greatest valley widths occur within the delta (not an alluvial valley). The Guadalupe (and San Antonio) delta is a bay head delta and as is bounded by older Pleistocene margins.

The Guadalupe meander belt width also displays considerable spatial variability. Between New Braunfels and Seguin the river is generally incised, and the meander belt width is appreciably low (< 0.5 km). Downstream of Seguin, however, meander belt width increases to 0.9 km. An abrupt increase occurs at 93 km, to 1.9 km width, and the river maintains a wide meander belt relative to valley width to about 50 km (Figure 4.1.4). Although the Guadalupe receives a large contribution of discharge and sediment from Coleto Creek (39 km) and the San Antonio Rivers (15 km), downstream of about 50 km the meander belt width slightly decreases in width, and this represents the transition to the delta. The location of the abrupt increase in valley width and decrease in meander belt width represents a *hinge-point*, and is related to changes in fluvial processes and floodplain characteristics, and the location is probably controlled by the Sam Fordyce Fault Zone (Morton and Donaldson, 1978; Schumm et al., 2000).

The lower San Antonio River valley extends 220 km from below the Balcones Escarpment Zone (at the Salado Creek confluence) to the Gulf of Mexico (Figure 4.1.3). The upper segments of the study reach are incised and the valley width is appreciably low. Until 160 km the valley width is < 0.3 km and displays little variability. The narrow valley controls migration and the development of the meander belt, as in many segments the width of the meander belt is about equal to valley width (Figure 4.1.4). Downstream of this section, until about 35 km, the width of the San Antonio valley varies considerably, from as low as 0.23 to as high as 4.26 km (Figure 4.1.3). The lower 45 km of valley has conspicuous Deweyville meander bights that result in local increases in valley width. Down valley of 35 km the valley is considerably wider and is effectively a delta, although the San Antonio does not join the Guadalupe until 15 km, which is associated with an abrupt increase in meander belt width.

The noted differences in the location and frequency of oxbow lakes (Figure 4.3.4) along the study rivers is informative, and the presence (or absence) of oxbow lakes can be seen as a surrogate for a variety of fluvial processes significant at the valley-scale. The high frequency of oxbow lakes along the Brazos River between about 200 and 150 km is associated with a wider meander belt, which confirms that the meander belt in this section is laterally active and possibly older. Although oxbow lakes are not as abundant upstream or downstream of this segment, other types of floodplain lakes, especially old channel lakes (not depicted here), are abundant. The similarity in size, geology, and hydrology between the Guadalupe and San Antonio River basins makes for an appropriate comparison. The upstream most oxbow lakes for the Guadalupe and San Antonio Rivers are located at about the same valley distance, which must in part be controlled by the lack of accommodation space (high Wv/Wmb %). The size (width) of the

Guadalupe meander belt is considerably larger than the San Antonio. This is likely because the San Antonio has lower rates of channel migration and transports a higher percentage of its sediment as wash load (silt/clay). Additionally, the lower reaches (downstream of 51 km, but especially 32 km) of the San Antonio River are dominated by avulsions rather than lateral migration (Engel and Curran, 2008), with the discharge and sediment load transported by two channels (downstream of 24 km). While both the Guadalupe and San Antonio Rivers have conspicuous abandoned meander belts within the lower reaches of their valleys (e.g., Figure 2.2), the Guadalupe also includes oxbow lakes. Within the lower reaches of the valleys, the delta, the greater cohesion and lower energy (lower slopes) may limit lateral migration and oxbow lake formation (Morton and Donaldson, 1978).

It is interesting to note that for all three rivers, the frequency of oxbow lakes is greatest within about the middle reaches of the alluvial valleys (Figure 4.1.4). This may represent the right combination of sufficient stream power and coarse sediment to laterally migrate (erode) and create meander bend cut-offs, and with sufficient space for their preservation.

### 4.2. Floodplain Lake Connectivity

Three floodplain lakes were identified for assessing hydrologic connectivity with the main-stem Guadalupe channel (Figure 4.2.1). The lakes included two oxbow (style) lakes associated with the modern (late Holocene) hydrologic regime and represent different end-members along a continuum of geomorphic adjustment initiated following a meander cutoff and oxbow lake formation (e.g., Gagliano and Howard, 1983; Saucier, 1994). The valley side lake located within an ancestral Deweyville Guadalupe River meander bend that was formed during a much higher period of streamflow than present. Thus, the selection of lakes represents a spectrum of possible meander lake environments located along Texas coastal plain rivers.

Floodplain lake connectivity with the main-stem Guadalupe River channel was assessed by analyzing and comparing several types of primary (field) and secondary data. Connectivity with the main-stem Guadalupe River was assessed by comparing the variability in floodplain lake stage with the Guadalupe River stage. InSitu ® LevelTroll 500 vented pressure transducers were used to record measurements of water pressure (kPa) and temperature (degrees Celsius) at user selected time intervals. These data are used by the sensor hardware to directly estimate of lake stage “tied in” to an artificial vertical datum. The units are installed with the sensor at the lake bed, and a vented cable with download terminal is housed above the expected level of maximum stage. The vented cables equalize internal instrument pressure with atmospheric pressure, which could otherwise influence stage estimates. The sensors were installed in December 2006 and February 2007. The lake stage data was examined in relation to river discharge at the Guadalupe River at Cuero and the Guadalupe River at Victoria (Table 4.2.1).

Pressure transducers were installed by mounting a PVC pipe to an 8 ft metal fence post, which was pounded into the lake bed with a sledge. In the case of the Horseshoe Lake and Cuero ’98 Oxbow Lake the vented cable was run along the lake bed to a fence post installed adjacent the lake shore. The download port was mounted at the top of the fence post to ease with data downloading. The data was periodically downloaded every three to six months, although at Linn Lake the presence of alligators occasionally hindered access.

**Cuero Oxbow (1998), Guadalupe Valley, TX**

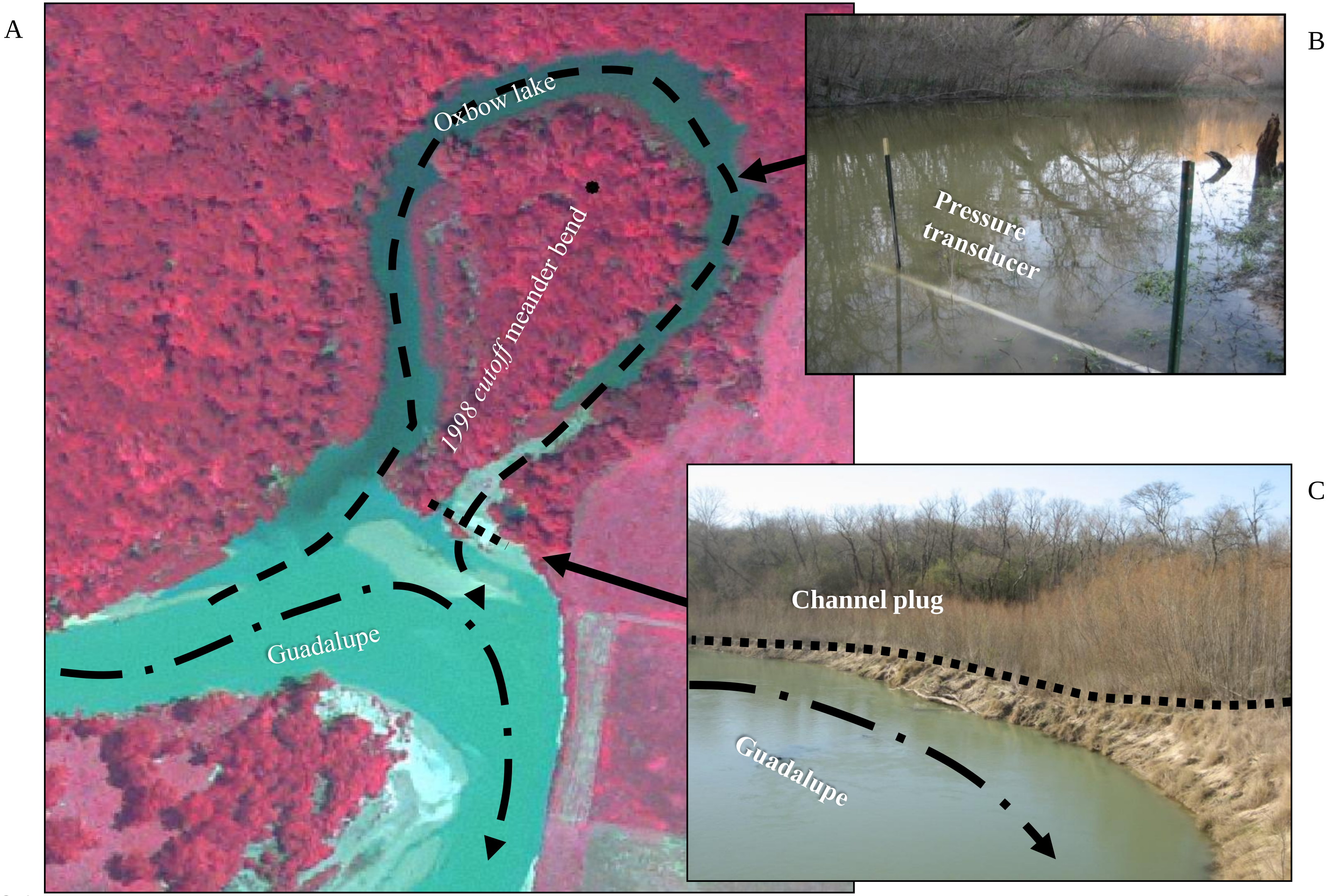



Figure 4.2.1

**Horseshoe Lake, Guadalupe River, TX**

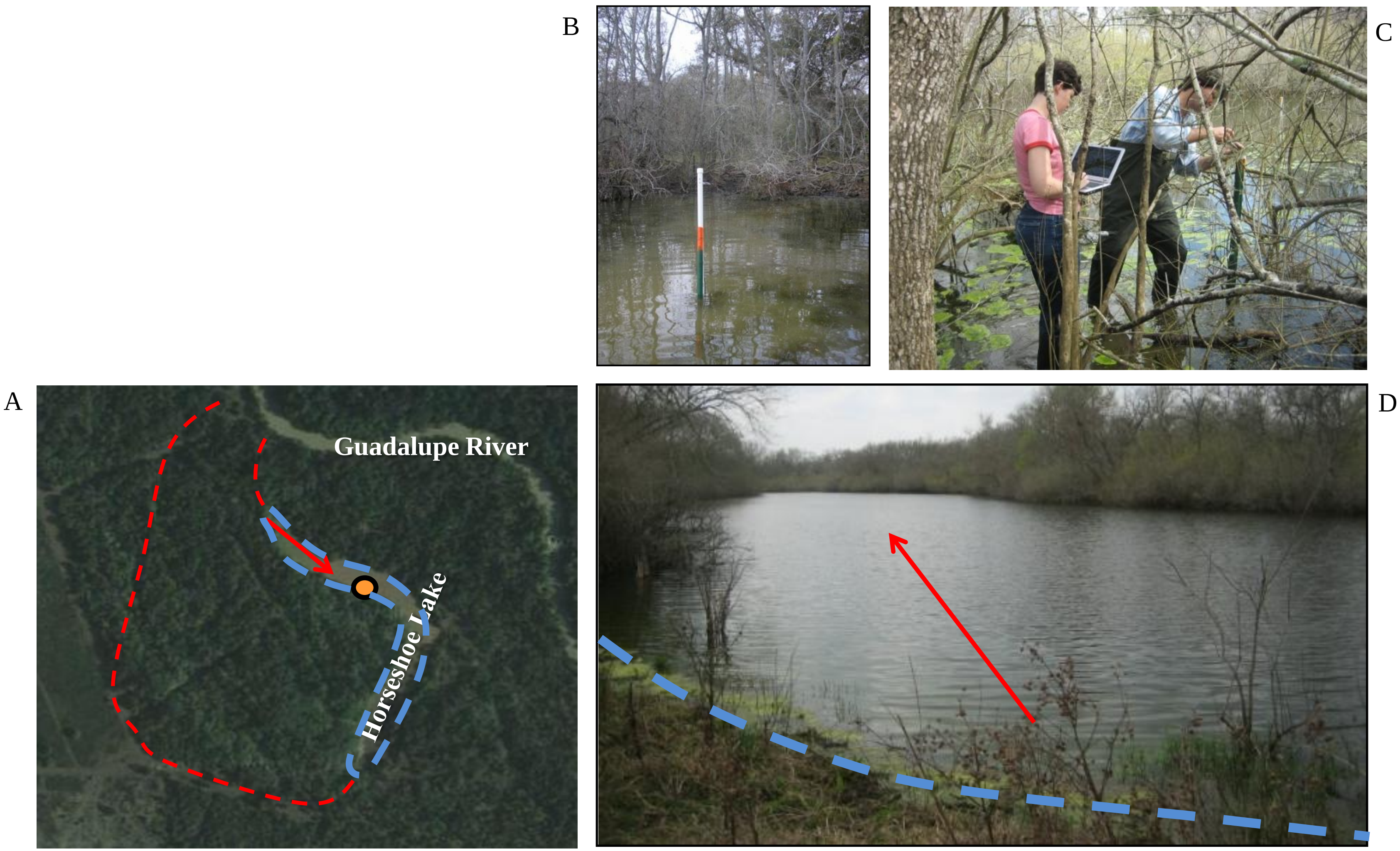



Figure 4.2.1. Continued…

**Linn Lake, Guadalupe Valley, TX**

A


B

C

Figure 4.2.1. Continued…

The difference in surface water elevation between the Guadalupe River with Horseshoe Lake and Cuero ’98 Oxbow Lake was measured by simple level and rod surveying procedures on May 17, 2007. The surface elevation of Horseshoe Lake relative to the Guadalupe River stage was shot with a single setup, while three setups were required at Cuero ’98 Oxbow Lake because of the dense vegetation and channel plug topography. The water surface elevation of the floodplain lakes was calculated by estimating the elevation slope along the channel bank surface to the upstream gauging station. Because of the size and complexity of the Linn Lake site, the elevation of the lake surface was estimated by using the LiDAR DEM.

The period of data collection in this study represents the longest record of continuous floodplain lake stage monitoring in the published literature (with exception of permanently mounted lake stage recorders operated by government agencies). More importantly, the prolonged study period provided the opportunity for monitoring to span a range of possible hydroclimatologic scenarios for the Texas coastal plain, including prolonged dry and wet periods associated with the most severe drought (September, 2007 to October, 2009) since the 1950s, and flooding associated with El Niño (Oct., 2009 to June 2010 (NWS forecast).

**Cuero ’98 Oxbow Lake**

Cuero ’98 Oxbow Lake is located about 2 km southwest of Cuero and about 500 m upstream from the Highway 87 bridge. The lake formed by a meander neck cutoff during the great Guadalupe River flood of October 17-18, 1998, the largest recorded flood (> 100 yr RI) in the Guadalupe basin and estimated at 3 to 4 times the prior largest flood (Slade and Persky, 1999). Thus, the exact age of Cuero ’98 Oxbow Lake is known. By October, 2002 rapid sedimentation had resulted in coarse grained (sandy) “plugs” within the upstream and downstream ends (entrance) of the oxbow (field observations). Within the basin of the oxbow lake, fine grained (clay/silt) slackwater deposits are draped over a distinctive pool – riffle channel bed geometry, resulting in shallow pools at very low stage (field observations). Because the oxbow has only recently formed it retains a high (> 6 m) cutbank along the outer lake perimeter. The size of the lake is 0.0183 km$^2$.

Table 4.2.1. Pressure Transducer Data for Guadalupe River Floodplain Lakes

| Location (Lat/Long) | Lake size (km$^2$)** | Installation (begin logging) | Removal (stop logging) | Span of Record, yrs | Sampling interval (period) | USGS streamflow gauge (#) and channel distance (km) to gauge |
|---|---|---|---|---|---|---|
| Horseshoe Lake (28 42.531, 97 00.947) | 0.02 | Dec. 13, 2006 | May 7, 2010 | 3.39 yrs* | 3 hr int. (12/13/2006 – 12/15/2007); 0.5 hr int (12/15/2007 – 6/16/2008: 23:00); 1 hr int. (12/9/2008: 15:00 to 5/7/2010: 12:00) | Guadalupe River at Victoria (08176500) 19.1 km upstream |
| Cuero ’98 Oxbow Lake (29.075045, 97.32901 ) | 0.02 | Feb. 25, 2007 | May 7, 2010 | 3.20 yrs | 1.0 hr (12/15/’07, 10:00), 0.5 hr (12/15/’07: 11:00-05/07/’10: 10:00) | Guadalupe River at Cuero (#08175800), 2.52 km upstream |
| Linn Lake (28 36.410, 96 58.221) | 2.98 | Dec. 13, 2006 | Dec. 9, 2008 | 1.99 yrs | 3 hr (12/13/’06: 17:00 to 12/15/’07: 14:00) 0.5 hr (12/15/’07: 15:00 to 12/9/’08: 11:00) | Guadalupe River at Victoria (08176500) 8.6? 41.9 km upstream |

* PT unit stopped logging 6/16/2008: 14:15, unit replaced 12/9/2008

** measured in GIS from DOQQs

The pressure transducer was installed about 3 m from the lake shore, away from low hanging branches and in as deep as water as could be identified, with the vented download cable running up the high cutbank to a secure fence post installed atop the high floodplain (low terrace). The data was continuously logged for 3.2 yrs, from Feb. 25, 2007 to May 7, 2010. The pressure sampler was set at a high logging frequency (1 hr and 0.5 hr) because of the presumed dynamic nature of the oxbow lake hydrology.

The 3.2 yrs of high resolution data illustrates the variability in water surface elevation for a newly formed oxbow lake along a coastal plain river valley for three full wet and dry seasons, spanning the spectrum of possible Texas hydroclimatologic scenarios. The period of record illustrates that that the Cuero oxbow lake exhibits strong hydrologic connectivity with the Guadalupe River, as peaks and recessions are nearly synchronous (Figure 4.2.2-3). Minor discharge events (> 16 % flow duration) results Cuero 98 Oxbow Lake connectivity. During "normal" flow conditions the lake stage is at about the same elevation as the Guadalupe River stage, an indication of groundwater transmission through the coarse channel plug. Lake level fluctuation responds to minor increases in discharge, as the threshold discharge required for connectivity is just 73 $m^3/s$, appreciably less than the overbank discharge for the Guadalupe River at Cuero. The maximum range (variability) in lake stage over the monitoring period was 6.93 m. This represents the difference between a large discharge event on May 1, 2007 (682 m3/s) and an extended low flow period for the Guadalupe, caused by the drought of 2008-2009. This extreme hydrologic event resulted in complete desiccation of the lake bed, which exhibited deep mud cracks. Lake levels declined after June 2008 and were uniformly low until a single event occurred April 19, 2009. Drought conditions resumed, and lake levels quickly declined after recession of this event. The prolonged dry period ended in late September 2009 with the onset of El Niño conditions. A large event on October 5, 2009, the fifth highest lake level over the study period, represented the beginning of a pronounced wet period with sustained moderate lake levels.

During the period of stage monitoring the lake was connected from 19 discharge pulses, with individual pulses having an average duration (time length) of 11.2 days. This high duration, however, is skewed towards a single 86.4 day discharge pulse that spanned from June 30 to September 24, 2007. This was ultimately triggered by an unusually cool and wet summer, resulting in above average monthly streamflow. Without this anomaly the average discharge pulse was 7.28 days.

Table 4.2.2. Summary data for lower Guadalupe River floodplain lake connectivity

| FOR STUDY PERIOD* | Horseshoe Lake | Linn Lake | Cuero '98 Lake |
|---|---|---|---|
| Avg. Elevation of Lake (MASL) | 14.01 | 4.15 | 42.91 |
| $Q_{-LP}$ ($m^3/s$)** | 240 | 102 | 73 |
| # of Discharge Pulses*** | 13 | 16 | 19 |
| Max. Stage Range (m) | 1.24 | 3.93 | 6.83 |

* for see table period of data logging, **$Q_{-LP}$ ($m^3/s$): threshold discharge for lake pulse, or , minimum discharge required for surface hydrologic connectivity; *** number of river discharge pulses over the period of data logging

Bivariate plots between river discharge and lake stage provide a means to further characterize the complexity of connectivity that exists between rivers and floodplain lakes, and consideration of other controls (Figure 4.2.3). The large discharge pulse that occurred in late April and early May, 2007 is an ideal event because it is rather discreet, and was the largest single event during the period of monitoring (at Cuero). The relation between discharge and lake stage reveals very little scatter, minor nonlinearity at higher discharges, and negligible negative

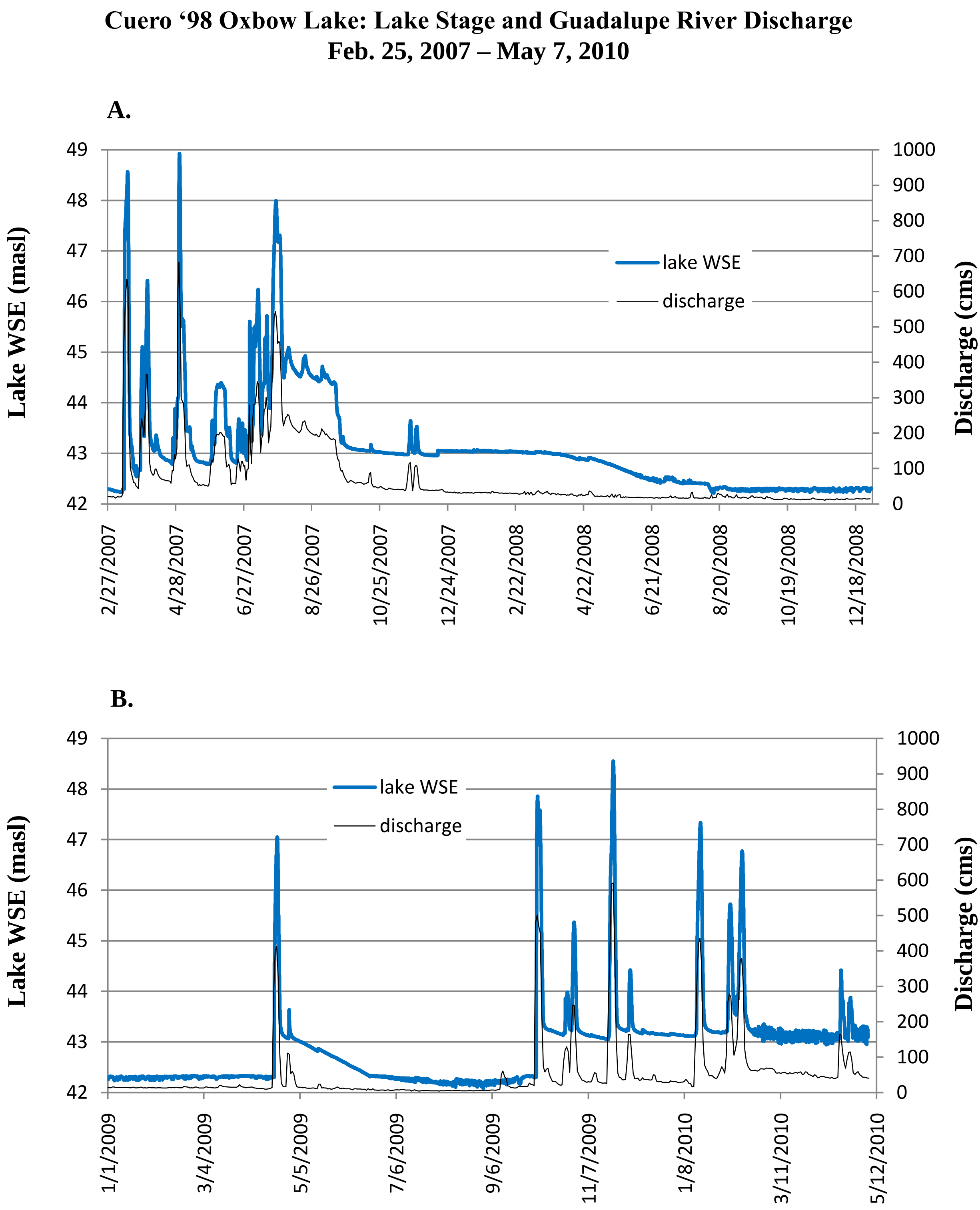



Figure 4.2.2. Lake water surface elevation (WSE) at Cuero '98 Oxbow Lake and discharge (cubic meters per second) for the Guadalupe River at Cuero. A. Feb. 25, 2007 to Dec. 31, 2008. B. Jan. 1, 2008 to May 7, 2010. The monitoring period spans two wet periods and a severe drought.

**Relation Between Discharge and Lake Surface Elevation:**
**Cuero '98 Oxbow Lake: April 27, 2007 – May 11, 2007**

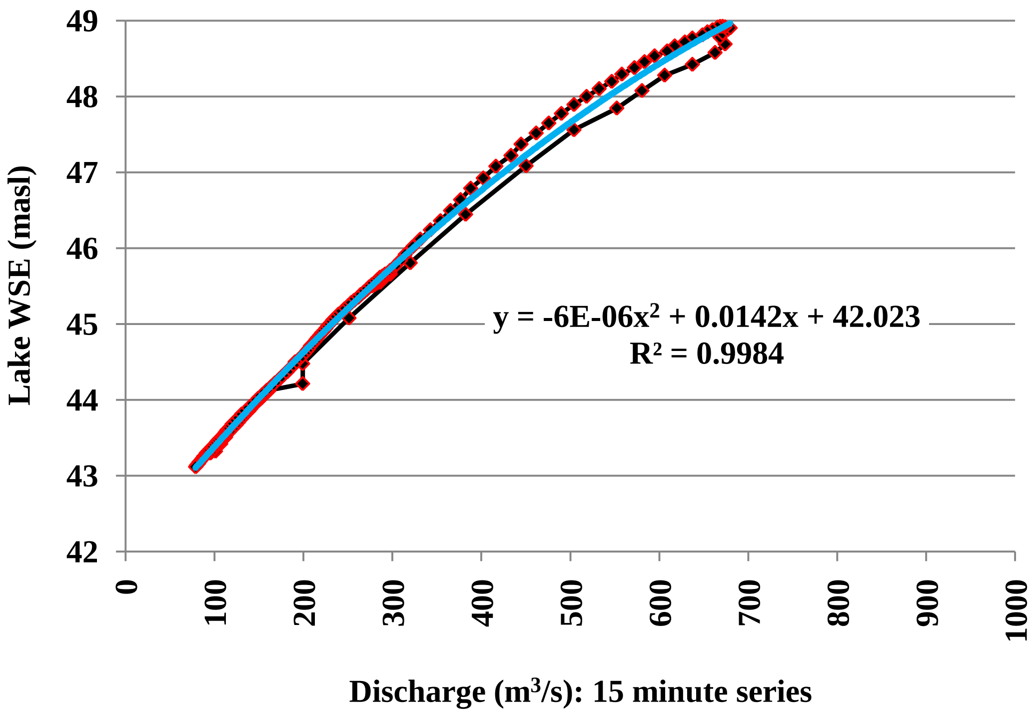



Figure 4.2.3. Relation between discharge (m3/s) and lake stage (WSE) for Cuero '98 Oxbow Lake for a discreet pulse spanning from April 27, 2007 to May 11, 2007. The data are at 30 minute resolution. The peak in discharge and lake stage are essentially synchronous, although lake stage is about 0.2 m to 0.3 m higher on the receding limb of the hydrograph, reflecting slower rates of drainage .

(counterclockwise) hysteresis. After connection, Cuero '98 rapidly infills and does not exhibit a substantial time lag between peak discharge and peak lake stage. The slight nonlinearity at Q exceeding ~500 is likely associated with inundation of the inside bank of the lake (point bar surface). The event peaked at 678 $m^3/s$, which exceeds flood stage (at Cuero). However, the outer bank of the oxbow lake (the cutbank side) was not overtopped because the (prior) meander bend was cut into a low terrace. The relation exhibits minor negative hysteresis during lake drainage, with lake stage being about 0.2 m to 0.4 m higher on the recessional limb of the hydrograph. The slight curvilinear pattern at higher discharges results in lake stage being best predicted by a $2^{nd}$ order polynomial model, with discharge accounting for 99% of the variability in lake stage. The statistical fit between discharge and lake stage did not improve by "lagging" the discharge to account for the travel distance between the upstream gauging station.

**Horseshoe Lake**

Horseshoe Lake is a shallow (< 1m depth) arcuate oxbow lake located 19.1 km (channel dist.) downstream of Victoria, and is immediately adjacent to the Guadalupe River (Figure 4.2.4-5). It is currently 0.020 $km^2$ in size (NHD data), about average for the Guadalupe, and because of infilling it is considerably smaller than its original extent. The upstream and downstream segments of the oxbow are completely infilled with sediment, subsequently buried by natural levee deposits associated with the modern channel. There is no direct surface (e.g., batture) connection with the Guadalupe River below flood stage and the topography between the lake and channel is flat. During about average conditions lake stage is about 0.3 m below the "relict" channel bank (floodplain surface), although the bank height is obviously variable (by about 0.5 m based on field observations). Topographic surveying established that the elevation of the lake

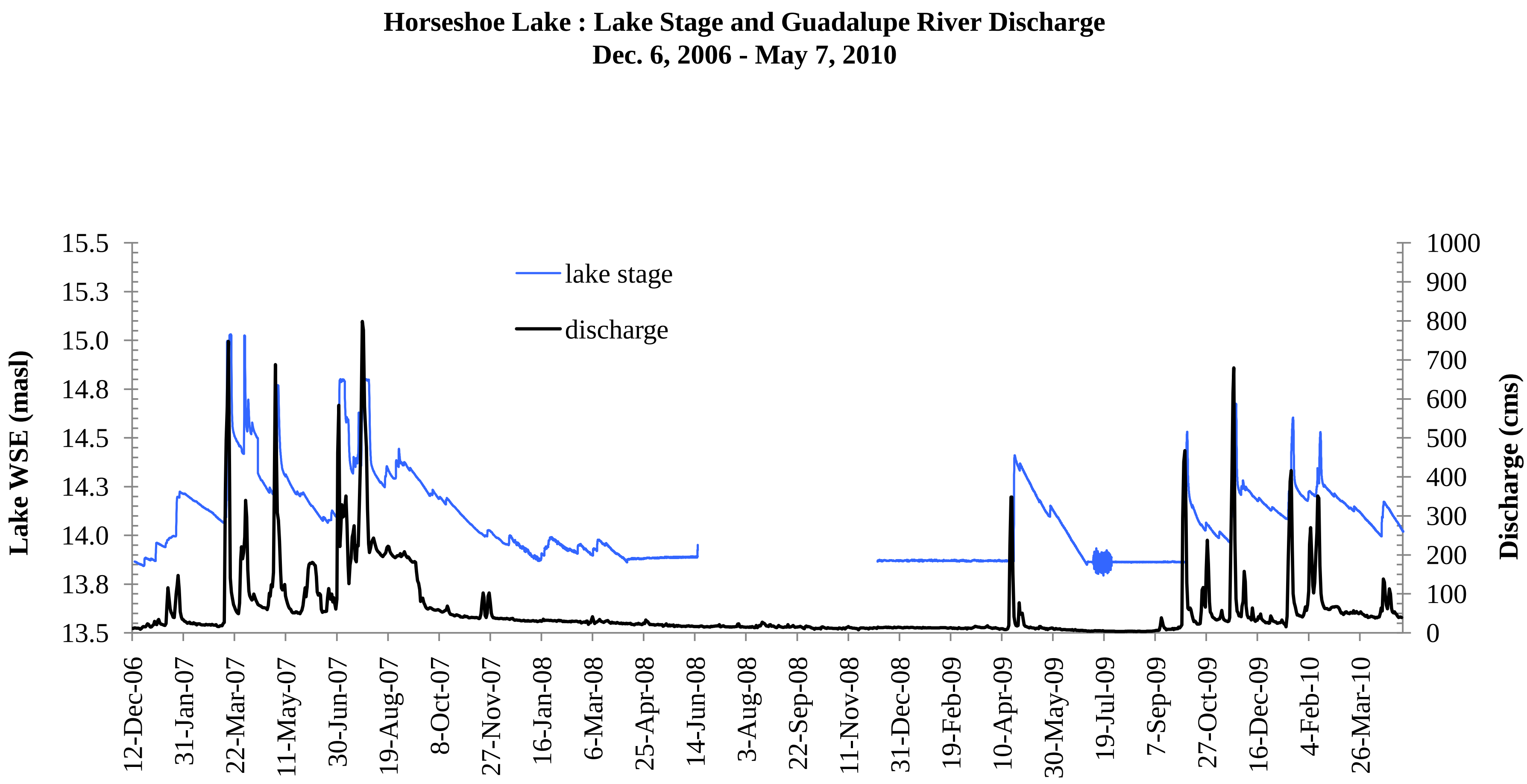



Figure 4.2.4. Lake water surface elevation (WSE) at Horseshoe Lake and discharge (cubic meters per second) for the Guadalupe River at Victoria. The gap of missing lake stage data is because of pressure transducer malfunction, although no pulses were missed. The lake stage data were logged at 1 hr and 3 hr intervals.

**Complex Relation Between Discharge and Lake Surface Elevation:**
**Horseshoe Lake: March 13, 2007 – March 22, 2007**

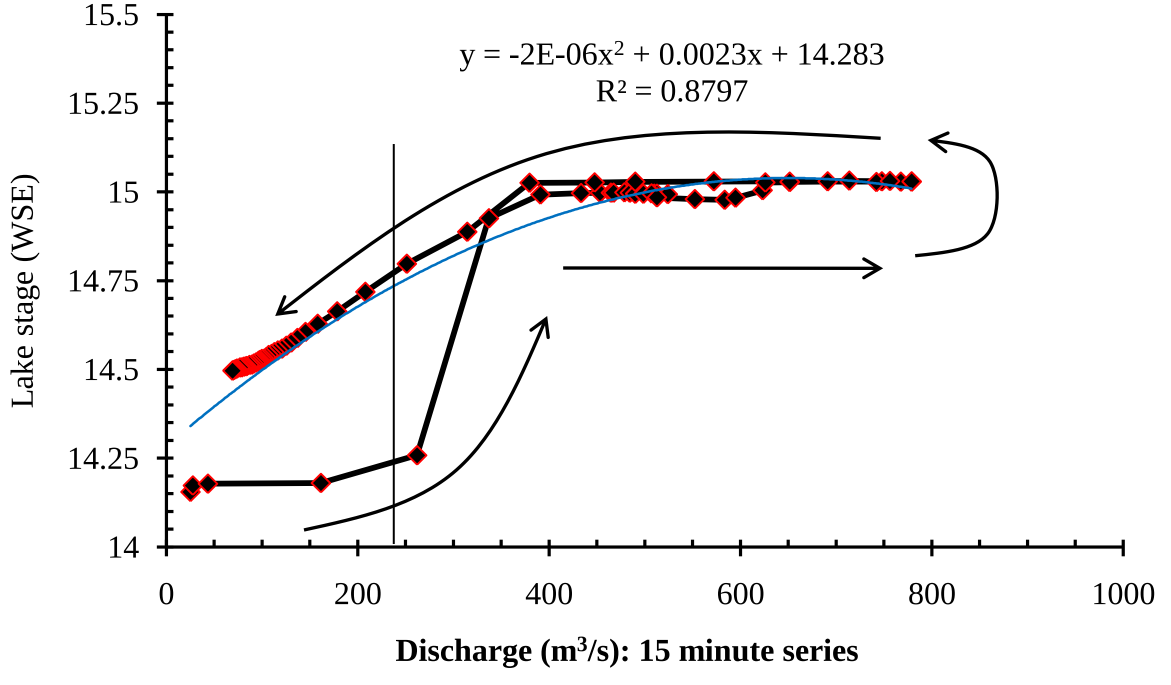



Figure 4.2.5. Lake stage abruptly increases at the pulse threshold, peaks in about 6 hours, and then abruptly levels off. The maximum stage of ~15 probably represents the maximum flood stage for this portion of the Guadalupe floodplain. The data are at 3.0 hour resolution. The vertical line represents the pulse threshold. Discharge is lagged by 9 hours, (based on the upstream travel rate of flood crest).

surface is 2.31 m higher than the adjacent river stage during about “normal” discharge (58.6 $m^3/s$) conditions (May 17, 2007). The natural levee on the floodplain associated with the cutbank side of Horseshoe Lake is partially buried by overbank deposits from the modern flood regime. Horseshoe Lake is largely infilled with > 5.5 m of fined-grained deposits (see section 4.3), with water depths (at ~base stage) not exceeding 0.5 m (based on sounding in boat). Thus, Horseshoe Lake represents nearly the final stages of the oxbow lake cycle. The property owner, a direct descendent of the original European settlers, had claimed that the lake never dried up, and fish were observed in the lake at normal stage. A couple of months before the lake completely dried up many large fish (gar ?) were observed in a couple of small (~15 m diameter) shallow pools. The lake is ~0.5 km from the valley bluff and is therefore not likely supplied water by non-alluvial aquifers. Examination of a high resolution LiDAR DEM and recent DOQQ (at high flow conditions) delineates several minor floodplain channels that likely supply Horseshoe Lake with river streamflow and sediment, as well as runoff supplied from local drainage sources within the floodplain, which ultimately derive from sloughs (old channels) up valley and zero-order basins along the bluff line. Additionally, a Guadalupe River crevasse downstream of the oxbow flows back towards Horseshoe Lake. Further, examination of the LiDAR DEM clearly shows that the Horseshoe Lake site is actually two different “oxbow like” features, with the inner oxbow representing a meander bend that eroded into an older oxbow (?) lake. This information was not represented in USGS 1:24,000 topographic maps, NHD, or DOQQs, the most consulted geospatial data sets utilized to identify and map floodplain lakes. Finally, the LiDAR data illustrates the challenge in assigning floodplain lakes, particularly older lakes, to discreet classes. Horseshoe Lake may be an old channel lake rather than an oxbow lake.

The pressure transducer at Horseshoe Lake was located about 10 m from the lake shore (at time of installation) away from low hanging branches and in as deep as water as could be identified. The data spans a 3.39 yr period, between Dec. 13, 2006 to May 7, 2010 and was logged at 3 hr, 1 hr, and ½ hr intervals. The instrument malfunctioned June 16, 2008 and was replaced in December 9, 2008. Because of the ongoing drought, however, no pulses were missed.

Over the period of record Horseshoe Lake levels display the sharp influence of large individual discharge pulses superimposed across wet and dry phases (Figure 4.2.4-5). In comparison to Cuero '98 Lake stage, Horseshoe Lake displays less variability because of the higher threshold discharge required for connectivity, and the greater time required for lake stage recession. The crest of individual pulses are distinctly flat, an indication that this represents about the maximum flood levels across this reach of the Guadalupe floodplain. Over the study period there were 13 connections with the Guadalupe River. The maximum range in stage over the study period was 1.23 m. Horseshoe Lake requires about two to three months to recede, depending on whether it is interrupted by additional pulses and seasonal evaporation. The pulse on April 19, 2009, for example resulted in a 0.5 m increase in lake stage that required two months for lake levels to recede (June 22). A smaller event seems to have influenced lake stage recession, but over half of the stage recession can simply be explained by monthly evaporation rates for Victoria County.

Although Horseshoe Lake is immediately adjacent to the main-stem Guadalupe River the relation between discharge and lake stage is not simple, but is rather complex, highly variable, and nonlinear. Although some of the variability can be attributed to the Victoria gauging station being 19.1 km upstream of Horseshoe Lake, the complexity of the discharge and lake stage relations could also be influenced by local runoff sources. This includes Coleto Creek (1,566 sq. km), which drains into the Guadalupe just downstream of Horseshoe Lake. Additionally, the dense clayey lake basin likely limits inputs of Guadalupe groundwater and impedes drainage through the alluvium.

The relationship between discharge ($m^3/s$) and lake stage (WSE) at Horseshoe Lake for a discreet flood pulse spanning from March 13, 2007 to March 22, 2007 is examined in Figure 4.2.5. The relation exhibits a pronounced flattening of lake stage after a relatively low discharge threshold is exceeded. This is because of the shallow lake basin, and confirms soundings from December 2006 that measured the lake bed at ~1 m below the floodplain surface. Thus, the maximum lake stage is a good indicator of the maximum flood height associated with the discharge event at this section of the floodplain. The recession of lake stage exhibits a substantial lag as discharge declines below about 400, resulting in counterclockwise hysteresis on the lower discharges.

Using a second-order polynomial model, discharge explains 88% of the variability in stage. The relation between the two variables improved significantly when Q was lagged. In this case Q was lagged by 9 hours, which is based on the upstream travel time of the flood crest and the distance between Horseshoe Lake and the Victoria gauging station. However, for Horseshoe Lake there was not a single lag time that was effective, as the time gap between discharge peak and lake stage peak varied from 9 hours to 33 hours. One possible explanation for this has to do with the antecedent stage levels prior to the forthcoming event. In contrast to Cuero ’98 Oxbow lake, sequential discharge pulses events are less predictable because of the existing high lake stage levels.

### Linn Lake

Linn Lake is a valley side lake located within a Deweyville meander loop of the ancestral Guadalupe River, a topographic depression formed between the modern Guadalupe meander belt ridge and the Pleistocene (Beaumont) valley margins. The lake is much larger (2.98 $km^2$) than oxbow lakes. Because of the size, age, and location the hydrology of Linn Lake appears more complex than of recently formed oxbow lakes. The distance from the Guadalupe River to Linn Lake varies along the length of the lake, ranging 0.32 km to 3.5 km (from cutbanks of meander bends). Because of the extensive size of the lake it was impractical to attempt to survey between the Guadalupe River and lake margins. The availability of secondary geospatial data, however, including DOQQs and a LiDAR DEM, provided an opportunity to qualitatively consider local influences on Linn Lake hydrology. Prior to overbank conditions, small crevasse-like channels likely supply streamflow to Linn Lake. These data also reveal that Linn Lake is supplied runoff from "local" sources, including several first- and zero-order basins from the bounding terrace, direct precipitation over the lake basin, as well as a drainage from valley side lakes (Guadalupe River paleochannels) located upstream (north) of Linn Lake. Additionally, because Linn Lake borders the western valley wall it is likely supplied groundwater via seepage through the porous sandy Pleistocene terrace. These local sources of water are in addition to the drainage of Coleto

**Linn Lake Stage and Guadalupe River Discharge**
**Dec. 13, 2006 – Dec. 6, 2008**

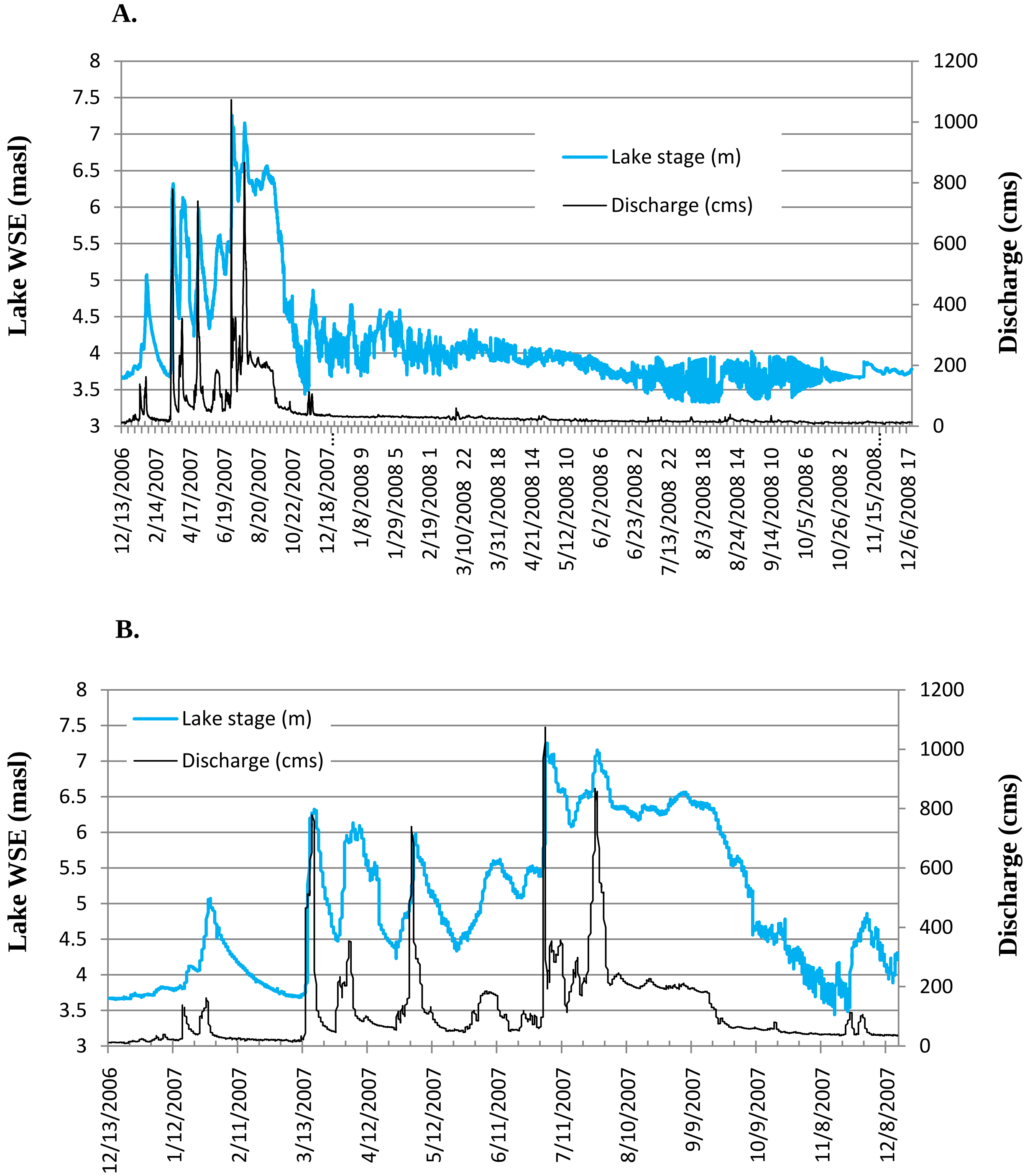
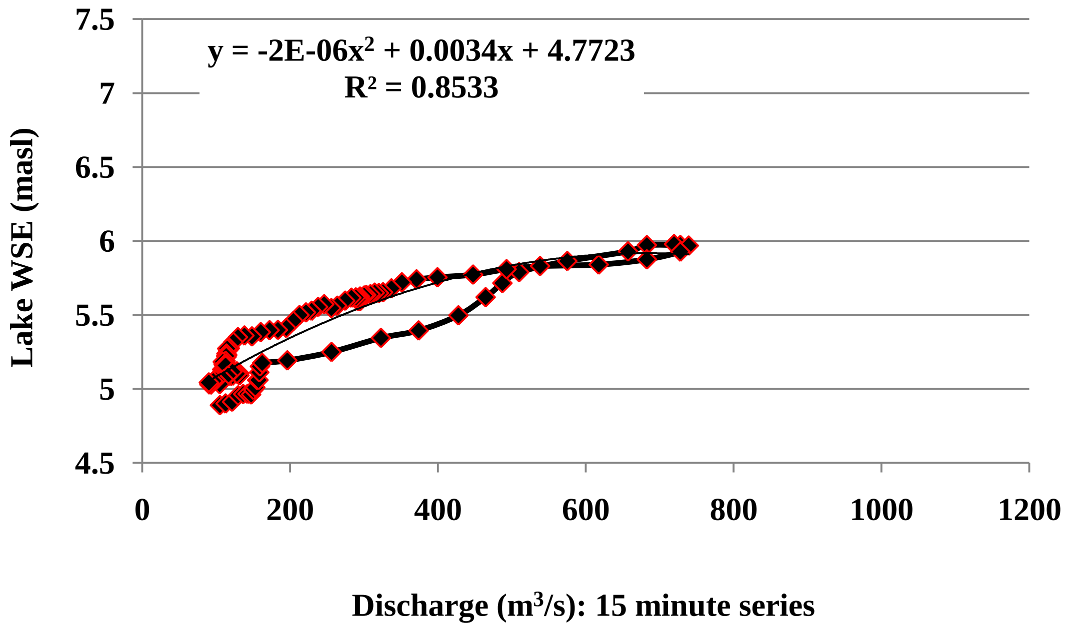



Figure 4.2.6. Linn Lake water surface elevation (WSE) and discharge (cubic meters per second) for the Guadalupe River at Victoria. A. Dec. 13, 2006 to Dec. 6, 2008. B. Subset of wet period from Dec. 13, 2006 to Dec. 31, 2007.

**Relation Between Discharge and Lake Surface Elevation:**
**Linn Lake: April 29, 2007 – May 14, 2007, July 2, 2007 – July 6, 2007**



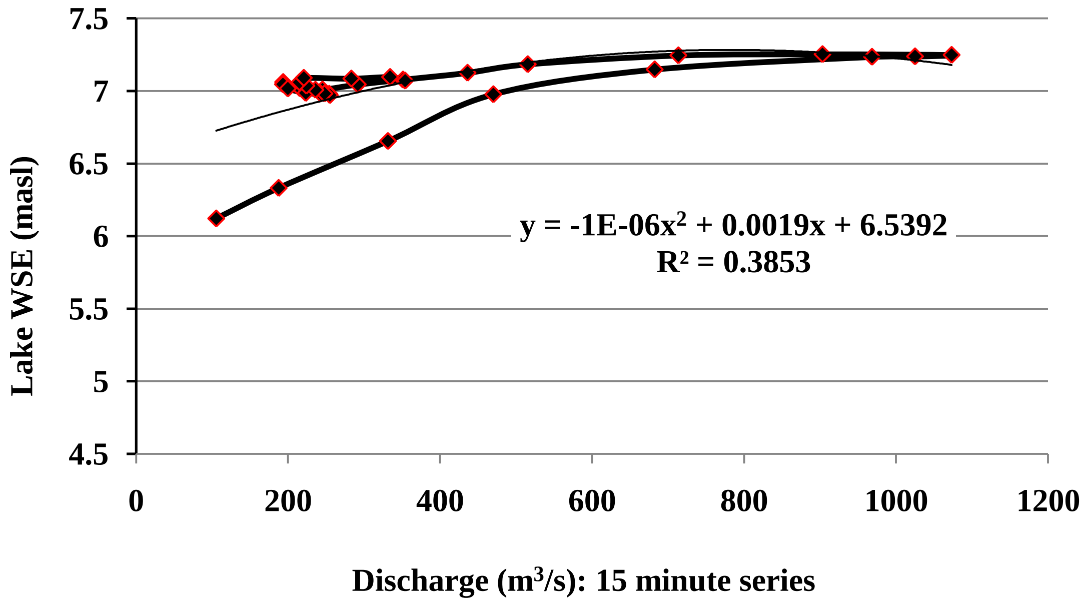




Figure 4.2.7. Relation between discharge (m3/s) for the Guadalupe River at Victoria and lake surface elevation (WSE) for Linn Lake for two discreet pulses, illustrating the influence of sequential events on lake stage variability. A. April 29, 2007 to May 14, 2007. The peak in discharge and lake stage is nearly synchronous, although lake stage is associated with a sharp flattening at a Q of 510. B. July 2 – July 6, 2007. The largest discharge pulse during the period of record. The rate of increase in lake stage diminishes as Q increases beyond 470. Stage is slightly higher during flood recession.

Both curves were better fit with a 2nd Order Polynomial model. For both curves the pattern is counter-clockwise. The Q is lagged by 1.63 days because of the upstream distance to the Victoria gauging station. The data is at 3.0 hr resolution.

Creek, which discharges into the Guadalupe River several kilometres upstream of Linn Lake, but downstream of the USGS gauging station at Victoria. At high stage levels Linn Lake is drained by Linn Creek, a small (~11 m width) crevasse-like channel controlled by a low culvert, which discharges into the Guadalupe River 1.9 km downstream of the southern lake rim.

The pressure transducer was located about 50 m from the lake shore (at time of installation) beyond a thick stand of reeds in as deep as water as could be identified. The data was continuously logged from Dec. 13, 2006 to Dec. 9, 2008. The unit was removed while the lake bed was completely dry, as it was noted that the unit had been disturbed, either by humans or cattle grazing in the dry lake bed. Although the download cable had been severed, the PT unit was not damaged and continued to log data.

The ~2 year record for Linn Lake illustrates the variability in water surface elevation for a large coastal plain river valley lake at a seasonal resolution. In particular, the period of study is ideal for characterizing the hydrologic response of a large lake to an anomalous wet and dry spring and summer (Figure 4.2.6-7). The data for Linn Lake exhibits strong hydrologic connectivity with the Guadalupe River, with > 1 m increases in lake stage associated with minor discharge pulses. The threshold discharge required for connectivity being 102 $m^3/s$. Of note is that this is considerably below the overbank discharge for the Guadalupe River at Victoria, which could be because of the crevasse and side channels being connected at a lower threshold than overbank conditions. After connection, Linn Lake rapidly infills, requiring less than a couple of days. Stage recession and lake drainage requires at least a couple of months if not interrupted by an additional pulse. Although Linn Lake is large and is located far from the main-stem channel, the hydrology is more dynamic than Horseshoe Lake, which is likely due to the contribution of small local channels. The range in stage over the two year period was 3.93 m.

A prolonged high stage period begins in early spring and persists until early fall, 2007. This period is associated with six discharge pulses, as well as a period of sustained high discharge. The slight difference in lake stage associated with two sequential large events suggests that Linn Lake was close to its maximum stage (~7.3 m) for the late June / early July 2007 discharge event. Climatically, this period was associated with cooler temperatures and higher than normal summer precipitation totals and cloud cover (reduced evaporation). Beginning in the late fall of 2007 the stage of Linn Lake drops to an average of about 4.0 m. This period was associated with fewer westerly migrating frontal precipitation events and reduced cloud cover over Central Texas. With the exception of a few minor pulses this condition persisted through the remainder of the monitoring period and is associated with the drought of 2007 - 2009. Thereafter, the very low streamflow and dry conditions are associated with a drop in lake stage, to about 3.7 m. The frequent minor stage variability (~0.5 m) from about July to November 2008 is associated with instrument "noise" rather than actual stage changes. Indeed, the lake at this time had completely dried up and the lake bed had deep desiccation cracks.

Bivariate plots between river discharge (at Victoria) and lake stage for individual pulse events reveals considerable scatter, strong nonlinearity, and typical reverse (counterclockwise) hysteresis (Figure 4.2.7). The scatter is likely a function of the multiple local hydrologic sources, and because of the travel time for discharge waves from Victoria to Linn Lake. The April 29 to May 14, 2007 event is characterized by a nonlinear pattern, with an initial rapid increase in lake stage as the lower portions of the lake depressions are infilled, but a flattening at high discharge levels because of Guadalupe flood waters spreading across a larger surface area. Discharge and stage levels slowly recede, and stage levels are about 0.3 to 0.4 m higher on the recessional limb. The July 2 to July 6, 2007 pulse represents a sequential event. Because of the slow recession of lake levels (drainage and evaporation), the lake stage was already high at the onset of the discharge pulse. Lake levels underwent only a minor reduction in stage during the recession of the flood pulse. Although the relation between discharge and lake stage was better fit with a 2$^{nd}$ order polynominal model than a simple least-squares linear regression procedure, the overall predictability of lake levels from discharge data is not very high for large sequential events, as the index of model fit was just 0.39. This is probably valid for large floodplain lakes. The statistical fit of the model improved when discharge was "lagged" to account for the difference in travel times between Linn Lake and the upstream gauging station (Victoria). The event depicted, for example, is lagged by 1.63 days. There was not, however, a specific lag time which works best for all events. The ability to model (predict) lake stage connectivity from simple discharge records is a valuable tool in floodplain hydrology and lake management. However, in terms of sequential pulses (events) the predictability of lake stage from discharge data declines, particularly at high discharge and stage levels.

### 4.3. Lake Sedimentation

Lake sedimentation results in changes in lake depth and lake area and is assessed by analysis of field data. The field approach to floodplain lake sedimentation was examined from an historical (Quaternary) and process based approaches. The methods for the historical sedimentation approach involved description and sampling of sedimentary deposits obtained from standard coring procedures, as well as a couple of floodplain trenches. The process approach requires field measurements at the lake surface. Because the process based approach is so specialized it is not possible to purchase readymade equipment or instrumentation for measuring single event or annual sedimentation. This equipment must be constructed especially for the particular field setting in question. Following reconnaissance field work, several procedures were attempted, including 1. Artificial grass mats, 2. Shallow buckets (with concrete pad), 3. Wooden stakes, and 4. Post inundation (flood) sediment sampling.  For all approaches sediment samples were analyzed for particle size determination in the geomorphology laboratory in the Department of Geography and the Environment, with several samples from the historical approach submitted to a contract laboratory (Beta Analytical) for AMS radiocarbon analysis.

In addition to directly sampling lake sediments, several cores and trenches were taken in the floodplain at key stratigraphic and geomorphic locations to assist with constraining the age of the lakes. This included coring through the relict natural levee deposits associated with the lake at Horseshoe Oxbow Lake site, at Bird Sanctuary Oxbow Lake site, McNeil Oxbow Lake site, and at the Rail Road Avulsion site. The natural levee is the landform created by the process of overbank sedimentation, and is specifically associated with flood processes. Similar to active channels, oxbow lakes and abandoned channel lakes also have a natural levee associated with their channel bank. The base of the natural levee delimits the time at which flood sedimentation became a significant process at a particular point on the floodplain, and a (radiocarbon) date at the base of such strata thefore provides a maximum age to the channel. After a channel cuts off (or avulses), the lake begins to infill, but the natural levee also gets buried by fine-grained overbank deposits, which are distinct (fine-grained, cohesive, darker, and organic rich). Thus, by dating the overbank deposits atop the relict natural levee it provides the age of the lake (a minimum date for the cutoff). The benefit of this approach is that it is much less time consuming and requires fewer resources than lake coring.

The field work to study sedimentation also involved laboratory work for particle size analysis. Two approaches were used for particle size analysis, including manual and laser granulometry. The manual approach utilizes two techniques, which included hydrometer analysis for fine sediments (silt and clay $< 0.0625$ mm) and wet sieving for sands ($> 0.0625$ mm). For a detailed overview of the manual approach, see Gee and Bauder (1986). The laser granulometry (*Fritsch Analysette 22*) approach analyzes particle size by measuring the dispersion (scattering) of the laser as it passes through a sediment solution. This approach was used for the core at Horseshoe Lake obtained in spring 2009. After the sediment sample size distribution is determined, the particle size data is plotted on a cumulative curve, with particle size as the X-axis and cumulative percent finer on the Y-axis. The shape of the curve relates to the sorting of the sample during a flood event.

**Cuero ’98 Oxbow Lake:**

Because the age of Cuero ’98 Oxbow Lake is firmly established field work focused on characterizing variability in sedimentation rates, which are usually high in newly formed oxbows. The field efforts involved several approaches to examine sedimentation, including coring, stakes, and sediment traps. Table 4.3.1 presents the results of the sedimentation studies based on short- and long-term estimates.

Table 4.3.1. Sedimentation in floodplain lakes along the Lower Guadalupe River, Texas

| Sedimentation in Floodplain Lakes along the Lower Guadalupe River, Texas | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Procedure** | **Environment** | **Date or Time span** | **Time** | **Sediment Depth cm** | | **Sedimentation Event cm** | **Sedimentation Rate cm/yr** |
| **Horseshoe Lake Oxbow (southwest of Victoria)** | | | | | | | |
| 3 Sed. traps (bucket type) | Lake | 12/13/06–12/9/08 | 1.99 yrs | Avg. = 1.3 cm | | | 0.65 |
| 4 Sed. traps (grass mats) | Lake | 2/25/09–* | | | | | |
| Coring and $^{14}C$ dating** | Lake | 4/8/09 | 2,375 | | | | 0.22 |
| **Cuero '98 Oxbow Lake** | | | | | | | |
| 2 sed. markers (stakes) | Lake plug | 5/17/07 – 5/7/10 | 2.98 yrs | 27.2 cm, 12.5 cm | | | 6.65 |
| 4 sed. markers (stakes) | Lake | 5/17/07 – * | | | | | |
| 6 Sed. traps (grass mats) | lake (slackwater) | 5/3/09-7/25/09 (April 28 event) | ~0.07 yrs | 3.93(cm) | | > 0.39 | |
| 5 Post-event samples | Lake | 3/28/09 event | | 6.5 cm avg. | | 6.5 | |
| Coring | Lake | 10/18/98-5/3/09 | 10.55 Yrs | + > 400 cm | | | > 37.91 |
| Coring | Lake | 3/25/07-5/3/09 | 2.1 yrs | 18.75 cm | | | 8.93 |
| **McNeil Oxbow site** | | | | | | | |
| Coring and $^{14}C$ dating** | Lake | 3/25/'07 | 3,150 | 490 cm | | | 0.16 cm/yr |
| | | | | | | | |
| | | | | | | | |
| **Linn Lake (near McFaddin)** | | | | | | | |
| 4 Sed. traps (bucket type) | Lake | 12/13/06-12/9/08 | | | | | |
| **Bird Sanctuary Oxbow Lake (west of Victoria)** | | | | | | | |
| 2 Sed. traps (grass mats) | Lake | 11/12/06 - * | | | | | |
| **Pridham Lake (southwest of Victoria)** | | | | | | | |
| 6 Sed. traps (grass mats) | Lake /overbank | 11/12/06 - * | | | | | |
| **Gonzales Oxbow (southwest of Gonzales)** | | | | | | | |
| 36 Post-event samples | lake | 7/7-12/02 event | | 10.71 cm | | 10.71 | |

** sedimentation apparatus not recovered because of possible disturbance (natural or human) or burial; ** see Table 4.3.4 for radiocarbon dates*

A 4.0 m core (preceded by several exploratory cores) did not reach a coarse grained channel plug or channel bed unit, but rather consisted of nearly homogeneous fine-grained cohesive sediments with isolated sandy lenses (field texture). Thus, a conservative (minimum) sedimentation rate for Cuero '98 Oxbow Lake since forming 10.55 yrs ago is 37.91 cm/yr. This high rate of sedimentation is not unusual for a newly formed oxbow, and most of the sedimentation was probably from a few large events within the first few years. In comparison to the 37.91 cm/yr rate, additional field evidence suggests that sedimentation rates are already declining.

Field work on March 25, 2007 was preceded by a fairly large flood event, with a peak discharge of 634 $m^3/s$ (0.61% flow duration). This event deposited a 13.5 cm thick deposit of sediment of variable grain size. Of note was a 6.5 cm fine-grained (clay and silt) layer with microlaminations displaying a fining-up grain size trend, a signature slackwater deposit (e.g., Bridge, 2003). This unit was deposited atop a thick (7 cm) sand layer, with few (< 10%) large clasts (10 – 20 mm). Subsequent coring (May 3, 2009) re-established the coarse lens, and measured an additional 11.5 cm of deposits. Thus, over a 2.1 yr period the lake had a sedimentation rate of 8.93 cm/yr.

Oxbow lakes usually undergo high sedimentation rates at the channel plug (entrance/exit to the channel). Indeed, two wooden stakes installed May 17, 2007 and retrieved May 7, 2010 provided a means to estimate sedimentation rates to the entrance of the channel. The rate of sedimentation over the 2.98 yr period yielded 27.2 and 12.5 cm of fine sand and silt deposits (field texture), resulting in sedimentation rates for the ~3 yr period of 9.12 and 4.19 cm/yr, respectively.

Of note is that the channel plug deposits are not associated with slackwater sedimentation, but are associated with bedload traction as evidenced by sedimentary ripples.

A moderate event of 413 $m^3/s$ occurred April 20, 2009 and maintained connectivity for two additional days. The slow recession of the lake provided an opportunity to examine the fine-grained component of the slackwater deposition (Table 4.3.2). Six sediment traps (artificial grass mats, 50 x 50 cm) were installed along the lake bed May 3, 2009 on the receding limb of the discharge hydrograph and during lake stage recession. Five sediment traps were retrieved after recession, and after the lake had dried up (there were no further connections) by about mid-June (based on pressure transducer data and a later field visit). The five sediment traps collected an average of 0.39 cm of fine sediment (clay and silt), having an average $D_{50}$ of 0.002 mm.

Table 4.3.2. Cuero '98 Oxbow Lake: Slack water Sedimentation: April 20, 2009 event

| Sediment trap # (grass mat) | Avg. Depth (cm) | Grain size ($D_{50}$ mm) |
|---|---|---|
| 1 | 0.37 | 0.003 |
| 2 | 0.58 | 0.002 |
| 3 | 0.22 | 0.002 |
| 5 | 0.37 | 0.001 |
| 6 | 0.43 | 0.002 |

**Horseshoe Lake Sedimentation:**

The sediment sampling at Horseshoe Lake was focused towards two objectives, to determine the age of the channel cutoff and the subsequent rates of sedimentation and infilling. This included deployment of sedimentation traps to sample short-term sediment pulses, and coring to examine longer term rates of sedimentation. Sedimentation traps were constructed from shallow flat buckets (10 cm depth, 30 cm diameter) with a 5 lb concrete pad (for stability), and were

## Horseshoe Lake Sediment Trap Samples: 12/6/'06 – 12/09/'08

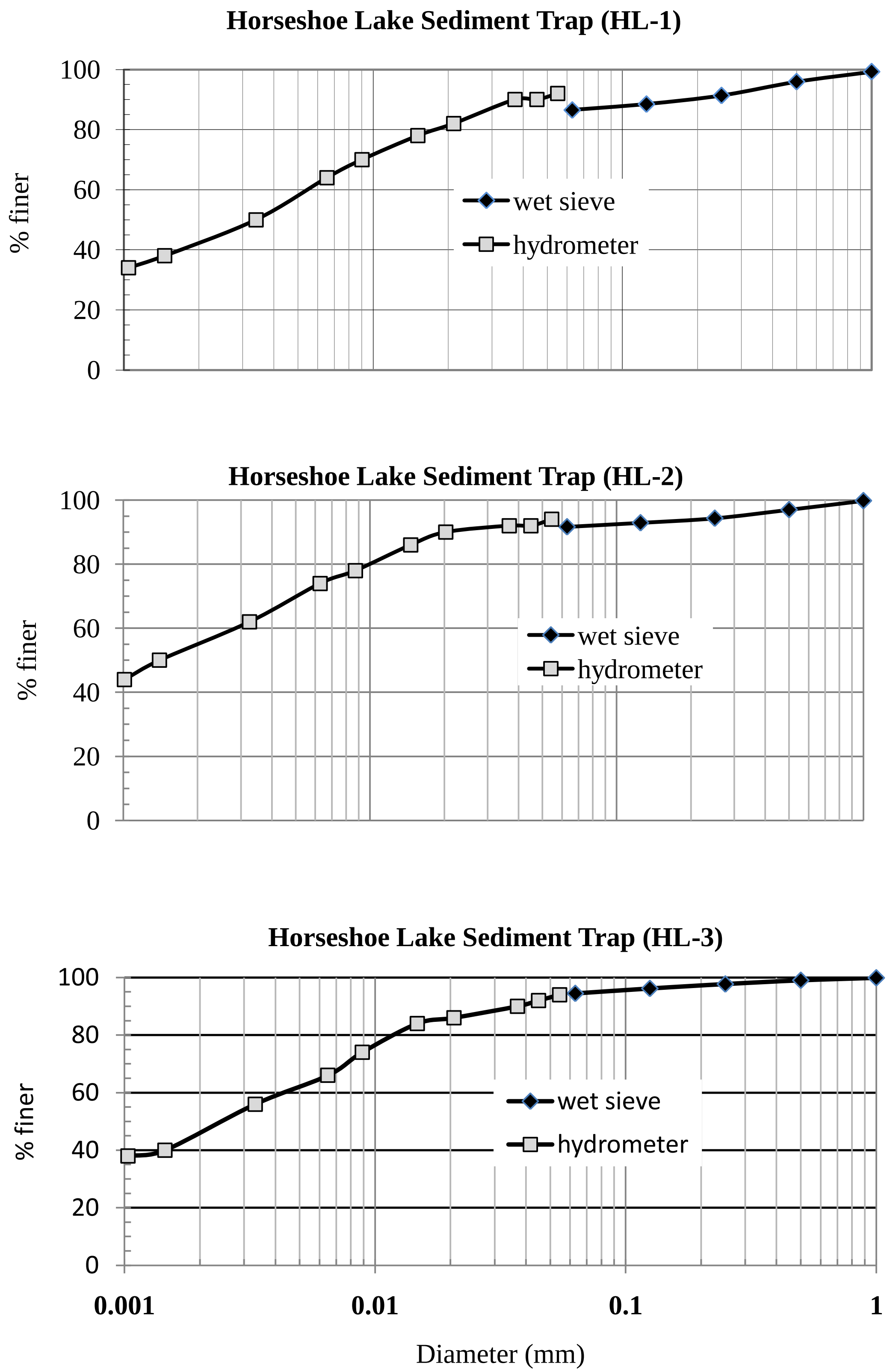



Figure 4.3.1. Sedimentary grain size curves for the sedimentation traps (buckets) from Horseshoe Lake.

# Sediment Profile of Natural Levee Core (GF0X-1) at Horseshoe Lake

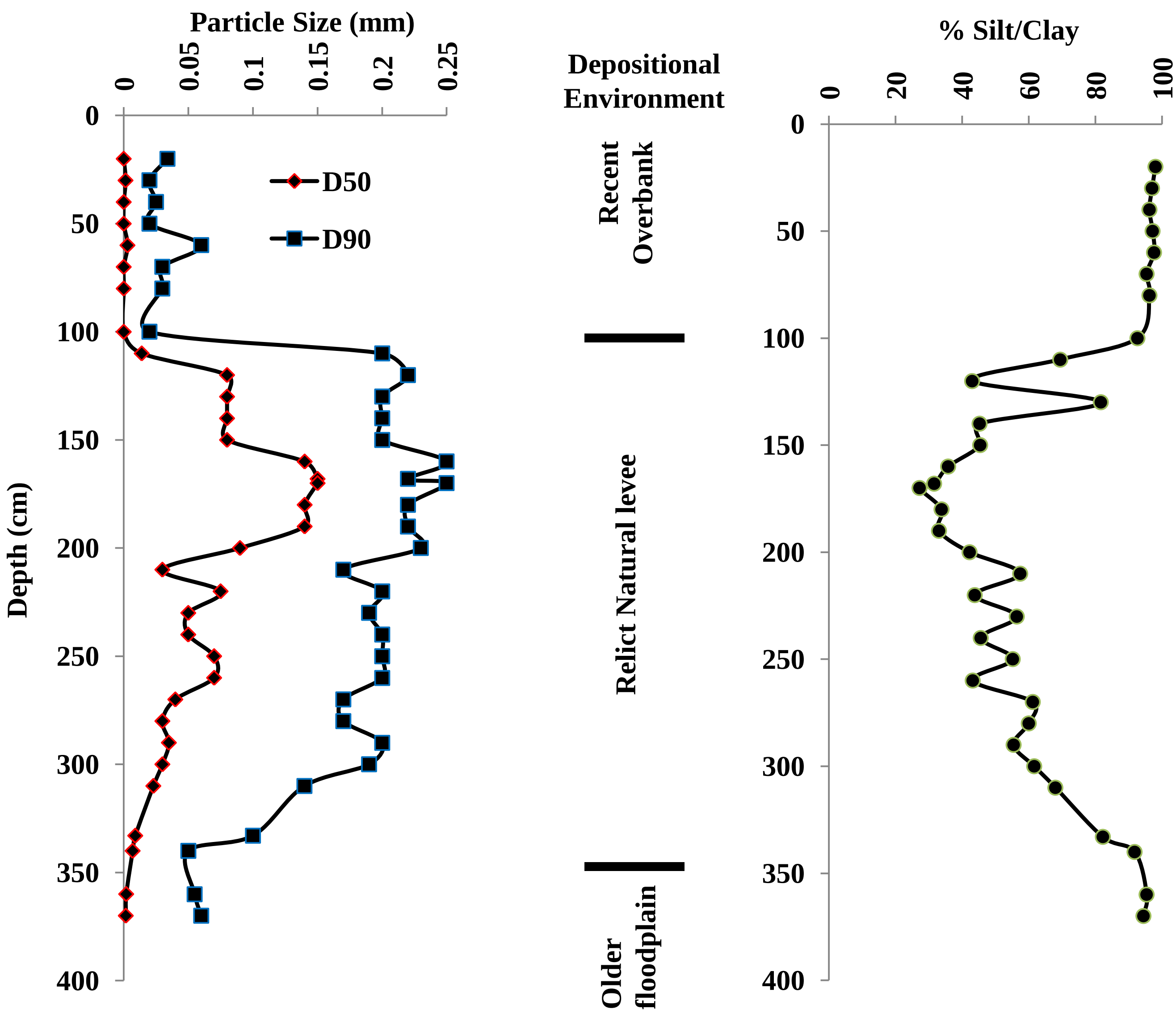



Figure 4.3.2. Sedimentary characteristics of the core through the natural levee and overbank deposits at Horseshoe Lake

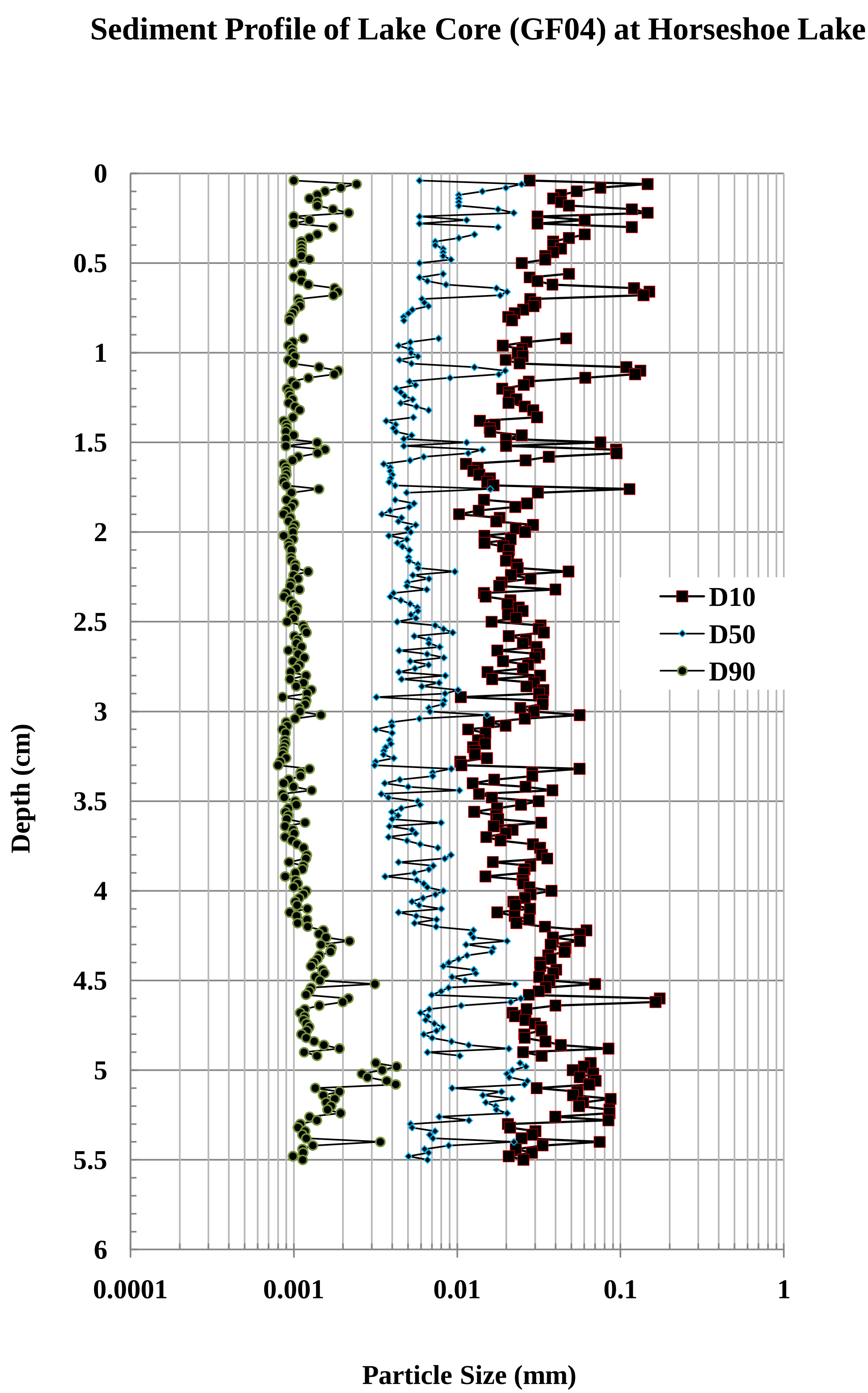



Figure 4.3.3. Sedimentary grain size curves for lake core at Horseshoe Lake.

installed in shallow water (Avg. depth = 35 cm) December 13, 2006, with the intent of sampling deposits associated with winter/spring discharge pulses. The placement of the sediment traps along the extent of the lake was designed to test for spatial variability in sediment size and sediment thickness, with our working hypothesis being that the traps closer to the river would logically have coarser and thicker deposits. The traps were retrieved December 9, 2008, representing two complete years of Texas hydroclimatology and associated seasonal sedimentation (Table 4.3.1).

Over the study period Horseshoe Lake received an average of 1.3 cm of fine sediment (Figure 4.3.1). The $D_{50}$ was 0.002 mm, clay (Table 4.3.3), and the average sedimentation rate was 0.65 cm/yr. Considering the field research design, the homogeneity of the deposits is impressive. While the sediment traps were installed for two years, the sediment must have been deposited during the first year. Lake stage increased soon after installation, by late December, and had fully receded by April, 2008. No subsequent pulses were recorded before the traps were retrieved in December, 2008, and the lake bed was nearly bone dry at this time. In terms of sediment pulses, Horseshoe Lake stage experienced six sediment pulses from the Guadalupe River which spanned from March 13, 2007 to September 9, 2007. Although there was not record flooding the summer was wetter than average and was characterized by sustained rainfall, anomalous for central Texas and in strong contrast to the subsequent 2 yr drought. Additionally, bracketing this period were higher Horseshoe Lake stages in mid to late January and in late November that do not coincide with Guadalupe River threshold discharge pulses. Thus, these phases of high lake stage must be associated with local sources of runoff, which could include discharge from Coleto Creek (1,566 sq. km), which drains into the Guadalupe just downstream of Horseshoe Lake.

Table 4.3.3. Horseshoe Lake Sedimentation: 12/13/’06 – 12/9/’08

| Sediment traps (buckets) | Depth | Grain size ($D_{50}$ mm) |
|---|---|---|
| HL-1 | 1.2 cm (n=18) | 0.003 |
| HL-2 | 1.5 cm (n=20) | 0.001 |
| HL-3 | 1.2 cm (n=20) | 0.002 |

Long term sedimentation was estimated from coring and radiocarbon dating of associated samples at key stratigraphic locations. Two coring approaches were used, including lake coring and coring through the natural levee associated with the relict meander. The context for the latter approach is that natural levee formation is associated with an active channel, which floods and deposits coarse sediment adjacent to its bank. Thus, when the oxbow lake was formed, natural levee sedimentation (coarser deposits) should also abruptly diminish, and the site becomes dominated by fine-grained overbank processes associated with the active but more distant Guadalupe channel. Thus, a $^{14-}$C date of the fine-grained organic deposits at the top of the coarse natural levee unit may coincide with the time of cutoff. One limitation to this approach is that after cutoff, the channel can be reoccupied during flood events and produce coarse overbank deposits. This scenario is particularly common for floodplain lakes within old channels that were avulsed rather than classic “oxbow” lakes. Additionally, the focus area of sedimentation changes because of lateral channel migration.

A 3.5 m core (GFOX-1) was obtained atop the natural levee associated with the oxbow, about 10 m from the relict cutbank (see Table 4.3.4 for location). The sedimentary profile in Figure 4.3.2. illustrates the change in sediment size associated with a core that penetrates a relict natural levee that has been buried by recent over bank deposits. The recent fine-grained overbank deposits are 100 cm in thickness and have an average D50 of < 0.001 mm, and consist of 98 % of sediment finer than sand (silt/clay). The contact with the relict natural levee is abrupt, and immediately results in an increase in particle size, with the sediment size at 120 cm having a $D_{50}$ of 0.08 mm and with 69.4 % of the sediment being finer than sand. The base of the relict natural levee is more transitional with the older floodplain surface, but can be discerned at 333 cm, which has a $D_{50}$ of

0.009 mm and an increase in 82.2 % silt/clay. More telling is the $D_{90}$, which decreases to 0.05 mm at 340 cm. The "coarsening-up" trend in particle size for the natural levee (333 cm to 100 cm) is not unusual, and is an indication that the channel was actively migrating while the natural levee was being constructed.

Organic material sampled at three locations within the fine-grained overbank sequence near the contact with the natural levee surface was $^{14-}$C dated (Table 4.3.4). The $^{14-}$C dates were obtained at 92 cm, 96.5 cm, and 99.5 cm had dates of 980 +/- 40yrs, 1,080 +/- 40 yrs, and 1,130 +/- 40 yrs BP, respectively. This yields an average sedimentation rate of 0.09 cm/yr since 1,130 BP. Two additional dates at 337 cm and 347 cm, the base of the natural levee, were dated at 2,480 +/- 40 yrs and 2,370 +/- 40 yrs BP, respectively. Thus, the natural levee sequence had an average rate of sedimentation of 0.14 cm/yr. The higher rate of sedimentation for the natural levee in comparison to the recent overbank sequence is not unexpected because the source of sediments is immediately adjacent the channel.

A detailed deep 550 cm core from the lake basin (GF04) was described and sampled at 2 cm increments (Figure 4.3.3). The particle size trends for $D_{50}$, $D_{90}$, and % silt/clay display three sub-trends within the core. From 550 to 420 cm the $D_{50}$ there is a declining trend in particle size, but with several coarser spikes. The sediment colour was mainly bluish gray (Gley-2 5/5b) and dark grayish brown (2.5 Y 4/2), reduction of minerals. This portion of the core is interpreted to represent the initial phases of lake sedimentation. The particle size from 420 cm to 180 cm is finer-grained and more homogeneous, and was dark gray, very dark gray, and dark olive brown (2.5 Y 4/1, 3/1 and 3/3) in colour. This section is interpreted as the lake deposits after the lake had been

Table 4.3.4. Radiocarbon dates of lower Guadalupe Valley floodplain deposits.

| AMS RADIOCARBON ($^{14}C$) DATES OF LOWER GUADALUPE VALLEY (TEXAS) FLOODPLAIN DEPOSITS TEXAS WATER DEVELOPMENT BOARD FLOODPLAIN LAKE STUDY | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Sample ID** | **Beta ID** | **Conventional Radiocarbon age*** | **Proc.** | **Material (wash prep)** | **Lat.** | **Long.** | **Date of field sample** |
| **Horseshoe Lake Oxbow (southwest of Victoria) (overbank / natural levee)** | | | | | | | |
| **OX1-0.9-0.93** | 232965 | 980 +/- 40 BP | AMS | Charred (alkali/acid wash) | 28 42.43 | 97 0.79 | 2/25/07 |
| **GFOX 1-1-10 95-98** | 238368 | 1080 +/- 40 BP | AMS | Organic sed. (acid wash) | 28 42.43 | 97 0.79 | 2/25/07 |
| **GFOX1-1-10 99-100** | 238369 | 1,130 +/- 40 BP | AMS | Organic sed. (acid wash) | 28 42.43 | 97 0.79 | 2/25/07 |
| **GFOX 335-340** | 238370 | 2,480 +/- 40 BP | AMS | Organic sed. (acid wash) | 28 42.43 | 97 0.79 | 2/25/07 |
| **GFOX** 345-350 | 238371 | 2,370 +/- 40 BP | AMS | Organic sed. (acid wash) | 28 42.43 | 97 0.79 | 2/25/07 |
| **Old Channel Lake (rail road avulsion site southwest of Victoria) (overbank)** | | | | | | | |
| **GF RRA 01-30** | 238372 | 170 +/- 40 BP | AMS | Organic sed. (acid wash) | 97 1.22 | 28 46.94 | 3/26/07 |
| **McNeil Oxbow (upstream of Victoria) (lake bed / overbank)** | | | | | | | |
| **MC 01-4.90** | 238373 | 3,150 +/- 40 BP | AMS | Organic sed. (acid wash) | 28 53.51 | 97 6.13 | 3/25/07 |
| **MC-01-4.90** | 232963 | 2,780 +/- 40 BP | AMS | Organic (alkali/acid wash) | 28 53.51 | 97 6.13 | 3/25/07 |
| **Horseshoe Lake Oxbow (southwest of Victoria) (lake bed)** | | | | | | | |
| **GF-0-004-2.68** | 270287 | 2,910 +/- 40 BP | AMS | Organic sed. (acid wash) | 28 42.52 | 97 0.94 | 4/08/09 |
| **GF-0-004-4.18** | 270288 | 1,540 +/- 40 BP | AMS | Organic (acid wash) | 28 42.52 | 97 0.94 | 4/08/09 |
| **GF-0-004-4.60** | 270289 | 550 +/- 40 BP | AMS | Organic (alkali/acid wash) | 28 42.52 | 97 0.94 | 4/08/09 |
| **GF-0-004-5.02** | 270290 | 2,500 +/- 40 BP | AMS | Organic sed. (acid wash) | 28 42.52 | 97 0.94 | 4/08/09 |
| **GF-0-004-5.36** | 270291 | 2,250 +/ - 40 BP | AMS | Organic sed. (acid wash) | 28 42.52 | 97 0.94 | 4/08/09 |
| Radiocarbon age determination ($^{14}C$) by Beta Analytic Radiocarbon Dating Laboratory, Miami, FL (USA)<br>* BP = years before present, ** AMS = Accelerator Mass Spectrometry | | | | | | | |

sealed off. During this phase of lake development there is essentially no sand entering the lake basin. More significantly, this must have represented a rather quiescent hydrologic period, or that the channel was further away from the lake basin. Above 180 kh there is an increasing trend in particle size, with greater variability. Notable are a number of sandy spikes during this phase of lake infilling, as this period of infilling was associated with a more dynamic lake environment. It is tempting to suggest that this represents a more dynamic hydrologic regime (increase in flooding) for this portion of the floodplain, but as this is a meandering river it could simply represent the active channel migrating closer to the lake basin; near its current position. Two dates of organic sediments near the bottom of the core at 5.36 and 5.02 m returned dates of 2,250 +/- 40 yrs and 2,500 +/- 40 yrs BP, respectively (Table 4.3.4). This would result in a minimum age for the lake and conservative sedimentation rates of 0.20 cm and 0.23 cm. Other radiocarbon dates located higher in the core, however, returned variable dates which in part could be due to the introduction of reworked materials.

**McNeil Lake Oxbow and vicinity**

The McNeil Lake Oxbow lake site and vicinity is located about halfway between Victoria and Cuero. This is an interesting segment of the Guadalupe valley, with the floodplain a complex assemblage of floodplain lakes formed by meaner neck cutoffs and local avulsions. The surface area of McNeil Lake (author's name for lake... McNeil is the property owner) based on NHD data is 0.035 $km^2$, but because of infilling it is much smaller than the original geomorphic extent. This is especially apparent when examining the LiDAR data for this vicinity. Several of the features are completely infilled, although they are easily inundated by low discharge pulses (field observations), or from precipitation local runoff sources within valley. Floodplain lakes formed by recent local avulsions retain high connectivity via batture channels. Field work efforts at this site were directed towards two fronts, including 1. Coring and radiocarbon dating of an infilled floodplain lake to constrain the age of channel abandonment and long-term rates of floodplain lake sedimentation, and 2. Characterizing the perimeter flood deposits with the idea of establishing reference horizons that can then be used to map across larger areas of the floodplain, thereby being able to assign different floodplain lakes to specific time-frames.

Manual coring to a depth of 6.15 m penetrated through the channel fill and into (likely) the channel plug deposit, possibly the paleo channel bed. The top 0.55 m of this unit was a typical upper channel fill deposit, consisting of thick dark organic rich clayey ($D_{50}$ mm = 0.0015 and 0.004) unit that was black (10 YR 2/1) and very dark brown (10 YR 2/2) in colour. An organic sample within heavy clay at 4.9 m provided an AMS $^{14-}$C date of 3,150 +/- 40 yrs BP (before present), establishing a long-term sedimentation rate at 0.16 cm/yr. (see appendix for field notes and grain size curves). The organic sample material was obtained in a heavy dark reddish gray (2.5 YR 3/1) clayey unit with a $D_{50}$ of 0.001 mm. This unit is deposited atop more than 1.2 m of lighter coloured (2.5 YR 5/1 and 4/1) fine sand and silty sand. This unit has a $D_{50}$ of 0.06 mm, 0.1 mm, and 0.02 mm at 5.54 m, 5.95 m and 6.15 m (maximum depth of core), respectively. The thick lower coarse unit is interpreted as the top of the channel plug, deposited soon after the time of the cutoff. Thus, the date in the organic rich clayey unit should represent the onset of lake sedimentation at about the time that the river channel became a lake basin.

Two trenches were excavated with a backhoe to characterize the stratigraphy (flood deposits) and soil profiles in the vicinity of the McNeil oxbow site, for the purpose of using the stratigraphic profiles for further field mapping to constrain the age of other floodplain lakes. Each trench was described at 10 cm intervals for Munsell Colour, field texture (% clay), and the presence of mottling, organic matter, and especially sand lenses. Additionally, 39 samples were analyzed for particle size by hydrometer and wet sieving in the Geomorphology and Geoarchaeology Laboratory in the Department of Geography and the Environment. Trench 1 (MC02) was excavated near the active channel and consisted of a dark greyish brown (10YR 4/2) and brown (10YR 5/3 4/3) top soil, which was essentially burying coarser natural levee deposits that were light coloured (10 YR 7/2, 7/3, 7/6) fine sandy and silty/sandy ($D_{50}$ = 0.13 mm). Trench 2 was excavated near the edge of a long paleochannel (MC03) floodplain lake and consisted of texture similar to trench 1, with the exception of a thick sandy units at 3.2 m, and stronger pedogenic development (lower Munsell #s and greater mottling), which would be expected of older flood deposits. Although datable material was sampled, it was not submitted for radiocarbon analysis.

Of note is that the depth of the core and the minimum age for Horseshoe Lake and McNeil Lake are not too different (Table 4.3.4). Thus, while these two lakes are on opposite sides of the valley they could be associated with the same channel belt. Clearly additional dating would be useful to hone in on the geomorphic evolution of this section of the Guadalupe valley.

**Gonzales Oxbow Lake**

A detailed study of oxbow lake sedimentation near Gonzales associated with a large flood event in July, 2002 provides an ideal complement to the existing study (Figure 4.3.4). The oxbow lake is located ~2 km west of Gonzales, and ~1 km upstream of the Guadalupe River confluence with the San Marcos River. The flood, the third largest at the Gonzales gauging station (since 1977), had a peak discharge of 1,557 $m^3/s$ on July 7. Equally impressive is that the duration of the event resulted in 14.42 days of oxbow lake connectivity. The geomorphic setting is a typical meandering reach of the Guadalupe River with low rates of lateral migration. The Gonzales Oxbow Lake is a partially infilled oxbow lake basin. The NHD lake surface consists of three small pools having a combined water surface area of 0.002 $km^2$, although the geomorphic extent of the lake basin is estimated at 0.051 $km^2$ (based on field surveying and GIS estimate from DOQQ). The depth of the oxbow lake ranges from 2.08 to 3.32 m (relative to floodplain elevation along cutbank), based on topographic surveying. Thus, the amount of infilling is less than Horseshoe Lake oxbow, but certainly much greater than at Cuero '98 Oxbow Lake. Field observations and testimony from the property owners confirm that the lake levels are ephemeral, and the oxbow usually dries up during the summer. An important feature of this oxbow lake, which is common but not at all constant along oxbow lakes in general, is the presence of a well defined "batture" channel. Batture channels (e.g., Gagliano and Howard, 1984; Guccione et al., 2002) are short narrow channels inset into oxbow lake deposits which connect main-stem channels with the lake basin. Batture channels are important because they enable connectivity and sediment dispersal at sub-bankfull conditions, increasing the duration of a flood pulse. The batture channel is located at the upstream limb of the oxbow, whereas the downstream limb has infilled with lacustrine deposits and is capped by a natural levee from the Guadalupe River. Field work at the site began as flood waters were receding, with field sampling in the oxbow lake occurring into spring 2003. The sampling protocol was similar to other established post-flood event sedimentation studies (e.g, Kesel et al., 1974; Gomez et al., 1997). The field work actually occurred after an additional large event in October, 2002, but the July samples able to be identified because the fall leaf drop

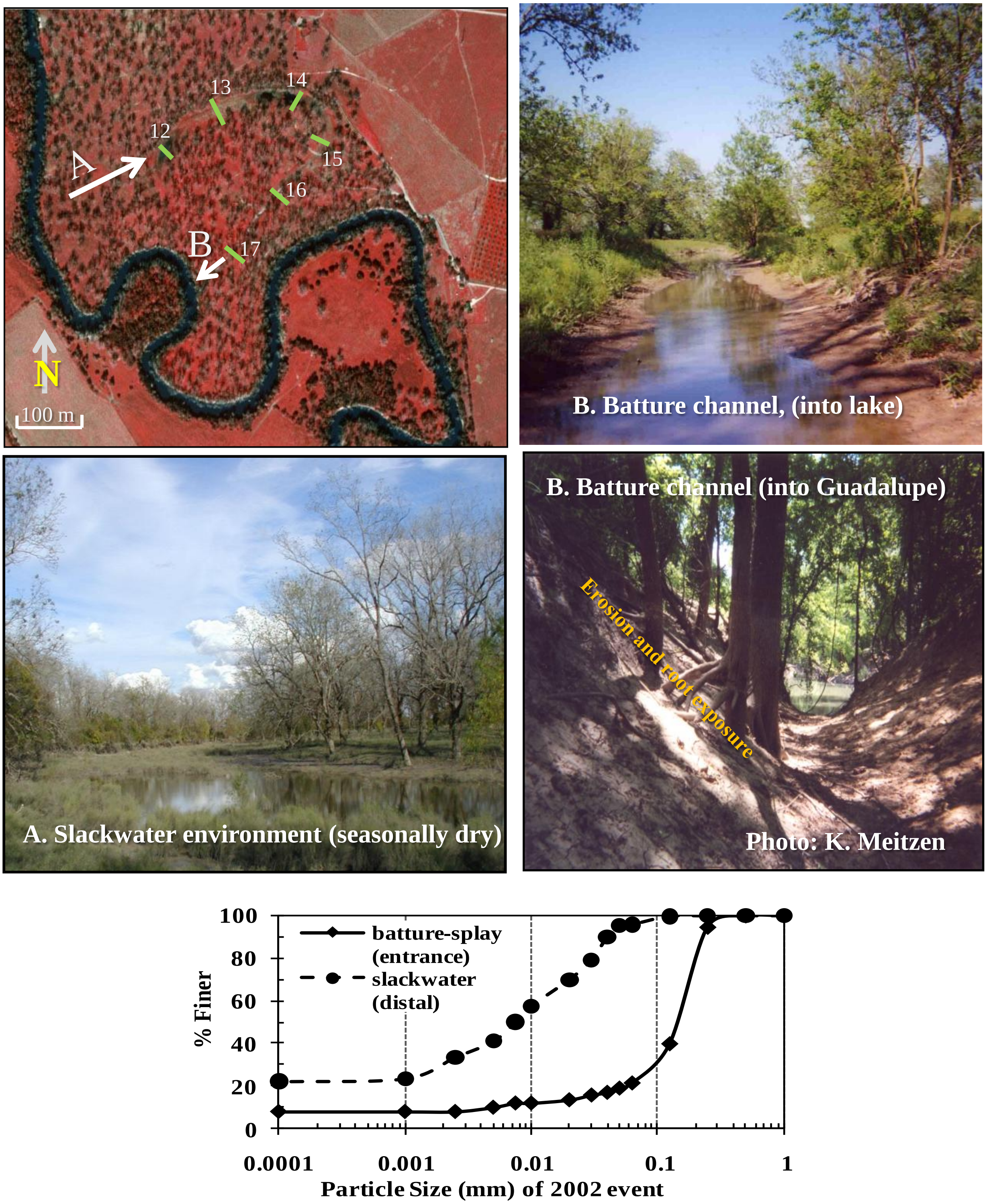



Figure 4.3.4. Oxbow lake along Guadalupe River near Gonzales, ~1 km upstream of San Marcos River. The site illustrates the influence of connectivity pathways on oxbow lake sediment dispersal. The photos represent different environments of inilling , including low energy slackwater (A) and fine-grained deposits and high-energy batture channel (B) associated with coarser deposits (grain size curve). See table for flood deposit characterization for each transect.

occurred prior to the October event, resulting in the July flood deposits being easily distinguishable.

Flood deposits were sampled at twenty eight locations along six transects (Figure 4.4.4) that spanned the range of depositional micro-environments within the oxbow lake. This included the high energy batture channel entrance zone to low energy slackwater sites at the distal end of the oxbow lake. The average depth of sedimentation was 10.71 cm (std. dev. = 5.87 cm), with an individual maximum thickness of 28.75 cm and a minimum flood deposit thickness of 1.15 cm (Table 4.3.5). The maximum thickness of deposits occurred along transect gz16, which is ~250 m beyond the entrance to the oxbow through a high energy batture channel via a "jet-like" zone. The median ($D_{50}$) particle size of sediment for the 28 samples averaged 0.083 (mm); fine sand. In general, finer-grained deposits were located within the slackwater setting, but there was considerable variability (Table 4.3.5). Thus, this case study illustrates that older oxbows also can exhibit highly variable rates of sedimentation and grain size, although the batture channel is *key* to this occurring because of representing a conduit for siphoning coarser suspended sediments lower in the water column, and by increasing the duration of the event.

Table 4.3.5. Oxbow Lake Sedimentary Characteristics of 2002 flood, Gonzales

| Station | Avg. Sediment thickness, cm (# of samples) | Particle size, $D_{50}$ (mm) |
|---|---|---|
| gz12 | 9.7 (5) | 0.041, 0.034, 0.026 |
| gz13 | 9.0 (4) | 0.061, 0.036, 0.011 |
| gz14 | 12.6 (4) | 0.056, 0.035, 0.046 |
| gz15 | 12.9 (4) | 0.094, 0.035, 0.007 |
| gz16 | 12.5 (7) | 0.057, 0.187, 0.165, 0.211 |
| gz17 | 6.6 (4) | 0.063, 0.088, 0.057, 0.023 |

**Other sites**

Sediment traps were installed in several other floodplain lakes along the lower Guadalupe valley, but unfortunately had been disturbed or were lost. This includes four sediment traps (shallow buckets) installed at Linn Lake in December, 2006 that were recovered in December 2008, but were not useful because of having been disturbed by cattle or possible wave action. Sedimentation traps not recovered include four artificial grass mats (50 x 50 cm) installed in Horseshoe Lake, and six grass mats installed in and adjacent to Pridham Lake and an unnamed oxbow (style) lake (Bird Sanctuary) west of Victoria.

**4.4. Discharge and Suspended Sediment Dynamics for the lower Brazos, Guadalupe, and San Antonio Rivers**

The analysis of lake stage data clearly illustrates distinct styles of connectivity for different types of floodplain lakes. This suggests the need to also consider the dynamics of discharge and suspended sediment transport. Unfortunately there are not many comprehensive suspended sediment data sets that span long periods and the range of hydroclimatic conditions for Texas rivers. Several data sets, however, of suitable quality are available for stations located along the lower reaches of the study rivers. Suspended sediment sampled in association with the USGS's National Stream Quality Accounting Network (NASQAN) is available for the Brazos River at Richmond, the Guadalupe River at Victoria, and the San Antonio River at Goliad (Table 4.4.1). Included in the data set are suspended sediment concentration (SSC) in mg/L, percent silt/clay (e.g., wash load) (% < 0.0625 mm), and suspended sediment discharge (tons/day), which is directly computed from SSC and Q. The period of data spans about twenty years for each station. However, while the data for the Brazos River at Richmond is nearly continuous, the sediment data for the Guadalupe River at Victoria and the San Antonio River at Goliad is infrequent and include fewer than twenty samples per year.

A comparison of the summary data (Table 4.4.1) shows the annual and daily averages for the study rivers. The average Guadalupe and San Antonio Rivers transport about the same sediment load, although the Guadalupe River transports a higher percentage of its sediment load as sand. While the higher percentage of silt/clay transported by the San Antonio does not appear significant, it may be indicative of fundamental differences between the two rivers. The Guadalupe has far more oxbow lakes than the San Antonio Rivers, which are associated with the process of bank erosion and lateral migration. The Guadalupe receives a greater proportion of its drainage from the lower Tertiary units of the coastal plain and along reaches is clearly reworking Pleistocene Deweyville deposits, which collectively represent a source of sand. Additionally, the lower reaches of the Guadalupe receives drainage from a number of moderate basins draining the clastic Tertiary units, such as Peach Creek. Coleto Creek (1,566 sq. km) discharges into the Guadalupe River downstream of the Victoria station and appears to have a high bed load (Morton and Donaldson, 1983; field observations).

Table 4.4.1. Availability of USGS NASQAN Suspended Sediment Data for Study Rivers

| Gauging Station | Data type* | Period of Record | Number of daily values | Avg. SSC | Avg. % silt/clay | Avg. Daily SSQ | Annual SSQ (tons/yr) |
|---|---|---|---|---|---|---|---|
| Brazos River at Richmond (08114000) | SSC; SSQ | Jan. 1, 1966 – Sept. 30, 1986 | 7,552 | 572 | NA | 30,328 | 11,069,720. |
| Guadalupe River at Victoria (08176500) | SSC; % silt/clay; SSQ | Jan. 8, 1973 – Aug. 25, 1994 | 157 | 127 | 82.9 | 1,385 | 505,525. |
| San Antonio River at Goliad (08188570) | SSC; % silt/clay; SSQ | Oct. 30, 1972 – Aug. 25, 1994 | 164 | 278 | 91.2 | 1,350 | 492,750. |

*Data type: SSC = suspended sediment concentration (mg/L); % silt/clay = percentage of sediment finer than 0.0625 mm (sand); SSQ = suspended sediment discharge (tons/day), which is directly computed from SSC and Q

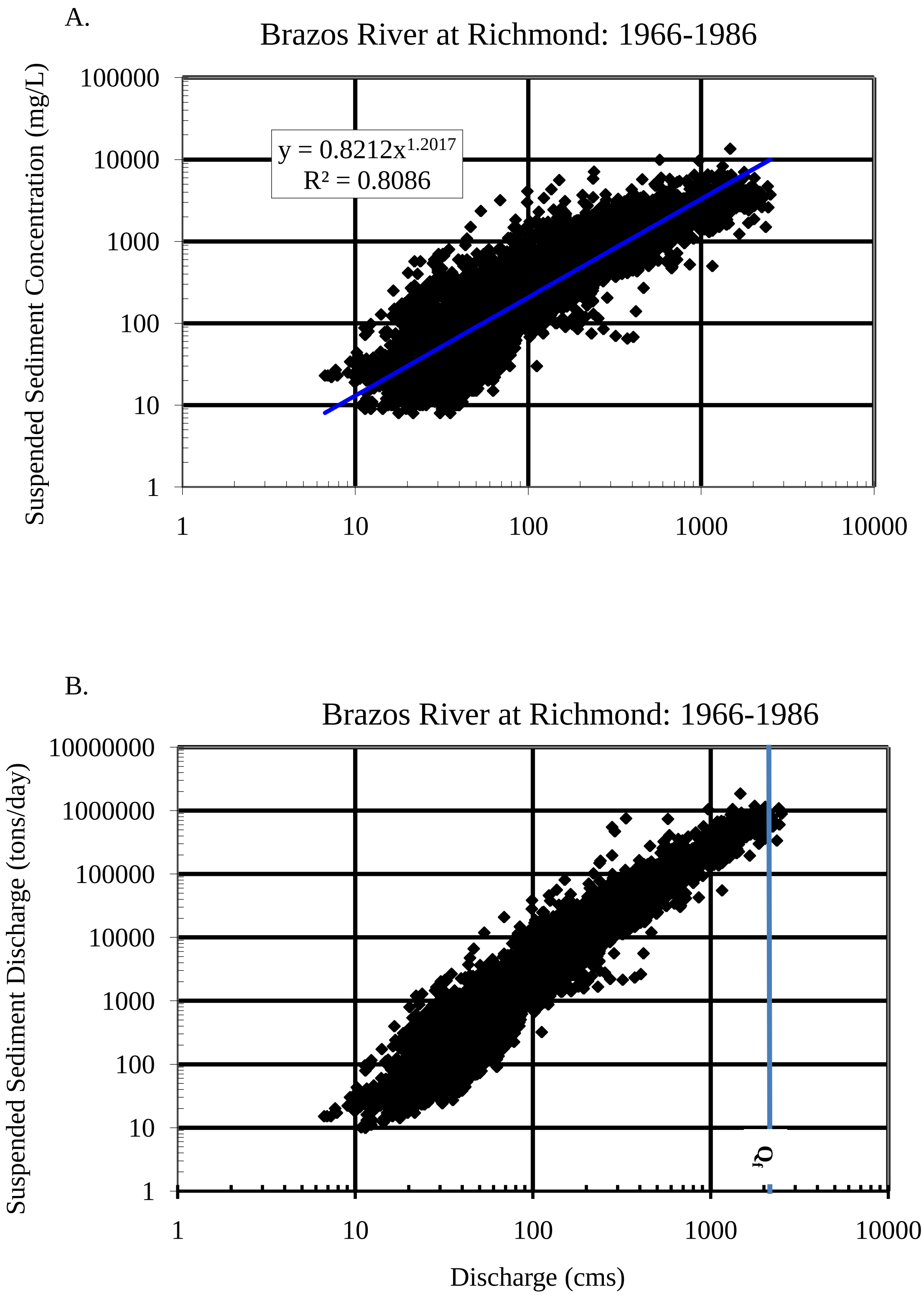



Figure 4.4.1. Relationship between discharge (cubic meters per second) and A. suspended sediment concentration (mg/L), SSC and B. Suspended sediment discharge (tons/day), SSQ. Data source: USGS.

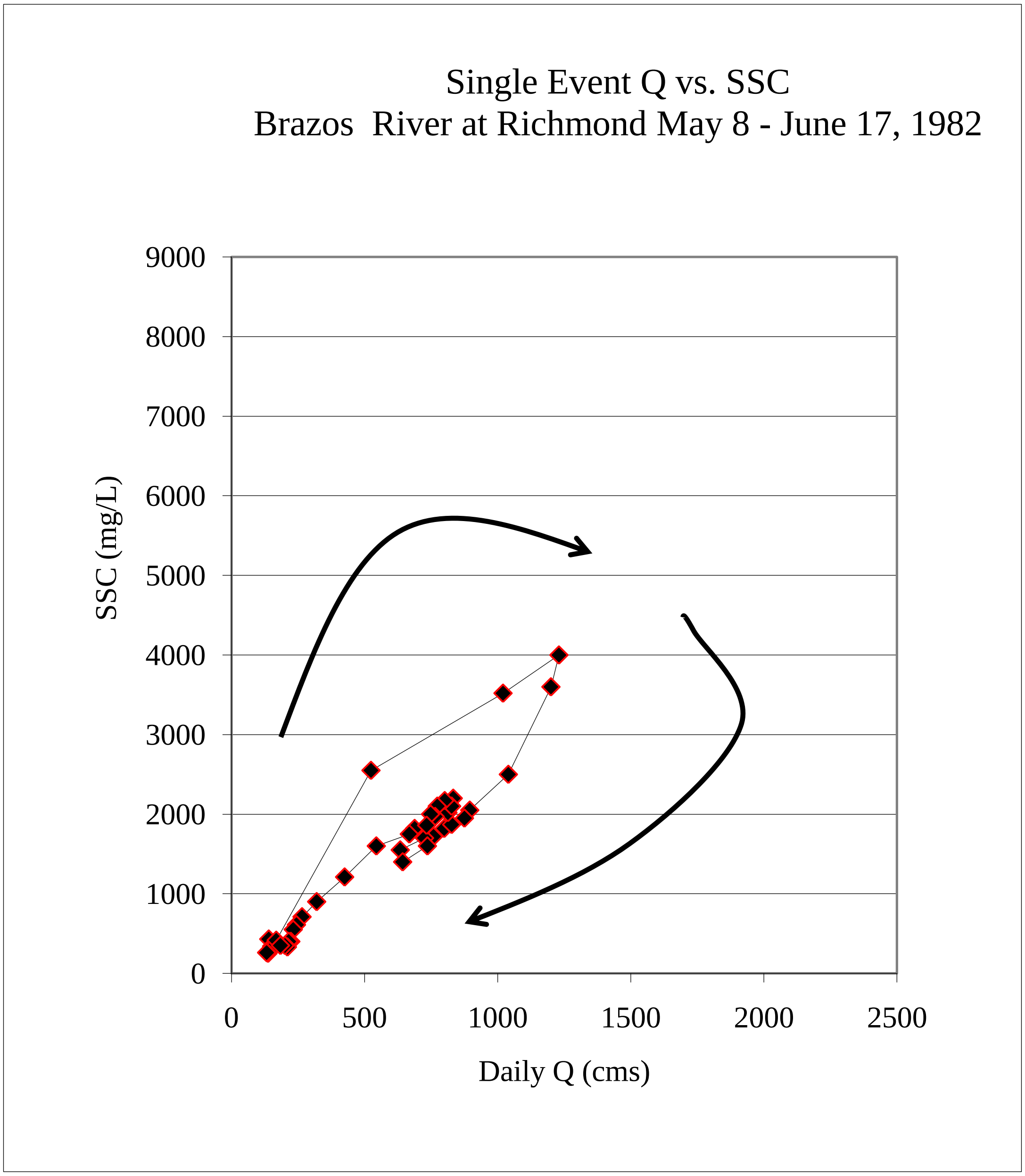



Figure 4.4.2. Relationship between discharge (cubic meters per second) and suspended sediment concentration (mg/L). Data source: USGS.

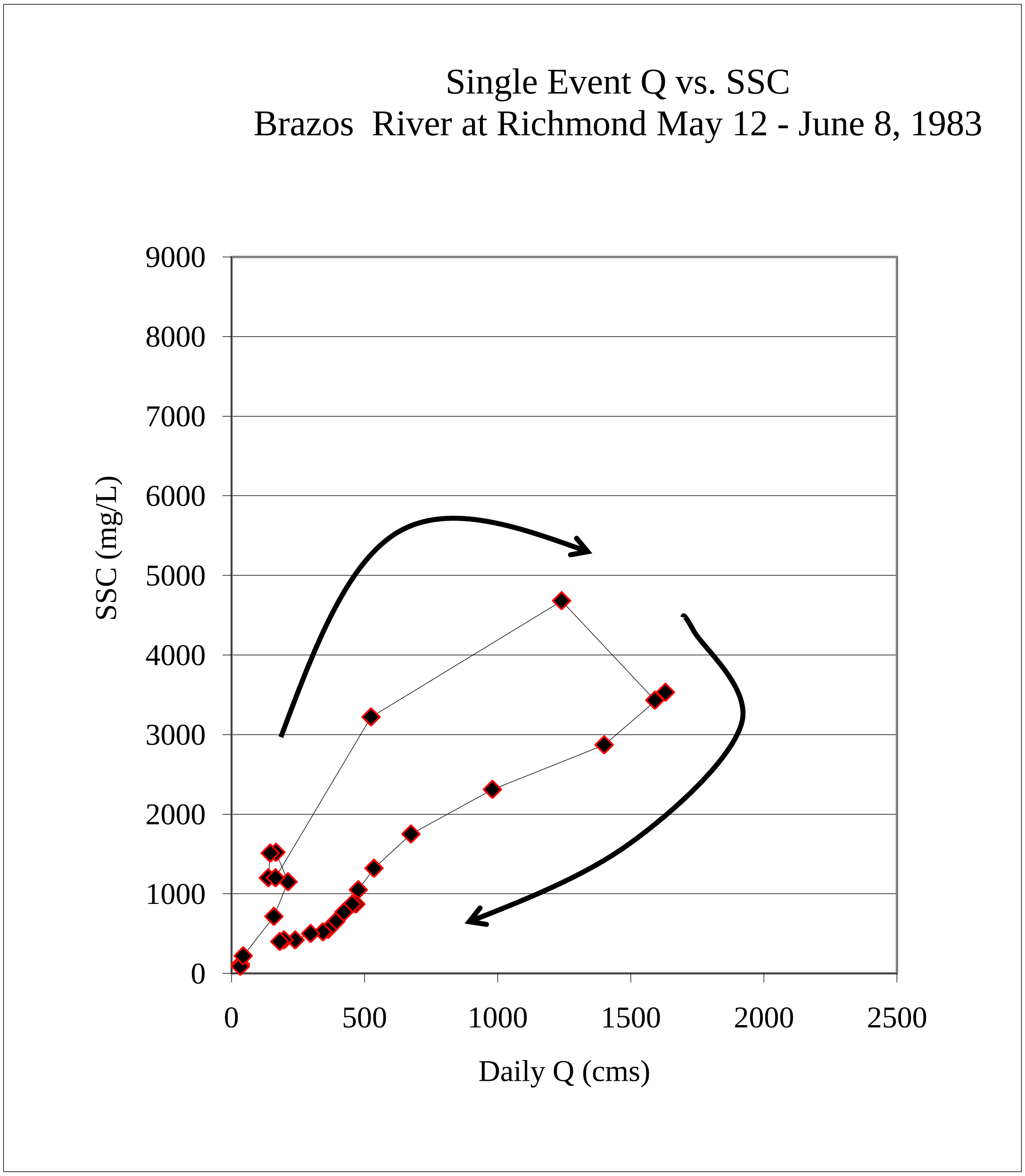



Figure 4.4.2. Continued.

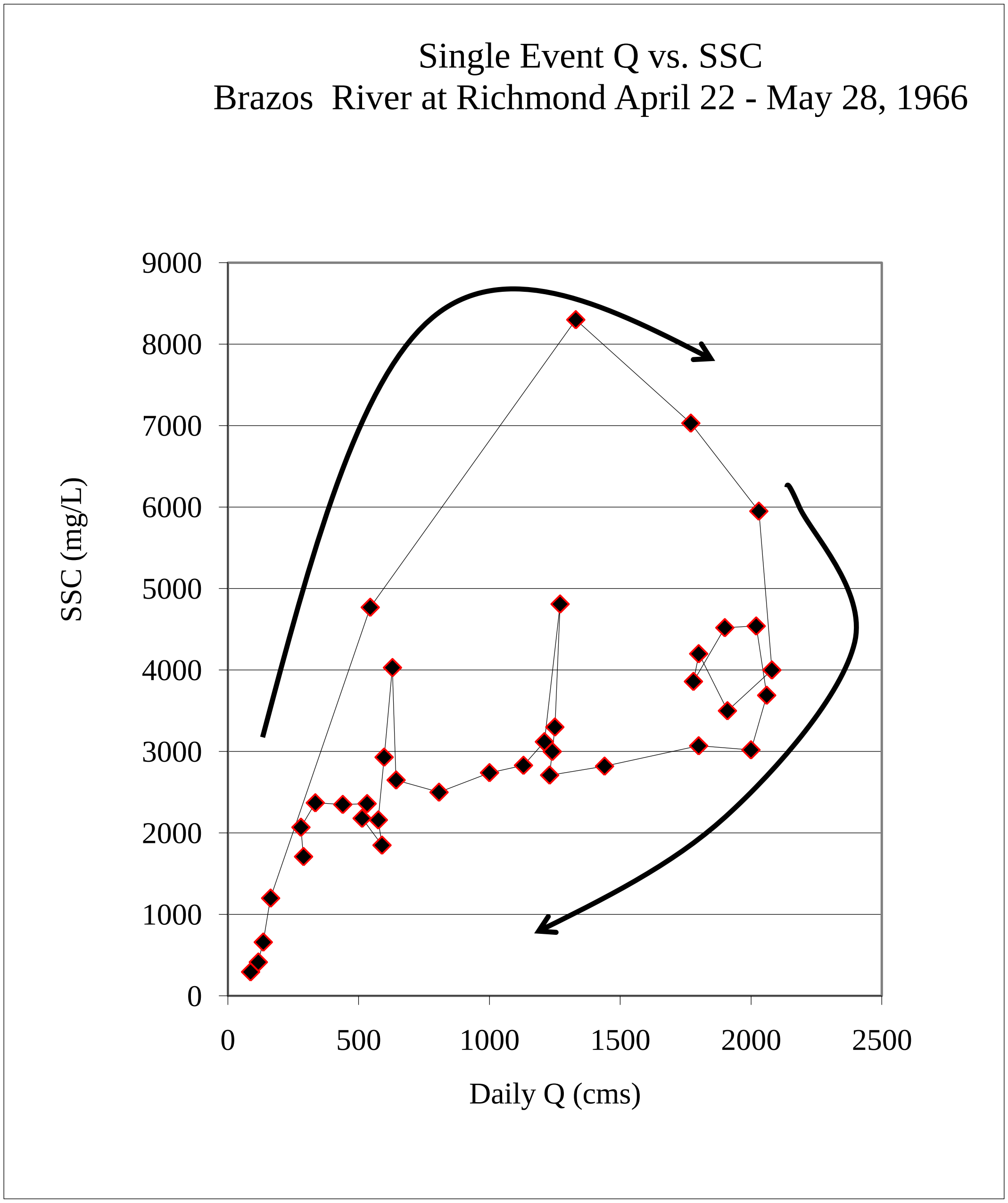



Figure 4.4.2. Continued.

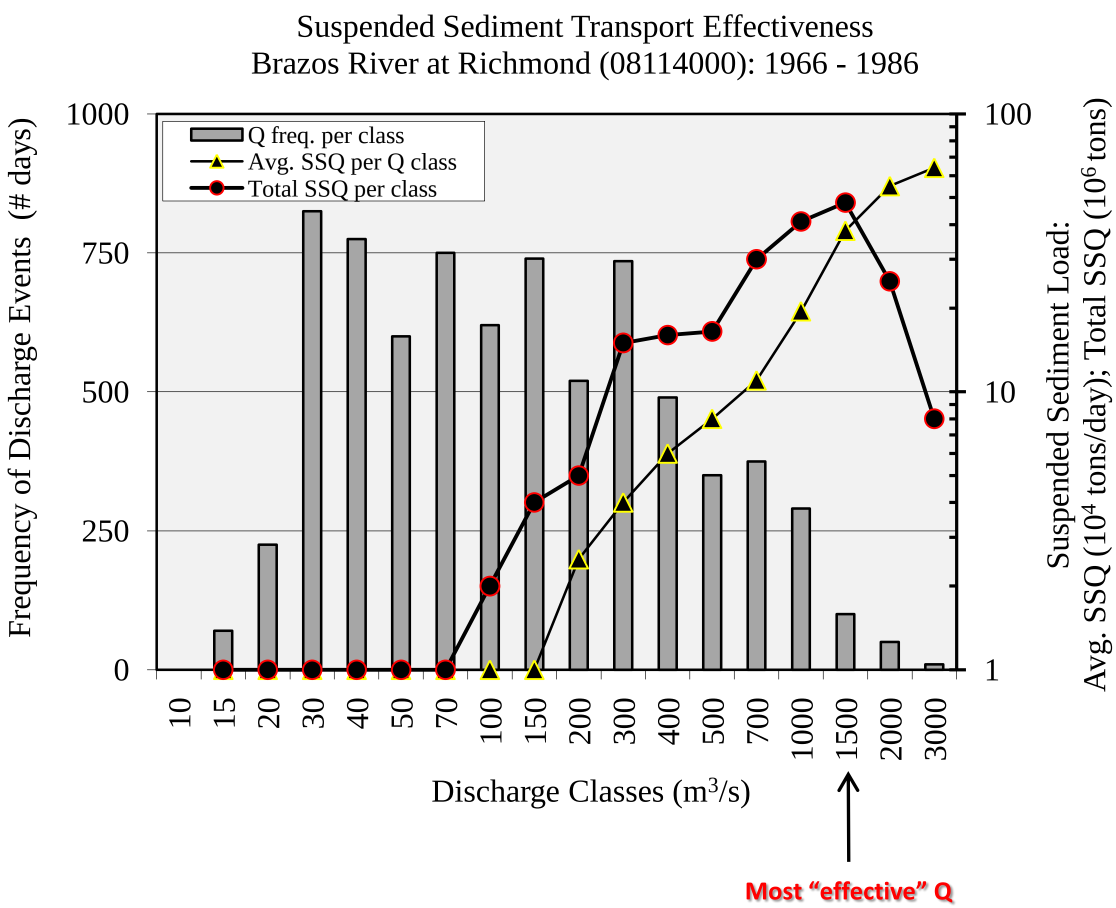



Figure 4.4.3. Magnitude and frequency analysis for suspended sediment discharge for the Brazos River at Richmond. Data source: USGS.

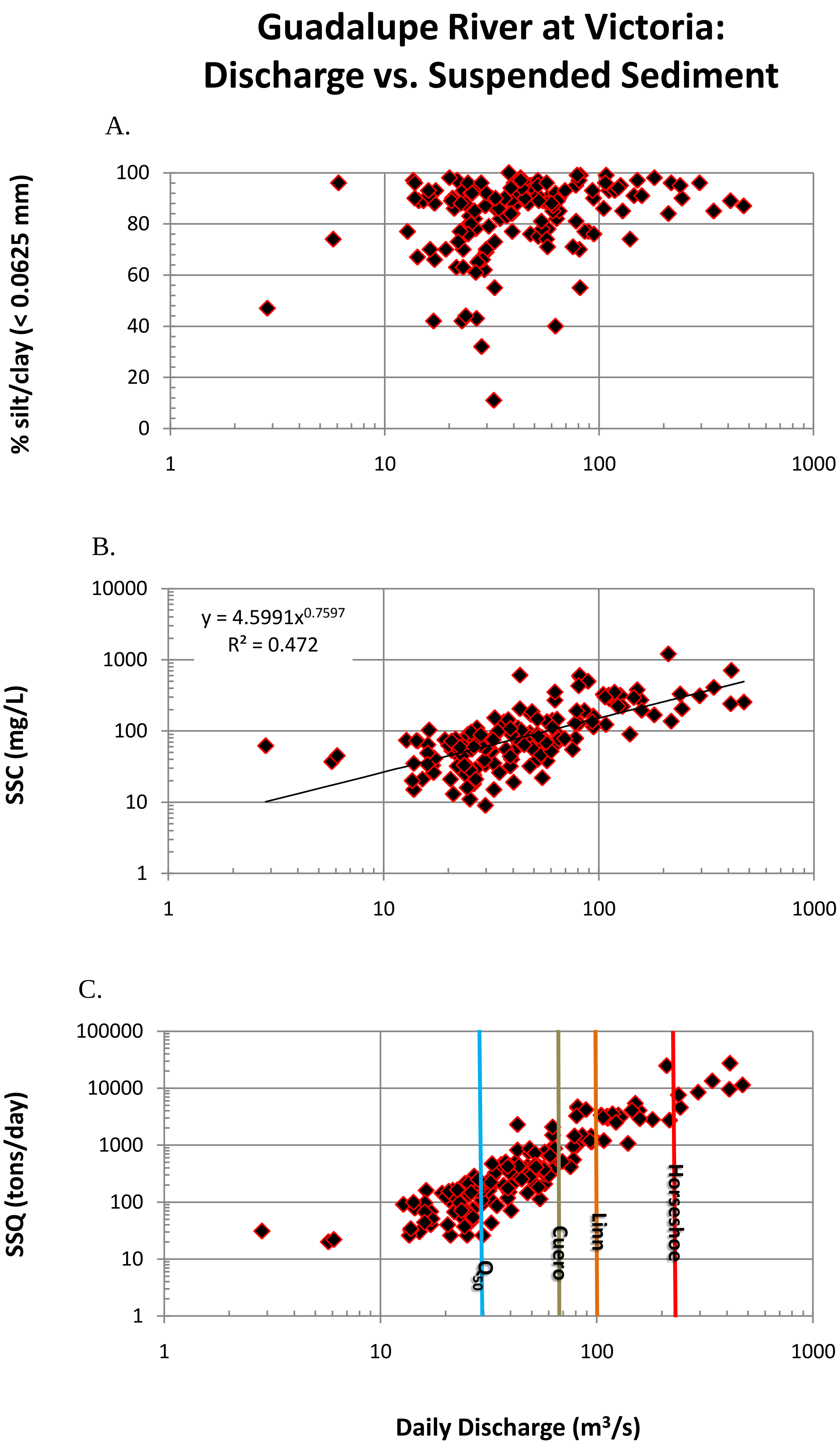



Figure 4.4.4. Relationship between discharge (cubic meters per second) and A. percent silty/clay, B. suspended sediment concentration (mg/L), SSC, and C. Suspended sediment discharge (tons/day), SSQ for the Guadalupe River at Victoria. Data source: USGS.

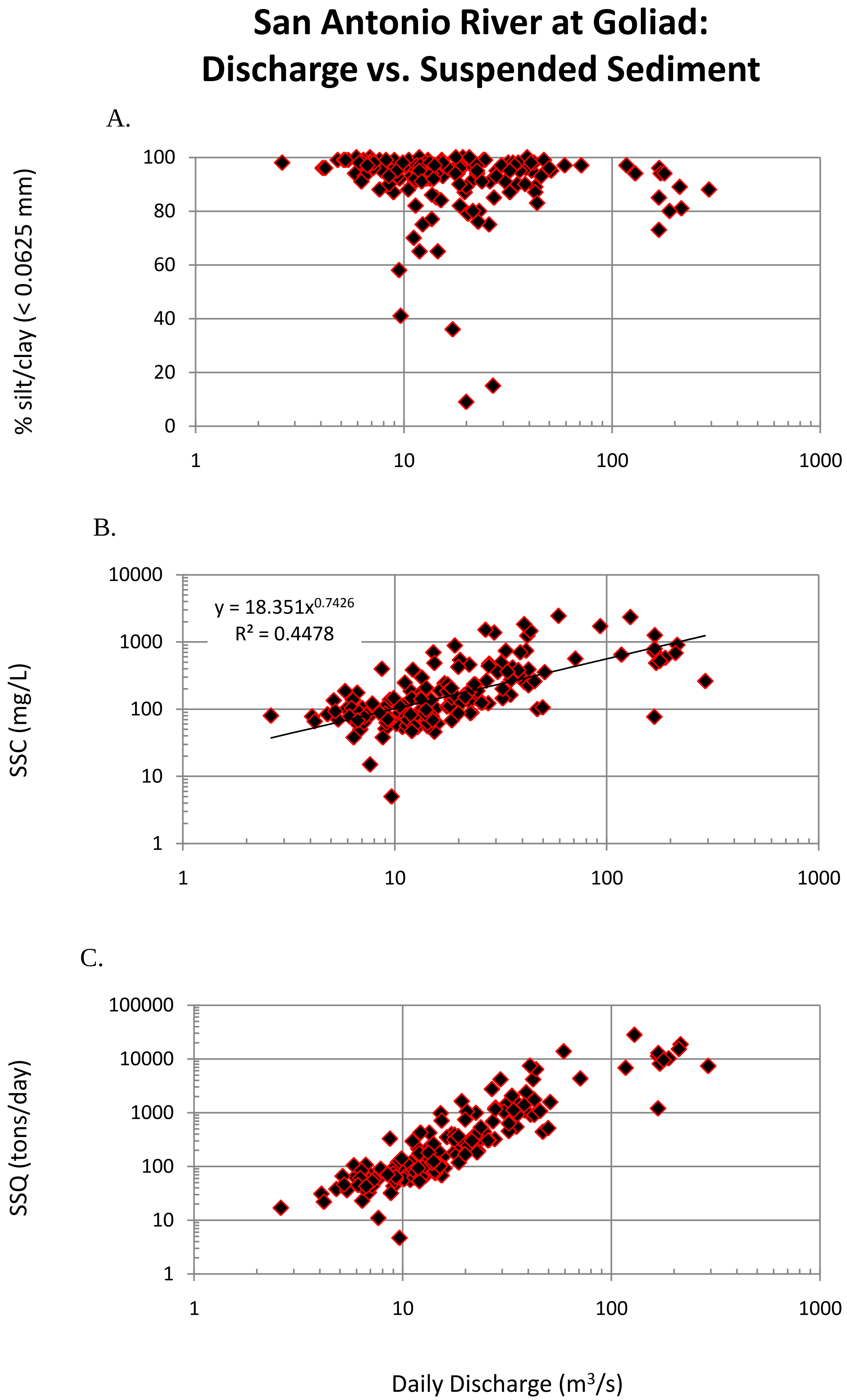



Figure 4.4.5. Relationship between discharge (cubic meters per second) and A. percent silty/clay, B. suspended sediment concentration (mg/L), SSC, and C. Suspended sediment discharge (tons/day), SSQ. For the San Antonio River at Goliad. Data source: USGS.

Because the suspended sediment data for the Brazos River at Richmond includes frequent daily values the record provides an opportunity to consider discharge – suspended sediment relationships over varying temporal scales. For a 20.7 year period (1966-1986) the Brazos River transported an average annual sediment load of 11,068,720 tons/yr (Table 4.4.1), which is the highest annual sediment load of Texas' large rivers (Meade and Parker, 1984; Mossa et al., 1993; Hudson 1993). The relationship between discharge and suspended sediment concentration (SSC) displays a strong statistical relationship (Figure 4.4.1), with Q explaining 82 percent of the variability in SSC. The data is fit with a power function, suggesting a linear relationship for log-10 transformed values. The upper discharge ranges, however, clearly display greater variability in SSC, as SSC flattens at it reaches a threshold of about 600 m3/s. Some of the scatter at the higher discharge values is likely associated with flushing of the wash load and hysteresis (Hudson and Mossa, 1997), that is, the lag (in time) between suspended sediment concentration and discharge. Most rivers display positive hysteresis, with the time between the peak Q and peak SSC increasing as a function of scale (Hudson, 2003), but also related to the supply and possible exhaustion of the wash load (Hudson, 2003).

The frequent value for the Brazos at Richmond station provides an opportunity to examine single event relations between discharge and suspended sediment concentration (SSC). Individual discharge pulses display several unique types of Q – SSC relations, and several are displayed in Figure 4.4.2. A common relation is that SSC is lower on the receding limb of the hydrograph for the same discharge. This is displayed in Figure 4.4.2 for an event that occurred between May 8 and June 17, 1972, with SSC ~1,000 mg/L lower for the same discharge on the receding limb of the hydrograph. This suggests a pronounced "exhaustion" effect, and this contention is supported for the additional pulse at about 750 m3/s which does not result in appreciably higher SSC. A classic hysteresis effect is exhibited for the discharge pulse spanning from May 12 to June 8 , with SSC peaking one day prior to the discharge peak, and at a discharge which is 350 $m^3$/s less than the peak event.

A larger hysteresis loop, associated with a larger discharge event, is observed for the pulse occurring between April 22 and May 28, 1966. The SSC peaks at a Q of 1,330 $m^3$/s, four days prior to the peak Q of 2,080 $m^3$/s. Additionally, the SSC on the falling limb of the hydrograph is over 5,000 mg/L less than the peak SSC, illustrating strong dilution and flushing of the silt/clay component of the sediment load. Such large disparities between SSC for the same Q make modelling SSC particularly challenging. An additional feature of this Q – SSC relation are the two "spikes" in SSC near the end of the event. Such deviations can be associated with collapse of saturated bank material during flood recession, representing an abrupt but temporary increase in SSC (Knighton, 1998).

An additional perspective on discharge – suspended sediment relations is to consider the effectiveness of discharge events in transporting sediment, which relates to the amount of "work" accomplished by a specific discharge event (e.g., Wolman and Miller, 1960). By summing daily values of suspended sediment discharge (SSQ) according for specific discharge categories (Q classes based on Searcy, 1959), the most "effective" discharge can be estimated. As can be seen in Figure 4.4.3 the most "effective" discharge class for the Brazos River at Richmond occurs within the 1,000 to 1,500 $m^3$/s range. This is a discharge range that is relatively frequent, and Hudson and Mossa (1997) have shown that 75% of the total SSQ was transported in only about 9% of the time.

Indeed, the most effective discharge class for the Brazos River at Richmond occurs well below the threshold flood discharge ($Q_f$), which is 2,265 $m^3/s$ (from NWS).

While the relationship between discharge and suspended sediment discharge (SSQ) suggests a stronger fit than SSC, a statistical trend test for Q vs. SSQ is not attempted because SSQ is computed directly from Q and thus violates the statistical assumption of independence. Nevertheless, the plot is useful for considering the amount of sediment transported for various discharge magnitudes. The implications of the relation are that it provides insight into the sediment load at specific floodplain lake connectivity thresholds. Unfortunately, prior research on oxbow lake connectivity for the Brazos River is located adjacent to the next upstream or downstream gauging stations, and thus it is difficult to speculate about suspended sediment load volumes for floodplain lakes that are connected at discharge magnitudes below flood stage ($< 2,265$ $m^3/s$) adjacent to the Richmond vicinity.

Data for the Guadalupe (Figure 4.4.4) and San Antonio (Figure 4.4.5) Rivers are much sparser than for the Brazos, and only infrequent daily suspended sediment values are available (Table 4.4.1). The Guadalupe displays considerable scatter for the relation between Q and % silt/clay, which is because of the wash load being less dependent than sand on discharge magnitude (e.g., shear stress), as much of the wash load is supplied by hillslope runoff processes rather than being entrained from the cannel bed (Knighton, 1998). The relation between Q and SSC shows that discharge explains about 47% of the variability in suspended sediment concentration, with the reduced variability being a function of SSC also including sand which is discharge dependent (Knighton, 1998). The relation between Q and SSC is linear, and little exhaustion is noted at high discharge events. This may be because of the abundance of sand within the lower Guadalupe, or because of the closer proximity of tributaries draining sandy units results in low travel times for sediment to reach the gauging station during large events.

The prior analysis of hydrologic connectivity provides a framework for considering the relation between Q and SSQ. While the Cuero '98 Oxbow Lake is upstream of Victoria, the connectivity is likely representative of most recently formed oxbow lakes along the lower Guadalupe, or other Texas river valleys that undergo large variations in stage. Cuero '98 Oxbow, Linn Lake, and Horseshoe Lake are hydrologically connected with the Guadalupe River at discharge events at 73, 102, and 238 $m^3/s$, respectively. These threshold events have average suspended sediment concentrations at 125, 180, and 290 mg/L. Nevertheless, the magnitude and frequency of events must be considered. Standard flow duration values calculated from daily streamflow values extending back to 1934 for Victoria and 1964 for Cuero reveals that threshold (connectivity) discharge events are equal or exceeded 17.0, 10.7, and 3.6 % of the time for Cuero '98 Lake, Linn Lake, and Horseshoe Lake, respectively. Thus, while the average unit rates of lake sedimentation for strongly connected floodplain lakes should be less, the higher frequency and duration of connectivity suggests that cumulative sedimentation rates are much higher for Cuero '98 Oxbow Lake than Horseshoe Lake or Linn Lake. Indeed, this rudimentary analysis is supported by the geomorphic change that is rapidly occurring within Cuero '98 Oxbow Lake, as manifest in rapid aggradation and progradation of a clastic wedge of deposits into the lake basin.

Data for the San Antonio River at Goliad is similar in terms of the length of record, but is appreciably different from the Guadalupe record at high discharge magnitudes, which represent critical flow magnitudes from the standpoint of geomorphic processes. The San Antonio displays strong non-linearity at larger discharge events, exceeding ~90 $m^3/s$. This may be caused by the higher wash load resulting in stronger hysteresis and/or sediment exhaustion during sequential events. Additionally, the San Antonio has fewer tributaries supplying discharge in the lower reaches of the basin upstream of the Goliad gauging station.

Unfortunately the absence of an extended continuous suspended sediment data for the Guadalupe and San Antonio Rivers prohibits the analysis of single event Q – SSC relations, or a magnitude – frequency analysis such as conducted for the Brazos River. It would be useful if floodplain lake hydrology and sedimentation studies were conducted adjacent to stream gauging stations with extended continuous suspended sediment records. Analysis of Q and SSQ from the perspective of identifying the "effective" threshold suggests a useful framework for understanding the timing and delivery of riverine sediments to floodplain lakes.

## 5. Summary

Floodplain lakes are common to Texas coastal plain river valleys. Floodplain lakes vary in their geomorphic and hydrologic characteristics and are considered dynamic features that change over time. This study investigates geomorphic, hydrologic, and sedimentary characteristics of floodplain lakes along three coastal plain rivers, the Brazos, Guadalupe, and San Antonio Rivers of South Central Texas. The study sites span the alluvial valleys and deltas, from the Balcones Escarpment Zone to the Gulf of Mexico.

The purpose of this study was to examine geomorphic and hydrologic characteristics of floodplain lakes in different stage of development within the alluvial valleys of three coastal plain rivers in Texas, specifically the Brazos, Guadalupe, and San Antonio Rivers.

The study objectives are examined within four major research thrusts, including 1. A geomorphic and geographic analysis of floodplain lakes in relation to channel and valley characteristics along the entire reaches of the Brazos, Guadalupe, and San Antonio Rivers (study objectives 1, 2, 3, 4, 5, 9), 2. Analysis of hydrologic connectivity for three floodplain lakes along the Guadalupe River (study objective 7), 3. Analysis of floodplain lake sedimentation along the Guadalupe River (study objective 9), and 4. An analysis of discharge – suspended sediment dynamics of the lower Brazos (at Richmond), Guadalupe (at Victoria), and San Antonio Rivers (at Goliad), with a focus on the Brazos River (study objectives 6, 8).

The major data sets were obtained from field work, laboratory analysis, and government agencies, which included geospatial, hydrologic, and suspended sediment data. Secondary geospatial data sources included 2005 and 2006 high altitude aerial photos as digital orthophoto quarter quadrangles (DOQQ) (1 m resolution), digital topographic maps (1:24,000), high resolution hydrographic data from the National Hydrographic Dataset (NHD), various historic maps and aerial photographs from the University of Texas Library and TNRIS, and LiDAR (Light Detection and Ranging) data from the TNRIS. Discharge (daily and fifteen minute values) were supplied from the USGS, as was NASQAN suspended sediment data. Fieldwork was conducted for obtaining lake stage data recorded by data loggers attached to vented submersible pressure transducers, topographic surveying, floodplain coring and trenches to examine sedimentary profiles and to obtain samples for sedimentologic and radiocarbon analysis. The data were collected and analyzed using conventional methods cited in the scientific literature pertaining to floodplain hydrologic and geomorphic investigation.

The two major floodplain lake types along Texas coastal plain rivers are oxbow lakes from lateral erosion and meander neck cut-offs, and lakes associated with abandoned channel courses, which include valley lakes adjacent to valley margins. Other less abundant, but not uncommon, lake types include arcuate lakes formed within meander swale and elongated lakes caused by flood scour (crevasses). The analysis reveals considerable differences between the San Antonio, Brazos, and Guadalupe Rivers in terms of the frequency (#) and area ($km^2$) of floodplain lakes. Oxbow lakes are far less common along the San Antonio valley (# = 12, 0.3 $km^2$) than the Guadalupe (# = 47, 1.1 $km^2$) or Brazos (# = 45, 5.1 $km^2$). The area of abandoned channel lakes, however, appears to be greater. Without considering valley side lakes, for example, the area of abandoned channel lakes in the Brazos valley is 7.13 $km^2$. Although the Brazos River is considered a classic meandering river associated with numerous oxbow lakes, many of the floodplain lakes along the Brazos River are actually formed from abandoned channels caused by "local" avulsions rather than oxbow lakes formed by meander neck cutoffs (lateral erosion). For this reason the function and evolution of these lake types should also be examined and valued, and floodplain managers should be cautioned against relying too heavily upon the "classic oxbow" model as the penultimate floodplain lake type. There are no significant relationships between oxbow lake area and lake distance from the main-stem channel, probably because of river migration after the lake is formed. The distribution of floodplain lake types is somewhat related to valley scale geomorphic controls, particularly the ratio between meander belt width ($W_{MB}$) to valley width ($W_V$), a scale independent geomorphic index relevant to hydrologic and geomorphic processes. The spatial frequency of oxbow lakes along a river valley is probably a good relative indicator for lateral migration and meander belt evolution. Oxbow lakes along the Brazos, Guadalupe, and San Antonio Rivers are concentrated in the middle reaches of the alluvial valleys, which is likely due to spatial, hydraulic, and sedimentary controls.

The study noted a number of discrepancies between what are classified as lakes on NHD, DRG, and DOQQ data sets, which are commonly utilized in assessment of river valley environments for floodplain management. Data from the USGS's NHD is not without issues when mapping floodplain lakes, but it is especially useful for mapping floodplain lakes along extensive reaches of large river valleys, and for this reason could be beneficial to government agencies interested in the broader distribution of floodplain lake types for multiple large river valleys. The approach, however, does require substantial effort to build the data base and requires experience and background in the concepts of fluvial geomorphology within the context of large coastal plain river valleys.

Lake stage data obtained from pressure transducers installed in three floodplain lakes along the Guadalupe River were used to examine surficial hydrologic connectivity in relation to streamflow. The lake stage data extends from December 13, 2006 to May 7, 2010, and is thus inclusive of seasonal flow variability for different floodplain lake types within South-Central Texas. Importantly, the data represents a unique hydrologic archive because of being collected during extreme hydrologic conditions, notably a severe drought and a very wet and active flood season associated with El Niño conditions. The three lakes monitored during the study period include an ~eleven year old oxbow lake near Cuero, an old (> ~2,600 yrs BP) oxbow lake downstream of Victoria (Horseshoe Lake), and a large valley side lake (Linn Lake) near McFaddin, Texas. Because the data was obtained over the same period it enables a direct comparison of connectivity between different types of floodplain lakes. Connectivity occurred for all floodplain lake types and was activated by different processes, including overbank, side channel, and local sources. The data reveals considerable variability and complexity in the frequency, duration, and magnitude of hydrologic connectivity with the Guadalupe River, and these settings should be seen as typical of coastal plain floodplain lakes in *general*. Recently formed oxbow lakes are dynamic hydrologic environments. These lakes exhibit variability in stage that is more similar to the main-stem channel than with older oxbow lakes. Older oxbow lakes adjacent to the main-stem channel are effectively "sealed" from the main-stem channel and are less hydrologically dynamic, and are infilled with > 5 m of fine-grained sediment. Although being immediately adjacent to the river channel these oxbow lakes exhibit less flow variability than large valley side lakes if they are not connected to the main-stem channel with a batture channel.

Sedimentation rates were estimated several ways, including long-term estimates with radiocarbon dating and annual and single event sedimentation rates by employing sedimentation traps and post-flood sediment sampling. Since forming October 17, 1998, sedimentation rates have been > 37 cm/yr for the Cuero '98 Oxbow lake, with single event rates as high as 6.5 cm. In contrast, the rate of sedimentation for an old infilled oxbow was only 0.65 cm/yr; an order of magnitude lower. The data supports the idea that annual sedimentation rates (cm/yr) and single-event deposition (cm) is far greater for recently created oxbow lakes than older infilled oxbows, although exceptions occur if surface (topographic) connectivity is maintained (batture channels). Radiocarbon dating of two floodplain lakes at different locations within the lower Guadalupe valley results in minimum ages of 3,150 +/- 40 BP and 2,500 +/- 40 BP, resulting in an estimate of long-term sedimentation rates of 0.16 mm/yr and 0.17 mm/yr, respectively.

The Brazos River annually transports $11.1 \times 10^6$ tons of sediment to the near shore coastal zone, while the Guadalupe and San Antonio collectively transport about $1.0 \times 10^6$ tons/yr. The Brazos River transports the majority of its sediment load by relatively moderate discharge events, which was quantitatively defined as the "effective" discharge. The Guadalupe and San Antonio Rivers display differences in the transport of suspended sediment, with the San Antonio River displaying sediment exhaustion during large events, which is likely because of the higher wash load. Analysis of single event bivariate relationships of daily values of discharge (SSQ) and suspended sediment concentration (SSC) for the Brazos River illustrates the complexity in sediment transport processes, particularly associated with hysteresis patterns for high magnitude sequential discharge pulses (the Guadalupe and San Antonio did not have sufficient data sets for this analysis). Such analysis provides a useful framework for considering the sediment flux into floodplain lakes associated with hydrologic connectivity.

This study has provided data to quantify the range of variability in sedimentary and hydrologic processes between a very old and very recent oxbow lake, but additional research is required to further characterize oxbow lakes in the middle phases of evolution (e.g., the oxbow model). Additionally, Texas coastal plain river valleys include several distinctive types of floodplain lakes that are highly variable in size and stage of development and are uniquely influenced by hydrologic, geomorphic, and sedimentary processes. Considering their prominence within the modern floodplain environments, more attention should be devoted to understanding their fundamental hydrologic and sedimentary processes.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Appendix 1. Field trips

| Field Trips for TWDB Project | | | |
|---|---|---|---|
| Date | Location | Purpose | Days |
| | | | |
| Nov. 11-12, 2006 | Lower Guadalupe and San Antonio | Site evaluation; field access and permissions, Sedimentation traps | 3 |
| Dec. 12 - 14, 2006 | Lower Guadalupe and San Antonio | Site evaluation; installation of pressure transducers; permissions and access | 3 |
| Feb. 24 - 25, 2007 | Lower Guadalupe; Cuero and Victoria vicinity | Site evaluation; field permission and access; lake and floodplain coring; installation of pressure transducers and data download | 2 |
| March 24-26, 2007 | Lower Guadalupe, Cuero and Victoria vicinity | Coring; download pressure transducer data; site evaluation and access | 3 |
| May 14, 2007 | Lower Guadalupe, Cuero and Victoria vicinity | Surveying, sedimentation stakes; lake water samples | 1 |
| May 17, 2007 | Lower Guadalupe, Victoria vicinity | Soil/sediment trench description and sample | 1 |
| Dec. 15, 2007 | Lower Guadalupe | Download pressure transducers | 1 |
| Dec. 9, 2008 | Lower Guadalupe | Retrieve sedimentation traps; Download pressure transducers | 1 |
| Feb. 25, 2009 | Lower Guadalupe, Victoria and vicinity | Oxbow coring; sedimentation traps | 1 |
| April 8, 2009 | Lower Guadalupe, Victoria and vicinity | Oxbow coring | 1 |
| May 3, 2009 | Lower Guadalupe, Cuero | Sedimentation traps, oxbow coring | 1 |
| July 27, 2009 | Lower Guadalupe; Cuero and Victoria vicinity | Retrieve sediment mats; download pressure transducer data | 1 |
| Nov. 8, 2009 | Lower Guadalupe; Cuero and Victoria vicinity | Download pressure transducer data; lake water samples | 1 |
| May 7, 2010 | Guadalupe and San Antonio Valleys; Cuero and Victoria vicinity | Remove pressure transducers and sedimentation stakes; field site evaluation | 1 |
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