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Long-term total suspended sediment yield of coastal Louisiana rivers with spatiotemporal analysis of the Atchafalaya River Basin and Delta Complex

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LONG-TERM TOTAL SUSPENDED SEDIMENT YIELD OF COASTAL LOUISIANA RIVERS WITH SPATIOTEMPORAL ANALYSIS OF THE ATCHAFALAYA RIVER BASIN AND DELTA COMPLEX

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ABSTRACT

The modern day Mississippi River Delta Plain and the Louisiana Chenier Plain have been greatly altered through anthropogenic changes to course and hydrological conditions of the Mississippi River and local rivers, most notably by levees that have excluded the Mississippi River from the delta plain. This has slowed accretion and increased land loss destroying vast quantities of marsh, endangering many coastal communities. This master's thesis examined long-term total suspended sediment yield of four Chenier Plain rivers, total suspended sediment yield of the Mississippi River under different flow conditions, and total suspended sediment dynamics of the Atchafalaya River in relation to Atchafalaya River Delta Complex growth and Atchafalaya River Basin sedimentation. Results estimated average annual total suspended sediment yield to coastal Louisiana of 176.3 megatonnes (MT), with the Mississippi River contributing 72% and the Atchafalaya River contributing 28%. The Chenier Plain rivers contributed a negligible amount to this total, averaging annually 342,950 tonnes, with the Sabine contributing 62% to this total (213,100 tonnes), while the Calcasieu River supplied 46,850 tonnes, Mermentau River 40,200 tonnes, and Vermilion River 42,800 tonnes. The hydrograph-based approach for quantification of actual available total suspended sediment of the Mississippi River identified the rising limb of the flood pulse during Action Stage (12.1-14.6 m) and Flood Stage (14.6-16.8 m) maximized total suspended sediment with 28.9 MT supplied. Atchafalaya River Delta Complex growth rate was 2.8 km^2 yr^{-1} (1989-2010). Both Atchafalaya River Morgan City subdelta (ARSD) and Wax Lake Outlet Subdelta (WLSD) growth rates were influenced by large floods that helped maintain positive growth rates, and tropical systems that decreased growth rates over the period. Average annual sedimentation rate in the Atchafalaya River Basin (ARB) was estimated between 30.4-79.1 mm yr^{-1}, while total suspended sediment

retention averaged 5.3 MT yr^{-1} (1996-2010), but interannual variation demonstrates that the ARB has reached an equilibrium and resembles a fluvially dominated system rather than lacustrine or palustrine system. Results from this study provide an exhaustive understanding of riverine sediment availability to coastal Louisiana and the impacts on coastal evolution, providing information that land managers can use to model restoration of coastal Louisiana.

CHAPTER 1: INTRODUCTION

Globally deltas are home for hundreds of millions of people and a countless number of species. The fertile land where alluvium and freshwater meets the sea creates a bounty that has been used by man to support important economies and major cities throughout the world. Each delta is unique, shaped by boundary conditions and forcing factors that can be classified into three general categories: river dominated, tide dominated, or wave dominated (Galloway 1975). Within these categories deltas can take on much different morphologies based on sediment load and discharge (catchment characteristics), accommodation space, coastal bathymetry, coastal energy, and density differences (Syvitski and Saito 2007).

Holocene deltaic environments started developing once the global sea level stabilized during a sea level still stand period 5,000-7,000 years ago (Frazier 1967; Amorosi and Milli 2001). The natural evolution of a delta is controlled tightly by the factors listed previously, and under natural conditions undergoes a dynamic stable equilibrium punctuated by transgressive and regressive stages depending on sea level rise, local tectonics, and river power. This natural cycle has been altered greatly as human influence has increased to a scale that impacts entire catchments. With increases in farming, dams, and river training structures (levees, bank stabilization, channel straightening, check dams etc.) altering inputs and local morphology deltas have responded accordingly.

The Mississippi River Deltaic Plain in coastal Louisiana, USA is one of the most highly engineered and developed deltas in the world. The Mississippi River that feeds the delta has a total length of 5,969 km with a catchment that comprises 3,224,535 km^2 of mostly farmland, and has many dams along its major tributaries. The river is continuously leveed for 2445 km, starting in south Illinois all the way to the outlet at the delta mouth in Louisiana, thus ensuring no flooding of the delta plain and no river avulsion. Because of the hydrologic alterations, the deltaic plain has seen approximately 4877 km^2 of low-lying coastal land become submerged since 1932 (Couvillion et al. 2011), with peak delta plain loss

being reported on the scale of 60-75 km^2 per year from the 1960's to the 1980's (Britsch and Dunbar 1993; Barras et al. 2003). Although, land loss has not been universal along the delta plain, with prograding delta features at the mouth of the Atchafalaya River, the largest distributary of the Mississippi River.

The Atchafalaya River has been a distributary of the Mississippi River as far back as the 1500s (Fisk 1952). As a distributary, it is more than 308 km shorter than the Mississippi River (from where the rivers intersect) and because of this the Atchafalaya River has a more favorable gradient when compared to the Mississippi River (Fisk 1952). Due to the more favorable gradient in conjunction with human alterations to the Mississippi River and Atchafalaya River a better defined channel began to form in the mid-1900s, which increased the flow volume going down the Atchafalaya River (Roberts et al. 1980). With fears of the Atchafalaya River capturing the majority of the flow of the Mississippi River, the Old River Control structure was constructed in 1963 under the Flood Control Act of 1954, which maintains approximately 25% of the Mississippi River discharge and all of the Red River discharge going down the Atchafalaya River. Even with more regulated flow, increased discharge volume over time led to many of the open water areas in the Atchafalaya Basin accumulating sediments and losing much of the swamp and open water habitat due to lacustrine delta formation (Tye and Coleman 1989). With many of the open water areas becoming sediment filled sedimentation in the Atchafalaya Bay began to become noticeable in the 1950s with the formation of a subaqueous delta (Shlemon 1975). Since 1973 there has been an increase in subaerial delta formation at Wax Lake Outlet (a man-made canal connected to the Atchafalaya River) as well as at the main channel of the Atchafalaya River (Roberts 1997).

Land loss in coastal Louisiana has not been isolated to the Mississippi Deltaic Plain, but has also been occurring in the Louisiana Chenier Plain, a physiographic region west of the Mississippi Deltaic Plain. The Louisiana Chenier Plain is named after the oak trees that line the beach ridges, (Chêne- French for oak). It is located west of the Mississippi River Deltaic Plain in southwestern Louisiana, comprising an area of approximately 5,000 km^2 and a coastline of about 200 km. The Louisiana Chenier Plain was

created by western movement of Mississippi River sediments along the coast (Penland and Suter 1989). During periods when the Mississippi River discharged further west, more readily available riverine sediment allowed for progradation of the Chenier Plain coast. During periods when the Mississippi River avulsed eastward, the Chenier Plain coastline was sediment starved and reworked by wave erosion creating transgressive chenier ridges of shell and sand (Russel and Howe 1935; Hoyt 1969; McBride et al. 2007). These ridges are interspaced with lowland marsh plains formed during periods of high sediment input (Russell and Howe 1935; McBride et al. 2007). The Louisiana Chenier Plain is bisected by four, north to south flowing rivers; Sabine River, Calcasieu River, Mermentau River, and Vermilion River. All of the rivers have been highly altered with dams, locks, dredged channels, permanent openings to the Gulf of Mexico, as well as the east to west traveling Gulf intercoastal waterway that connects the once separate rivers.

The modern Mississippi River Deltaic Plain and interior portions of the Louisiana Chenier Plain are undergoing land loss due to subsidence that has been accelerated by anthropogenic changes to the course and catchment characteristics of the Mississippi River as well as hydrologic alterations to the rivers that bisect the Chenier Plain. Subsidence is one of the major factors that reshape river deltas after avulsion and subsequent abandonment. Subsidence dictates accommodation space, progradation speed, or lack of progradation if sediment inflow to the delta cannot keep up with subsidence rate. Louisiana has one of the highest rates of relative sea level rise in the world with estimates between 1.09-1.19 cm yr^{-1} (Penland and Ramsey 1990). The relative sea level rise is greater due to high rates of subsidence. There have been many different explanations of why subsidence is high in Louisiana, with the main reasons being; (1) tectonics (fault processes and halokinesis), (2) Holocene sediment compaction, (3) sediment loading, (4) glacial isostatic adjustment, (5) fluid withdrawal, and (6) surface water drainage and management (Yuill et al. 2009). Each explanation comes with different rates of subsidence due in part to either different measurement techniques or from multiple processes working in conjunction (Meckel 2008). Whatever the true cause, the problem still exists of land loss and inundation of land due to sea

level rise and storm events, endangering many coastal communities and industries (Blum and Roberts 2009).

The Mississippi River Delta development and maintenance depends on sediment supply from the Mississippi River. After the great flood of 1927 flood control measures were implemented in order to ensure that the Mississippi River stayed within its banks and did not flood farmland and communities close to the river (MRC 2007). In addition to flood controls there have been many dams completed along the Missouri River, a major tributary of the Mississippi River. Other engineering structures that have altered the natural state of the river have been meander cutoffs, river-training structures, bank revetments, and dikes (Kesel, 2003). Due to the many alterations to the river and catchment (soil conservation) it has been estimated that sediment load reaching the delta has been reduced by 50% to 70% (Keown et al. 1986; Kesel 1988). Sediment loads prior to the 1960s reached upwards of 400 $x10^6$ tonnes yr^{-1}, while current estimates are only to 115 to $130x10^6$ tonnes yr^{-1}(Horowitz 2010) for the Mississippi and $172x10^6$ tonnes yr^{-1} for the Mississippi and Atchafalaya combined (Meade and Moody 2010). This reduced sediment supply limits opportunities for the river to create new wetlands and it has been postulated by Blum and Roberts (2009) that current sediment levels would not be able to counterbalance future sea level rise.

With land loss endangering coastal communities, state and federal agencies have been working together to implement various restoration projects ranging from rebuilding barrier islands to marsh restoration (CPRA 2012). To achieve restoration goals, a comprehensive understanding of sediment availability is needed. Sediment resources have been identified as offshore shoals from previous delta complexes as well as fluvial sediments derived from the Mississippi River (Khalil et al. 2010). Most calculations of riverine suspended sediment supply have only been long-term studies on trends (as introduced above), and have neglected other coastal riverine resources. What still has not been identified is the actual amount of available sediment for restoration, and how changes in sediment dynamics may affect coastal evolution.

The objective of this thesis research was to answer the principal question of what is the actual amount of riverine suspended sediment that is discharged to coastal Louisiana. This question is broken down into four separate chapters that detail sediment dynamics of three distinct areas along coastal Louisiana. The second chapter presents a study completed on the rivers that bisect the Louisiana Chenier Plain. The study quantifies suspended sediment yield of the Sabine River, Calcasieu River, Mermentau River, and Vermilion River, investigates seasonal and interannual variations of suspended sediment transport, and discusses potential impacts on Chenier Plain management. The third chapter focuses on the amount of suspended sediment available from the Mississippi River. Calculations are completed using different river stages at Red River Landing, LA to understand changes in suspended sediment dynamics during flood pulses, between different flood magnitudes, as well as during the rising and receding limb. Chapter three is discussed with current and future diversion management considerations. Chapters four and five focus on suspended sediment dynamics of the Atchafalaya River. These studies examine long-term suspended sediment dynamics of the Atchafalaya River, explore a spatial based sedimentation estimate technique for the Atchafalaya River Basin, and quantify Atchafalaya River Delta Complex growth and discuss it in light of suspended sediment discharge from the Atchafalaya River. Chapters two, three, four, and five are written as stand-alone manuscripts that have been accepted, reviewed, or submitted to peer-reviewed journals.

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CHAPTER 2: RIVERINE SEDIMENT INFLOW TO LOUISIANA CHENIER PLAIN IN THE NORTHERN GULF OF MEXICO[1]

2.1 INTRODUCTION

Riverine sediments are integral resources to coastal environments influencing geological and hydrological processes (Masselink and Hughes 2003). Much of southern Louisiana has been formed by Mississippi River sediments through the natural process of river avulsion and subsequent delta switching. The Chenier Plain, a physiographic province in southwestern Louisiana, has similarly been influenced by the movement of the Mississippi River sediment plume (Penland and Suter 1989). In general, when compared with the barrier islands along Louisiana's coast or the Mississippi Deltaic Plain, the Chenier Plain is less well known. Nonetheless the area has gone through many anthropogenic alterations that have exacerbated natural land loss.

The Chenier Plain comprises an area of approximately 5,000 km^2 and a coastline of about 200 km. The land cover is dominated by location sensitive salt, brackish, intermediate, and fresh marshlands (Gammill 2002). The lowland marsh is interspaced by chenier ridges formed during transgressive phases when the Mississippi River sediment plume is unable to reach the plain (for details regarding Chenier Plain formation see Russell and Howe 1935, Hoyt 1969, and McBride et al. 2007). Bisecting the plain are four north to south flowing rivers, Sabine River, Calcasieu River, Mermentau River, and Vermilion River. The Sabine River has a drainage area of 25,267 km^2 with a total length of 893 km bordering Texas and Louisiana draining into Sabine Lake before the Gulf of Mexico (Phillips 2003). The Calcasieu River drainage basin is 9,780 km^2

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and the river is 322 km long and discharges into Calcasieu Lake before the Gulf of Mexico (Nichol et al. 1992). The Mermentau River basin is 16,997 km^2 with a length of 115 km discharging into Grand Lake before reaching the Gulf (USACE). The Vermilion River is 116 km long with a basin area of 4,470 km^2 draining into Vermilion Bay (U.S EPA 2001; USACE 2004). The Mermentau River and Vermilion River basins are dominated by agriculture and the Calcasieu River and Sabine River basins are dominated by forest (Table 2.1).

Table 2.1. Land use conditions of four river basins draining into the Louisiana Chenier Plain, U.S.A.

River Basin	**Drainage size (km^2)**	**Land Use (%)**				
		Agriculture	**Forest**	**Wetlands**	**Urban**	**Water**
Sabine[a,b]	25,267	14	54	17	6	9
Calcasieu[c,d]	9,780	26	51	12	3	8
Mermentau[e,f]	16,997	67	7	16	3	7
Vermilion[g]	4,470	40	22	33	5	<1

[a] Phillips, 2003,.[b] USGS, 2011.[c] Nichol et al., 1992.[d] LDEQ, 2001.[e] USACE. [f] Baker, 1999.[g] US EPA Region 6, 2001.

During the past half century all of the rivers have been hydrologically altered substantially. The Sabine River has been dammed in several locations and its lower estuary has been dredged for navigational purposes. The estuary of the Calcasieu River has also been dredged with a permanent opening to the Gulf of Mexico. Along the Mermentau River many freshwater locks have been installed in order to control saltwater intrusion; its lower portion has been dredged and channelized. The Vermilion River receives freshwater from the Atchafalaya River via the Teche-Vermilion pumping station in order to prevent salt water intrusion. Each basin has been connected by an east to west canal (GIWW, the Gulf Intercoastal Water Way). These modifications have altered the hydrological conditions allowing for greater tidal prism, saltwater intrusion, and greater connectivity of the basins that make up the Chenier Plain

(Gammill 2002). The locks added to exclude salt water have potentially raised inner plain water levels. Much discussion has centered on whether salinization or higher water levels has led to more marsh loss, but regardless proper management is needed to maintain healthy marsh. This is especially true as the main discharge of the Mississippi River through the Plaquemines/Balize (birdfoot) delta has left much of the Chenier Plain sediment starved except for portions that are closest to Atchafalaya Bay (Draut et. al 2005). Land loss (taking in account for land gains) has been approximately 146 km^2 between the years from 1988 to 2010 (Couvillion et al. 2011) and, for the 2005 hurricane season alone, an area of about 218 km^2 was estimated to be lost (Barras 2007).

With the Chenier Plain being highly modified and cut off from the main Mississippi River sediment plume, other sediment resources within the plain have become increasingly important in order to counteract natural land loss from coastal erosion and marsh subsidence (CPRA 2010). One possible sediment resource located in the Chenier Plain is sediment from the four rivers that drain through the plain. Until now, however, no report has been published on sediment loads from these rivers and little is known about their impact on sediment accumulation within the Chenier Plain. As Campbell and others (2005) postulated, future restoration projects in this coastal region must direct attention toward obtaining essential data along the Chenier Plain. This study aimed to fill the knowledge gap and provide useful information to coastal resource policy makers in developing plans and strategies for regional sediment management. The primary purpose of the study was two-fold: (1) to quantify long-term suspended sediment delivery from Sabine River, Calcasieu River, Mermentau River, and Vermilion River, and (2) to investigate the effect of hydrometeorological conditions on seasonal and inter-annual trends of suspended sediment transport.

2.2 METHODS

2.2.1 Long-term Discharge, Sediment, and Precipitation Data

The four rivers that feed the Chenier Plain have been well gauged by the United States Geological Survey (USGS) (Figure 2.1). Daily mean discharge data were collected from the USGS stations along these rivers for the period 1990-2009. The stations were chosen based on their proximity to the mouth of the river to account for both optimal drainage representation and minimal tidal influence. Specifically, the locations were Sabine River near Bon Wier, TX (USGS 08028500), Calcasieu River near Kinder, LA (USGS 08015500), Mermentau River at Mermentau, LA (USGS 08012150), and Vermilion River at Perry, LA (USGS 07386980) (Figure 2.2). Discharge data were also collected from Sabine River at Toledo Bend Reservoir near Burkeville, TX (08025360) for the period 1990-2009 and from Bayou Teche at Arnaudville (07385500) and Adeline Bridge near Jeanerrette, LA (07385765) for the period 1997-2006. Long-term data on riverine total suspended solids (TSS) were obtained from the Louisiana Department of Environmental Quality (LDEQ), collected mostly monthly at the following stations: Sabine River west of Merryville, LA (LA110201_00), Calcasieu River near Kinder, LA (LA030103_00), Mermentau River at Mermentau, LA (LA050401_00), and Vermilion River at Perry (LA060802_00) (Figure 2.1). In addition, we gathered precipitation data for the period 1990-2009 to assess the hydrometeorological effect on sediment transport. The data were obtained from four weather stations of the United States Southern Regional Climate Center (all except Port Arthur, Texas located in Louisiana): Alexandria (Station#: 160098), Lafayette (165026), Lake Charles (165078), and Port Arthur (417174). Discharge, precipitation, and TSS (excluding Toledo Bend and Bayou Teche discharge) were analyzed using seasonal Mann-Kendall test for trend using DOS based program developed by USGS (Helsel et al. 2005). A

regression was completed on Toledo Bend reservoir discharge and Sabine River discharge at Bon Wier. The discharge difference at Arnaudville and Jeanerette was used as the amount diverted to the Vermilion River from Bayou Teche. This amount was subsequently subtracted from annual discharge for the period 1997-2006 and regression on precipitation and discharge was then completed for the Vermilion River.

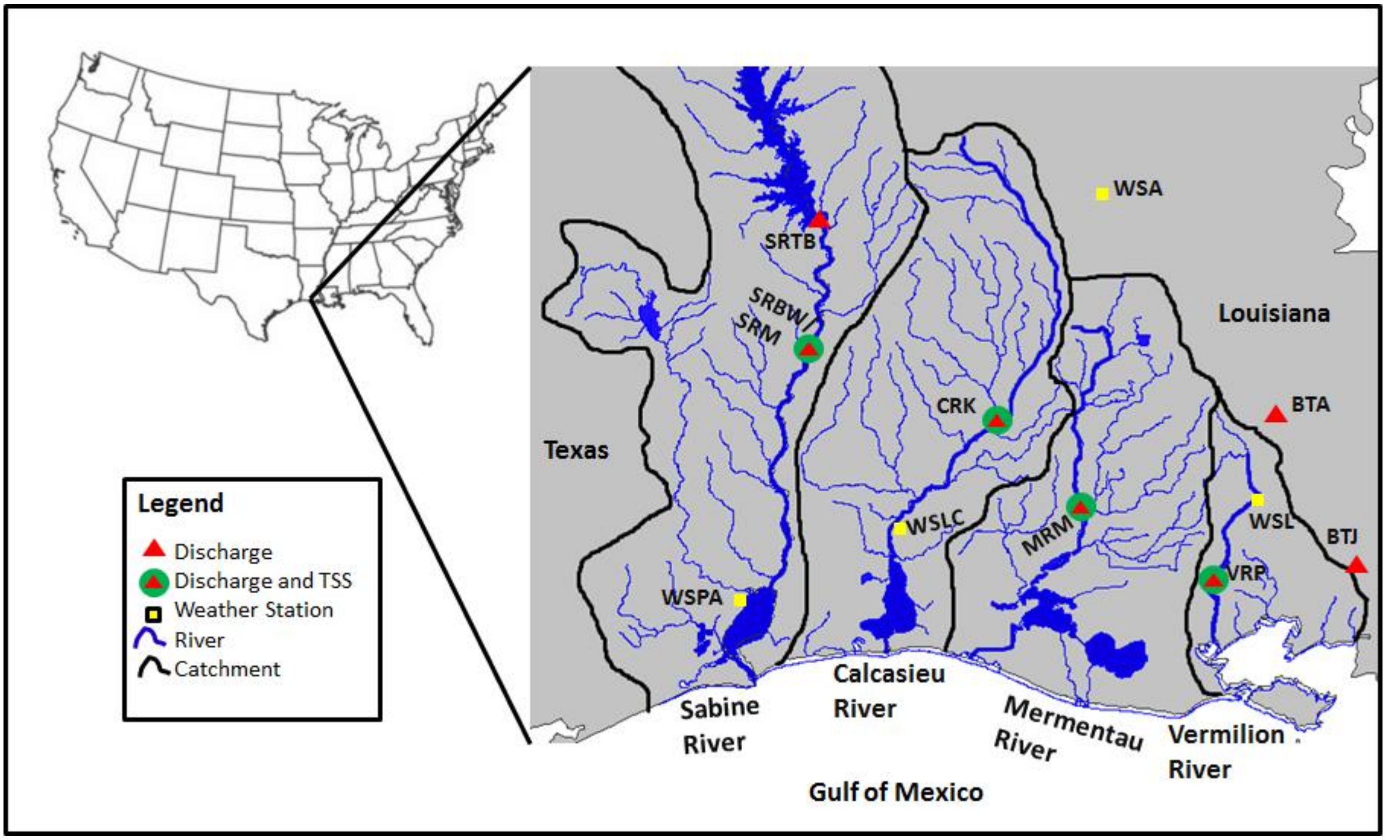

Figure 2.1. Geographical location of the Chenier Plain in Louisiana, USA (bounding coordinates 29.75, -93.88 and 29.59,-92.05), and the location of USGS river gauging stations, LDEQ TSS collection sites, and weather stations. Abbreviated names are Sabine near Bon Wier, TX (SRBW), Sabine River west of Merryville, LA (SRM), Sabine River at Toledo Bend Reservoir near Burkeville, TX (SRTB) Calcasieu near Kinder, LA (CRK), Mermentau River at Mermentau, LA (MRM), Vermilion River at Perry, LA (VRP), Bayou Teche at Arnaudville (BTA), and Bayou Teche at Adeline Bridge near Jeanerrette, LA (BTJ). Weather station names are Alexandria (WSA), Lafayette (WSL), Lake Charles (WSLC), and Port Arthur (WSPA).

Figure 2.2. Pictures of the Chenier Plain rivers near the USGS recording stations. A. Sabine River, B. Calcasieu River, C. Vermilion River, and D. Mermentau River.

2.2.2 Sediment Load Calculation

To estimate daily sediment load, a sediment rating curve was developed for each river based on:

$$S=aQ^b \tag{1}$$

where S is the daily suspended sediment load, Q is discharge, a and b are constants (Miller 1951, Glysson 1987). The equation can be log transformed to:

$$ln(S)=ln(a) + bln(Q)+\varepsilon \tag{2}$$

where ε is the random error that is normally distributed (Helsel and Hirsch 2002). For each river best fit equations were produced on log transformed discharge from the USGS and load calculated from TSS (LDEQ) and discharge (USGS). The equation for the Sabine River used monthly means of discharge and load, the rest of the equations used all available daily data. The log transformed equations were:

Sabine River: $$ln(S)=-1.384 + 1.3927\ ln(Q) \tag{3}$$

Calcasieu River: $$ln(S)=-0.3815 + 1.1852\ ln(Q) \tag{4}$$

Mermentau River: $$ln(S)=-0.0604+ 1.1434\ ln(Q) \tag{5}$$

Vermilion River: $$ln(S)=0.8834+ 1.1469\ ln(Q) \tag{6}$$

The above equations obtained the following regression coefficients (3) r^2=0.96, (4) r^2=0.75, (5) r^2=0.85, and (6) r^2=0.67 (see Appendix Figure A1).

The accuracy of the predicted value was evaluated by % difference between measured loads calculated from sampled TSS values and measured discharge against values predicted from the equations only using the measured discharge, based on Horowitz (2003):

%difference= [(predicted value)-(measured value)/(measured value)]x100 (7)

Daily sediment load estimated using these equations was summed up for total monthly, annual, interannual, and seasonal fluxes in sediment yield for a 20-year period from January 1990 through December 2009. The seasonal Mann-Kendall non-parametric test was performed to determine trend in discharge and sediment loads during the study period.

2.3 RESULTS

2.3.1 Long-term Discharge and TSS Concentration

Over the period from 1990 to 2009 the Sabine River, when compared to the other rivers, had the highest average daily discharge of 219 $m^3 s^{-1}$ (std: ±242), ranging between 11 and 2561 $m^3 s^{-1}$. The Vermilion River showed the lowest average daily discharge of 33 $m^3 s^{-1}$ (±33), varying from zero flow to 396 $m^3 s^{-1}$. Daily discharge of the Mermentau River and Calcasieu River averaged 82 $m^3 s^{-1}$ (±104) and 72 $m^3 s^{-1}$ (±126), respectively (Table 2.2).

Table 2.2. Average daily discharge and average TSS with minimum, maximum, and standard deviation for four rivers to the Louisiana Chenier Plain, U.S.A..

River	**AVG Daily Q ($m^3 s^{-1}$) (min-max; ±std)**	**AVG TSS (mg L^{-1}) (min-max; ±std)**
Sabine	219 (11-2561; 242)	17 (1-88; 12)
Calcasieu	72 (4-1910; 126)	18 (4-84; 13)
Mermentau	82 (0-1177; 104)	26 (4-280; 33)
Vermilion	33 (0-396; 32)	56 (4-566; 61)

All these rivers, except the Vermilion River that received water from the Atchafalaya River, showed a decreasing trend in discharge in the past 20 years. The trend was, however, only statistically significant with the Sabine River (seasonal Mann-Kendall, p=0.05) (Figure 2.3). All these rivers, except for the Sabine River that is dammed for the Toledo Bend Reservoir, showed a close, positive precipitation-discharge relationship (r^2=0.68, 0.82, and 0.75 for the Calcasieu River, Mermentau River, and Vermilion River, respectively) (see Appendix Figure A2). The Sabine River discharge was better described by discharge from the Toledo Bend reservoir (r^2=0.98) rather than precipitation in the lower basin (r^2=0.42). The Vermilion River discharge had a stronger relationship with precipitation after diversions from Bayou Teche were accounted for (r^2=0.79). Mean daily discharge diverted from Bayou Teche was 17 $m^3 s^{-1}$, representing approximately 52% of the total discharge of the Vermilion River. All four rivers showed a clear seasonal trend with higher flow during the winter and spring months and lower flow during the summer and fall months (Figure 2.4).

The Sabine River showed a long-term average TSS of 17 mg l^{-1} (std: ±13) with a range from 1 to 88 mg l^{-1}. TSS for the Calcasieu River during the same period averaged 18 mg l^{-1} (±14), but was as low as 4 mg l^{-1} and as high as 84 mg l^{-1}. The Mermentau River TSS during the study period averaged 26 mg l^{-1} (±34), with a minimum of 4 mg l^{-1} and a maximum of 280 mg l^{-1}. Mean TSS of the Vermilion River was 56 mg l^{-1} (±62) with a minimum of 4 mg l^{-1} and a maximum of 566 mg l^{-1} and with a significant decreasing trend (seasonal Mann-Kendall, p=.01; Table 2.2). In general, as with the river discharge, TSS concentration of the four rivers showed a seasonal trend with higher values during the winter and spring and lower values during the late summer and fall (Figure 2.5). The trend was especially prevalent in the Mermentau River and Vermilion River, whose drainage basins were predominantly agriculture in land use.

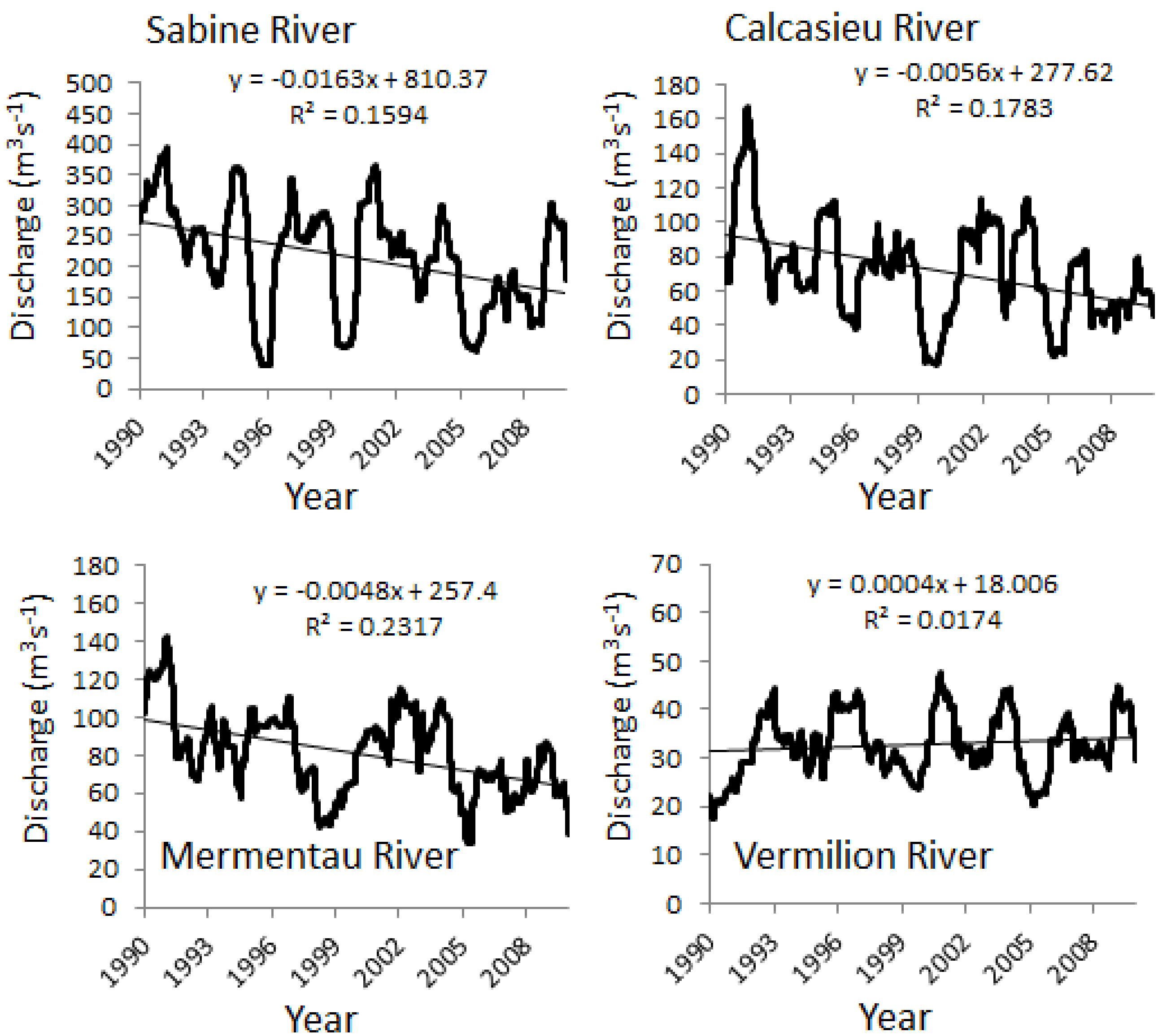

Figure 2.3. Annual 365-day moving average of discharge from the Sabine River, the Calcasieu River, the Mermentau River, and the Vermilion River.

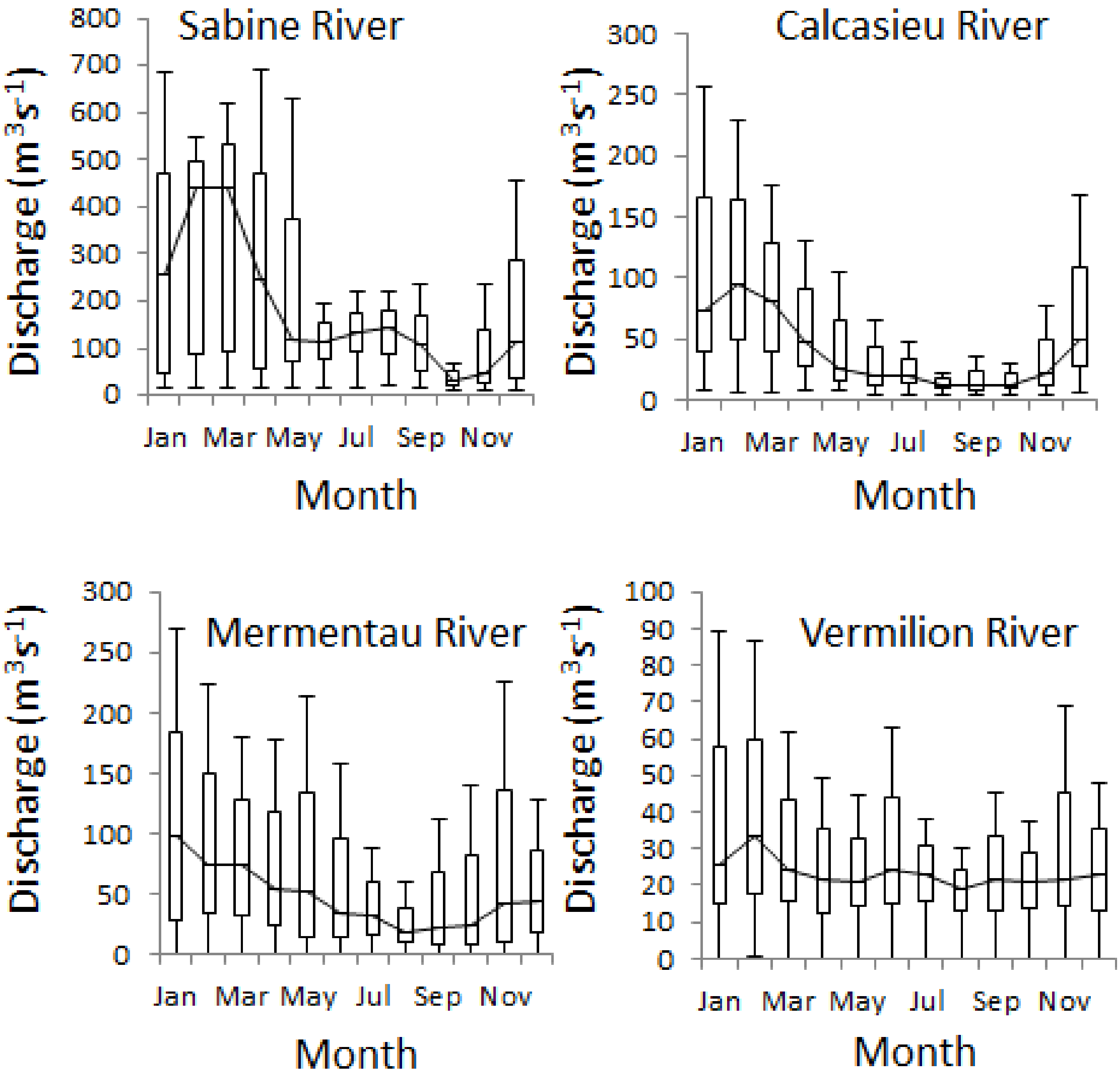

Figure 2.4. Monthly median discharge for Sabine River, Calcasieu River, Mermentau River, and Vermilion River with error bars representing 90 % (top) and lowest discharge value (bottom).

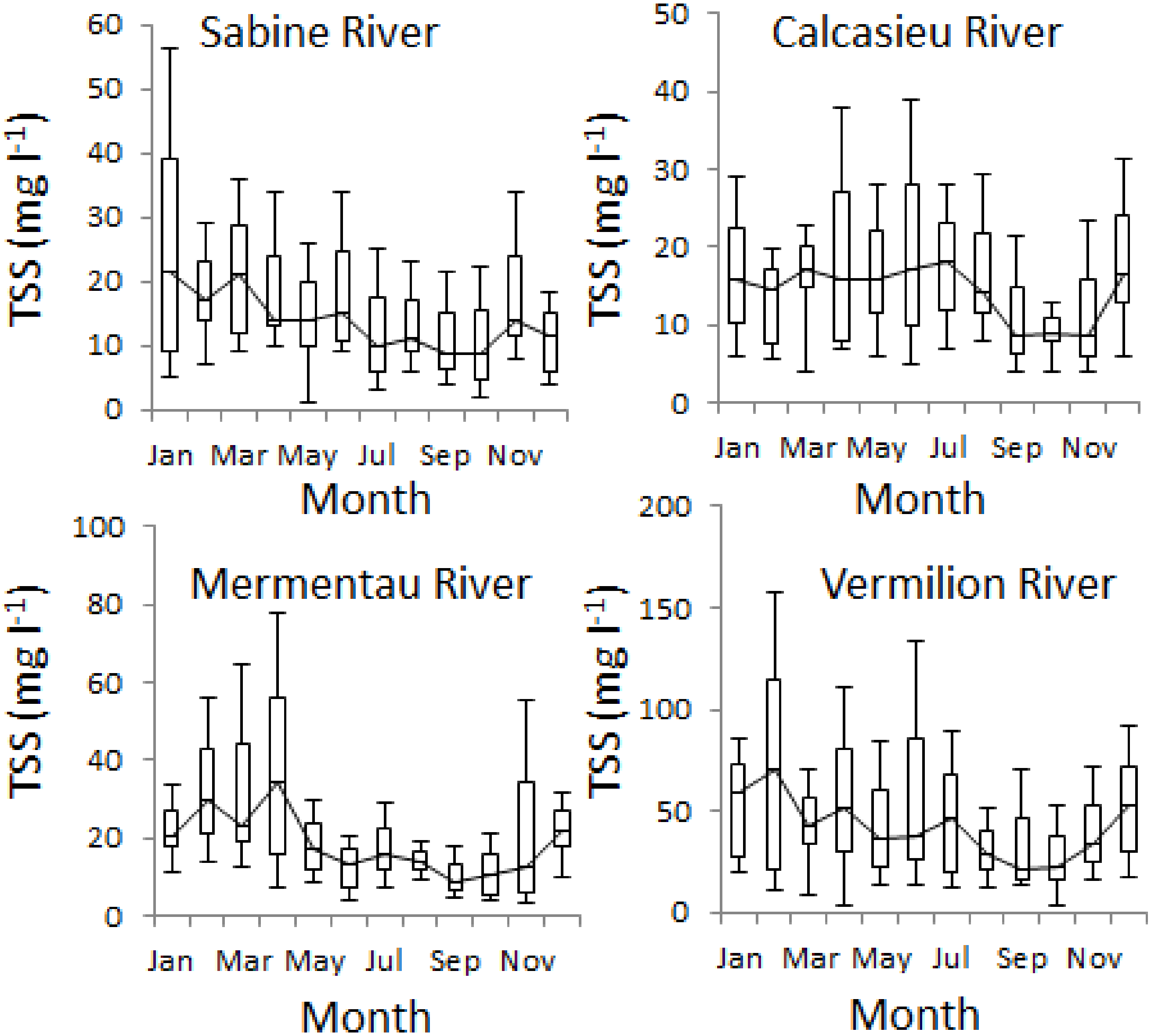

Figure 2.5. Monthly median TSS concentrations of waters collected from the Sabine River, Calcasieu River, Mermentau River, and Vermilion River.

2.3.2 Seasonal Trend of TSS Loads

Seasonally, the rivers showed a trend with higher daily TSS loads in the winter and spring and lower in the fall (Figure 2.6), corresponding to the flow conditions and TSS concentration changes (Figures 2.4 and 2.5). Mean monthly daily load for the Sabine River during the study period was 568 tonnes with the highest average load in March (1,326 tonnes) and the lowest average monthly load in October (148 tonnes). The Calcasieu River had a mean monthly daily load of 129 tonnes with January averaging the highest load (250 tonnes) and August averaging the lowest load (20 tonnes). The Mermentau River averaged a monthly daily load of 157 tonnes, with January having the highest average load (242 tonnes) and August the lowest (47 tonnes). The Vermilion River mean monthly daily load was 138 tonnes, February averaging the highest (189 tonnes) and August averaging the lowest (80 tonnes). Comparably, the Sabine River and Calcasieu River showed much higher variation in monthly TSS load than the Mermentau River and Vermilion River whose basins were largely irrigated for agricultural cropping systems.

2.3.3 Interannual Variation in TSS Loads

TSS loads of all the four rivers showed large annual variation (Table 2.3, Figure 2.7). The Sabine River had an annual average TSS yield of 213,100 tonnes, varying largely from 16,000 tonnes in 1996 to 417,000 tonnes in 2001. TSS yields of the Calcasieu River fluctuated from 12,000 tonnes in 2000 to 118,000 tonnes in 1991, averaging 46,850 tonnes per year. Relatively, TSS yields of the Mermentau River and Vermilion River showed much less variation, fluctuating from 14,000 tonnes in 2000 to 93,000 tonnes in 1991 and from 13,000 tonnes in 1991 to 70,000 in 2004, respectively. The interannual variation of TSS yields for each river can be explained by

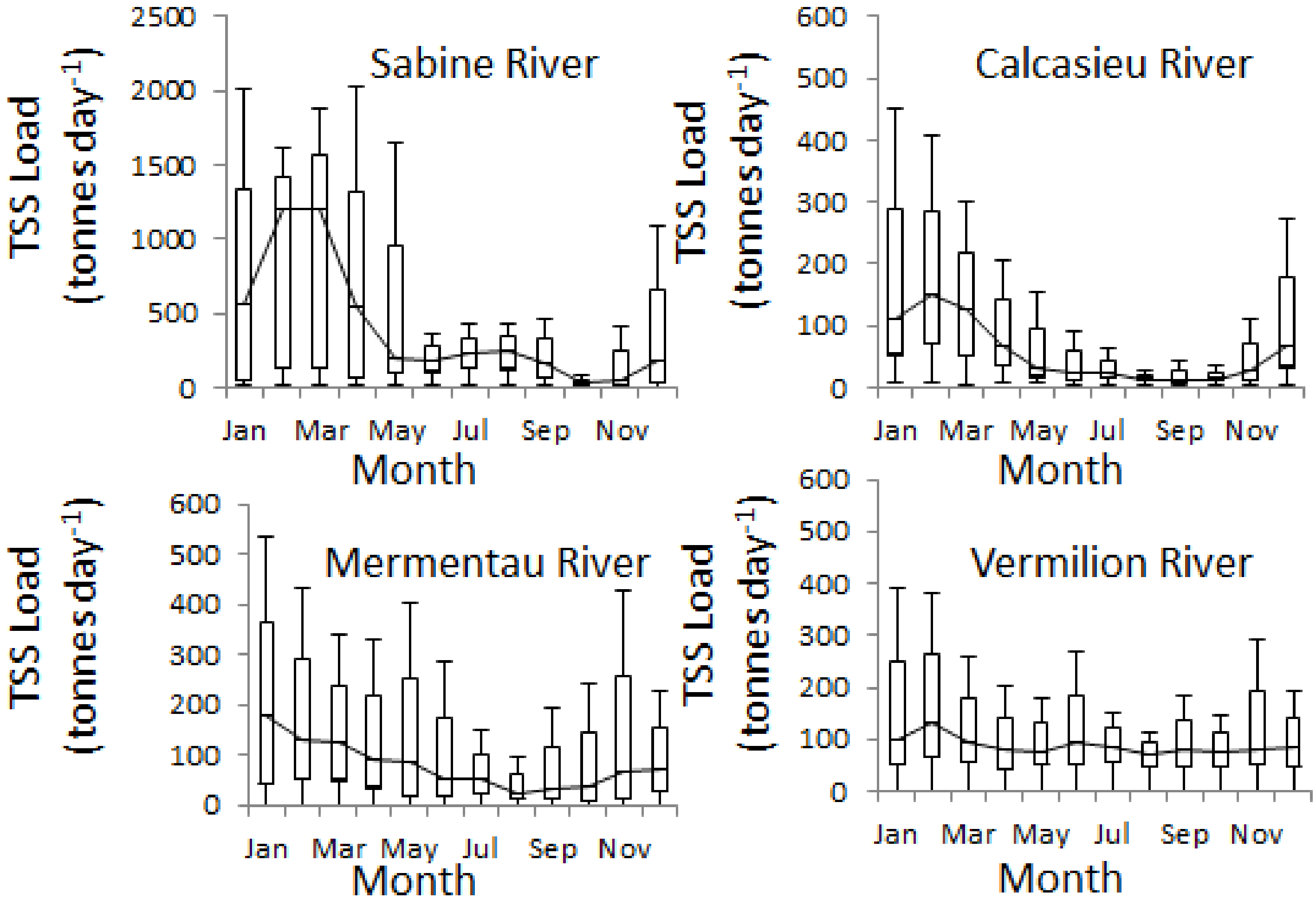

Figure 2.6. Monthly median sediment load for all four rivers, 1990-2009.

the interannual variation in discharge, with yields increasing linearly with increasing discharge (Figure 2.8). Annual total TSS yields from the four rivers varied from 100,000 and 121,000 tonnes in 1996 and 2000, two drier years during the study period, to 629,000 and 611,000 tonnes in 1991 and 2001, two wetter years (Table 2.3). Annual total TSS yields from the four rivers were highly dependent on the Sabine River, the largest river in the study. Higher or lower total annual yields were reflected mainly by the variation in Sabine River's discharge as affected by the upper basin precipitation and Toledo Bend reservoir management (see section 2.4.1). There was a decreasing trend in annual sediment yields from 1990 to 2009 for the Sabine River,

Calcasieu River, and Mermentau River, but the trend was only statistically significant for the Sabine River (seasonal Mann-Kendall, p=0.03) (Figure 2.7).

Table 2.3. Annual total river discharge (10^6 x m3) and TSS yield (tonnes) from four rivers to the Louisiana Chenier Plain, U.S.A. The years of 1996 and 2000 were driest and the years of 1991 and 2001 were wettest.

Year	**Total Discharge**	**TSS Yield**				
		Sabine	**Calcasieu**	**Mermentau**	**Vermilion**	∑
1990	12,612	275,000	42,000	31,000	23,000	371,000
1991	21,442	405,000	118,000	93,000	13,000	629,000
1992	12,589	245,000	40,000	37,000	40,000	362,000
1993	13,895	235,000	49,000	51,000	59,000	394,000
1994	11,662	195,000	40,000	35,000	43,000	313,000
1995	14,583	300,000	78,000	20,000	52,000	450,000
1996	4,477	16,000	21,000	33,000	30,000	100,000
1997	14,309	292,000	48,000	48,000	48,000	436,000
1998	13,543	266,000	63,000	32,000	37,000	398,000
1999	10,639	243,000	35,000	15,000	43,000	336,000
2000	5,065	56,000	12,000	14,000	39,000	121,000
2001	18,354	417,000	65,000	58,000	71,000	611,000
2002	13,798	213,000	66,000	63,000	36,000	378,000
2003	9,241	151,000	28,000	38,000	28,000	245,000
2004	16,508	282,000	78,000	66,000	70,000	496,000
2005	7,690	114,000	22,000	26,000	31,000	193,000
2006	6,403	56,000	32,000	32,000	37,000	157,000
2007	9,348	141,000	36,000	30,000	52,000	259,000
2008	8,748	135,000	30,000	32,000	42,000	239,000
2009	12,205	225,000	34,000	50,000	62,000	371,000
Total	237,110	4,262,000	937,000	804,000	856,000	6,859,000
Average	11,856	213,100	46,850	40,200	42,800	342,950

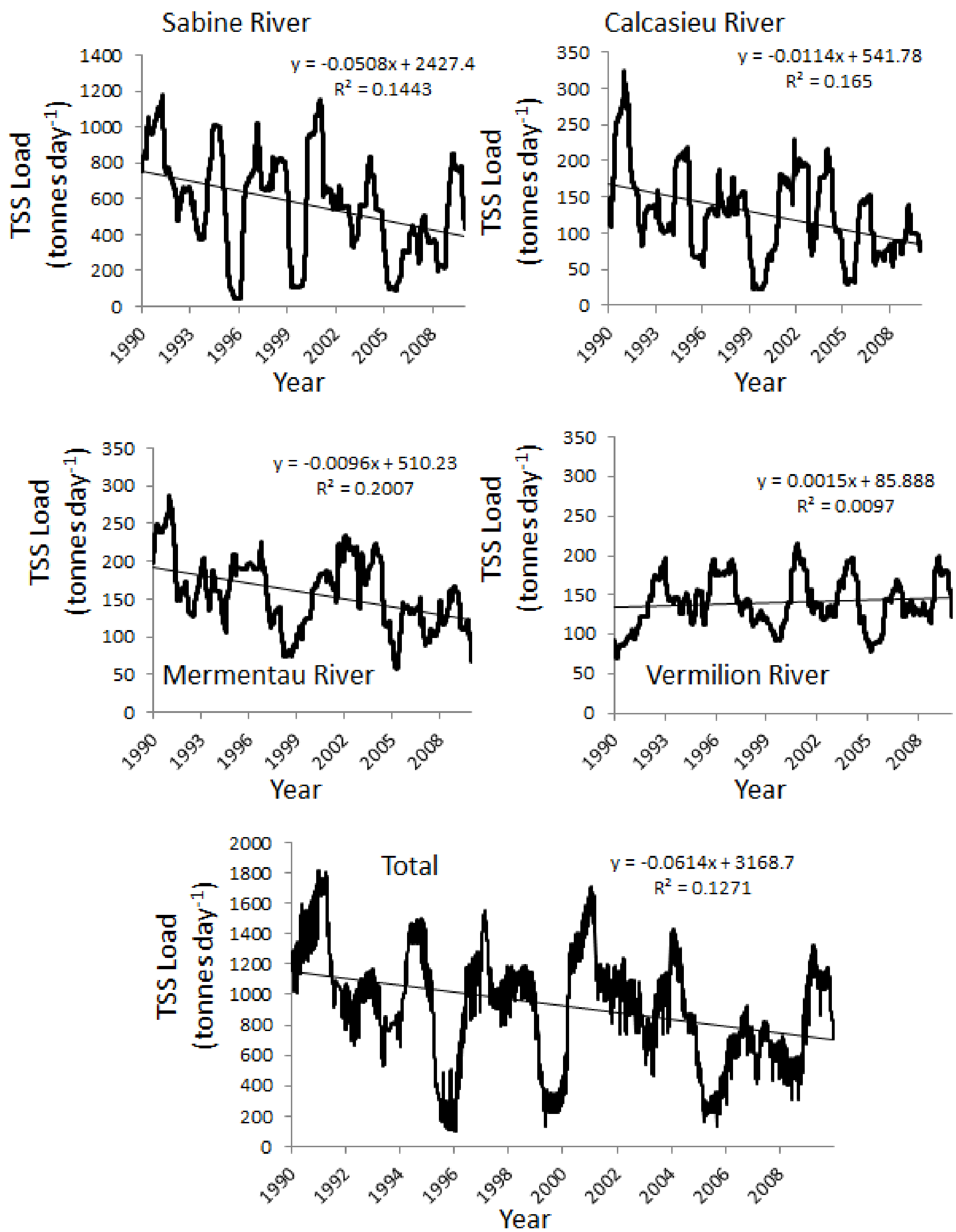

Figure 2.7. Annual 365-day moving average of sediment load.

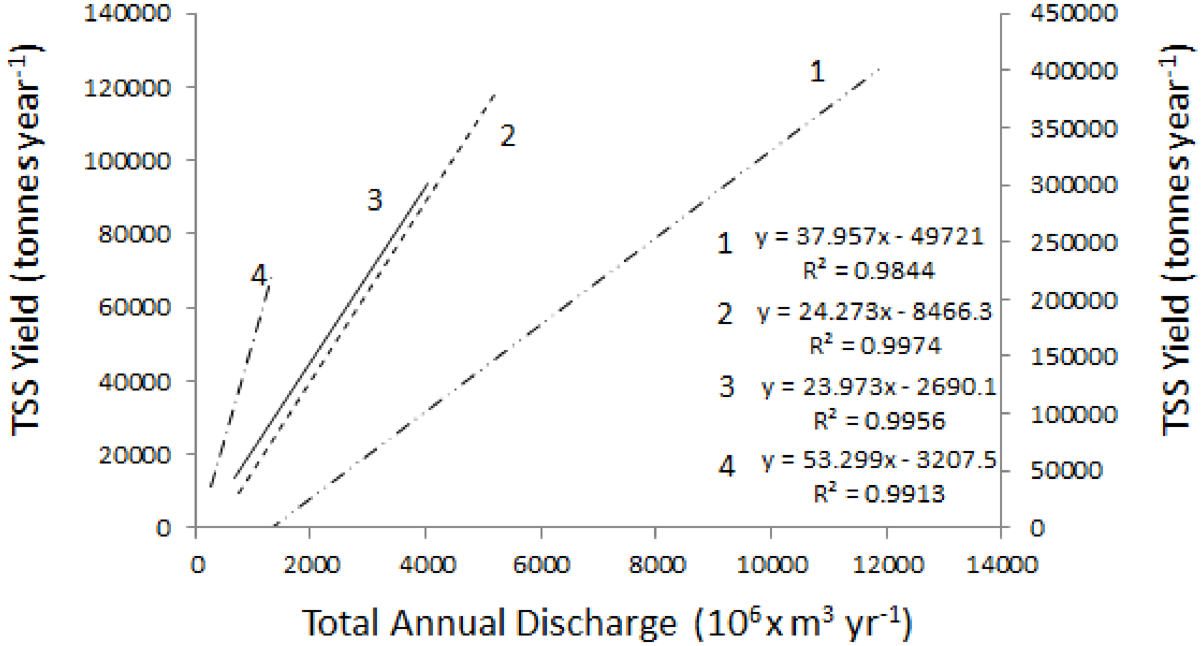

Figure 2.8. Total annual sediment yield plotted against total annual discharge for each river . 1. Sabine River, 2. Calcasieu River, 3. Mermentau River, and 4. Vermilion River

2.4 DISCUSSION

2.4.1 Hydrometeorological and Land Use Effects on Sediment Loads

Seasonal trends in discharge were controlled by the hydrometeorological conditions of the region. Higher flow in the winter and spring months and lower flow during the summer and fall occurred in all the rivers. During the summer months high evapotranspiration in conjunction with sporadic rainfall caused discharge to decrease. The winter months with low evapotranspiration and greater rainfall amounts allowed for greater runoff and discharge. This affected sediment loads during the time periods with higher sediment loads occurring during the months that had higher discharges. However, the Vermilion River did not show large discharge variation between seasons, primarily a result of the regulated inflow from the Atchafalaya River

by the Teche-Vermilion pumping station (USACE 2000) adding both freshwater and sediment into the system.

All the rivers except the Vermilion River experienced decreasing TSS load over the entire study period. This was a direct response to declining discharge corresponding to decreasing trend in precipitation. The Vermilion River is unique with discharge remaining nearly steady and high TSS elevating sediment load. The elevated TSS cannot be fully explained by land use because it would be expected that the Mermentau River (67% agriculture) to have comparable or higher TSS than the Vermilion River (40% agriculture). A direct relationship between higher TSS and agriculture has been found in many studies (e.g., Lenat and Crawford 1994; Ahearn et al. 2005). The elevated TSS for the Vermilion River can be explained by additions from Bayou Teche, subsequently from the Teche-Vermilion pumping station. As discussed earlier, the diversions from Bayou Teche can account for up to 52% of the discharge of the Vermilion River. This can contribute 60 (median) to 100 (mean) tonnes of sediment daily, equating to 44%-72% of the total daily sediment load of the Vermilion River. Although the diversions from Teche-Vermilion pumping station added to the sediment load, in a historical context this may not be unusual because before the Atchafalaya River was confided by levees the Vermilion River was naturally connected (USACE 2000). The other rivers better reflect land use within their basins with the Sabine River and Calcasieu River that are heavily forested having comparably lower TSS than the Mermentau River.

During the study period measured TSS concentrations did not show a long-term change in any of the rivers except the Vermilion River, suggesting that the hydrologic modifications during this study period did not have a significant effect on suspended sediment in the lower reach of the rivers. It could be argued that even though the Sabine River, Calcasieu River, and

Mermentau River have been heavily hydrologically modified, the main factor that controls the rivers sediment load is changes in discharge. Phillips (2003) made a similar observation concerning the lower Sabine River, reporting that although the lower Sabine River has been dammed at Toledo Bend reservoir the expected change in sediment transport, sand supply, or channel morphology had not occurred. This finding implies that the sediment regime of the river has not changed from the previous pre-dam state (less hydrologically modified) and, thus, sediment from the lower Sabine River must be coming from sources in the lower part of the river. The other rivers do not have the same dam modification as the Sabine River, but nonetheless have had many modifications and yet TSS has not changed with the largest factor affecting sediment load being discharge changes. The Vermilion River is the exception as it is heavily influenced in its flow and sediment concentration by water introduced from the Atchafalaya River via the Teche-Vermilion pumping station.

2.4.2 Sediment Source and Potential for Future Chenier Plain Development

From all four rivers, we estimated an average annual delivery of 342,950 tonnes of sediment. This amount is likely an underestimation as it has been documented that sediment rating often results in underestimation of sediment loads (Walling 1977; Ferguson 1986 and 1987; Helsel and Hirsch 2002). In our study loads may possibly have been underestimated between 8.5%-37.6% (eq. 7). The Calcasieu River sediment loads could be underestimated by 8.5% (eq. 4), predicting 49,071 tonnes when actual was 53,652 tonnes. The linear regression for the Sabine River underestimated sediment loads by 10.1% (eq. 3), predicting 176,803 tonnes when the actual load was 196,592 tonnes. The linear regression for the Mermentau River (eq. 5) underestimated by 37.6% (actual 41,307 tonnes vs. predicted 25,782 tonnes), and the Vermilion River loads were underestimated by 33.8% (actual 54,120 tonnes vs. predicted 35,810 tonnes).

This can be seen graphically in Figure 2.8 with observed and estimated loads plotted against flow exceedance interval. Underestimation occurred except for the highest flows (0-10% exceedance) for the Sabine River, underestimation for high to low flows (10-90% exceedance) for the Calcasieu River, the Mermentau River had all flow ranges underestimated, and the Vermilion

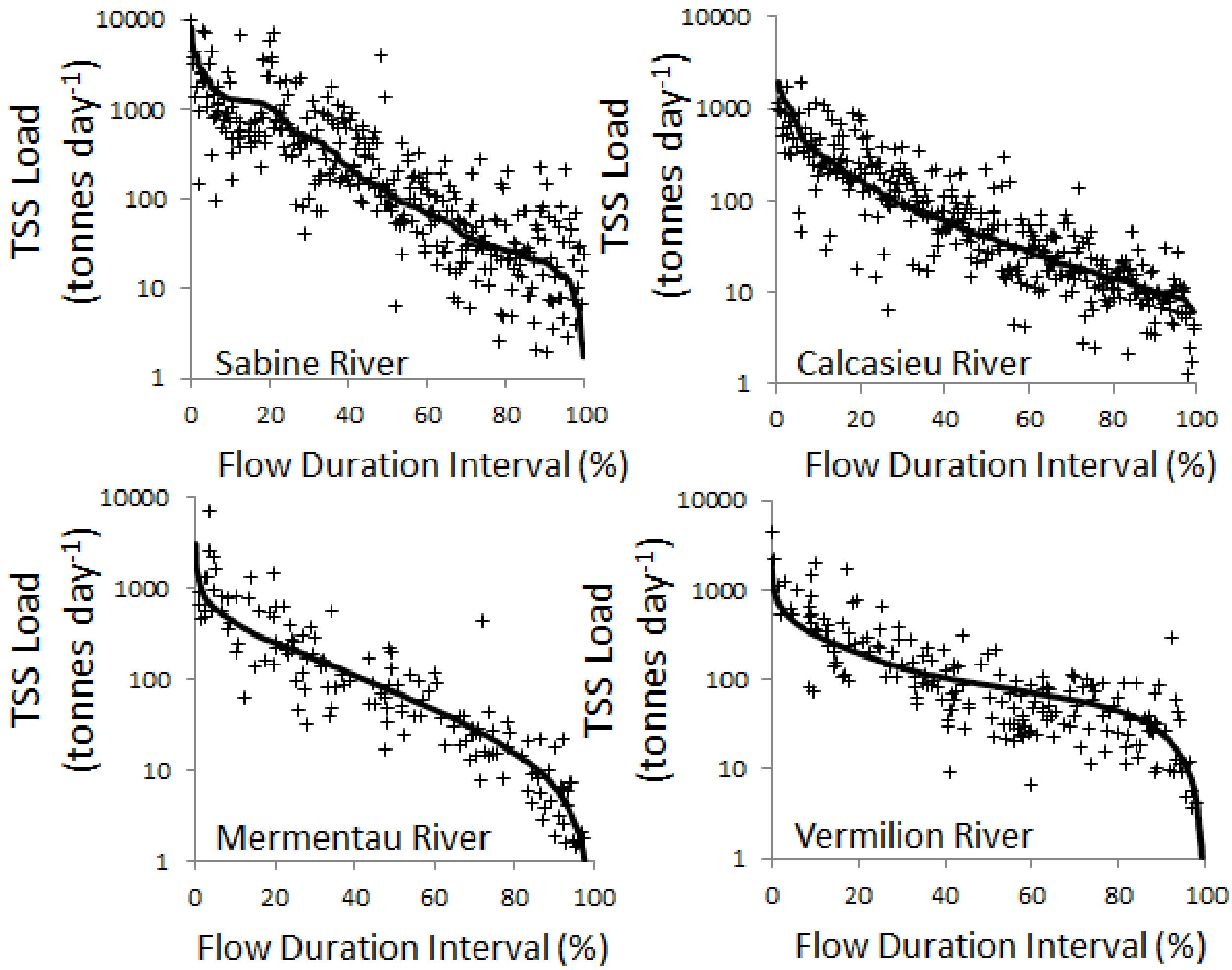

Figure 2.9. Observed sediment loads calculated from LDEQ TSS samples and estimated sediment loads plotted using flow exceedance. The smooth line is estimated loads and the individual markers are observed loads.

River had higher flows (0-40%) and the lowest flow periods underestimated (90-100%). The larger percent underestimation for the Vermilion River and Mermentau River could also be due to the fact that the discharge gauging stations used for this study experienced reversals of flow during certain time periods, reducing the amount of data used for developing sediment rating curves. For all the rivers a more comprehensive sediment sampling regiment would produce more accurate estimations, especially for different flow regimes (e.g., high vs. low flow, rising vs. receding limb of a hydrograph), which cannot be covered by a monthly sampling regiment that only takes a snapshot of sediment in the river at that time period.

Despite the possible underestimation our study provides a plausible range of total sediment yields and insight into their seasonal and interannual variability. Hypothetically, the estimated annual total yield from all the rivers (342,950 tonnes yr^{-1}) would be sufficient to replenish the 200 km (200,000 m) Chenier Plain coastline to 1 m depth by 1 m width (200,000 m^3) assuming a sediment bulk density of 1.5 tonnes m^{-3}, and that all sediment was delivered to the coast. This of course would be the best case scenario. There has been observed progradation for the Sabine River and Calcasieu River east and west of the river mouths. Even with this local progradation research by McBride and others (2007) classified the river mouths of the Mermentau River, Calcasieu River, and Sabine River as wave-dominated, tide-dominated/mixed, and tide-dominated. The progradation has been attributed to littoral flow of sediment and subsequent regressive land/ridge building at the mouths of the Calcasieu River and Sabine River and lateral accretion at the mouth of the Mermentau River (McBride et al. 2007). It is not uncommon for coastal plain rivers to be unable to overcome the tidal/wave force due to low power from low slope, river meanders, and estuaries. This can cause much of the sediment to be deposited in the upper portions of the estuary or within the alluvial plain (Barret 1971; Phillips

and Slattery 2006). Calcasieu Lake, the estuary that the Calcasieu River flows into before the Gulf of Mexico, demonstrates this being classified as wave dominated with fluvio-deltaic deposits terminating 31 km from the coast (Dalrymple et al. 1992; Nichol et al. 1992; McBride et al. 2007). The low river power compounded by the decreasing discharge and sediment load lessens the likelihood that these rivers will be significant sources of sediment to coastal portions Louisiana Chenier Plain.

The greatest asset to the coastal Chenier Plain is from the Atchafalaya River sediment that has been documented by Huh et al. (1991) and Draut et al. (2005) as accreting on the eastern coastline of the Chenier Plain. In a recent study, Xu (2010) reported an annual average sediment yield of 53 x 10^6 tonnes for the Atchafalaya River. Certainly, when compared with the large quantity of sediment from the Atchafalaya, sediment delivery from the four rivers in this study (0.34 x 10^6 tonnes yr^{-1}) appears to be insignificant. However, this sediment source can be crucial for the inner portions of the Chenier Plain that are undergoing wetland loss and salt intrusion due to alterations to the natural hydrologic state of the rivers. Under a best case scenario there exists the potential that the average annual sediment yield from the four rivers could provide a thin cover of 2.3 x 10^7 m^2 of sediment to the depth of 1 cm (assuming sediment bulk density of 1.5 tonnes m^{-3} and average annual load of 0.34 x 10^6 tonnes). This would not be enough to cover the entire 5,000 km^2 plain, but could counter localized subsidence that varies between 0.5-2.5 cm yr^1 (Shinkle and Dokka 2004).

Proper management of the sediment resources for the Chenier Plan is complex because of the extensive hydrological alterations. Water movement in each basin has been altered from the natural north-south direction to east-west for the Gulf Intercostal Water Way (38 m wide and 4 m deep) connecting the Sabine River Basin and Calcasieu River Basin and Calcasieu River Basin to

the Mermentau River Basin. Mouth bars at the entrance to the estuaries have been removed and dredging of channels has created year round openings to the Gulf of Mexico. A better understanding of how dredging the Calcasieu River (122 m wide and 12 m deep), Sabine-Neches ship channels (152 m wide and 12 m deep narrowing to 61 m wide and 9 m deep), and the Mermentau River Gulf of Mexico Navigation channel (67 m wide and 5 m deep) impacts sediment is necessary to understand how sediments move throughout the plain and estuaries. Current annual dredging from the Sabine-Neches and Calcasieu River ship channels ranges from 2,000,000 to 6,000,000 tonnes, with possible increases due to channel expansion (USACE 2010). All of the dredge cannot be attributed to riverine sediments, but regardless these channels represent a large sink for sediment. It is known that the channels create greater tidal prism as well as permanent outlets for the rivers to flow down during ebb tides or high flows, losing sediment and freshwater that would be trapped in the basins. Recent work completed by Mesehle and Miller (2009) to model Chenier Plain hydrodynamics indicate that all the freshwater reaches the Gulf, except in areas where locks prevent freshwater loss. This model is still in preliminary stages and thus greater commentary on how freshwater moves throughout the plain cannot be made (see Meselhe and Miller 2009 for more information of the regional model). Using hydrologic models in conjunction with these estimated sediment loads could help better understand where riverine sediments move within the Chenier Plain, but current knowledge is limited. A possible solution to better track sediment movements would be using satellite imagery to classify clear water and turbid water (riverine influenced) areas in conjunction with gauge data as has been done by Allen et al. (2008) for the Atchafalaya basin. Also, there needs to be consideration that the Sabine River accounts for 62% of the sediment load to the Chenier Plain. Currently, this river only has influence on its own basin and part of the Calcasieu River

basin. If restoration efforts were to be seriously taken there would need to be a concerted effort to either use the Sabine River as a sediment and freshwater source or to find another source, such as the Atchafalaya River. Even with limited understanding of sediment movements the sediment yield estimates are suitable for ongoing projects that are targeted at restoring freshwater marshland, especially for areas that are using dredged materials or rock dikes in order to trap sediments for rebuilding lost land (CPRA 2010).

2.5 CONCLUSIONS

This study is the first comprehensive assessment on river flow conditions and sediment inflow to the Louisiana Chenier Plain in the Northern Gulf of Mexico. Although the quantity of sediment delivered by these rivers is relatively low, the resource is important for creating new wetlands in the interior portions of the plain that have been affected by saltwater intrusion and land loss. If a serious effort to restore the Chenier Plain to pre-development conditions is to be undertaken, all of the hydrological modifications would have to be reversed, channels allowed to be silted in and the Gulf Intercoastal Waterway closed. This is unrealistic, given the complexity of political, economic, social, and cultural factors, and thus it is up to land managers to make decisions about what current characteristics of the Chenier Plain are worthy of saving or trying to restore. With economic interests influencing many decisions, especially for the Sabine River Basin and its deep water port, it becomes imperative to have a dialogue and coordination between land managers, conservation agencies, and local, state, and federal agencies about the future of the Chenier Plain. A long term perspective needs to be taken instead of short-term risk management economic gain outlook. The riverine sediment yields calculated in this study provide a long-term look into other sediment sources that could be utilized in current or future

restoration efforts and, if utilized effectively, could go towards helping maintain the Louisiana Chenier Plain.

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CHAPTER 3: A HYDROGRAPH BASED SEDIMENT AVAILABILITY ASSESSMENT WITH IMPLICATIONS FOR MISSISSIPPI RIVER DIVERSION MANAGEMENT

3.1 INTRODUCTION

The Mississippi River Delta Plain in Louisiana, USA has undergone extensive land loss during the past century (Couvillion et al. 2011). Peak delta plain loss occurred from the mid-1950s until the 1970s at rates between 60-75 km^2 yr^{-1} (Britsch and Dunbar 1993; Barras et al. 2003), but possibly exceeded 100 km^2 yr^{-1} (Gagliano et al. 1981). Couvillion et al. (2011) have estimated that a total of 4877 km^2 of land has been submerged since 1932. Land loss has been attributed to both natural and anthropogenically exacerbated reasons (Walker et al. 1987; Kesel 1989; Yuill et al. 2009). These include subsidence, erosion, relative sea level rise, and loss of connectivity to the Mississippi River. With land loss endangering coastal communities, various restoration projects have been developed in the past two decades (LDNR 1998; CPRA 2012). In recent years much discussion has centered on diverting Mississippi River water and sediment to build and maintain coastal wetlands.

The United States Army Corps of Engineers (USACE) have built three large river diversions for the sole purpose of restoration in southeast Louisiana: Caernarvon, Davis Pond, and West Bay. The first two are managed to reduce estuarine salinity, while the latter is designed to bring sediment to the disappearing wetlands. Caernarvon Diversion Outfall Management Project, located on the east bank of the Mississippi River at river mile 82, was opened in August 1991 and is capable of discharging 227 m^3 s^{-1} of freshwater to Breton Sound Basin (Sable and Villarrubia 2011). Davis Pond Freshwater Diversion (DPFD), located on the west bank of the Mississippi River at river mile 118, has been in operation since July 2002 and is

capable of introducing a maximum of 302 $m^3 s^{-1}$ of freshwater to Barataria Basin (LDNR 2005). Current discharge management at both of these locations is based on salinity, with lower salinity during the spring (higher discharge) and higher salinity during the summer and fall (lower discharge) (OCPR 2011). To maintain the salinity gradient, the diversions are nearly continuous (OCPR 2011; Moore et al. 2011). Despite careful planning and many years of operation, a recent study (Kearney et al. 2011) found no significant changes in either relative vegetation or overall marsh area from 1984 to 2005 in zones closest to the diversion inlets. The lack of positive response to the freshwater diversions has been attributed to inappropriate timing of discharge, insufficient discharge magnitude (need >100 $m^3 s^{-1}$ to induce sheet flow needed to carry sediment across the marsh at Caernarvon Diversion, while DPFD is too small and channelized to induce sheet flow (OCPR 2010), and/or overloading of nutrients affecting sediment stability (Snedden et al. 2007; Kearney et al. 2011).

The West Bay Sediment Diversion was designed for sediment capture. Completed in November 2003 on the west bank of the Mississippi at river mile 2.9 (7.6 km from the Head of Passes), the planned discharge was 396 $m^3 s^{-1}$ when the Mississippi River was at 50 % discharge, but since construction the diversion has increased to 765 $m^3 s^{-1}$ (Carter 2003; USACE 2009). It has been reported that the diversion could be impacting navigational interests in the area while not producing land growth within 5 years (Brown et al. 2009; Barras et al, 2009; Heath et al. 2010). This has prompted USACE to draft plans to close the diversion. New sediment diversions further up river are under study (Myrtle Grove) or proposed for future investigation (Moffatt and Nichol 2008; CPRA 2012). However, there lacks a guideline that effectively addresses various interests, such as maintaining navigation, managing fisheries and wetlands, while still efficiently using diversions to capture sediment.

A number of studies have examined long-term annual sediment loads of the Mississippi River. These studies have documented a decreasing trend of riverine sediment attributed to dams, land management, and other river engineering structures (Kesel 1988; Meade and Moody 2010; Horowitz 2010). Different estimates of annual suspended sediment load for Tarbert Landing, MS (longest continuous, 50 years, recording station above tidal reach) are found in literature. Differences in estimates are mainly due to calculations for different time periods, for instance, 140 MT (megatonne) (Kesel 1988), 130 MT (Horowitz 2010), 115 MT (Meade and Moody 2010), or an overall average of 150 MT for 1963-2005 (Thorne et al. 2008). These estimates provide important trend data and are useful for understanding long-term sediment yield dynamics associated with river engineering, climate, and land use changes. However, they offer little insight into actual sediment availability under different river flow conditions, for example, the amount of sediment during high winter and spring flows.

The significance of the flood pulse with regards to sediment transport and healthy maintenance of river floodplains and deltas has long been recognized (Junk et al. 1989; Day et al. 1995; Sparks 1995; Bayley 1995; Walling and He 1998; Allison and Meselhe 2010). In Louisiana, it has been observed that stable marshes in the Mississippi River Delta Plain receive input of sediments and freshwater during the spring flood (Baumann et al. 1984). Mossa (1996) indicated that the highest sediment concentrations occurred during the rising limb, while recent work by Allison et al. (2012) reinforced these findings. From these papers there is a general understanding that the rising limb provides more sediment, and that high discharge has a greater total suspended sediment load than low discharge. With this said, there is a knowledge gap concerning the quantity and variability of total suspended sediment (coarse and fine suspended material) from the Mississippi River during its flood pulse (discharge >18,000 m^3s^{-1}) and

between different flood peaks. This was highlighted by Allison and Meselhe (2010) questioning the length and interannual variation of flow periods during which riverine coarse material can be obtained. Filling this gap in knowledge is crucial for effective sediment and diversion management in the future.

The main goal of the study was to determine the amount of total suspended sediment that is available at various river stages during the flood pulse and how this could translate to diversion management. Specific objectives were threefold: (1) calculating long-term total suspended sediment yield of the Mississippi River at Tarbert Landing, MS (2) determining how much total suspended sediment load occurs during different stage intervals, specifically Moderate Flood Stage, Flood Stage, and Action Stage at Red River Landing, LA, and (3) identifying suspended sediment concentration and total suspended sediment load during the rising and receding limb of the flood pulse as well as during different stage intervals on the rising limb and receding limb. Information gained from this study is discussed in light of using the flood pulse for diversion management through a method of Controlled Overbank Sedimentation (COS; Xu and Rosen 2012) that would maximize the flood pulse and sediment for a more natural diversion without degrading other functions of the Mississippi River.

3.2 METHODS

3.2.1 River Stage Classification for Sediment Availability Assessment

Daily stage data for the period 1 January 1980 to 31 December 2010 were collected from the United States Army Corps of Engineers (USACE) for the Red River Landing (RRL) station in Louisiana (30°57’39”N, 91°39’52”W; river mile 302.4). This station is used by the U.S. National Oceanic and Atmospheric Administration (NOAA) for river flood forecasting in the

Mississippi River Delta Plain. In this study we employed the NOAA defined stage categories to assess sediment availability at different river stages, which include (1) Action (stage=12.1 m), (2) Flood (stage=14.6 m), (3) Moderate Flood (stage=16.8 m), and (4) Major Flood (stage= 19.5 m). These stage divisions were used for the following reasons: (1) the categories are already in use for flood preparedness by NOAA and can, therefore, be easily recognized and understood by land managers and the general public, (2) the river discharge at Action Stage exceeds 15,000 m^3s^{-1}, the threshold where large quantities of course materials are found in suspension (Allison and Meselhe 2010), (3) Action Stage is based off of river morphology (start of overbank flooding at Raccourci Island, see Figure 3.1) and thus more representative of flood progression than stage categories at other stations downriver. RRL is close to the Tarbert Landing (TBL, about 6 km downstream, Figure 3.1) station in Mississippi. While the former has the longest continuous stage data, the latter has the longest continuous discharge and total suspended sediment datasets. Therefore, the information from these two stations provides the best indication of available sediment to the Mississippi River Delta Plain.

To determine the duration of each flood stage and when SSC maxima occurred, a flow duration curve was used that had SSC plotted with corresponding stage. In addition, a stage-discharge curve was created in order to determine daily discharge corresponding to the flood stages. River discharge was found to be 18,000 $m^3 s^{-1}$ at Action Stage, 25,000 $m^3 s^{-1}$ at Flood Stage, and 32,000 $m^3 s^{-1}$ at Moderate Flood Stage. Thus, Action Stage corresponded to a stage of 12.1m and discharge of 18,000 to 25000 $m^3 s^{-1}$, Flood Stage corresponded to a stage of 14.6 m and discharge of 25,000 to 32,000 $m^3 s^{-1}$, and Moderate Flood Stage corresponded to a stage of 16.8 m and discharge > 32,000 $m^3 s^{-1}$ (Table 3.1). From here on these ranges will be discussed as Action Stage, Flood Stage, and Moderate Flood Stage. During the 31-year period of this study

river stage at RRL never reached Major Flood (19.5 m) and thus the stage category was never used.

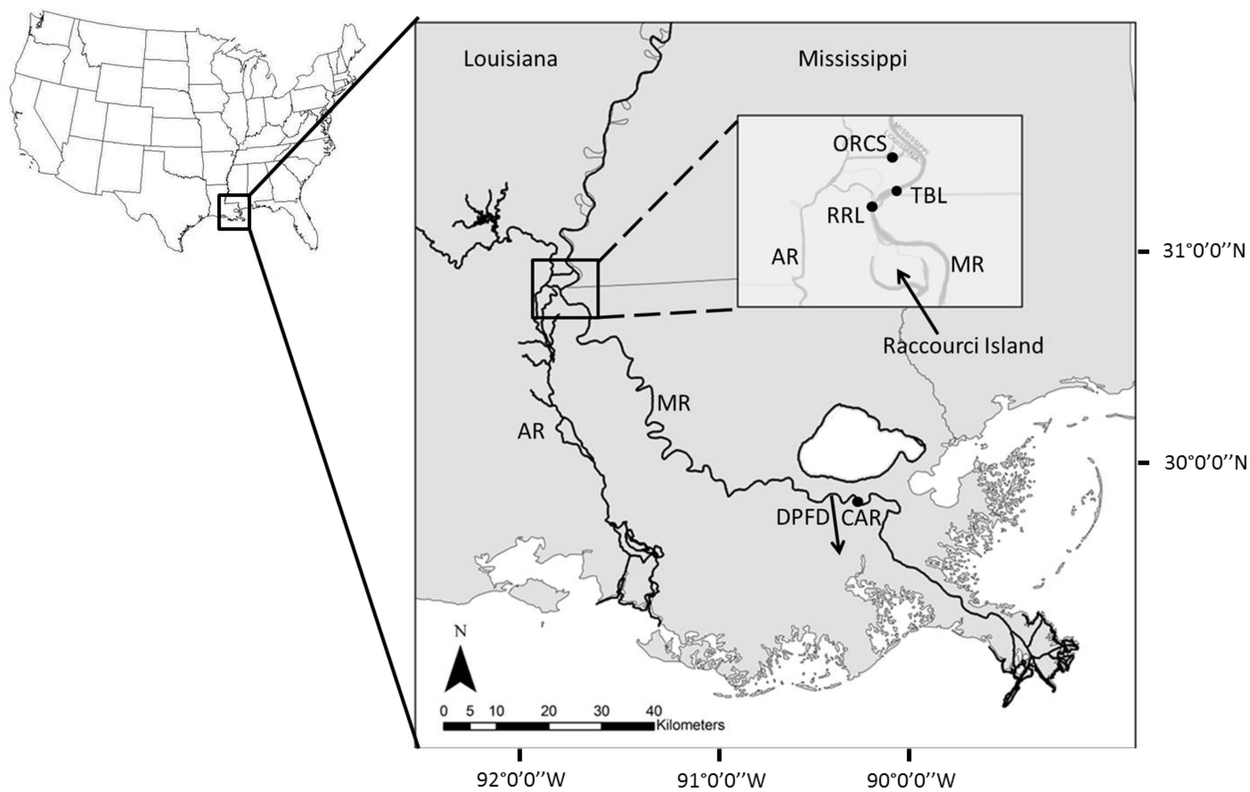

Figure 3.1. Lower Mississippi River (MR) with the locations of Old River Control Structure (ORCS) where approximately 25% of the Mississippi River's water is diverted into the Atchafalaya River (AR); Tarbert Landing (TBL) where long-term discharge and suspended sediment records are collected for this study; Red River Landing (RRL) and Carrolton, New Orleans (CAR) where river stage data are used for this study; and Davis Pond Freshwater Diversion (DPFD).

Table 3.1. NOAA stage category with corresponding river stage at Red River Landing, LA and corresponding discharge at Tarbert Landing, LA.

Category	**Stage (m)**	**Discharge (m^3s^{-1})**
Action Stage	12.1 to 14.6	18,000 to 25,000
Flood Stage	14.6 to 16.8	25,000 to 32,000
Moderate Flood Stage	>16.8	>32,000

3.2.2 Suspended Sediment Concentration and Load Calculation

To quantify total suspended sediment loads, suspended sediment concentration (SSC, mg l^{-1}) data and daily river discharge (m^3 s^{-1}) were obtained from the United States Geological Survey (USGS) and USACE for the Tarbert Landing (TBL) station (31°00'30"N, 91°37'25" W; river mile 306.3) over the period 1 January 1980 to 31 December 2010. Suspended sediment sampling at TBL varied over the time frame between 4-8 verticals and 2-5 samples per vertical, completed 14 to 31times a year using isokinetic point samples (P-61, P-63, D-96, and D-99) (see Thorne et al. (2008), Skinner (2007), Edwards and Glysson (1999), and Beverage (1987) for more specifics on error and sampling technique). Long-term total suspended sediment loads (SSL) were estimated using sediment rating curves based on measured sediment load and river discharge. Daily suspended sediment load was calculated using:

$$SSL \text{ (tonnes day}^{-1}) = [Q \text{ (m}^3 \text{ s}^{-1})] [SSC \text{ (mg l}^{-1})] (0.0864) \qquad (1)$$

Both linear and polynomial suspended sediment rating curves were applied with and without smearing correction. Polynomial smearing correction provided the closest approximation to the calibration dataset. Smearing correction was followed using the methods of Duan (1983). The calibration dataset consisted of enough data so that a smearing correction value was calculated and applied on an annual basis. The sediment rating curve utilized for total suspended sediment load calculation at Tarbert Landing, MS was:

Mississippi River: $$lnSSL = -0.4987(lnQ)^2 + 3.8469(lnQ) + 6.0336 \quad (2)$$

Where *lnSSL*= natural logarithm of daily total suspended sediment load in tonnes day^{-1} and *lnQ*= natural logarithm of discharge in $m^3\ s^{-1}$. The above equation achieved regression coefficient of r^2= 0.80 (Appendix Figure A3). Using the equation daily total suspended sediment load was computed for 1 January 1980 to 31 December 2010.

3.2.3 Hydrograph-based Sediment Yield Quantification

Flood durations on the hydrograph were selected manually based on peak discharge exceeding Action Stage. Starting dates of the floods were chosen based on the lowest discharge immediately preceding the flood after previously receding discharge. Ending dates were chosen based on the lowest discharge succeeding the flood before the next rising discharge. The hydrograph was subsequently split into rising and receding limbs with the peak discharge for the flood being the delimiter. Once rising and receding limbs were established, total suspended sediment loads were calculated for each limb using equation 1. These loads were subsequently divided into the stage categories (Action, Flood, and Moderate Flood) on the rising and receding limbs with average, minimum, and maximum values for each limb and stage category calculated.

SSC and SSL were analyzed based on stage category (Action, Flood, and Moderate Flood). SSC and SSL were then analyzed based on the corresponding limb of the hydrograph (rising/receding) and limb with stage category. Where applicable total, mean, median, minimum, and maximum values were calculated for SSC and SSL based on the aforementioned classifications. Trends were tested in the long-term data using Seasonal Mann-Kendall test for trend using a DOS based program developed by the USGS (Helsel et al. 2006). Differences in SSC and SSL for stage categories and limb were determined using Kruskal-Wallace and Mann-

Whitney (SSC and SSL for stage categories), or Mann-Whitney (difference between rising and receding limb) using SAS software (SAS Institute Inc., Cary, NC, USA 2008).

3.3 RESULTS

3.3.1 Sediment Availability under Different River Stages

From 1980 to 2010 the Mississippi River at Tarbert Landing, MS averaged 127 megatonnes (MT) of total suspended sediment annually, with a daily average load of 347,000 tonnes (Table 3.2). The highest annual yield was in 1982 (189 MT) and lowest annual yield was in 2006 (74 MT). Between the years 1980-1989 there was a significant decreasing trend in total suspended sediment load (Seasonal Mann-Kendall, p=0.046), followed by a slight, statistically insignificant upward trend through 2010 (Figure 3.2). These trends observed are better accounted for by changes in SSC (62%) than by changes in discharge (51%). SSC was highest in 1982 with an average of 368 mg l^{-1} and lowest in two dry years, 1988 and 1989, with averages of 162 mg l^{-1} and 163 mg l^{-1}. Since 1990, SSC has trended significantly upward (Seasonal Mann-Kendall, p=0.022, Figure 3.2). On the other hand discharge did not show a clear trend over the entire study period.

Hydrologically, from 1980 to 2010, the Mississippi River transported significantly different amounts of total suspended sediment under variable flow regimes (Table 3.2). About 32% (or 1256 MT) of the total suspended sediment yield was transported by the river at its Action Stage, ranging from a high of 92.5 MT in 1993 to a low of 5.21 MT in 2006. Flood Stage accounted for 17.6% (691 MT) of the total suspended sediment yield over the period, with a high of 58.26 MT in 1985 and a low of 7.17 MT in 1988. The river delivered only 5% (225 MT) of

the total suspended sediment yield at its Moderate Flood Stage, with a high of 56.85 MT in 1983 and a low of 2.1 MT in 1989.

Table 3.2. Long-term sediment yield for the Mississippi River at Tarbert Landing, MS and for flood stages, Moderate Flood, Flood, and Action.

Year	Overall	Moderate Flood	Flood	Action	Total[a]
1980	117,290,000		28,160,000	9,330,000	37,480,000
1981	102,360,000			24,290,000	24,290,000
1982	189,040,000		19,610,000	89,240,000	108,850,000
1983	171,650,000	56,850,000	22,850,000	59,480,000	139,190,000
1984	177,040,000	15,720,000	44,850,000	36,420,000	96,980,000
1985	157,330,000		58,260,000	39,080,000	97,340,000
1986	155,210,000			75,140,000	75,140,000
1987	107,490,000		10,720,000	30,070,000	40,780,000
1988	79,310,000		7,170,000	36,020,000	43,190,000
1989	84,710,000	2,100,000	21,980,000	29,350,000	53,430,000
1990	135,620,000	11,690,000	49,630,000	32,930,000	94,240,000
1991	121,920,000	21,720,000	36,740,000	38,620,000	97,080,000
1992	92,550,000			27,260,000	27,260,000
1993	178,670,000	21,270,000	33,540,000	92,500,000	147,310,000
1994	97,050,000	3,580,000	39,720,000	12,980,000	56,280,000
1995	88,190,000	6,460,000	10,400,000	29,740,000	46,600,000
1996	117,430,000		22,590,000	39,998,000	62,590,000
1997	127,080,000	24,750,000	14,160,000	52,330,000	91,250,000
1998	159,720,000		51,120,000	53,880,000	105,010,000
1999	129,690,000	8,470,000	25,080,000	39,580,000	73,120,000
2000	79,400,000			8,650,000	8,650,000
2001	159,620,000		29,340,000	57,600,000	86,940,000
2002	99,090,000		30,440,000	28,670,000	59,110,000
2003	109,790,000		18,670,000	23,940,000	42,610,000
2004	144,470,000		14,200,000	61,650,000	75,840,000
2005	87,720,000	8,710,000	10,450,000	27,740,000	46,900,000
2006	73,640,000			5,210,000	5,210,000
2007	115,720,000		9,030,000	29,750,000	38,790,000
2008	166,260,000	31,110,000	32,700,000	44,690,000	108,500,000
2009	160,530,000	13,360,000	19,810,000	69,990,000	103,160,000
2010	143,520,000		29,850,000	50,660,000	80,510,000
Total	3,929,110,000	225,800,000	691,080,000	1,256,790,000	2,173,660,000
% of Total		5.7%	17.6%	32.0%	55.3%
Average	126,750,000	17,370,000	26,580,000	40,540,000	70,120,000

[a] The sixth column total is for the combined flood stages.

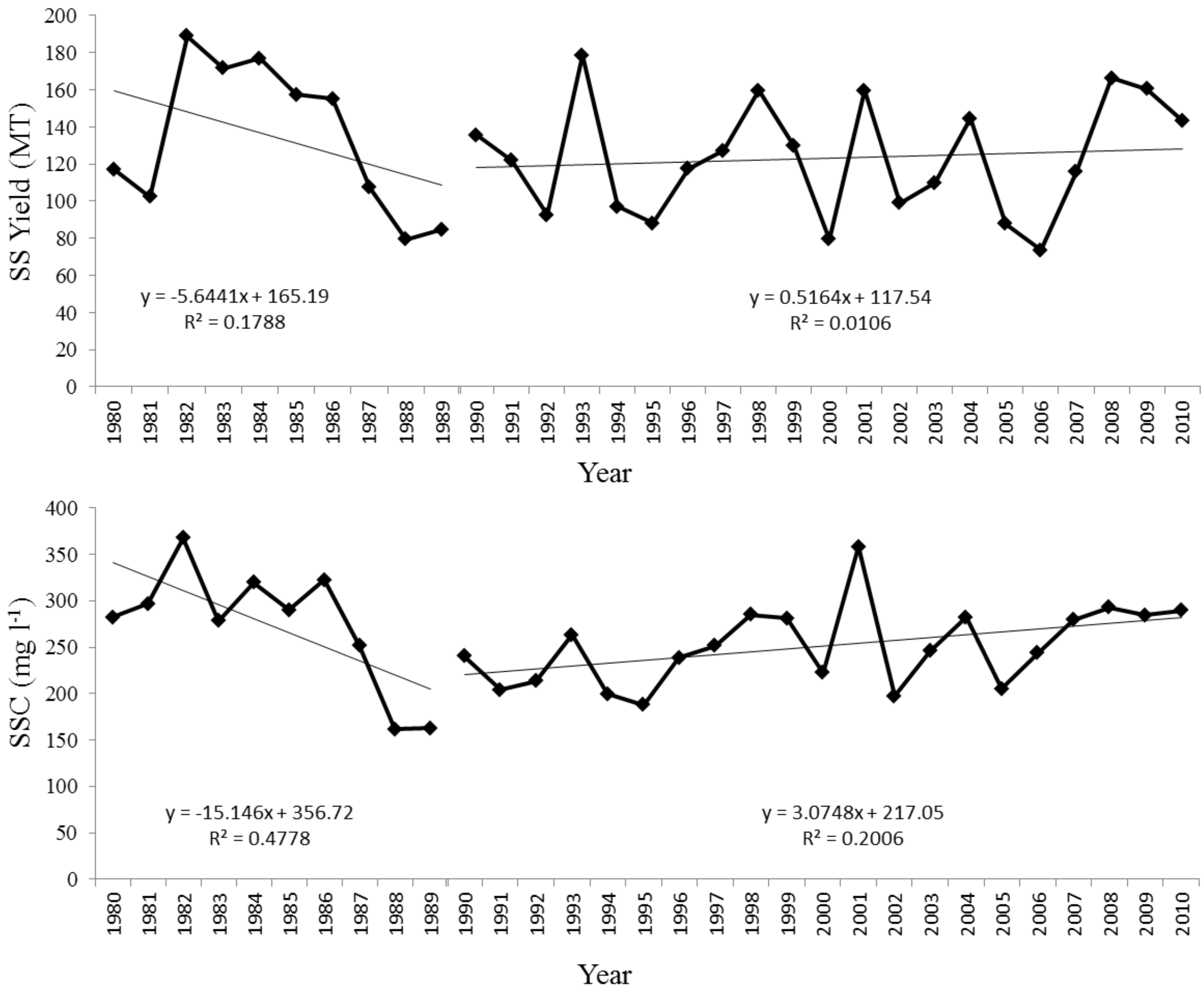

Figure 3.2. Annual total suspended sediment yield in megatonnes (top) and mean suspended sediment concentration in milligrams per liter (SSC, bottom) for the Mississippi at Tarbert Landing, MS from 1980-2010.

Moderate Flood Stage had the largest average daily SSL, 695,000 tonnes, due to high flow volume, but had the lowest average SSC, 178 mg l^{-1} (Table 3.3). Action Stage had the greatest average SSC, 313 mg l^{-1}, but lowest daily SSL, 537,000 tonnes. Flood Stage SSC and SSL were intermediate between both of these stage classes (Table 3.3). SSL and SSC were significantly different among the stage categories (Kruskal-Wallace, Mann-Whitney, $p<0.05$). There was an

inverse relationship between stage and SSC when the river was above Action Stage. The highest average SSC was reached at the stage level between 30% and 40% on the duration curve (Figure 3.3).

Table 3.3. Average duration, suspended sediment concentrations (SSC) and loads under different flow regimes from 1980 to 2010.

	Moderate Flood	Flood	Action
Days	25	42	76
SSC (mg l^{-1})			
Mean	178	266	313
1-Day Min	79	126	122
1-Day Max	306	604	992
Sediment Load (tonnes)			
Daily Mean	695,000	624,000	537,000
1-Day Min	419,000	370,000	285,000
1-Day Max	834,000	958,000	846,000

[a] Mean values are averages for the entire period. Min and Max values are the largest and smallest values recorded during the period. Days represent the average number of days stage remains in the different stage categories.

3.3.2 Sediment Availability on Rising and Receding Limbs

The Mississippi River displayed significantly higher SSC (mean: 317 mg l^{-1}, Mann-Whitney, $p<0.0001$) and SSL (mean: 593,999 tonnes, Mann-Whitney, $p<0.0001$) on its flood rising limb than on the receding limb (SSC: 235 mg l^{-1}, SSL: 429,255 tonnes) (Table 3.4). Rising limb at Moderate Flood Stage was the exception, where SSC was significantly lower (187 mg l^{-1}, Kruskal-Wallace, Mann-Whitney, $p<0.001$) than SSC at the other stage categories on the rising limb. Daily average SSL on rising limb was lower at Moderate Flood Stage (570,838

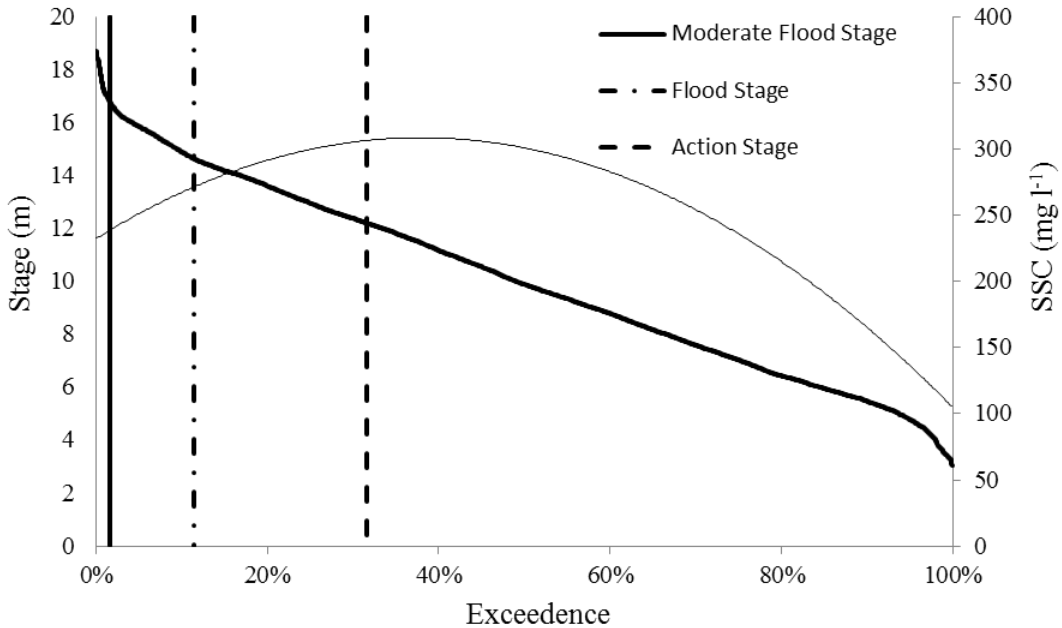

Figure 3.3. Stage (bold line) plotted on percent exceedance. Suspended sediment concentration (SSC, thin line) is plotted with corresponding stage exceedance value and does not represent SSC exceedance. Line at 31.5% exceedence corresponds to Action Stage, line at 11.4% exceedence to Flood Stage, and line at 1.7 % exceedence to Moderate Flood Stage.

tonnes) than at Flood Stage (670,480 tonnes) and Action Stage (709,048 tonnes) (Table 3.4). On average, rising limb Flood Stage lasted for 23 days providing a total yield of over 15.4 MT, followed by rising limb Action Stage with an average of 19 days, producing approximately 13.5 MT (Table 3.4). The greatest one day SSC occurred during rising limb Action Stage (992 mg l^{-1}) and the lowest SSC occurred during the rising limb and receding limb Moderate Flood Stage (79 mg l^{-1}). The receding limb, when compared to the rising limb, showed lower average SSC and lower average SSL for all stage categories, with receding limb Flood Stage and Action Stage having significantly lower SSC and lower SSL (Kruskal-Wallace, Mann Whitney, $p<0.05$, Table 3.4).

Table 3.4. Sediment concentration and load on the rising and receding limbs of the flood hydrograph for different stage categories. [a]

		Days	Total Yield	SSL	SSC
Rising Limb	**Moderate Flood**	15	8,562,570	570,838 (182,002)	187 (79-306; 60)
	Flood	23	15,421,040	670,480 (213,827)	277 (126-604; 93)
	Action	19	13,471,912	709,048 (309,478)	383 (188-992; 164)
Receding Limb	**Moderate Flood**	8	3,624,056	453,007 (140,076)	145 (79-229; 45)
	Flood	15	8,171,415	544,761 (196,208)	227 (126-366; 73)
	Action	14	6,256,516	446,894 (140,818)	245 (122-496; 82)

[a] Days (mean), total yield (mean, tonnes), mean suspended sediment load(SSL) (standard deviation), and mean suspended sediment concentration (SSC, mg l^{-1}) (minimum-maximum; standard deviation).

3.3.3 Flood Peak and Sediment Availability

During the period 1980 to 2010, Moderate Flood Stage (>16.8 m) was observed in 13 years and Flood Stage (14.6 m – 16.8 m) in 26 years, while Action Stage (12.1 m- 14.6 m) was attained every year (Table 3.5). Flood Stage was the flood peak for 13 years and Action Stage was the flood peak for 5 years. Years in which the flood peak stage was greater than 16.8 m (Moderate Flood Stage), on average, had longer flood duration in each stage category, but average SSC and average SSL was lower during the flood for each stage category when compared to years that peaked between 14.6 m -16.8 m (Flood Stage) or 12.1 m -14.6m (Action Stage) (Table 3.5). Moderate Flood Stage, during years that peaked at this stage (>16.8 m), had

significantly lower SSC (Kruskal-Wallace, Mann-Whitney $p<0.01$) than any other stage. Flood Stage for years that peaked between 14.6 m -16.8 m averaged significantly higher SSC (Kruskal-Wallace, Mann-Whitney, $p=0.0361$) and SSL (Kruskal-Wallace, Mann-Whitney $p<0.0001$) than Flood Stage of years that peaked at >16.8 m. Action Stage average SSL was also significantly higher during years that peaked at 14.6 m -16.8 m when compared to years that peaked at >16.8 m (Kruskal-Wallace, Mann-Whitney, $p<0.0001$). Years that peaked between 12.1 m - 14.6 m had the highest average SSC, but only significantly higher than Action Stage during years that peaked at >16.8 m (Kruskal-Wallace, Mann-Whitney, $p=0.0398$) (Table 3.5).

During the years in which the flood was greater than 16.8 m, 13% of the total suspended sediment yield occurred during Moderate Flood Stage, 21% during Flood Stage, and 33% during Action Stage. As a percent of the total suspended sediment yield above the start of Action Stage, Moderate Flood Stage accounted for 20% of the total suspended sediment, Flood Stage accounted for 31%, and Action Stage accounted for 49%. Years that peaked between 14.6 m - 16.8 m had Flood stage, on average, account for 19% of the total suspended sediment yield and Action Stage account for 32% of the total suspended sediment yield. As a percent of the total suspended sediment yield above the start of Action Stage, Flood Stage accounted for 37% of the total sediment yield and Action Stage 63%. Years that peaked between 12.1 m – 14.6 m, 24% of the total suspended sediment yield occurred during Action Stage.

The winter flood had higher average SSC for all stage categories (values in mg l^{-1} descending from highest stage category, Winter: 216, 331, 322, Spring: 166, 246, 307) (Figure 3.4). However, the spring flood had greater average SSL in the Moderate Flood Stage (702,000 tonnes) and Action Stage categories (549,000 tonnes) when compared with the winter flood (Moderate Flood Stage: 664,000 tonnes; Action Stage: 528,000 tonnes) (Figure 3.4). The

Table 3.5. Average days, suspended sediment concentration, daily load, and yield during years that peaked at Moderate Flood Stage, Flood Stage, and Action Stage. [a]

			Stage During Flood		
	Stage (m)		**Action Stage**	**Flood Stage**	**Moderate Flood Stage**
Flood Peak	**>16.8**	**Days**	86	47	25
		SSC	300 (136.30)	243 (76.36)	178 (60.97)
		SSL	505,000 (90,461)	590,000 (114,101)	695,000 (102,689)
		Total Yield	43,430,000	27,730,000	17,375,000
	14.6-16.8	**Days**	74	38	
		SSC	316 (155.93)	296 (122.13)	
		SSL	571,000 (107,702)	666,000 (11,1054)	
		Total Yield	42,254,000	25,308,000	
	12.1-14.6	**Days**	51		
		SSC	352 (134.75)		
		SSL	549,000 (100,061)		
		Total Yield	27,999,000		

[a] Flood peak indicates the stage where the annual flood peaked. Stages used for peaks are equivalent to Moderate Flood Stage, Flood Stage, and Action Stage. Basic statistics shown are mean days, suspended sediment concentration (SSC) (mean; standard deviation), suspended sediment load (SSL, mean; standard deviation), and average annual total suspended yield during stage.

Mississippi River had nearly identical discharge at Action Stage during both spring and winter floods (Figure 3.4).

3.4 DISCUSSION

The results presented offer a number of important insights into the sediment dynamics and availability associated with river flow conditions. Previous studies have shown a declining trend in Mississippi River sediment discharge following the 1950s to 1960s construction of dams, cutoffs, training structures, and bank stabilization structures (Keown et. al 1986; Kesel 1988, 2003; Meade and Moody 2010). Meade and Moody (2010) reported an overall decline in the long-term trend (1950s to 2000s) of total suspended sediment loads at TBL. Our analysis shows that there was actually an upward shift of SSL since the early 1990s (Figure 3.2). Horowitz (2010) suggested the change started in 1993, while we believe the long-term decline of Mississippi River SSL ended in 1989. This trend was not caused by changes in discharge, but by changes in SSC. From 1980 to 1986 SSCs were elevated compared to the rest of the time period. Following 1986, the Mississippi River at TBL went through dramatic SSC reduction from an average of 323 mg l^{-1} in 1986 to a low of 162 mg l^{-1} in 1988. Since 1989, there has been great fluctuation but an overall general increase in average SSC from 163 mg l^{-1} in 1989 to 289 mg l^{-1} in 2010. The years 2008, 2009, and 2010 are notable because SSCs are all in the top ten for the time period (1980-2010). The reduction of SSC that and discharge that occurred from 1986-1989 could have been related to a severe drought that affected the Midwestern United States that did not officially break until 1990 (Trenberth and Guillemot 1995). Another possibility is that the opening of the Auxiliary Structure at Old River Control Structure (ORCS) in December 1986 could have affected sediment concentrations by diverting a greater portion of the sand load

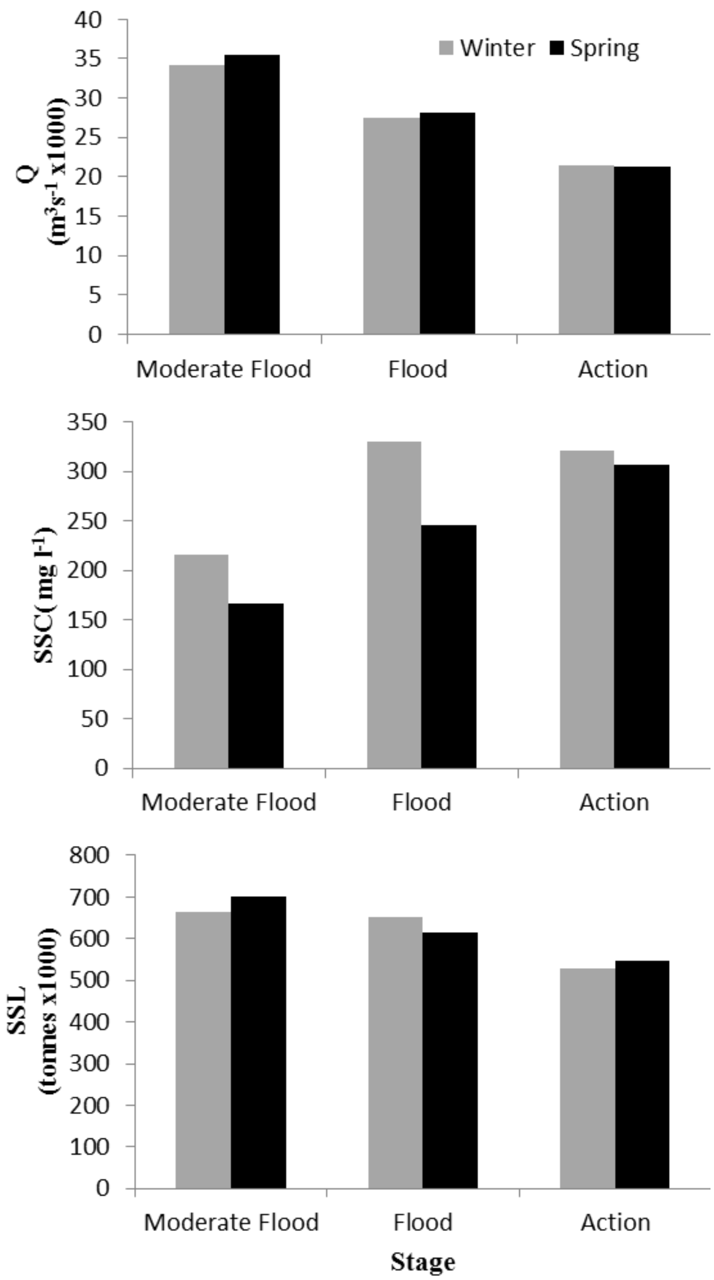

Figure 3.4. Mean river discharge (Q), suspended sediment concentration (SSC), and suspended sediment load (SSL) under three stage categories during spring and winter floods.

(Copeland and Thomas 1992). The increase after 1989 may reflect suspended sediment slowly reaching equilibrium following the severe drought of 1988 to1990, opening of the Auxiliary

Structure in 1986, and large flood of 1993. The trend suggests that without any further major alterations to Mississippi River engineering, land use changes, or drastic climate shifts, current sediment load will likely remain stable for the foreseeable future.

There is little doubt that the most important stage values for sediment diversion are those greater than 11.0 m stage at RRL. Our analysis identified that Moderate Flood Stage had low SSC, but high discharge, thus maximizing freshwater rather than total suspended sediment. SSC was maximized just before Action Stage, above the 15,000 m^3 s^{-1} threshold (Figure 3.3). The higher SSC, in combination with the longer duration that the hydrograph stayed in Action Stage and Flood Stage, produced the greatest total suspended sediment yield. Over the period, regardless of flood pulse rising limb or receding limb, discharge during these stages produced an average yield of 26.6 MT during Flood Stage and 40.5 MT during Action Stage (Table 3.2). Between different years Flood Stage was consistent, providing on average 27.7 MT during years that peaked at > 16.8 m (Moderate Flood Stage) and 25.3 MT during years that peaked between 14.6 m to 16.8 m (Flood Stage). Action Stage displayed the same consistency with 43.4 MT (flood peak>16.8 m), and 42.3 MT (flood peak between14.6 m -16.8 m). The overall consistency between years was due to higher average SSC during years that peaked at 14.6 m - 16.8 m (Flood Stage) making up for differences in duration (Table 3.5). Mossa (1996) identifies that differences in SSC between annual floods can be attributed to the peak of SSC occurring earlier during large floods and nearly coincident with the peak during minor floods. Successive flood events produced a decrease in magnitude of the SSC peak (Mossa 1996). If there was a winter flood before the spring flood there was lower SSC during the spring flood. This is demonstrated in the results for the seasonal analysis where higher SSC was observed during the winter flood (Figure 3.4).

On the flood pulse portion of the hydrograph, our study showed that SSC is maximized on the rising limb during Action Stage and Flood Stage. Other studies on the lower Mississippi River corroborate this finding (Mossa 1996; Allison et al. 2012) with Mossa (1996) describing the sediment peak occurring more than 40 days before the discharge peak, and Allison et al. (2012) indicating that sediment maxima occurs during a one week period on the rising limb. Snedden et al. (2007) also reported that sediment delivery through the Caernarvon Diversion Outfall Management Project was greatest during the rising limb. In our study the rising limb, of an average flood pulse, provided 13.5 MT at Action Stage and 15.4 MT at Flood Stage. To put this in perspective, this amount of sediment is comparable to the average amount, 20 MT (Xu and Wang in review), that is discharged through Wax Lake Outlet, a man made diversion created on the Atchafalaya River (largest Mississippi River distributary) in 1942 to alleviate flooding in Morgan City, LA. Since 1973 Wax Lake Outlet has seen subaerial land growth, generating one of the few prograding coasts in Louisiana (Roberts et al 2003). This indicates the importance of implementing sediment diversions during the early portion of the flood pulse to maximize total suspended sediment capture.

Quantifying the amount of total suspended sediment passing TBL gives a good indication of the available sediment resource to the Mississippi River Delta Plain. Still, translating the sediment loads calculated for TBL to diversions further down river requires careful analysis on river hydraulics and bed sediment. Allison et al. (2012) identify this, quantifying that 43% of the total suspended sediment load bypassing TBL (river mile 306.3) was retained along the river stretch to Belle Chasse, LA (river mile 75.9). This is corroborated by other research that found the low stream velocity near Belle Chasse, LA caused the bed fraction to be composed of greater quantities of silt/clay compared to areas further upriver, (Allison and Meselhe 2010; Demas and

Curwick 1988; Galler and Allison 2008). Even with this different dynamic at Belle Chasse, LA, this section of the river still maintains a similar hydrograph pattern to Tarbert Landing, MS, including higher SSC during the rising limb and decreasing at higher discharges and the receding limb (Allison and Meselhe 2010). The similar hysteresis at Belle Chasse, LA would indicate that effective management of sediment diversions in the reach extending upstream to TBL should take advantage of stage to maximize sediment.

Building upon the previous statement, an example of how stage hydrograph sediment analysis can benefit freshwater diversion projects can be drawn from Davis Pond Freshwater Diversion (DPFD) (river mile 118), 42.1 river miles upstream of Belle Chasse, LA and 24 miles west of New Orleans, LA (Figure 3.1). Current management strategies of Louisiana freshwater diversions have produced poor results (see introduction). An alternative approach could be taken where levees are dropped to the level of Action Stage allowing the flood pulse to act naturally through a process of Controlled Overbank Sedimentation (COS) (Xu and Rosen 2012). Use of the flood pulse has been proposed as an effective method to maintain deltas against relative sea level rise (Day et al. 1995). Observational data from Snedden et al. (2007) and Day et al. (2009) documented higher sediment concentration and therefore greater sedimentation behind the Caernarvon Diversion during the rising limb of winter or spring flood pulses. To implement COS at DPFD, an Action Stage can be determined based on the data from RRL using a two day lag (Figure 3.6). For instance, an equivalent Action Stage for Carrollton, New Orleans (river mile 102.8) east of the diversion, would be 2.9 m. Equivalent Flood Stage would be 3.73 m and Moderate Flood Stage would be 4.47 m. Current levees in this section of the river protect up to 7.3 m. If levee crest elevations were reduced to 2.9 m it would provide, on average, 137 days of freshwater and sediment, staying at Action Stage for 62 days, Flood Stage for 44 days, and

Moderate Flood Stage for 31 days (variability between years, 1993: 268 days, 2006: 4 days). Using this method would take full advantage of the flood pulse elevated total suspended sediment, and restore a more natural hydrological regime to the area.

Utilization of this hydrograph based approach could also be beneficial to diversion regulation of the Mississippi River's water into the Atchafalaya River at the Old River Control Structure (ORCS). Currently the structure controls an average diversion rate of approximately 25% (Horowitz, 2010). With the ability to estimate when the most sediment is arriving to the lower river via TBL (just south of the structure) the ratio being diverted can be adjusted between the Atchafalaya River and the Mississippi River. Based on this study's findings we suggest that

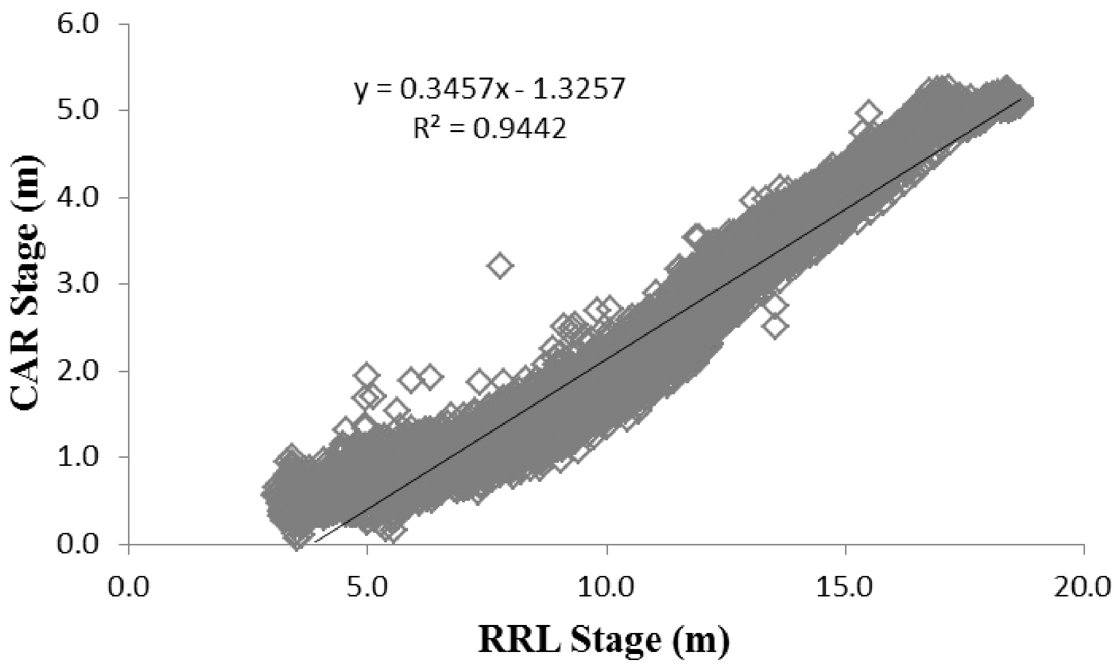

Figure 3.6. Relationship of the river stage between Red River Landing (RRL, river mile 302.4) and Carrolton, New Orleans (CAR, river mile 102.8)from 1980 to 2010. A two day lag was used to account for the distance between stations.

during the rising limb from Action Stage through Flood Stage the diversion ratio should be reduced so that more sediment is forced down the lower Mississippi River. The diversion ratio can be changed during higher discharges and receding limb to divert more water into the expansive Atchafalaya Basin. This would allow for effective flood management as well as decrease sedimentation within the basin by using a larger portion of the relatively sediment starved rising limb Moderate Flood Stage and receding limb. To implement such an aggressive plan would need much study, but could have beneficial results for both Mississippi River Delta management, and Atchafalaya River Basin management.

3.5 CONCLUSIONS

This study has analyzed sediment availability under different flow conditions of the lower Mississippi River at Tarbert Landing, MS using river discharge and sediment records from 1980 to 2010. It is the first detailed quantification of total suspended sediment resources from the river during its flood pulses to coastal Louisiana. Three important conclusions arise from this long-term data assessment:

1) A hydrograph-based analysis of sediment is critical for determining the actual availability of riverine sediment due to the variability of the quantity and timing of total suspended sediment during Mississippi River flood pulses. This can be completed for other river locations where sediment diversion is considered.

2) The high sediment load at Action Stage and Flood Stage provide approximately 50% of the total annual suspended sediment yield over a period of only 120 days. This implies that

sediment diversion outside of this period would be impractical highlighting the need to manage diversions to follow the natural flood regime.

3) The most effective sediment diversions will rely on discharge during the rising limb of flood pulses to capture the largest quantities of sediment. Knowing that discharge during the rising limb Action Stage and Flood Stage provide the greatest amount of sediment, managers can effectively operate diversions based on predictions of the timing of a flood pulse moving down the Mississippi River.

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CHAPTER 4: RECENT DECADAL GROWTH OF THE ATCHAFALAYA RIVER DELTA COMPLEX: EFFECTS OF VARIABLE RIVERINE SEDIMENT INPUT AND VEGETATION SUCCESSION

4.1 INTRODUCTION

Amongst coastal margins, deltas may be the most economically important regions, serving as transportation hubs and commercial centers while providing abundant natural resources that support large populations of people and wildlife. However, many of the world's deltas today are under unprecedented pressure from land loss due to reduced riverine sediment supply (e.g., Walling and Fang, 2003), coastal land erosion (e.g., Smith and Abdel-Kader 1988; Chen and Zong 1998), subsidence (e.g., Day et al. 1995; Syvitski et al. 2009), and sea level rise (e.g., Day et al. 1995; Gornitz, 1995). As with other delta regions, the Mississippi River Delta Plain has not been immune from land loss and has had one of the most significant conversions of land to open water, with over 4877 km^2 submerged since 1932, endangering large coastal communities (Couvillion et al. 2011). This loss has been attributed to rapid subsidence of Holocene strata (Törnqvist et al. 2008), exacerbated by the reduction in riverine sediment supply (Kesel, 2003), hydrocarbon extraction (Morton and Bernier 2010), local faults, and glacial isostatic adjustment (Yuill et al. 2009). With much of the delta plain under stress, research and management interests have been building in the Atchafalaya River Delta Complex (ARDC), the only noticeable prograding delta feature along the Mississippi River Delta coastline.

The Mississippi River enters the Gulf of Mexico through two distributaries: the Mississippi River main channel southeast of New Orleans, Louisiana and the Atchafalaya River located to the west on the Louisiana central coast. The Atchafalaya River is approximately 190

km long, flowing southwards through a levee-confined floodplain area of 4921 km^2, much of which is riparian forested swamps (Ford and Nyman 2011). Since the early 20^{th} century, due to human alterations to the Atchafalaya River and a more favorable gradient than the Mississippi River, a well-defined channel began to form, which increased the flow volume going down the Atchafalaya River (Fisk 1952; Roberts et al. 1980). The increased discharge caused many of the open water areas in the Atchafalaya River Basin to accumulate sediments, losing much of the open water and swamp habitat to lacustrine delta formations (Tye and Coleman 1989). With the open water areas sediment filled, formation of subaqueous deltas at the two outlets of the Atchafalaya River, Morgan City main channel (ARMC) and Wax Lake outlet (WLO), became noticeable in the 1950s (Shlemon 1975). Subaerial land started forming in 1972 and was accelerated by large floods that occurred from 1973 to 1975, forming the Atchafalaya River subdelta (ARSD) and Wax Lake Outlet subdelta (WLSD) (Roberts et al. 1980). With subaerial delta formation primary vegetation succession was able to begin with emergent plants colonizing once the delta islands reached intertidal elevations. By 1979 the Atchafalaya River delta had over 16 km^2 vegetated (Johnson et al. 1985).

Several factors may have affected deltaic growth of the ARDC: sediment load, tropical systems, cold fronts, and vegetation colonization. Rouse et al. (1978) observed high growth rate of the ARSD following the 1973, 1974, and 1975 river floods. Barras (2007) found that hurricane Rita in 2005 removed much of the submerged aquatic vegetation and floating vegetation in the ARDC, while also enlarging existing ponds. Hurricane Andrew in 1992 was documented adding, on average, 16 cm of accumulated sediment to marshes surrounding the Atchafalaya Bay (Guntenspergen et al. 1995), while Walker (2001) found that hurricanes can also cause sediment-laden water to be transported off the coast, away from the ARDC. Cold

frontal passage has also been documented transporting sediment out of Atchafalaya Bay, with an estimate of 400,000 tonnes per front, which equates to approximately 10.6 megatonnes (MT) during a year (Walker and Hammack 2000; Roberts et al. 2005). This erosion reduces the rate of subaerial delta development and leaves the delta features sandy (van Heerden and Roberts 1980). Johnson et al. (1985) noted that with the colonization of plant species (most notably *S. nigra*) physical processes were aided by biotic controls to enhance sedimentation and stabilization of the ARDC (Johnson 1985), although the long-term effect of vegetation on delta land growth in the ARDC is unclear. The above studies identify separate factors that have affected delta growth, but there has not been a systematic longer-term look into how the ARDC subdeltas have responded to varying sediment input and stressors.

With the decline of total suspended sediment throughout the Mississippi River (Horowitz 2010; Heimann et al. 2011) it has become imperative to track changes in total suspended sediment discharge to coastal Louisiana and the impacts on coastal processes. Sediment supply is one the most important components that shape delta growth (Orton and Reading 1993). However, it is unclear how much sediment is discharged from ARMC and WLO to the subdeltas. Previous studies have documented sediment discharge to the ARDC from sediment data collected from the upper Atchafalaya River (Rouse et al. 1978), but it was reported by Xu (2010) that there is a 9% sediment load reduction in the Atchafalaya River Basin before reaching the outlets, fluctuating with the river hydrological conditions. With new management plans that have suggested diversions from the Atchafalaya River to other coastal areas in Louisiana (CPRA 2012), there is an urgent need to have a comprehensive assessment on riverine sediment discharge, and how the quantity and fluctuation of the sediment discharge and vegetation succession may have influenced land growth in the ARDC. This assessment is critical since

different delta progradation at the two river outlets have been reported (e.g., Barras 2007; Xu 2010; Couvillion et al. 2011).

Using this background information, we conducted this study to take a longer-term (1989-2010) look at total suspended sediment discharge to the Atchafalaya River subdeltas below Morgan City and Wax Lake Outlet to assess how this may have affected delta land change over four approximately 5-year periods (i.e. 1989 to 1995, 1995 to 1999, 1999 to 2004, and 2004 to 2010). The primary purposes of the study were to determine the relation of ARDC development to total suspended sediment discharge from the river's two outlets, and assess the role that vegetation succession may have played in stabilizing newly created land. The results are discussed in light of the influencing factors introduced earlier.

4.2 THE ATCHAFALAYA RIVER DELTA COMPLEX

ARDC is composed of two subdeltas, Atchafalaya River subdelta (ARSD) and Wax Lake Outlet subdelta (WLSD), extending approximately from 29°23'N to 29°32'N in latitude and from 91°15'W to 91°30'W in longitude (Figure 4.1). Both of these features are building into the shallow, low energy (mean wave height ~0.5m), microtidal (mean tidal range 0.35m) Atchafalaya Bay and display typical lobate delta growth of a river dominated delta, based on Galloway's delta classification (1975). Current subaqueous delta clays extend out to the 8m isobath outside of the Atchafalaya Bay (Neill and Allison, 2005). The ARDC is fed by the Atchafalaya River that carries a portion of the Mississippi River's flow and the entire flow from the Red River. The flow portion from the Mississippi River is controlled by a diversion structure, the Old River Control Structure (ORCS) that was built in 1963 to prevent avulsion of the Mississippi River. Under normal flow conditions, the ORCS maintains 24±3% (Horowitz, 2010) of the Mississippi River discharge but approximately 30% to 60% of the Mississippi River's total

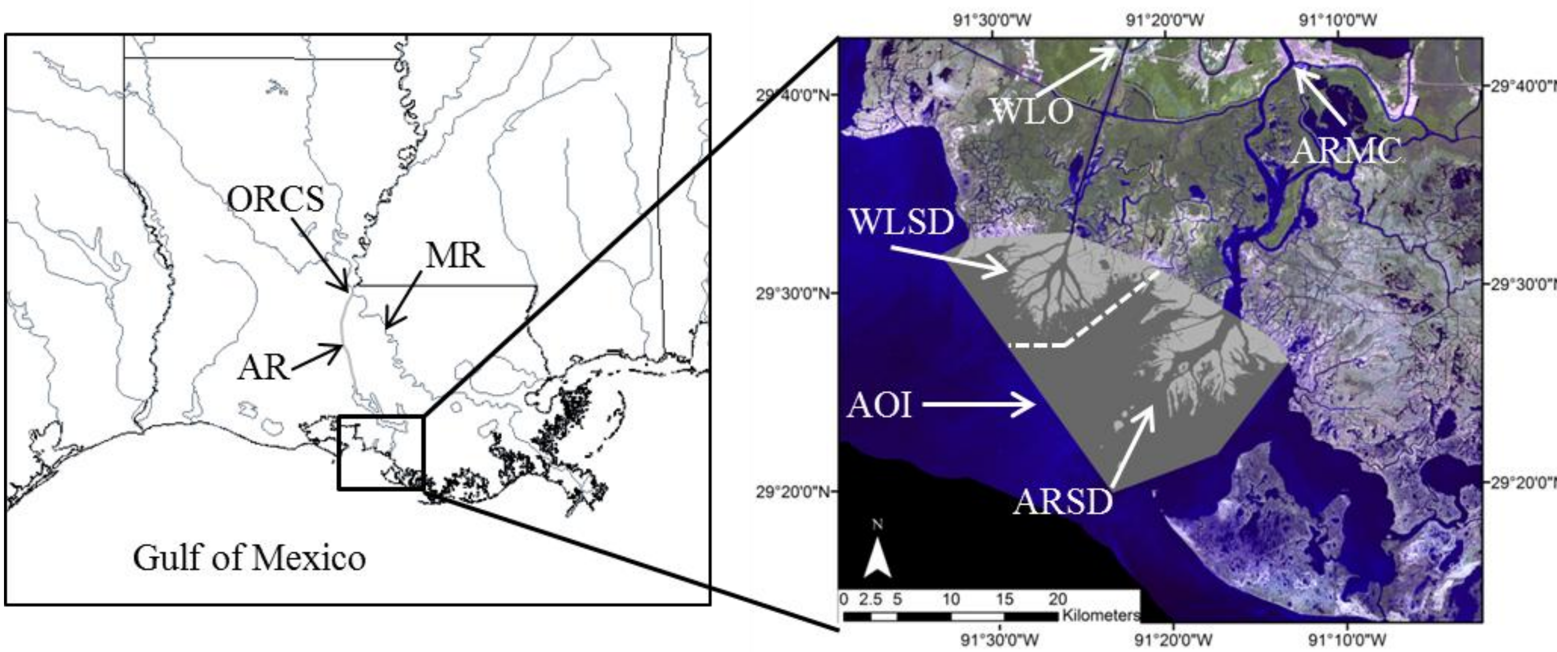


Figure 4.1. Map of study area, AOI (area of interest) is the area subsetted for analysis. Light gray area is land and dark gray is water, and the dashed white line demarcates the subsetted areas for the Wax Lake Outlet subdelta (WLSD) and the Atchafalaya River Morgan City subdelta (ARSD). ARMC is Atchafalaya River Morgan city station and WLO is Wax Lake Outlet station, where discharge and suspended sediment concentration were collected. Old River Control structure (ORCS) controls water flow from the Mississippi River (MR) to the Atchfalaya River (AR).

suspended sediment yield (Mossa and Roberts 1990; Horowitz 2010). In recent years, on average, the Mississippi River's water contributes about two thirds of the entire Atchafalaya's discharge, but the Red River could make up to 70% of the river discharge during the low flow period of the Mississippi River (Xu and BryantMason 2011). The ARDC is located in humid subtropical climate (Köppen climate classification *Cfa*) and is affected by tropical systems (hurricanes and tropical storms) and strong cold fronts. Vegetation of the ARDC varies by elevation and successional stage, but commonly found genuses are *Sagittaria, Salix, Typha, Polygonum, Nelumbo, and Phragmites.*

4.3 METHODS

4.3.1 Discharge, Total Suspended Sediment, and Tropical Systems

Daily mean discharge data were downloaded from the United States Geological Survey (USGS) website (http://waterdata.usgs.gov/la) for Lower Atchafalaya River at Morgan City, Louisiana (ARMC, 29°41'33.4"N, 91°12'42.6"W, Figure 4.1), and Wax Lake Outlet at Calumet, Louisiana (WLO, 29°41'52"N, 91°22'22"W, Figure 4.1). Discharge measurement did not begin at ARMC until October 1995. Missing discharge data for ARMC were estimated back to 1989 based off of a relationship from Xu and Wang (in review) using data collected by the United States Army Corps of Engineers (USACE) at a gauging station up river at Simmesport, Louisiana (ARS, 30°58'57"N, 91°47'54"W). The relationship was:

$$QARMC = 10894.31977 + 0.53129\ (QARS) \qquad (1)$$

where QARMC and QARS are the daily mean discharge passing ARMC and ARS in ft^3s^{-1}. Estimated discharge at ARMC was subsequently converted to m^3s^{-1}. Annual maximum discharge data were also used from the Atchafalaya River Simmesport, Louisiana to count the number of

large flood events (discharge >13,800 m^3s^{-1}, 34% flood exceedance). Suspended sediment concentration (SSC) data were downloaded from the USGS for ARMC and WLO. At ARMC and WLO, suspended sediment data are collected monthly during non-flood and bimonthly during flood seasons. During severe flood events, sediment data are collected more frequently by USACE and USGS. Suspended sediment data comprises both suspended sand and suspended mud and will be referred to as total suspended sediment.

Tropical systems that impacted the region were determined from Roth (2010). Both hurricanes and tropical storms were counted to determine the total amount of tropical systems that impacted Louisiana for each period during the study (Table 4.1).

Table 4.1. Names and strengths of tropical systems that impacted Louisiana from 1989 to 2010.

Name	**Year**	**Period**	**Category**	**Distance (km, direction)**
Andrew	1992	1989-1995	3	20, W
Opal	1995	1989-1995	3	408, E
Josephine	1996	1995-1999	TS	184, E
Danny	1997	1995-1999	1	85 E
Frances	1998	1995-1999	TS	532, W
Georges	1998	1995-1999	2	286, E
Allison	2001	1999-2004	TS	Direct Impact
Isidore	2002	1999-2004	TS	145, E
Lili	2002	1999-2004	1	63, W
Matthew	2004	2004-2010	TS	70, E
Katrina	2005	2004-2010	3	180, E
Rita	2005	2004-2010	3	236, W
Humberto	2007	2004-2010	1	246, W
Gustav	2008	2004-2010	2	70, E
Ike	2008	2004-2010	1	324, W

Category is the Saffir-Simpson scale and identifies the wind strength of the storm at landfall.
TS=Tropical storm, 63-118 km h^{-1}
Category 1= 119-153 km h^{-1}
Category 2=154-177 km h^{-1}
Category 3= 178-208 km h^{-1}
Period 1=1989-1995, Period 2=1995-1999
Period 3=1999-2004, Period 4= 2004-2010
Distance is the approximate distance the landfall was from ARDC

4.3.2 Total Suspended Sediment Discharge Calculation

Using SSC and daily discharge measured on the same dates, daily total suspended sediment load (SSL) was calculated as follows:

Daily SSL (tonnes day^{-1}) = [Q (m^3 s^{-1})] [SSC(mg l^{-1})] (0.00864) (2)

Long-term daily total suspended sediment loads for ARMC and WLO were estimated using log-log linear regression and log-log 2nd order polynomial regression equations relating measured daily total suspended sediment load to discharge:

Linear regression: $\ln(SSL)= \ln(a) + b\ln(Q)+ \varepsilon$ (3)

2nd order polynomial regression: $\ln(SSL)= \ln(a) + b\ln(Q) - c\ln(Q^2) + \varepsilon$ (4)

where SSL is daily total suspended sediment load, Q is discharge, a, b, and c are constants, and ε is lognormally distributed error (e.g. Miller 1951; Glysson 1987; Helsel and Hirsch 2002). Both linear and 2nd order polynomial sediment rating curves were calculated with and without smearing correction. Smearing correction was followed using the methods of Duan (1983). Long-term (using all the data) and three year sediment rating curves were developed separately for each station using both linear and 2nd order polynomial regression. Three year intervals were used because of no SSC values for 2006 at ARMC and WLO and only 6 SSC values available at WLO for the year 2007. The accuracy of the estimated values were evaluated by % difference between measured loads, calculated from equation 2, and estimated total suspended sediment load calculated from the sediment rating curves, based on Horowitz (2003):

% difference= [(predicted value)-(measured value)/(measured value)]x100 (5)

The rating curves with best fitting parameters (see Appendix Table A1) were selected to estimate total suspended sediment load (tonnes day^{-1}) and subsequently summed in order to obtain total suspended sediment yield (tonnes yr^{-1}) on the annual scale from 1989 to 2010. Trend in long-term SSC, discharge, and total suspended sediment yield was determined by Seasonal Mann-Kendall test for trend using a DOS based program developed by the USGS (Helsel et al. 2006).

4.3.3 Spatial Data Sets

For spatial land change analysis cloud free Landsat 5 images (Path 23, Row 40) for the years 1989, 1995, 1999, 2004, and 2010 (Table 4.2) were obtained from the USGS, Earth Resources Observation and Science Center. Dates of these images were also chosen based on river discharge (low discharge-September and October) and tide conditions to minimize water level effect on subaerial land assessment. Reported tide levels for the images were obtained from National Oceanic and Atmospheric Administration (NOAA) tide gauge at Grand Isle, Louisiana (29°15’24”N, 89°57’24”W, Table 4.2). Daily discharge data was used from ARMC (introduced earlier). River stage was not used because of its variability overtime due to changes in the river channel profile. Discharge was assumed to be consistent because it is re-calibrated every several years to account for changes in stage. The study area was limited to both delta features and marsh areas that were proximal to the ARDC (Figure 4.1).

Table 4.2. Tide and discharge (Q) data for the time of Landsat image capture, and annual tide (MSL, (min; max), and annual Q, (mean (min; max)) for the year the image was captured.

Date	**Tide (m)**	**Q (m^3s^{-1})**	**Annual Tide (m)**	**Annual Q (m^3s^{-1})**
9/2/1989	0.11	2828	0.03, (-0.67; 0.52)	4004, (1436; 7616)
10/21/1995	0.19	3475	0.13, (-0.41; 0.71)	3614, (1541; 7916)
9/14/1999	0.21	2403	0.14, (-0.42; 0.64)	3509, (1135; 8022)
9/27/2004	0.37	4604	0.16, (-0.41; 1.03)	4043, (1752; 6804)
10/30/2010	0.13	2938	0.22, (-0.38; 0.83)	4006, (1586; 6939)

4.3.4 Classification

Unsupervised classification was completed for each image using the ISODATA clustering method in ERDAS IMAGINE. The ARDC area was selected out from the original images based on the furthest extent of land and included some adjoining areas surrounding the deltas (Figure 4.1). Twenty-five classes were derived in the classification with the maximum number of iterations set to 12 and the convergence threshold set to 0.99. The 25 classes were subsequently categorized in three basic cover types: 1) water, 2) vegetation, and 3) barren. These classes were derived based on true color Landsat imagery as well as plotting the classes over feature space images of Landsat bands 3 and 4. The vegetation cover type did not discriminate between vegetation on land or floating on water, and from here on is discussed as vegetated land. After initial classification mixed classes were identified using a "cluster busting" technique that used a mask to select the mixed class from the original image so that re-classification of the mixed class could be completed.

4.3.5 Land Change Analysis

Land change was determined by completing a matrix analysis in ERDAS IMAGINE using consecutive images. This was done for image pairs of 1989 vs. 1995, 1995 vs. 1999, 1999 vs. 2004, 2004 vs. 2010, and 1989 vs. 2010. A land change image was produced for each time frame with classes that fell into 9 different categories; water no change, water to vegetation, water to barren, barren no change, barren to water, barren to vegetation, vegetation no change, vegetation to water, and vegetation to barren. Areas were calculated to determine changes over the different time frames. In all analyses land gain is the addition of the areas for water to vegetation and water to barren; land loss is the addition of the areas for vegetation to water and

barren to water. To complete separate area calculations for each subdelta the land change images were subset to select out the ARSD and the WLSD (Figure 4.1).

New land stability was determined in two steps: 1) selecting pixels that were converted from water to barren and water to vegetation, and 2) assessing if the classified pixel value changed back to water in the subsequent image. To complete this, a matrix analysis was run using the matrix analysis land change images with the next consecutive classified image, for instance, the 1989 vs. 1995 matrix analysis was done with the 1999 classified image. This allowed for the identification of whether new subaerial land was maintained or lost. This was completed for both subdelta subsets and as an additional analysis for land that was lost.

4.4 RESULTS

4.4.1 River Discharge and Total Suspended Sediment Yield

Over the 21-year period from 1989 to 2010, the Atchafalaya River had an average annual total flow volume of 200.0 km^3, varying between 122.7 km^3 (2000) and 252.8 km^3 (2009). About 118.7 km^3 of the average annual total flow volume (i.e. nearly 60%) passed through the ARMC outlet, with a low of 74.0 km^3 (2000) and a high of 164.1 km^3 (1993) (Figure 4.2). The river's other outlet, WLO, had an average annual flow volume of 81.3 km^3, varying between 48.8 km^3 (2000) and 115.2 km^3 (2009) (Figure 4.2). At the beginning of the study period (1989) ARMC discharged 65% and WLO 35% of the total flow volume, and the flow portions gradually changed to 53% for ARMC and 47% for WLO by 2010. The increasing trend of flow at WLO was significant ($p=0.0504$, seasonal-Mann-Kendall). This increase was triggered by a weir removal in 1994 that had previously constricted flow down WLO. During the entire 21 years of this study there were a total of 10 major flood events (when discharge was >13,800 m^3s^{-1} at

Atchafalaya River Simmesport, Louisiana), 5 of them occurred during 1989-1995, 2 during 1995-1999, none from 1999 to 2004, and 3 during 2004-2010 (Figure 4.3).

Table 4.3. Large flood events (>13,800 m^3s^{-1} at Simmesport, LA) with date of peak discharge.

Date	**Period**	**Discharge Peak (m^3s^{-1})**
6/11/1990	1989-1995	14,971
1/25/1991	1989-1995	16,244
5/18/1993	1989-1995	14,716
5/10/1994	1989-1995	13,895
6/17/1995	1989-1995	14,320
3/27/1997	1995-1999	18,027
2/15/1999	1995-1999	14,518
2/2/2005	2004-2010	14,914
4/24/2008	2004-2010	17,716
5/27/2009	2004-2010	15,650

Average suspended sediment concentration was higher at ARMC (242 mg l^{-1}) than at WLO (227 mg l^{-1}) (Figure 4.2). Annual average SSC at ARMC varied between 145 mg l^{-1} (2000) and 449 mg l^{-1} (1998), while annual average SSC at WLO varied between 136 mg l^{-1} (2000) and 351 mg l^{-1} (1998), with typically higher concentrations during high flow springs and lower concentrations during low flow summers and falls (data not shown). Over the study period, SSC decreased significantly at both ARMC (p=0.0235, seasonal Mann-Kendall) and WLO (p=0.0337, Seasonal Mann-Kendall). Over the entire 1989 to 2010 period, the Atchafalaya River discharged 1,121.0 MT of total suspended sediment to the ARDC, averaging annually 51.0 MT with a range from 21.9 MT (2000) to 94.8 MT (1998). ARMC discharged a total of 661.5 MT of total suspended sediment, averaging annually 31.8 MT, varying between 13.6 MT (2000) and 60.4 MT (1998) (Figure 4.2). WLO total suspended sediment discharge was 405.8 MT, averaging annually 19.2 MT, and ranging from 8.3 MT (2000) to 34.4 MT (1998) (Figure 4.2). ARMC accounted for 71% and WLO 29% of the total suspended sediment

discharged in 1989, while by 2010 ARMC accounted for 55% and WLO 45% of the sediment discharged. Over the 21-year period ARMC showed a significant decreasing trend in total suspended sediment yield ($p=0.0276$, seasonal Mann-Kendall), while no clear trend was observed at WLO. Between the four periods used in the spatial analysis total suspended sediment yield decreased from an average annual high of 67 MT yr^{-1} (1995-1999) to an average annual low of 41 MT yr^{-1} (2004-2010) (Figure 4.2).

4.4.2 Deltaic Land Change

From 1989 to 2010 the ARDC had a total new subaerial land gain of 62.0 km^2. Due to a loss of 3.1 km^2, the net subaerial land gain was 58.9 km^2 (Table 4.4). The delta complex experienced a decrease in its total land change rate from a high of 5.6 km^2 yr^{-1} (1989-1995) to a low of -0.4 km^2 yr^{-1} (1999-2004) (Table 4.4). The most recent period (2004-2010) saw a total land change rate of 2.1 $km^2 yr^{-1}$. The period 1999 to 2004 had the largest amount of land lost, 16.6 km^2, and least amount of new land created, 14.5 km^2. The largest land gain, 37.3 km^2, and smallest amount lost, 3.7 km^2, occurred from 1989 to 1995. Over the entire 21-year period annual land growth rate averaged 2.8 km^2 yr^{-1}.

From 1989 to 2010 ARSD at the Morgan City river mouth had a net land gain of 34.4 km^2 (or 58% of the total new land in ARDC), while WLSD at the Wax Lake Outlet river mouth had a net land gain of 24.6 km^2 (or 42% of the total new land in ARDC). Land growth at ARSD has been net positive throughout the study period, with the largest net gain of 14.6 km^2 during 1989-1995 (Figure 4.3A) and the lowest net gain of 2.5 km^2 during 1999-2004 (Figure 4.3B). Land growth of ARSD was influenced by the creation of dredge islands (especially apparent in 1989-1995 period classified as barren land). Land growth during the 1989-1995 and 1995-1999 occurred more prominently as mouth bar island formation and elongation of channel levee areas.

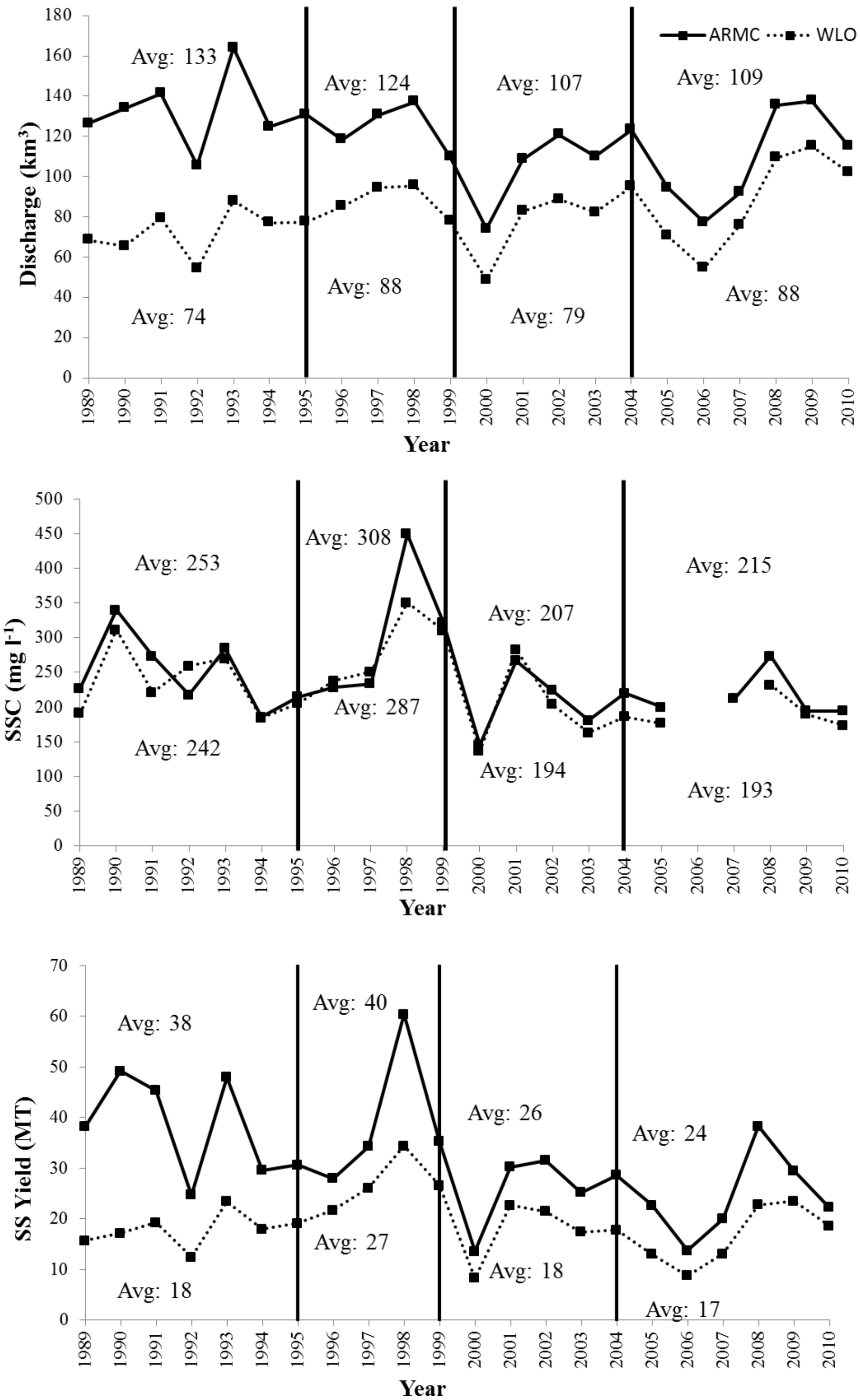


Figure 4.2. Annual river flow volume (km^3), average annual SSC ($mg\ l^{-1}$), and annual total suspended sediment yield (MT), for Atchafalaya River Morgan City (ARMC) and Wax Lake Outlet (WLO). Lines delineate between periods, values shown are mean annual values for each period

Table 4.4. Land gain and loss for each period.

Land Change (km^2)	1989-1995	1995-1999	1999-2004	2004-2010	1989-2010
Gain	37.3	24.1	14.5	20.0	62.0
Loss	3.7	9.5	16.6	7.1	3.1
Total Change	33.6	14.6	-2.1	12.9	59.0
Annual Change ($km^2\ yr^{-1}$)	5.6	3.6	-0.4	2.1	2.8

The 1999-2004 and 2004-2010 period saw more land creation in distal areas. Land growth at WLSD was much more variable with a net loss of 4.6 km^2 of land from 1999 to 2004 and the largest net gain of 19.0 km^2 from 1989 to 1995. Land loss during 1999-2004 was predominantlylocated in distal areas of the delta away from the river mouth. Growth during the 1989-1995 and 1995-1999 periods consisted of total mouth bar island creation whereas 2004-2010 growth mostly occurred near channel levee areas. The rate of land area growth for ARSD varied between 0.5 $km^2\ yr^{-1}$ (1999-2004) (Figure 4.3B) and 2.5 $km^2\ yr^{-1}$ (1989-1995) (Figure 4.3A), and for the entire period was 1.6 $km^2\ yr^{-1}$. Land change rates for WLSD fluctuated from a high of 3.2 $km^2\ yr^{-1}$ (1989-1995, Figure 4.3A) to a net loss of 0.9 $km^2\ yr^{-1}$ (1999-2004, Figure 4.3B) and for the entire period there was a net gain of 1.2 $km^2\ yr^{-1}$.

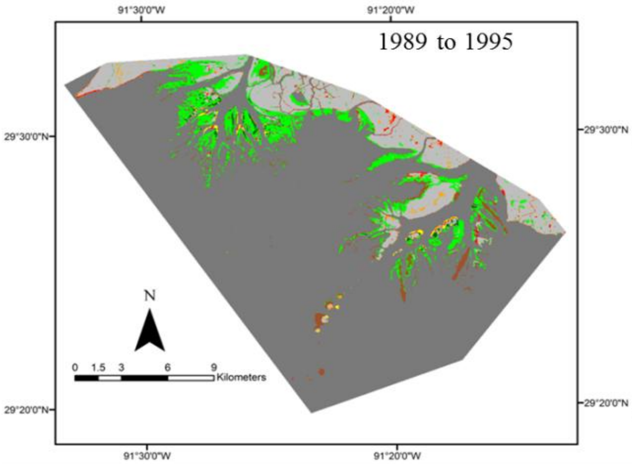
4.4.3 Vegetated Land Change

Of the 62 km^2 of new subaerial land gain since 1989, 87% of the land has been vegetated. For each period land classified as vegetated land was converted less readily to open water than barren. The percent average of barren land converted to water was 32.0% between years, compared to only 7.3% of vegetated land. On average 57% of barren land was converted to vegetated land whereas on average only 3.5% vegetated land was converted to barren land (Table 4.5). There was a net vegetated land loss over the period 1999 to 2004, with 12.6 km^2

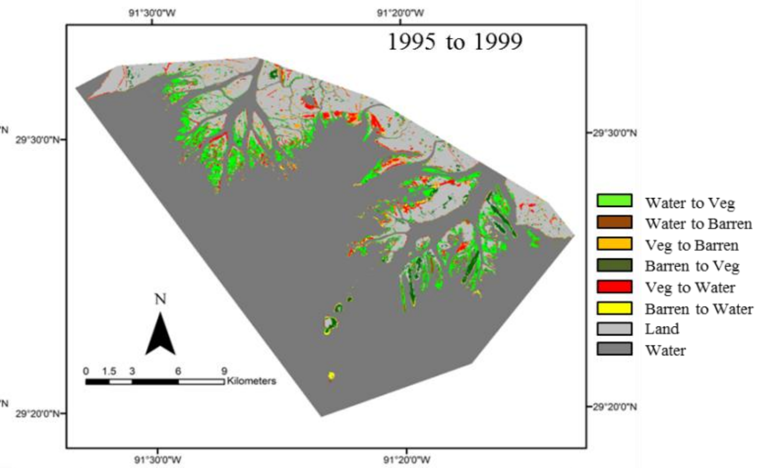
converted to open water (13% of the vegetated land in 1999) (Table 4.5). The largest net barren land loss also occurred over the same period, with 4.1 km^2 (39% of barren land in 1999) converted to open water (Table 4.5). The largest net vegetated land gain occurred over the period 1989 to 1995, with 25.7 km^2 added to the deltas. The largest net barren land gain occurred over the same period with 7.9 km^2.

ARSD accounted for 33.1 km^2 (61%) and WLSD accounted for 20.9 km^2 (39%) of the total newly vegetated land in the ARDC (1989-2010). The greatest net gain from open water to vegetated land in the WLSD was 16.6 km^2 over the period 1989 to 1995 (Figure 4.3A). Net vegetated land gain was found at WLSD during all periods except for 1999 to 2004 (Figure 4.3B). For the period 1989 to 1995, 87% of the net land gain was vegetated land, 86% for the 1995 to 1999 period, and 66% for the 2004 to 2010 period. Vegetated land made up 56% to 83% of land lost, although this was on average only 9% of the total vegetated land. The period 1999 to 2004 was the exception where there was a vegetated land loss at WLSD of 8.0 km^2, 16% of the total vegetated area in 1999, which contributed to 4.9 km^2 of total net loss (Figure 4.3B). On the other hand, a net vegetated land loss was not seen at ARSD throughout all four comparison periods. Net vegetated land gain accounted for 60% (1989-1995) to 91% (1999-2004) of the net land gain (Figure 4.3A, B). The greatest open water to vegetated land gain for ARSD was 9.9 km^2 for a net vegetated land gain of 8.6 km^2 (1989-1995). The least amount of net vegetated land gain at ARSD occurred from 1999 to 2004 with 2.3 km^2 added to the subdelta (Figure 4.3B). Vegetated land accounted for, on average, 62% of the land loss at ARSD, but this only amounted to 5.8% of the total vegetated surface.

A

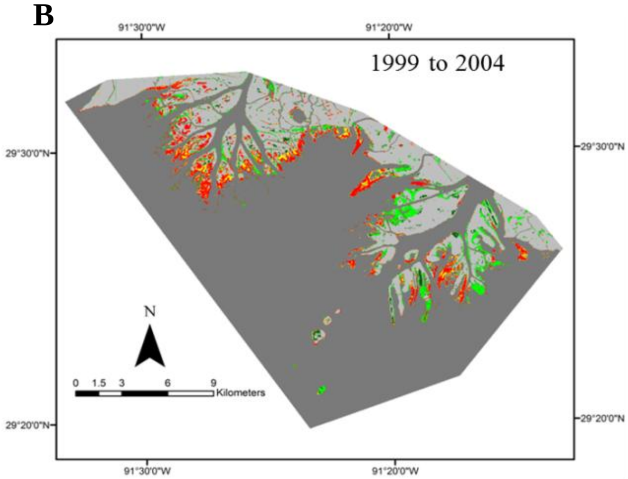


	WLSD		ARSD	
Class	**Area**	**Gain**	**Area**	**Gain**
Water to Veg	17.6	20.8	9.9	16.5
Water to Barren	3.2		6.5	
Veg to Barren	0.7		1.2	
Barren to Veg	1.7	**Loss**	0.7	**Loss**
Veg to Water	0.9	1.7	1.3	1.9
Barren to Water	0.8		0.7	
	Total	19.0	**Total**	14.6
	Rate	3.2	**Rate**	2.4

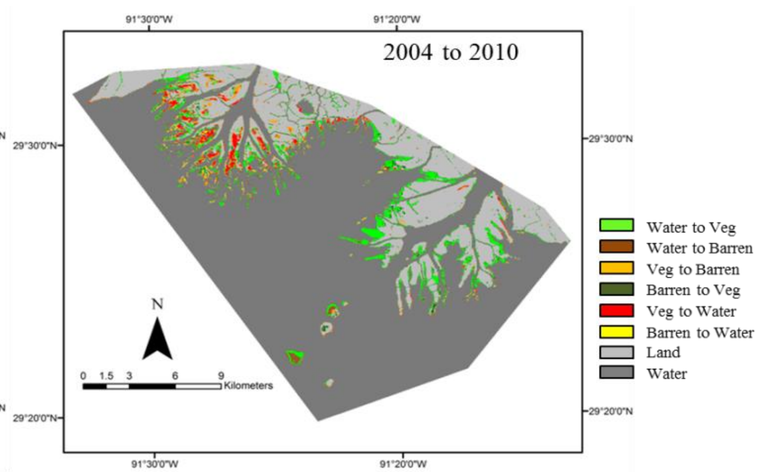


	WLSD		ARSD	
Class	**Area**	**Gain**	**Area**	**Gain**
Water to Veg	9.4	11.6	9.3	12.4
Water to Barren	2.2		3.1	
Veg to Barren	2.3		1.3	
Barren to Veg	2.3	**Loss**	5.0	**Loss**
Veg to Water	3.6	4.8	2.5	4.7
Barren to Water	1.3		2.1	
	Total	6.8	**Total**	7.8
	Rate	1.7	**Rate**	1.9

B



	WLSD		ARSD	
Class	**Area**	**Gain**	**Area**	**Gain**
Water to Veg	3.1	5.6	6.9	8.9
Water to Barren	2.5		2.1	
Veg to Barren	1.7		0.9	
Barren to Veg	2.2	**Loss**	2.9	**Loss**
Veg to Water	8.0	10.2	4.6	6.5
Barren to Water	2.2		1.9	
	Total	-4.6	**Total**	2.5
	Rate	-0.9	**Rate**	0.5



	WLSD		ARSD	
Class	**Area**	**Gain**	**Area**	**Gain**
Water to Veg	6.2	9.4	8.5	10.6
Water to Barren	3.2		2.1	
Veg to Barren	2.5		0.5	
Barren to Veg	2.2	**Loss**	2.8	**Loss**
Veg to Water	4.0	6.0	0.5	1.1
Barren to Water	2.1		0.6	
	Total	3.3	**Total**	9.5
	Rate	0.6	**Rate**	1.6

Figure 4.3.A, B. Land change for the Wax Lake Outlet subdelta (WLSD), and Atchafalaya River subdelta (ARSD). All values are km^2 except for rate, $km^2\ yr^{-1}$. Gain is the sum of water to barren and water to vegetation and loss is the sum of barren to water and vegetation to water.

4.4.4 Inter-periodic Fluctuation of Barren and Vegetated Land

Between the four periods, newly vegetated land was primarily sustained as vegetated land. At WLSD 74% of newly vegetated land (water to vegetation) in 1995 was sustained as vegetated in 1999 and 67% of the newly vegetated land in 2004 was sustained as vegetated in 2010. The exception was the period 1999 to 2004 (Figure 4.4). During this period, newly vegetated land from 1999 was converted to water at a slightly greater degree (47%) than being sustained as vegetated land (44%). ARSD newly vegetated land was sustained as vegetated land for each period (71%, 1995 to 1999 and 94%, 2004 to 2010), although there was a slight drop from 1999 to 2004 (59%, Figure 4.4). New barren land was for the most part converted to vegetated land during proceeding years except at WLSD. For both 1999 to 2004 and 2004 to 2010 WLSD new barren land was converted to water to a greater degree than vegetation (Figure 4.4). Vegetated and barren land that was converted to water remained predominantly water in subsequent years (Figure 4.5).

4.5 DISCUSSION

The Atchafalaya River Delta Complex is the only notable prograding delta feature along the Mississippi River Delta coastline in recent decades. For the past 21 years our study found an average growth rate of the entire delta complex of 2.8 $km^2\ yr^{-1}$, which was slightly lower than two other recent estimates: 3.1 $km^2\ yr^{-1}$ (1984-2004) by Xu (2010) and 3.2 $km^2\ yr^{-1}$ (1985-2010)

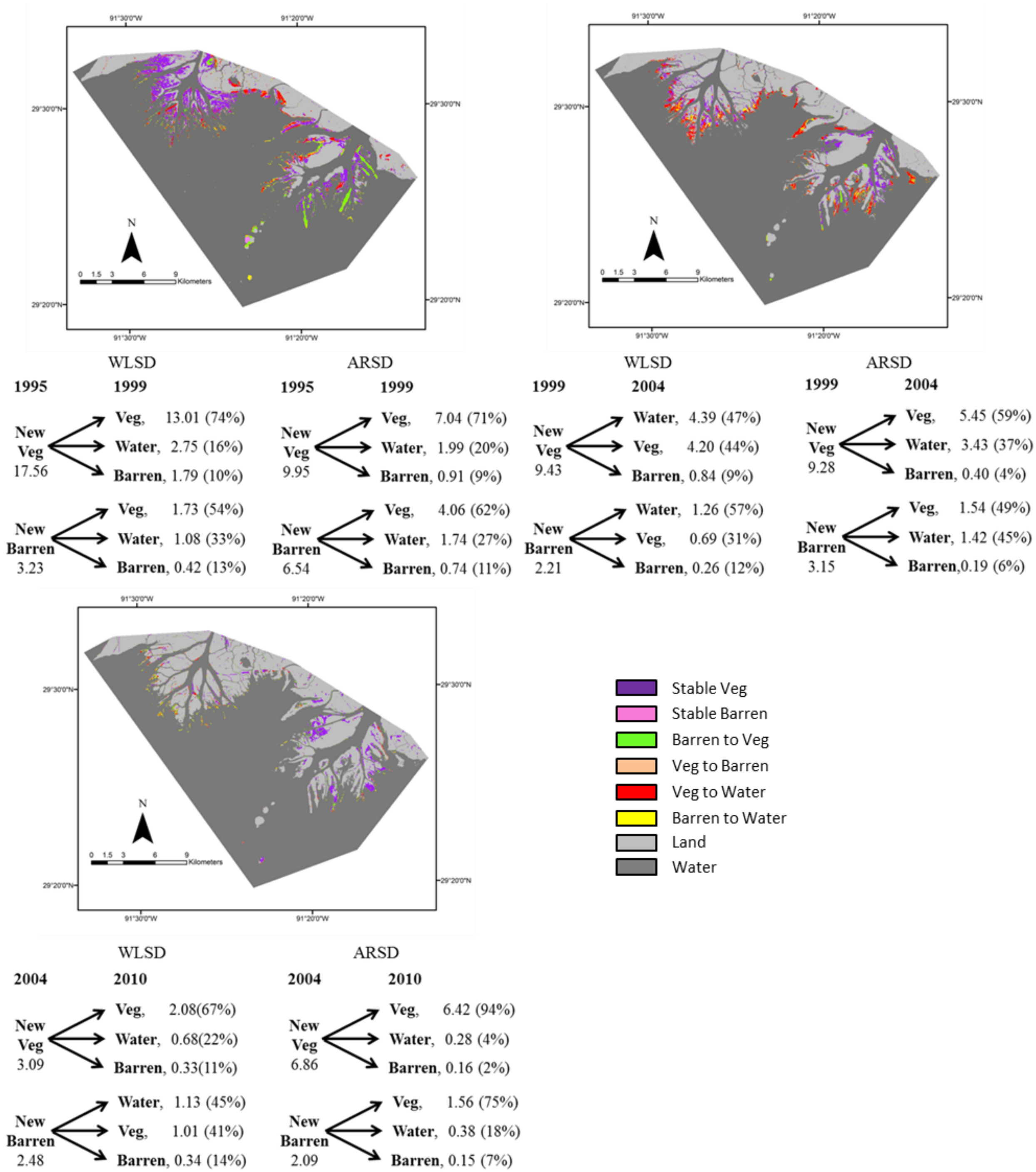


Figure 4.4. Maps of how newly emergent land changed over time for each subdelta. New Veg is newly emergent vegetated land and New Barren is newly emergent barren land. All values in km^2.

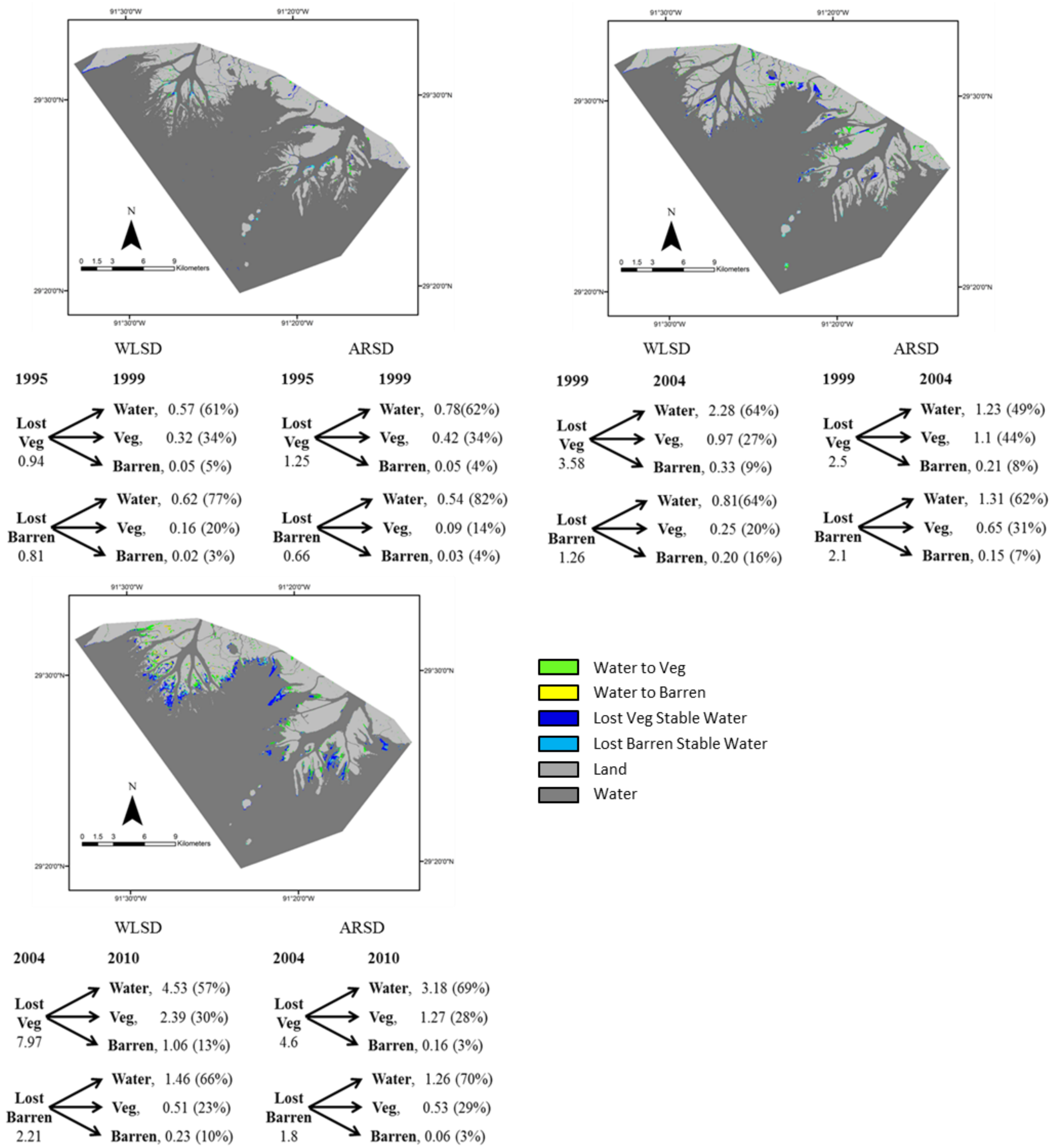


Figure 4.5. Maps of how lost land changes over time for each subdelta. Lost Veg is vegetated land that was converted to water. Lost Barren is barren land that was converted to water. All values in km^2.

by Couvillion et al. (2011). The two subdeltas of the ARDC exhibited slightly different growth rates: 1.6 $km^2 yr^{-1}$ for ARSD and 1.2 km^2 yr^{-1} for WLSD. Allen et al. (2012) had a similar estimated growth rate of 1.0 km^2 yr^{-1} for WLSD (1983 to 2010), and Xu (2010) estimated growth rates for the period 1984 to 2004 of 1.1 km^2 yr^{-1} (ARSD) and 2.0 km^2 yr^{-1} (WLSD). Overall, differences in these growth rate estimates are small and can be attributed to different time frames and aerial coverage.

Delta growth fluctuation among the periods is of great interest. There was a clear decreasing trend in delta growth from a high of 3.2 km^2 yr^{-1} (WLSD) and 2.4 km^2 yr^{-1} (ARSD) over the period 1989 to 1995 to a low of 0.6 km^2 yr^{-1} (WLSD) and 1.6 km^2 yr^{-1} (ARSD) over the period 2004 to 2010. Majersky et al. (1997) estimated similar rates for the earlier periods, 3.2 km^2 yr^{-1} (ARSD) and 3.0 km^2 yr^{-1} (WLSD), while Allen et al. (2012), looking at a later period (2002-2010), found that WLSD had no net gain. From 1999 to 2004 there was a net loss of land from the ARDC, which was driven by large losses of land from the WLSD. During this period the growth rates dropped to -0.9 km^2 yr^{-1} for WLSD and 0.5 km^2 yr^{-1} for ARSD. The declined growth rate at ARSD depicts a part of a longer trend, where high early rates, estimated at 6.5 km^2 yr^{-1} (1972 to 1976) (Rouse et al. 1978) and 5.8 km^2 yr^{-1} (1976-1981) (Roberts et al. 1997) fell sharply following 1981 and has continued a slight decline to the latest period (Figure 4.6). WLSD had much slower development, but eventually eclipsed ARSD growth rate during the 1980's, but since the mid 1990's growth rate at WLSD has declined below ARSD growth rate, despite the increased portion of flow and sediment through WLO. The more stable growth rates at ARSD could be attributed to the many dredge spoil islands created from deposits of the Atchafalaya River Bar Channel. Further studies are needed to determine the management effect on land growth in the ARDC.

Among the four study periods, the 1999 to 2004 period was the only period without a large flood event (discharge >13,800 m^3s^{-1}) (Figure 4.6). This period also had the highest recorded storm surge (3.75 m) caused by hurricane Lili in 2002 (SURGEDAT 2012). During this period we found a net land loss at the ARDC (Table 4.4) due solely to the 4.6 km^2 loss at WLSD (Figure 4.3B). In other periods the transport capability of large floods was still able to maintain positive growth (Figure 4.6). Rouse et al. (1978) indicated that the high growth rates observed during the initial stages of subaerial delta development (1972 to 1976) were fueled by two large floods over a three year period. The 1975 flood was much larger than normal producing 11.4 km^2 of new land, whereas the smaller 1974 flood created only 2.6 km^2 (Rouse et al. 1978). It is well known that large flood events often provide the greatest sediment delivery, and periods with low flow can result in decreased delta growth, even in rivers with high SSC such as the Yellow River in China (Chu et al. 2005; Wang et al. 2007). Nittrour et al. (2008) identified that bedform transport rate of the lower Mississippi River had a positive exponential correlation with discharge, indicating the importance of large discharge events for delivering coarse load. This is evidenced in our study by the increase in suspended sand load with increasing discharge at both ARMC and WLO outlets (Figure 4.7). The large quantity of coarse sediments provided by floods can be important for fueling delta growth by capping fine sediment deposits with a layer of course sediments that creates a substrate elevated enough for colonization of marsh species (van Heerden and Roberts 1988). Our study suggests that river floods are a major contributing factor to the variation in deltaic growth rate of ARDC, and that future growth of the ARDC will rely on a consistent frequency of large floods to counteract other stressors such as hurricanes, subsidence, and decreased SSC.

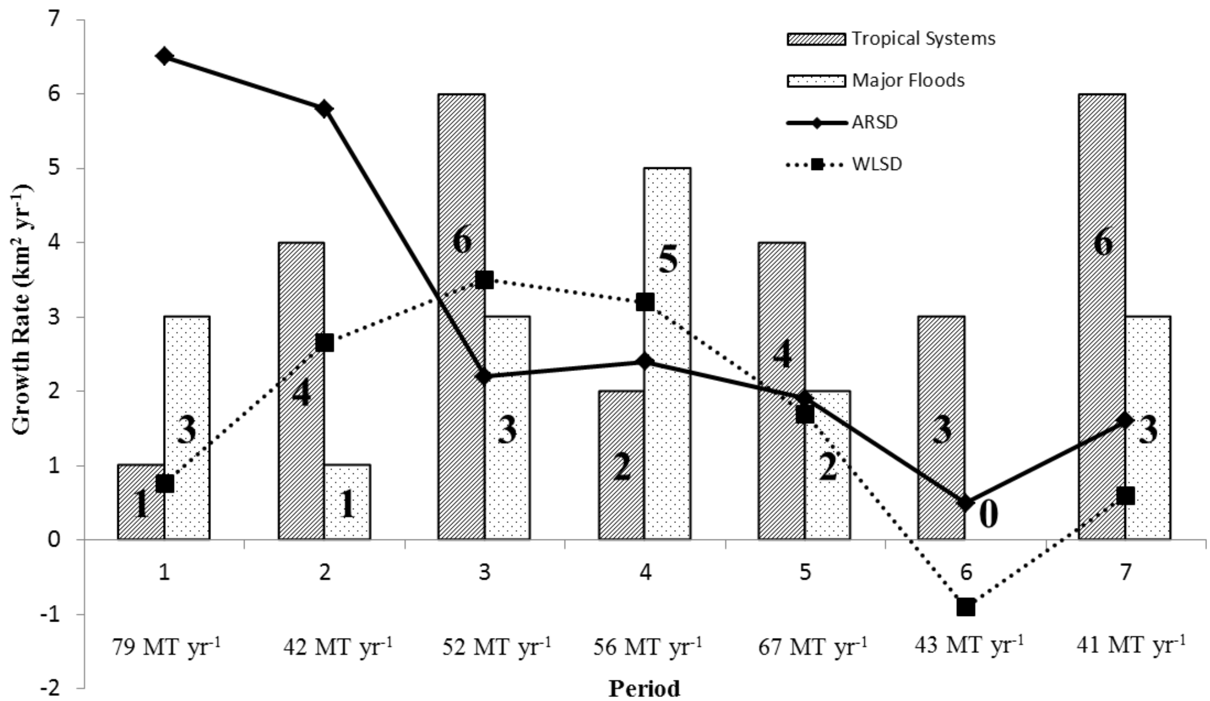


Figure 4.6. Land growth rates for the Atchafalaya River subdelta (ARSD) and Wax Lake Outlet subdelta (WLSD), number of tropical systems, and major floods (>13,800 m^3s^{-1}) for 7 periods starting from 1972 and ending in 2010. Period 1= 1972-1976, period 2= 1976-1981, period 3= 1981-1989, period 4= 1989-1995, period 5= 1995-1999, period 6= 1999-2004, and period 7= 2004-2010. Average annual total suspended sediment yield is listed below the horizontal axis in megatonnes per year (MT yr^{-1}). Growth rates for period 1 are from Rouse et al. (1978) (ARSD) and Roberts et al. (2003) (WLSD). Growth rates for period 2 and 3 are from Roberts et al. (2003). Tropical system counts are from Roth (2010) and average annual total suspended sediment yields prior to 1989 are from Xu (2010).

Tropical systems (hurricanes and tropical storms) have been documented causing variable affects to marshes, both physically destroying large areas (Barras 2007; Howes et al. 2010) and supplying sediment (Rejmanek et al. 1988; Nyman et al. 1995). Over the four periods in this study we found the most severe reduction in growth rate at the ARDC followed hurricane Lili in 2002. It was reported that the hurricane caused 7 km^2 of marsh loss approximately 21 km west of WLSD (Barras 2003). Although there is no documentation of land loss at the ARDC, Lili and the two additional tropical storms (Table 4.1) that affected the area during the 1999-2004 period

would have contributed to the negative growth rate. This is not a new phenomenon as observing growth rate estimates for previous periods would also seem to indicate that increases in tropical system frequency caused a reduction in growth rates (Figure 4.6). The periods of 1999-2004 and 2004-2010 present an interesting contrast. The latter period had two category 3 hurricanes make land fall in 2005 (Table 4.1) causing 23 km^2 of land loss in the region around the ARDC (Barras 2006), while the former only had one category 1 hurricane make land fall. Even with the land loss following the hurricanes during the 2004 to 2010 period, large flood events were able to counterbalance this loss to maintain a positive growth rate (Figure 4.3B). This again indicates the dominant role of large flood events for maintaining growth at the ARDC.

Over the study period there was decreasing suspended sediment concentrations observed at both subdeltas. The decreasing SSC observed over the period can be ascribed to decreasing SSC identified throughout the Mississippi River Basin (Meade and Moody 2010; Horowitz 2010). The SSC decline directly affects total suspended sediment input to the ARDC. The Yellow River in China has also gone through a reduction in sediment discharge from 1000 MT yr^{-1} to 150 MT yr^{-1} (Wang et al. 2007), contributing to a gradual erosion phase at the Yellow River Delta since 1996 (Chu et al. 2005). The defining difference between the Yellow River and the Atchafalaya River is that both flow and SSC of the Yellow River have declined greatly (Wang et al. 2007) whereas flow of the Atchafalaya River has stayed relatively constant over the past 21 years (Figure 4.2). This has enabled the continuation of large flood pulses to occur in the Atchafalaya River. If total suspended sediment supply to the ARDC does not decrease further, growth rates of the delta complex should maintain constant, as long as the flood pulse does not diminish.

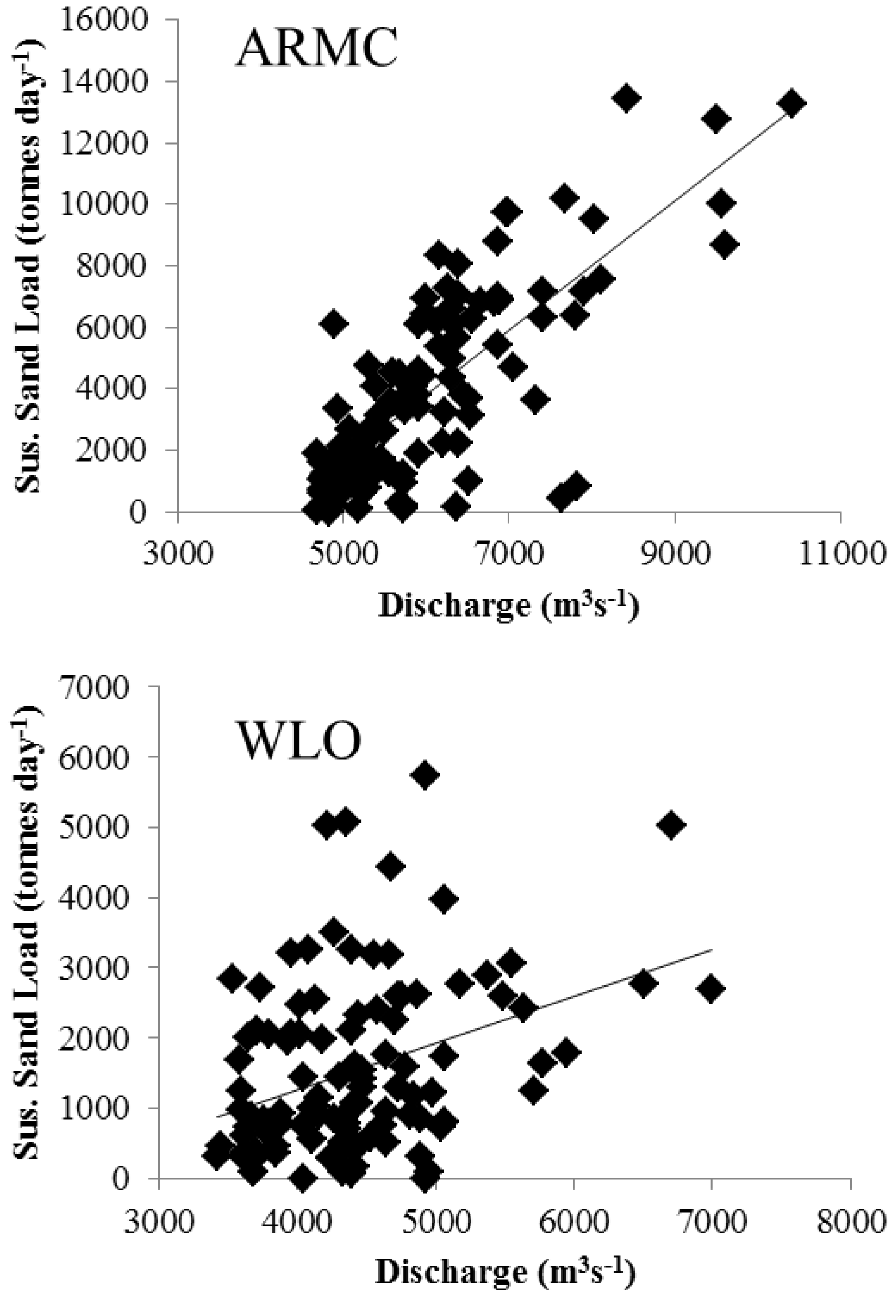


Figure 4.7. Daily suspended sand load (grain size >62.5µm) versus water discharge above 25% discharge exceedence (1989-2010) for the Atchafalaya River Morgan City (ARMC) and Wax Lake Outlet (WLO).

Vegetation colonization of deltaic land occurred rapidly in ARDC, with 87% of the new subaerial land since 1989 vegetated. Between the four periods vegetated land was not converted to water as readily as barren areas with, on average, only 7% of the vegetated land converted to water as compared to 32% of barren land. This may have been caused by greater sedimentation from vegetation influences and/or due to the stabilizing effect of root density. In an early study on vegetation succession in newly created land, Johnson et al. (1985) found that biotic enhancement of sedimentation only occurred with *S. nigra* (black willow) on the highest elevation areas of the delta (e.g. levee), while the majority of delta sedimentation was controlled by physical processes, indicating different species effect. Even at lower elevations where sedimentation is controlled by physical processes, vegetation may still be important because McGinnis (1997) found that soil strength (ability to resist erosion) in a Louisiana coastal marsh was a function of live root density.

We found that newly vegetated areas maintained vegetated in subsequent periods at greater than 60% in the ARDC (Figure 4.4). The only instance where newly vegetated land was converted to water at higher rates was during the 1999 to 2004 period (Figure 4.4), where WLSD lost 4.4 km^2 of newly vegetated land. As discussed earlier, this period was characterized by a lack of large floods, and 3 tropical system impacts. The combination of these factors could have generated this loss by salt water stress causing vegetation mortality while lacking large flood events to provide large quantities of sediment. Hurricanes can cause extended periods of saltwater intrusion, which can kill freshwater marsh vegetation, in addition to physically eroding away large areas of land (McKee and Mendelssohn 1989; Flynn et al. 1995; Steyer et al. 2007; Barras 2007). The land loss caused by tropical systems during the 1999 to 2004 period may not have been counterbalanced by enough sediment input in subsequent years from the lack of large

flood pulses. In addition, the lower sediment input may not have been able to offset subsidence rates, which could exceed 6.0 mm yr^{-1} due to compaction of new delta surface (Shinkle and Dokka 2004). This provides two important insights on vegetation stabilization of delta land. First, under reduced flow conditions vegetation alone may not be enough to maintain delta surface. This is supported by the findings of Neubauer (2008) that tidal freshwater marsh in active deltas in Louisiana was maintained through mineral additions. Second, that the stabilization displayed in other periods could have been land re-generation by large floods after high energy storm events followed by rapid vegetation colonization. Due to the lack of field surveys and a comparative design, our study cannot make a conclusive estimation as to the degree of vegetation stabilization in newly created land.

Two other factors may have affected our delta growth assessment: cold fronts and tidal variations. Cold front passage can cause water to flush out of the bay area and has been documented for being able to remove up to 10.6 MT of sediment annually from the Atchafalaya Bay (Walker and Hammack 2000; Roberts et al. 2005). Unlike tropical systems and floods, cold fronts occur every year and there is little variation between years, thus making their impacts relatively consistent, and not a driving factor in the overall changes observed (Hardy and Henderson 2003). Tides can also affect land estimates by affecting the amount of land surface visible. At the ARDC tide can cause the extent of land estimates to vary by as much as 30% (Allen et al. 2012), and this may have been the main cause for the small difference in delta growth rate estimates between this study's and others (Xu 2010; Couvillion et al. 2011). During our four study periods the difference in tides varied from 0.02 m to 0.24 m. For the periods 1989 to 1995 and 1995 to 1999 each subsequent image had higher tide, which may have made the land estimates to be conservative. For the period 1999 to 2004 tide was the highest and may have

exaggerated the net loss seen at the time. For the period 2004 to 2010 tide was the lowest for any image and thus could have caused a slight exaggeration of extent, adding to the gain seen during that period. The barren land class would have been affected by tide the most since these areas are most likely tidal flats so any variation in tide could have affected classification. Vegetated land was probably unaffected because the vegetation at lowest elevations (*S. platyphylla*, *N. lutea* and *S. latifolia*) grows taller (>0.8 m) than the tides observed and thus variations in tides between images would not have caused these areas to be classified differently.

4.6 CONCLUSIONS

This study shows that land growth of the Atchafalaya River Delta Complex in the past two decades was dictated by large flood events, while severe tropical systems temporarily impacted delta size to a large degree. Large floods were able to transport substantial quantities of sediment needed to create rapid subaerial land formation, which was followed by vegetation colonization. When compared to barren land vegetation succession provided stabilization. However, during the period with no large flood events the buffering effect of vegetation appeared to be limited against higher energy storm surges. The result implies that future growth and stabilization of the ARDC will mostly depend on sediment supply from the Atchafalaya River and storm weather conditions in the northern Gulf of Mexico. If sediment supply does decline in the future, delta growth will slow further and may also cause large flood events to be less effective at building land. Losses will likely be most apparent at WLSD that unlike ARSD does not have the additions of dredge spoil to create new land. With possible diversions of the Atchafalaya River water before reaching the subdeltas, future flood volumes might be reduced, slowing growth and possibly exacerbating erosion. Coastal Louisiana provides an interesting case study for other coastal regions around the world on how to manage sediment-starved deltas

in the 21st century. With human and environmental factors both influencing delta evolution, creative and forward thinking river and sediment management will dictate the fate of coastal Louisiana and the millions of people that call it home.

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CHAPTER 5: ESTIMATION OF SEDIMENTATION RATES IN THE DISTRIBUTARY BASIN OF THE MISSISSIPPI RIVER, THE ATCHAFALAYA RIVER BASIN, USA

5.1 INTRODUCTION

Coastal floodplains have a large capacity to trap riverine sediment and nutrients (Hupp 2000; Noe and Hupp 2009). With catchment wide changes to land cover and the construction of dams, levees, and river training structures, there have been major impacts on river sediment transport and the interaction of rivers with floodplains. Due to the variable nature of the impacts that these changes can have on coastal floodplains it makes it important to properly track sediment dynamics and how this influences floodplain sediment storage.

The Mississippi River system provides a good example of how changing hydrology and sediment dynamics can affect floodplains. In the upper Mississippi River dams and other river engineering structures on tributaries have caused decreased sediment supply to the lower Mississippi River (Meade and Moody 2010). Along the river man-made levees have confined the river to its channel to reduce flooding, but have effectively cut-off the floodplain and delta plain surrounding the river (Kesel 2003). The loss of mineral inputs and high subsidence rates has caused approximately 4900 km^2 of land loss in the delta plain (Yuill et al. 2008; Couvillion et al. 2011).

Management of the Mississippi River is complicated with the need to control flooding and land loss. One area that is heavily regulated by federal and state agencies is the largest distributary of the Mississippi, the Atchafalaya River. The Atchafalaya River is confined by levees creating the 35 km wide Atchafalaya River Basin (ARB), which is managed as a floodway for the Mississippi River. The ARB comprises an area of 4921 km^2, making it the largest river

swamp in the United States. The Atchafalaya River is about 307 km shorter than the Mississippi River to the northern Gulf of Mexico. Due to the more favorable gradient (Fisk 1952) in conjunction with human alterations to the Mississippi River and Atchafalaya River, a better defined channel began to form in the mid-1900s, which increased the flow volume going down the Atchafalaya River and into the ARB (Roberts et al. 1980). With fears of the Atchafalaya River capturing the majority of the discharge of the Mississippi River, the Old River Control Structure (ORCS) was completed in 1963 under the Flood Control Act of 1954 to stop the avulsion of the Mississippi River down the Atchafalaya River. ORCS maintains approximately 25% of the discharge of the Mississippi River entering into the Atchafalaya River (Horowitz 2010). Although discharge was controlled, previous accumulation of sediments had filled many open water areas in the ARB (Tye and Coleman 1989).

With much of the ARB sediment filled major management issues have arisen regarding habitat change of open water areas and forested wetlands to upland forest. The ARB is a designated floodway for the Mississippi River and major flood events are regulated through ORCS and an approximately 5 km wide spillway, the Morganza Spillway. Operation of the spillway occurs when river discharge exceeds 42,000 m^3s^{-1} at Red River Landing, Louisiana on the Mississippi River. The spillway was opened only twice (in 1973 and 2011) since its construction. As a result of previous sedimentation the ability to buffer flooding has been diminished and there are concerns that with continued sedimentation, open water and low elevation cypress forests will transition to higher elevation bottomland hardwood forest, decreasing capacity and limiting sheet flow (Atchafalaya Basin Advisory Committee 1998). Another problem related to rapid sedimentation in the ARB is that many backwater areas have become cut off and subsequently hypoxic (Sabo et al. 1999). This has negatively affected

biological communities within the ARB (Fontenot et al. 2001; Rutherford et al. 2001). Also, there is the hope that the ARB has the potential to reduce nitrogen before nutrient-rich Mississippi River waters enter the Gulf of Mexico (Xu 2006).

The first basin-wide maps of inundation and turbid water areas were completed by Allen et al. (2008), helping land managers better understand water distribution and flow patterns. Xu (2010) provided the first comprehensive long-term estimates of sediment inflow and outflow, providing insight on sediment dynamics during different hydrological conditions. Although this information is crucial for future management, the images do not provide information on sedimentation rate, while the sediment calculations do not provide separate estimates for the two outlets at Morgan City and Wax Lake Outlet.

The goal of this study was to add to previous work to help generate a better understanding of spatial sedimentation in the ARB as well as regional sediment resources in Louisiana by calculating total suspended sediment yield entering and exiting the ARB, and expanding the use of Allen et al. (2008) spatial datasets. The specific objectives of this study were: (1) to derive the best estimates of total suspended sediment inflow, total suspended sediment outflow, and retained sediment in the ARB by calculating total suspended sediment yields separately for Simmesport, Morgan City, and Wax Lake Outlet, and (2) to use remotely sensed images to estimate sedimentation rates based on sediment retention over time.

5.2 METHODS

5.2.1 Study Area

The Atchafalaya River is formed by the entire flow of the Red River combined with approximately 25% of the Mississippi River flow. The river travels 275 kilometers through south Louisiana from Simmesport, Louisiana (ARS 30°59’00” N, 91°12’43” W, Figure 5.1) to the outlets at Morgan City, Louisiana (ARMC, 29°41'33.4"N, 91°12'42.6"W, Figure 5.1), and Wax Lake Outlet at Calumet, Louisiana (WLO, 29°41'52"N, 91°22'22"W, Figure 5.1). The first 110 km of the river is confined to a well-defined channel bordered by levees. Below this it opens up to a 25-35 km wide floodplain leveed on the east and west. The river in this section is composed of anastomosing channels. The dominant cover types of the Atchafalaya River Basin are wooded lowland and cypress-tupelo (3581 km^2) with freshwater marshes (2092 km^2) in the lower distributary area (USGS 2001) and some agricultural fields in the northern channelized area. Climate of the region is humid subtropic (Köppen climate classification *Cfa*).

5.2.2 Riverine Sediment Load Estimation

Long-term discharge and sediment records were obtained from the United States Geological Survey (USGS) and the United States Army Corps of Engineers (USACE). All sites used in this study are dually maintained by the USGS and USACE. Daily mean discharge data for the Atchafalaya River at Simmesport, Louisiana (ARS, Figure 5.1) were downloaded from the USACE New Orleans district for the time period 1 January 1980 to 31 December 2010. Daily mean discharge data were downloaded directly from the USGS website (http://waterdata.usgs.gov/la) for Lower Atchafalaya River at Morgan City, Louisiana (ARMC, Figure 5.1), and Wax Lake Outlet at Calumet, Louisiana (WLO, Figure 5.1).

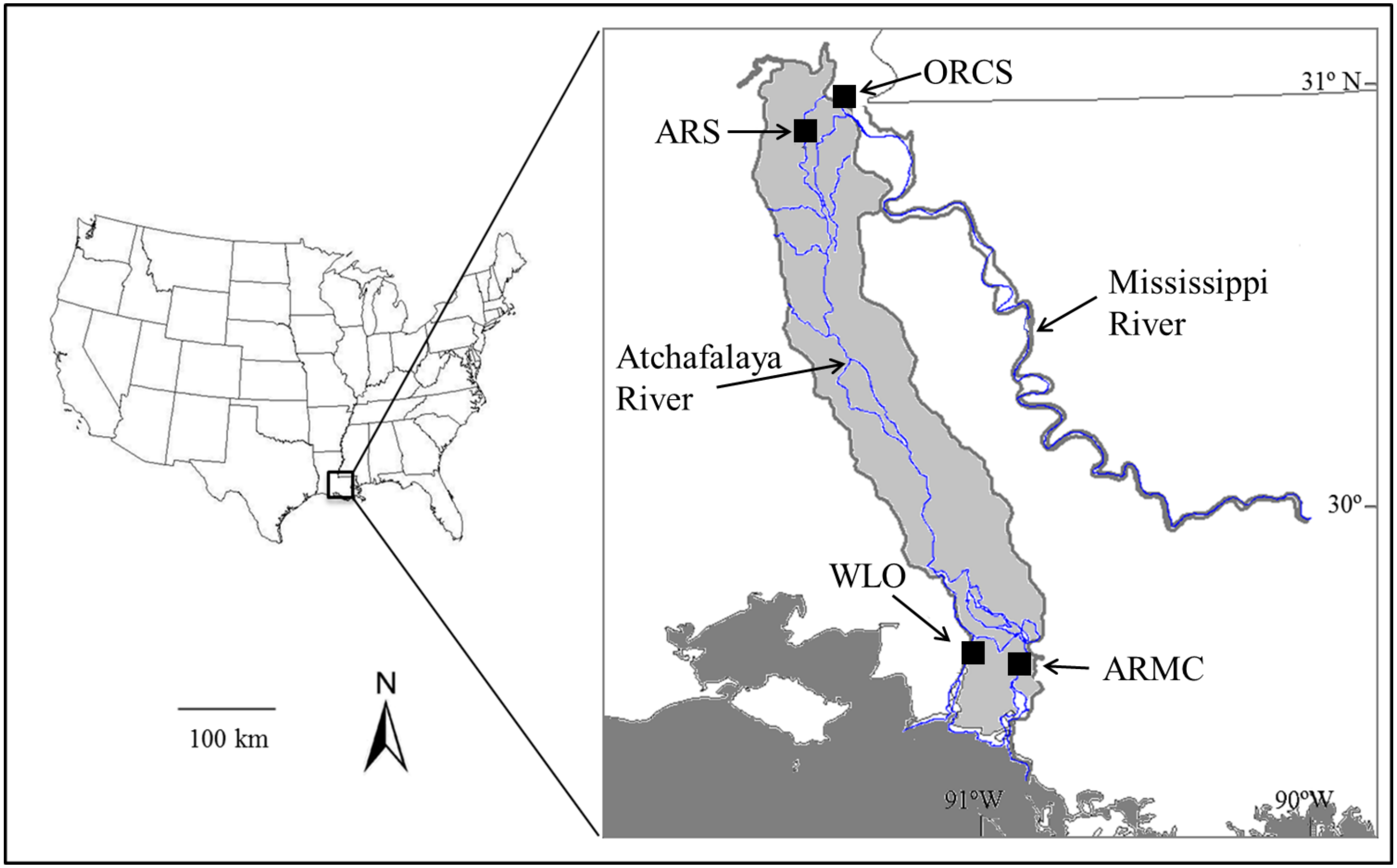

Figure 5.1. Atchafalaya River Basin (gray area) with the locations of Old River Control Structure (ORCS); Atchafalaya River Simmesport (ARS), Atchafalaya River Morgan City (ARMC), and Wax Lake Outlet (WLO).

Discharge measurement did not begin at WLO until June 1986 and at ARMC until October 1995. Missing discharge data for WLO and ARMC were estimated based off of a relationship from Xu and Wang (in review) using the gauging station up river at ARS. The equations used were:

$$QARMC= 10894.31977 + 0.53129\ (QARS) \qquad (1)$$

$$QWLO= 6290.27339 + 0.34707\ (QARS) \qquad (2)$$

where QARMC, QWLO, and QARS are the daily mean discharge passing ARMC, WLO, and ARS in $ft^3\ s^{-1}$. Using these equations discharge data were estimated back to 1 January 1980. The estimated discharge was only used to calculate sediment load for the spatial analysis, and not to determine trends. Suspended sediment concentration (SSC, mg l^{-1}) data were downloaded from the USGS for the same sites as the discharge data. The ARS suspended sediment data are collected bimonthly by the USACE during non-flood, and weekly during flood season. At ARMC and WLO, suspended sediment data are collected monthly during non-flood and bimonthly during flood seasons. During severe flood events, sediment data are collected more frequently by USACE and USGS.

Long-term total suspended sediment loads (SSL) were estimated using log-log linear regression and log-log 2nd order polynomial regression equations relating measured suspended sediment load to discharge. Total suspended sediment load was calculated using:

$$\text{Daily SSL (tonnes day}^{-1}) = [Q\ (m^3\ s^{-1})]\ [SSC(mg\ l^{-1})]\ (0.00864) \qquad (3)$$

Both linear and 2nd order polynomial sediment rating curves were calculated with and without smearing correction. Smearing correction was followed using the methods of Duan (1983). For

the ARS long-term (using all the data) and annual sediment rating curves were developed using linear and 2nd order polynomial regression. For the ARMC and WLO long-term (using all the data) and three year sediment rating curves were developed separately for each station using both linear and 2nd order polynomial regression. Three year intervals were used because of missing SSC values for 2006 at ARMC and 2006 and 2007 at WLO. Daily total suspended sediment load was estimated using the following formulas:

Linear regression: $\ln(SSL)= b\ln(Q)+ \ln(a) + \varepsilon$ (4)

2nd order polynomial regression: $\ln(SSL)= - c\ln(Q^2)+ b\ln(Q)+\ln(a) + \varepsilon$ (5)

where SSL is daily total suspended sediment load, Q is discharge, a, b, and c are constants, and ε is lognormally distributed error (e.g. Miller 1951; Glysson 1987; Helsel and Hirsch 2002). The accuracy of the estimated values were evaluated by % difference between measured total suspended sediment loads, calculated from equation 3, and estimated daily total suspended sediment load calculated from the sediment rating curves, based on Horowitz (2003):

% difference= [(predicted value)-(measured value)/(measured value)]x100 (6)

The rating curves with the best fitting parameters were selected to estimate total suspended sediment load (tonnes day^{-1}) and subsequently summed to estimate total suspended sediment yield (tonnes yr^{-1}) on the annual scale (see appendix Table A2). Daily total suspended sediment load estimated for spatial sedimentation rate calculation was completed by using the sediment rating curves that provided the closest approximation to the sampled data for the month in which the image was captured (see appendix Table A3).

5.2.3 Sedimentation Estimation

Atchafalaya River Basin (ARB) turbid water layers were downloaded from the USGS Atchafalaya Basin Program Natural Resource Inventory and Assessment System (http://abp.cr.usgs.gov/Map.aspx). Classification of Landsat imagery was completed by methods described in Allen et al. (2008). There were 30 total images spanning 1983 to 2010. Each image was classified into 6 different categories; Land, Open Turbid Water, Open Non-Turbid Water, Flooded Land Turbid Water, Flooded Land Non-Turbid Water, and Aquatic Vegetation. Only Open Turbid Water and Flooded Land Turbid Water classes were used because these areas were inferred to be directly influenced by the Atchafalaya River. Images used for sedimentation rate calculation had a net amount of suspended sediment trapped. Trapped amounts were determined as the difference between total suspended sediment load entering at ARS and exiting at ARMC and WLO for the day of the image capture. A lead was applied to ARS to compensate for the amount of time water takes to travel from ARS to ARMC and WLO. The mean lead was 2 days but varied between 0 and 4 days. Lead times were determined by comparing peaks and troughs of the hydrograph for all three sites. From the 30 images, 20 images had a net amount of retained sediment. Sedimentation rates were calculated using the amount of retained total suspended sediment (tonnes), several bulk densities, the volume of sediment, and turbid water area (m^2) derived from the classes introduced previously. The equations used were:

$$\text{Volume } (m^3\ day^{-1}) = [\text{SSL Retained } (\text{tonnes } day^{-1})] / [\text{Bulk Density } (\text{tonnes } m^{-3})] \qquad (7)$$

$$\text{Sedimentation Rate } (mm\ day^{-1}) =$$

$$([\text{Volume } (m^3\ day^{-1})] / [\text{Turbid Water Area } (m^2)])*1000 \qquad (8)$$

The bulk densities used for analysis were 0.5 g cm^{-3}, 0.7 g cm^{-3}, 0.9 g cm^{-3}, 1.1 g cm^{-3}, and 1.3 g cm^{-3} (g cm^{-3} to tonnes m^{-3} is a 1:1 conversion). For all calculations it was assumed that bulk density did not vary throughout the ARB. Values were averaged across years for each bulk density because extrapolating the individual daily estimate of sedimentation rate out to a yearly estimate of sedimentation rate does not account for the large temporal variability of inundation and total suspended sediment load in the ARB. Thus, a mean from the 20 images was assumed to better account for temporal variability and allow for a better yearly estimation of sedimentation rate.

A separate sedimentation rate analysis was completed for 2010 incorporating LIDAR data. 2010 LIDAR DEM imagery was produced by the National Geospatial Program (NGP) and USGS Coastal and Marine Geology Program (CMGP) with horizontal resolution of approximately 1 m and vertical resolution of approximately 1 m, captured over the period 2 December 2010 to 7 December 2010. The Landsat image classification was completed using the methods of Allen et al. (2008) for an image captured on 2/16/2010. The turbid water classes were overlaid on the 2010 LIDAR DEM to extract elevation for the turbid water areas. These areas were subsequently classified into 3 different categories; water, bottom land cypress forest (BLCF), and bottom land hardwood forest (BLHW) based on elevation. Water class consisted of areas classified as Open Turbid Water at all elevations. BLCF were areas that were identified as Flooded Land Turbid Water that were at elevations between -1 m and 4 m, and BLHW were areas identified as Flooded Land Turbid Water and were areas above 4 m. The bulk densities used for each class were 0.53 g cm^{-3} (water), 0.51 g cm^{-1} (BLCF), and 1.23 g cm^{-3} (BLHW). Classes, elevation, and bulk densities were derived from Scaroni (2011).

5.2.4 Statistical Analysis

Long-term trends in time-series data were tested for significance by the Seasonal Mann-Kendall test for trend using a DOS based program developed by the USGS (Helsel et al. 2006). Adjusted p values were used in order to account for serial correlation in discharge and SSL data. Multiple regression models were applied to determine which variables influenced suspended sediment yield, retained sediment, and estimated sedimentation rates. Beta coefficients were calculated to assess the relative magnitude of influence within the models. Pearson correlation coefficients were calculated to determine the strength of dependence between different variables. If not specified all uses of the term average and mean refers to arithmetic mean.

5.3 RESULTS

5.3.1 Discharge

Mean annual total flow volume over the period 1996 to 2010 at Atchafalaya River Simmesport (ARS) was 199.1 km^3, with a low of 129.2 km^3 (2000) and a high of 247.6 km^3 (2009) (Figure 5.2). The mean discharge split between Atchafalaya River Morgan City (ARMC) and Wax Lake Outlet (WLO) was 57 to 43. It is of note that over the period WLO gradually captured greater portion of the discharge, with the split in 2010 being 53 to 47. ARMC mean annual total flow volume was 112.3 km^3, varying between 74.0 km^3 (2000) and 137.6 km^3 (2009) (Figure 5.2). WLO mean annual total flow volume was 85.3 km^3, ranging from 48.8 km^3 (2000) to 115.2 km^3 (2009) (Figure 5.2). None of the stations had a significant trend, although discharge has been increasing at WLO and decreasing at ARMC, as described previously.

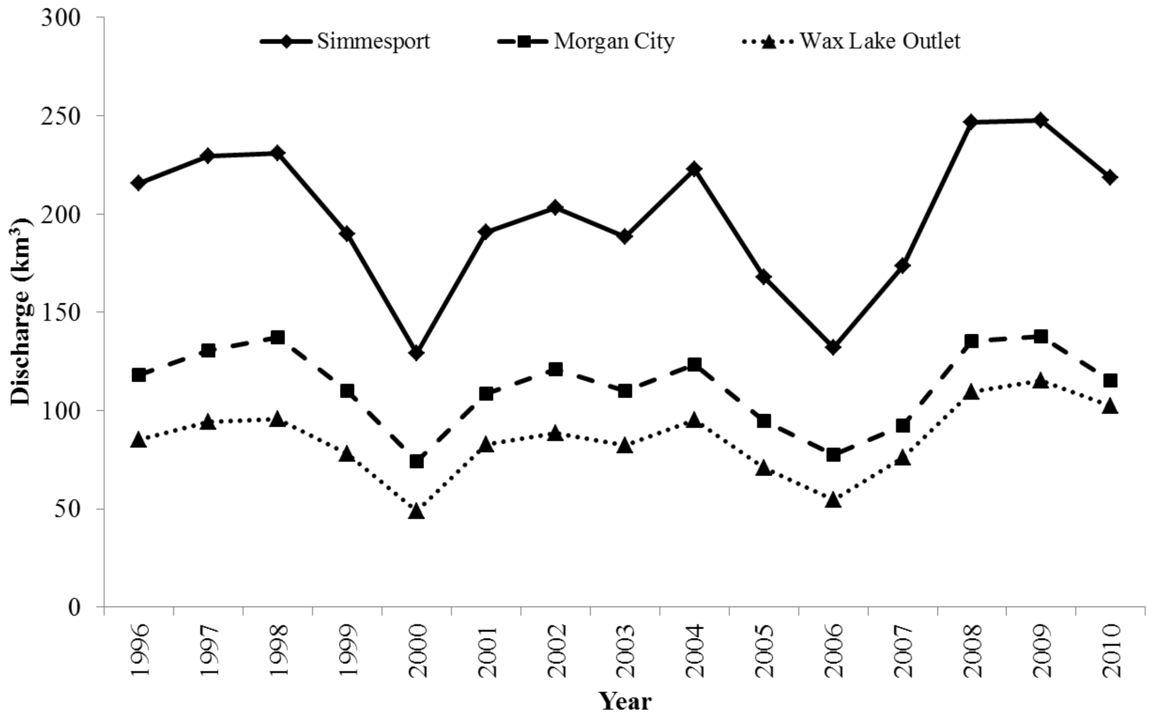

Figure 5.2. Total annual discharge volume of Atchafalaya River Simmesport (ARS), Atchafalaya River Morgan City (ARMC), and Wax Lake Outlet (WLO).

5.3.2 Suspended Sediment Concentration

ARS mean annual SSC was 259 mg l^{-1} and varied between 162 mg l^{-1} (2005) and 411 mg l^{-1} (2010) (Figure 5.3). ARMC mean annual SSC was 239 mg l^{-1}, with a low of 136 mg l^{-1} (2000) and a high of 449 mg l^{-1} (1998) (Figure 5.3). WLO mean annual SSC was 223 mg l^{-1}, and varied between 136 mg l^{-1} (2000) and 351 mg l^{-1} (1998) (Figure 5.3). ARMC had, on average, 10% higher SSC than WLO and over the period annual mean SSC was higher at WLO only three times. All sites had a decreasing trend, and it was significant at ARMC (Seasonal Mann-Kendall, $p=0.0356$) and WLO (Seasonal Mann-Kendall, $p=0.0019$).

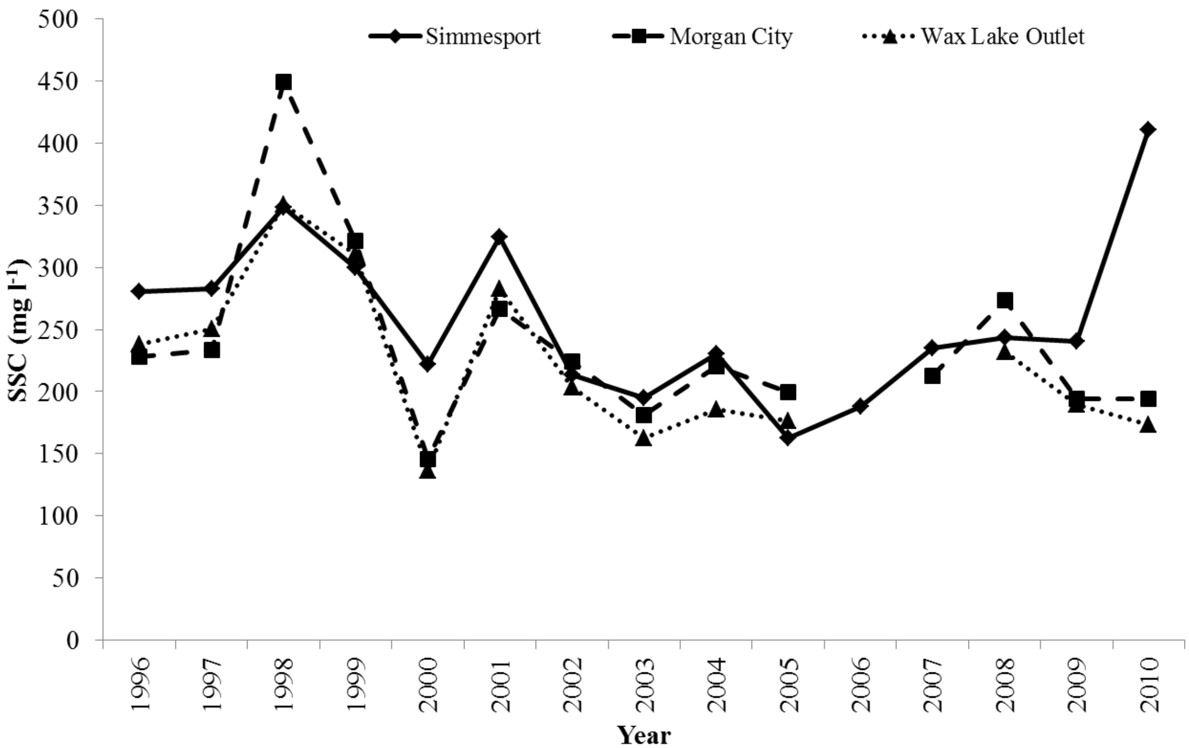

Figure 5.3. Suspended sediment concentration (SSC) for Atchafalaya River Simmesport (ARS), Atchafalaya River Morgan City (ARMC), and Wax Lake Outlet (WLO). 2007 for ARMC, and 2006 to 2007 for WLO have missing data.

5.3.3 Total Suspended Sediment Yield

ARS mean annual total suspended sediment yield was 54.0 MT over the period 1996 to 2010. During the period total suspended sediment yield varied between 26.0 MT (2006) and 88.0 MT (1998) (Figure 5.4). Total suspended sediment yield at ARS was influenced more by changes in SSC than discharge, with a 1 standard deviation increase in SSC causing a 0.71 standard deviation increase in the predicated total suspended sediment yield, whereas discharge only produced a 0.44 increase. ARMC mean annual total suspended sediment yield was 28.9 MT

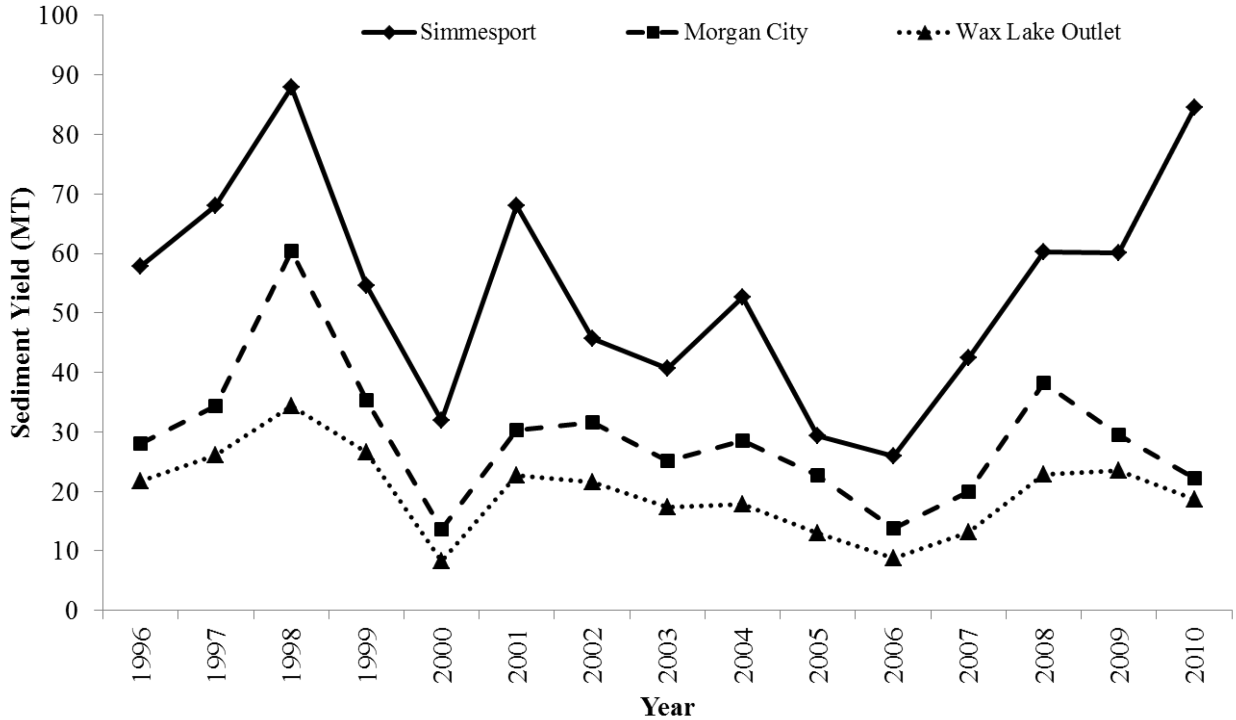

Figure 5.4. Total suspended sediment yield of Atchafalaya River Simmesport (ARS), Atchafalaya River Morgan City (ARMC), and Wax Lake Outlet (WLO)

and ranged between 13.6 MT (2006) and 60.4 MT (1998) (Figure 5.4). Total suspended sediment yield was influenced more by changes in SSC than discharge, with a 1 standard deviation increase in SSC causing a 0.75 standard deviation increase in the predicated total suspended sediment yield, whereas discharge only produced a 0.36 increase. WLO mean annual total suspended sediment yield was 19.8 MT and ranged between 8.3 MT (2000) and 34.4 MT (1998) (Figure 5.4). As with the other stations total suspended sediment yield was influenced more by changes in SSC with 1 standard deviation increase producing a 0.80 standard deviation increase in predicted total suspended sediment yield, while discharge only produced a 0.41 increase. All multiple regressions were able to explain more than 90% of the variation in total

suspended sediment yield. There was a decreasing trend of suspended sediment yield at each station, but this trend was not significant.

5.3.4 Suspended Sediment Retention

The difference between total suspended sediment inflow and outflow from the ARB (retained sediment) was, on average, 5.3 MT yr^{-1}, with a low of -7.4 MT in 2002 (net export out of the ARB) and a high of 43.6 MT in 2010 (Figure 5.5). Years with net retained total suspended sediment averaged 12.3 MT retained and years with net export averaged 5.1 MT exported. Not including 2010, the overall mean amount of retained sediment was 2.6 MT, while only looking at years with net retained sediment the mean was 8.4 MT. The average difference between SSC entering the ARB and exiting was 33.2 mg l^{-1}. This difference varied between -51.8 mg l^{-1} (1998, higher concentration at the outlets) and 226.9 mg l^{-1} in 2010 (Figure 5.5). Years with net retained total suspended sediment averaged a SSC difference of 68.0 mg l^{-1}, while years with net export averaged 13.3 mg l^{-1} (higher SSC at the outlets). Not including 2010, the overall mean SSC difference drops to 18.3 mg l^{-1} and for years with net SSC retention, 39.6 mg l^{-1}. The overall mean difference between discharge inflow and outflow was 1.5 km^3 annually, with a low of -6.2 km^3 in 2002 (net discharge out of ARB) and a high of 12.1 km^3 in 1996. Years with net total suspended sediment yield retention averaged 3.1 km^3 of retained discharge, while years with net total suspended sediment export averaged -0.99 km^3. SSC inflow at ARS affected the amount of retained sediment the greatest, with a 1 standard deviation increase in SSC at ARS yielding a 1.02 standard deviation increase in predicted retained sediment. This was followed by SSC at ARMC and WLO (1 standard deviation increase produced 0.87 standard deviation decrease in retained sediment), discharge at ARS (1 standard deviation increase produced 0.68 standard deviation increase), and combined ARMC and WLO discharge (1 standard deviation

increase produced a 0.66 standard deviation decrease in retained sediment). All four of these variables accounted for 91% of the variability in the amount of suspended sediment retained in the ARB.

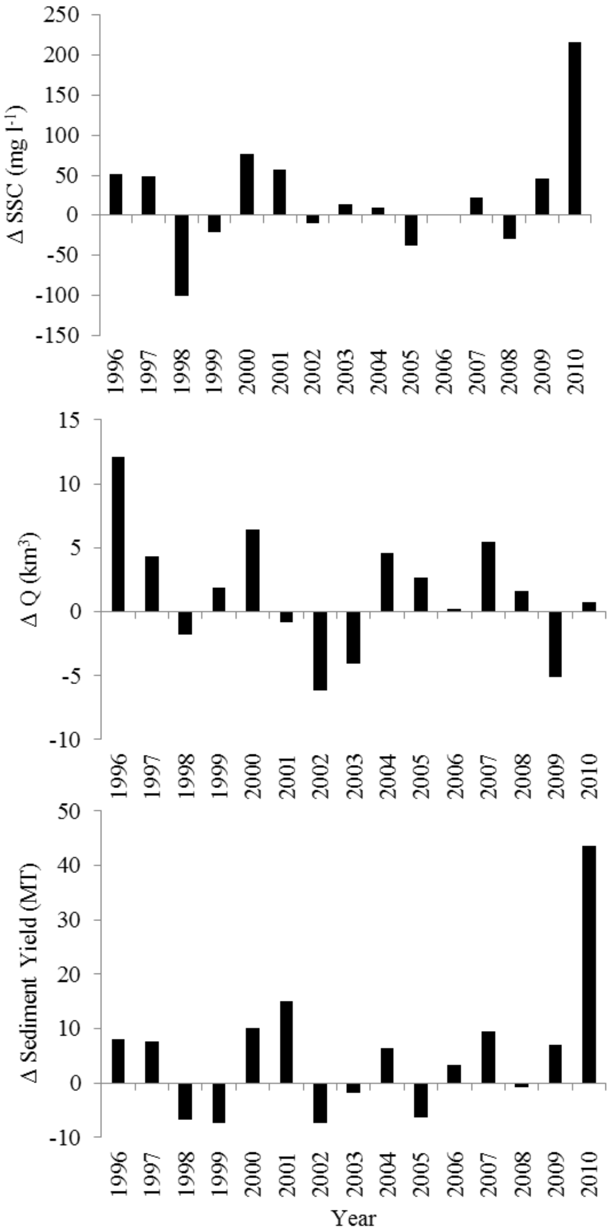

Figure 5.5. Difference (Δ) between (retained in the Atchafalaya River Basin) Atchafalaya River Simmesport (ARS) and the combined Atchafalaya River Morgan City (ARMC) and Wax Lake Outlet (WLO) for SSC (top), discharge volume (middle), and total suspended sediment yield (bottom). Positive values are net retention and negative values are net export.

5.3.5 Spatially Derived Sedimentation Rates

Sedimentation rates calculated from the images varied greatly, with values ranging between < 0.001 mm day^{-1} to 3.13 mm day $^{-1}$ (Table 5.1). Mean sedimentation rates for each bulk density, ranged between 0.083 and 0.217 mm d^{-1} (Table 5.1, lowest and highest values not used for calculating means). Assuming that the mean daily sedimentation rate values for each bulk density can be extrapolated out to annual values produces mean annual estimates between 30.4 and 79.1 mm yr^{-1} (Table 5.1). For each image the amount of retained suspended sediment varied between 113 and 248,699 tonnes, the amount of retained discharge varied between -708 (net export) and 777 m^{3}s^{-1}, and inundated area varied between 23 km^2 and 951 km^2 (Table 5.1). Calculated sedimentation rates were not correlated with turbid water area, retained discharge, or date. Calculated sedimentation was strongly correlated with the difference between SSC at ARS and the outlets (Pearson's Correlation Coefficient, $p<0.0001$).

5.3.6 2010 Analysis using LIDAR

Spatial analysis completed with 2010 LIDAR imagery and turbid water data from 2010 (Figure 5.6) had a total of 746 km^2 inundated with turbid water. This area was broken down to 178 km^2 of open water, 560 km^2 of bottom land cypress forest (BLCF), and 8 km^2 of bottom land hardwood forest (BLHW) (Table 5.2). A total of 58,389 tonnes of sediment was trapped in ARB when this image was taken (Table 5.2). Sedimentation rates calculated were; open water: 0.148 mm d^{-1}, BLCF: 0.153 mm d^{-1}, and BLHW: 0.06 mm d^{-1} (Table 5.2). This would, if these were mean daily sedimentation rates, extrapolate out to a weighted mean (by area) annual sedimentation rate of 55.1 mm yr^1.

Table 5.1. Sedimentation rate estimates with varying sediment bulk densities.

Date	Turbid Water (km^2)	Δ Sediment Load (t)	Δ Q ($m^3 s^{-1}$)	Sedimentation Rate mm day^{-1}				
				BD 0.5 g cm^{-3}	BD 0.7 g cm^{-3}	BD 0.9 g cm^{-3}	BD 1.1 g cm^{-3}	BD 1.3 g cm^{-3}
01/26/1985	951	130828	484	0.275	0.196	0.153	0.125	0.106
01/13/1986	323	45999	144	0.284	0.203	0.158	0.129	0.109
03/02/1986	456	43443	522	0.191	0.136	0.106	0.087	0.073
01/14/1992	761	119513	467	0.314	0.224	0.174	0.143	0.121
01/16/1993	597	248699	777	0.833	0.595	0.463	0.379	0.320
03/05/1993	478	76792	595	0.321	0.229	0.178	0.146	0.123
01/09/1996	203	113	-330	0.001*	0.001*	0.001*	0.001*	0.001*
01/25/1996	213	3973	-359	0.037	0.027	0.021	0.017	0.014
12/16/1998	215	44809	-190	0.417	0.298	0.232	0.189	0.160
01/20/2000	349	40998	-291	0.235	0.168	0.131	0.107	0.090
02/05/2000	23	36647	-331	3.133*	2.239*	1.741*	1.425*	1.205*
12/05/2000	147	19138	105	0.260	0.186	0.145	0.118	0.100
12/29/2000	241	17019	154	0.141	0.101	0.078	0.064	0.054
01/22/2001	296	23413	-228	0.158	0.113	0.088	0.072	0.061
02/18/2002	790	30766	708	0.078	0.056	0.043	0.035	0.030
03/22/2002	265	5281	-57	0.040	0.028	0.022	0.018	0.015
01/04/2003	486	10725	542	0.044	0.032	0.025	0.020	0.017
02/27/2008	577	4651	-708	0.016	0.012	0.009	0.007	0.006
03/01/2009	280	14288	-170	0.102	0.073	0.057	0.046	0.039
02/16/2010	755	58389	-311	0.155	0.110	0.086	0.070	0.059
			AVG mm day^{-1}	0.217	0.155	0.120	0.099	0.083
			AVG mm $year^{-1}$	79.1	56.5	44.0	36.0	30.4

Table 5.2. Turbid water area (TW), trapped sediment, bulk density, and estimated sedimentation rate based of 2010 LiDAR and 2010 turbid water area estimates for open water, bottom land cypress forest (BLCF), and bottom land hardwood (BLHW) areas.

Stage at BLR: 5.24 m	**Open Water**	**BLCF**	**BLHW**
TW Area (km^2)	178	560	8
Trapped Sed (t)	13,895	43,829	665
Bulk Density (g cm^{-3})	0.53	0.51	1.23
Sedimentation (mm d^{-1})	0.148	0.153	0.06
Sedimentation (mm yr^{-1})	53.9	56.0	23.2

5.4 DISCUSSION

5.4.1 Trend of Sediment Yield

This study provides the first comprehensive longer-term calculations of total suspended sediment yield exiting the ARB through ARMC and WLO. ARMC mean total suspended sediment yield was 28.9 MT yr^{-1}, while WLO averaged 19.8 MT yr^{-1}. Xu (2010) estimated 58.0 MT yr^{-1} for the outlets combined, whereas our estimate was 48.7 MT yr^{-1}. Xu (2010) did not provide separate estimates for the outlets and only used SSC from ARMC to calculate the combined sediment yield. From our study it was identified that ARMC had 10% higher SSC than WLO. The higher SSC at ARMC as well as different time frames (1974-2004) may explain the difference in sediment yield between Xu's (2010) and this study's estimates. Allison et al. (2012) estimated total suspended sediment yield separately for the period 2008 to 2010. Their estimate for ARMC was 27.9 MT yr^{-1} and WLO was 20.5 MT yr^{-1}. This is similar to our estimate of 30.0 MT yr^{-1} (ARMC) and 21.6 MT yr^{-1} (WLO) for the same time frame. ARS mean total suspended sediment yield, 54.0 MT yr^{-1}, was slightly lower than previous studies

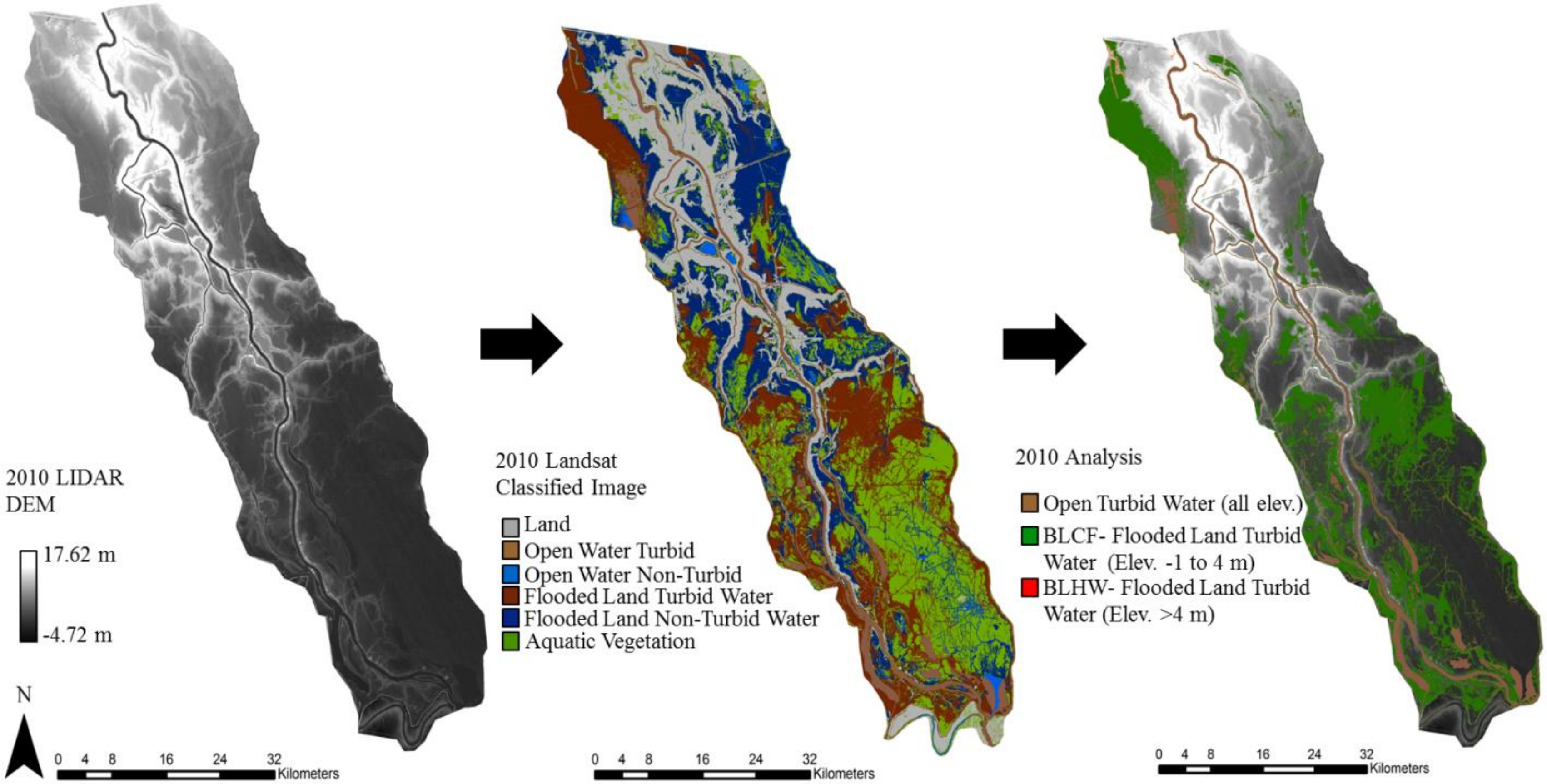

Figure 5.6. Flow chart of the maps used for the 2010 analysis. From left to right; 2010 LIDAR DEM, classified image of the Atchafalaya River Basin for the 16 February 2010, and map of derived classes using the LIDAR DEM and classified image overlaid on LIDAR DEM

Xu (2010) estimated ARS total suspended sediment yield at 64.0 MT (1974-2004) and Meade and Moody (2010) estimated 57.0 MT (1987-2006). Allison et al. (2012) estimated total suspended sediment yield at 71.0 MT (2008-2010), which was similar to our estimate of 68.3 MT for the same time frame. Difference in these estimates can be ascribed to different time frames, a general decrease in sediment yield from the Mississippi River over the past 50 years (Meade and Moody 2010), and different sediment rating curves applied to estimate loading (Horowitz 2003).

A slight decrease in total suspended sediment yield occurred over the past 30 years, which was driven by significant decreasing SSC at ARMC and WLO. The decreasing SSC could be linked to the decreasing SSC in the Mississippi River (Meade and Moody 2010; Horowitz 2010). Within the annual mean SSC data there are two peaks that stick out, one in 1998 at both ARMC and WLO, and the other in 2010 at ARS. The large peak in SSC at the outlets in 1998, that was not as pronounced at ARS, could be explained by bank failures resulting from the large flood the previous year (1997, highest peak discharge for period at ARS, 18,027 m^3s^{-1}). The Atchafalaya River at Simmesport is leveed and well confined in its channel, whereas the lower section of the river is non-engineered allowing for bank erosion and lateral migration, which in other non-engineered rivers has been documented as a major source of suspended sediment (Bull 1997; Dunne et al. 1998; Hudson and Kesel 2003). The peak in SSC at ARS in 2010 is harder to explain and could be either due to work on the channel or from sampling error.

5.4.2 Retained Sediment

On average, 5.3 MT yr^{-1} of total suspended sediment was retained in the ARB, which is 10% of the total suspended sediment input from ARS. Retention of sediment varied, with a net export of sediment occurring in some years. Years when there was a net export averaged 5.1 MT yr^{-1} exported or 9% more than what was input to the ARB from ARS. Years with net retention averaged 12.3 MT yr^{-1} (22%) of total suspended sediment retained, although not including 2010, estimated retained mean total suspended sediment decreases to 8.4 MT yr^{-1} (16%). Xu (2010) estimated an average of 5.7 MT yr^{-1} (9%) of retained sediment (1974 to 2004). Allison et al. (2012) estimated 23.1 MT yr^{-1} retained (2008 to 2010), slightly higher than our estimate, 16.6 MT yr^{-1}, for the same time frame. Hupp et al. (2008) estimated from in situ sedimentation data an average of 5.9 MT yr^{-1} deposited in backwater areas, although there was a net loss of sediment from the ARB during the study (2000-2003). The total amount of total suspended sediment retained (not including 2010) was 36.5 MT, which is only 5% of the total suspended sediment supplied (725.8 MT). This indicates that the ARB has reached equilibrium and its present form is more characteristic of a fluvial system. Hupp et al. (2008) also described that during their study on sedimentation (2000-2003), there was a net export of sediment out of the ARB, and that deposited material in backwater areas was most likely being counterbalanced by either bank erosion or in channel re-suspension of sediment. Mason et al. (2012) findings on nitrate removal also support this as there was no significant processing of nitrate, an indication of low retention time, and thus a system that is fluvial rather than palustrine or lacustrine.

The best explanatory variable for sediment retention was SSC entering the ARB from ARS, followed by SSC exiting through the outlets. It is known that differing discharge regimes can cause sediment deposition or re-suspension along the lowermost Mississippi River (Galler

and Allison 2008; Allison et al. 2012). Although, when qualitatively looking at different variables that could have affected retention or export of total suspended sediment on the annual scale it would seem that flood peak, discharge volume, and retained discharge during the same year played little or no role in the retention or export of total suspended sediment in the ARB (Table 5.3). This indicates that suspended sediment dynamics within the ARB are complicated by hydrological and climatological interconnections between different years. This was discussed earlier when in 1998 SSC at the outlets could have been elevated by bank failures caused by the large flood the previous year. Also, drought years when there is low discharge could induce greater channel sedimentation from low river velocity, producing greater sediment availability for the next year. Another consequence of droughts could be the drawdown of backwater areas allowing for greater accommodation for subsequent floods. This occurred in 2011, during which extreme drought conditions in Louisiana (NCDC 2012) helped mitigate flooding of the ARB from the opening of Morganza Spillway due to below normal water conditions and soil water content. Another complicating factor is rapid sedimentation that could change flow patterns between years. All of these factors could have influenced the retention of sediment between different years, and make it hard to pinpoint the defining factors that control sedimentation annually in the ARB.

5.4.3 Sedimentation Rate

The estimated mean sedimentation rates from the spatial datasets were higher than in situ measured mean sedimentation rates. Our mean sedimentation rates, estimated from a range of different bulk densities, varied between 30 mm yr^{-1} and 75 mm yr^{-1}. Hupp et al. (2008) observed mean sedimentation rates between 1.8 mm yr^{-1} and 42.0 mm yr^{-1} for various sites in the middle Atchafalaya Basin. Scaroni (2011) found mean sedimentation rates in the middle and lower

Table 5.3. Annual sediment retention in relation to flood peak, total discharge volume, and retained discharge.

	Flood Peak (m)			Total Discharge (km^3)			Discharge Retention (km^3)		
Sediment	**Low (<14.6)**	**Medium (14.6 -16.8)**	**High (>16.8)**	**Low**	**Medium**	**High**	**Retained**	**Exported**	**Equilibrium**
Retained	2	5	2	3	3	3	5	2	2
Exported	0	3	3	2	2	2	3	3	0

Values are count data for individual years, n=15 years.
Flood peak is for peak stage height on the Mississippi River at Red River Landing, Louisiana.
Total discharge counts are based on ranked annual discharge volume 1-5 (high), 6-10 (medium), 11-15 (low).

Atchafalaya Basin of 5.9 mm yr^{-1} (open water), 6.3 mm yr^{-1} (bottom land hardwood forest), and 7.7 mm yr^{-1} (cypress forest). Our estimated mean sedimentation rates using discrete bulk densities for the same cover types as Scaroni (2011), were 53.9 mm yr^{-1} (open water), 23.2 mm yr^{-1} (bottom land hardwood forest), and 56.0 mm yr^{-1} (cypress forest). Our estimates are much higher than Scaroni (2011), but fall close to the higher rates from Hupp et al. (2008).

From the sedimentation rates estimated in this study it was possible to estimate a time range for the amount of bottom land cypress forest that could be transformed to higher elevation bottomland hardwood forest. Using the low end estimates for sedimentation from the two methods (30.4 mm yr^{-1} and 55.8 mm yr^{-1}), mean area for turbid water flooded land class distributed over 0 m to 2 m, and assuming that the areas remain inundated year-round with sediment laden water, it can be estimated that approximately 273.2 km^2 of BLCF will be filled within 36 to 132 years. More precisely this represents 179.3 km^2 of land at the elevation 0 m filled within 71 to 132 years, 62.0 km^2 of land at 1 m filled in 54 to 99 years, and 31.9 km^2 of land at 2 m filled in 36 to 66 years. The total represents approximately 7% of the 3581 km^2 of forested wetlands in the ARB (USGS 2001), and is most likely a conservative estimate because of the use of mean values that may underestimate sedimentation in certain areas, as well as not accounting for the effects of large floods.

There are several reasons why our estimates are higher than those obtained from in situ studies. The main reason is that bulk density may not be negatively correlated with sedimentation rates as our calculation assumes. From ARB studies there does not seem to be a strong correlation (negative or positive) of bulk density and sedimentation rate (Hupp et al. 2008, Scaroni 2011). Other possible errors can stem from the total suspended sediment load calculation on the daily scale, which could have an error of ±100% (Horowtiz et al. 2001), the

lack of imagery for flood periods or summer months, and the inability to specify to greater precision different bulk densities for different areas.

The results from spatial analysis are promising because the method provides an easy and efficient way to analyze sedimentation basin wide, and could help management efforts by allowing for monitoring remotely rather than through costly trips. The use of the spatial sedimentation model also lends itself to modeling that tries to predict the future of coastal Louisiana, such as the modeling completed for Louisiana's 2012 Coastal Master Plan. Future work using this method would benefit from incorporating hydroperiod in the estimation. Hupp et al. (2008) found that hydroperiod in coordination with high connectivity with sediment laden water and slow velocity produced the highest sedimentation rates in the ARB. Estimation of sediment in the water could be refined by accounting for the decreased SSC away from main channels (Walling and He 1998). While, daily total suspended sediment load estimation would benefit from SSC being sampled on days when images are captured at the outlets and 2 days before the image at ARS.

5.5 CONCLUSIONS

The results from this study indicate that the Atchafalaya River Basin has reached equilibrium where there is no longer a large amount of net sediment retention. The system is apparently under fluvial rather than palustrine or lacustrine controls, with the Atchafalaya River meandering through an alluvial plain, depositing sediments along in-channel bars or during overbank floods, but counterbalancing this through lateral migration and bank erosion as well as channel scouring, while sediment retention in the basin occurs mainly in back water areas. Furthermore, this study demonstrates an approach of combining riverine sediment loads and spatial information on turbid water surface to derive sedimentation estimates. Greater

refinement of the method needs to incorporate hydroperiod, and differing suspended sediment concentration which could help generate more specific sedimentation estimates for different areas. Future management of the Atchafalaya River Basin will rely on spatial tracking of sedimentation to effectively monitor and predict where resources will be necessary to effectively maintain the river basin as a floodway and wildlife habitat.

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CHAPTER 6: SUMMARY AND CONCLUSION

This thesis research was completed as a comprehensive assessment of long-term riverine suspended sediment supply to the entire coastal Louisiana. The research comprised four studies that collectively addressed sediment dynamics of three coastal physiographic regions including the Louisiana Chenier Plain, the Mississippi River Delta, and the Atchafalaya River Basin and delta complex. The primary goal of this research was to characterize spatial and temporal riverine sediment distribution and to assess their actual sediment availability under different hydrologic conditions. Results from this research are summarized below.

The riverine total suspended sediment yield to coastal Louisiana averaged 176,343,000 tonnes annually. The Mississippi River delivered 72% of the total suspended sediment, while the Atchafalaya River delivered 28%. The Chenier Plain rivers delivered a negligible amount of total suspended sediment compared to the Mississippi River and Atchafalaya River. The average annual total suspended sediment yield of all four Chenier Plain rivers was 342,950 tonnes, with the Sabine River supplying 213,100 tonnes, the Calcasieu River 46,850 tonnes, the Mermentau River 40,200, and the Vermilion River 42,800 tonnes. The greatest resource that the Chenier Plain rivers provide is for small scale regional management of freshwater and sediment to interior portions of the Chenier Plain. With the Sabine River supplying 62% of the sediment load to the Chenier Plain serious restoration efforts would need to effectively use this resource to aid restoration plans that aim at maintaining freshwater marsh, and the natural hydrologic regime of the Chenier Plain.

The largest total suspended sediment resource to coastal Louisiana is the Mississippi River. Although the estimated average resource was 127 megatonnes (megatonne-MT, $10^{\wedge 6}$ tonnes) annually, the actual available amount for diversion is much lower. The greatest amount

of total suspended sediment was provided when stage exceeds 12.1 m , Action Stage at Red River Landing, LA (18,000 m^3s^{-1}), and starts to decline substantially after the stage of >16.8 m, Moderate Flood Stage (32,000 m^3s^{-1}). Action Stage and Flood Stage (14.6 to 16.8 m) maximize SSC providing an annual average of 67.1 MT during the entire flood pulse. Another important consideration for sediment management is when the sediment occurs during the flood pulse. The rising limb of the flood pulse contains the highest SSC and is maximized during Action Stage and Flood Stage providing a total actual divertible suspended sediment amount of 28.9 MT. Above Moderate Flood Stage and discharge on the receding limb are sediment starved and maximize freshwater and not sediment. Diversion management would benefit from plans that use the natural flood pulse to maximize suspended sediment going through the diversion. This can be done if diversion occurs during the rising limb during stages equivalent to Action Stage and Flood Stage.

The second largest riverine sediment resource to coastal Louisiana is the Atchafalaya River, providing 49 MT of total suspended sediment at the outlets to Atchafalaya Bay annually. The Atchafalaya River Basin traps 5.3 MT annually, although it would seem that the Atchafalaya River has reached equilibrium, as there are years that have net export. The use of Landsat imagery to predict sedimentation rate basin-wide provides estimates between 30.4 mm yr^{-1} to 79.1 mm yr^{-1}. Refinement of this method using LIDAR to predict land cover and subsequently bulk density reduces estimated sedimentation rates to 23.2 mm yr^{-1} to 56.0 mm yr^{-1}. Although this modeling is very coarse, the method does provide promising results that with better bulk density estimates, hydroperiod data, and better sediment load estimates could be refined to a point where land managers could use this as a tool to better manage sediment in the Atchafalaya River Basin.

The Atchafalaya River Delta Complex (ARDC) is one of the few areas where there has been prograding land along Louisiana's coastline. Since 1989 the land change rate was 2.8 km^2 yr^{-1}, although rates have been slowly decreasing from a high of 5.6 $km^2 yr^{-1}$ (1989 to 1995) to a low of -0.4 $km^2 yr^{-1}$(1999 to 2004). Atchafalaya River Morgan City subdelta (ARSD) had much more stable growth over the period with all the periods having net gain. The Wax Lake Outlet Subdelta (WLSD) was much more variable with the 1999 to 2004 period seeing a net loss -4.6 km^2. Both of the subdeltas saw decrease in land change rate, which was associated with an increase in tropical storm frequency, as well as variability of the flood magnitude of the Atchafalaya River. The largest factor affecting growth were major flood events (>13,800 $m^3 s^{-1}$ at) and tropical systems. There was a net land loss during the period 1999 to 2004 due to the absence of large flood events. Vegetation did have some stabilizing affecting on the ARDC when compared to barren areas, with vegetated land loss of 7.3% whereas barren land was lost 32.0% between years. Newly vegetated land remained land >60% between subsequent years, except for the period 1999 to 2004. This demonstrates that vegetation may not be able to maintain land by itself and reinforces the importance of large flood pulses for maintaining land and growth. If stable growth is to be continued at the ARDC suspended sediment load reaching the deltas needs to be stabilized or engineering efforts need to be taken to reduce the impacts of large storm events, especially during periods when there is a lack of large floods to offset losses.

With many future projects relying on fluvial sediment for restoration in coastal Louisiana, the calculations completed in this thesis research provide an important insight into actual available total suspended sediment. The future of coastal Louisiana rests upon taking advantage of the natural processes that shaped the coastline, instead of trying to maintain a static environment. Emphasis needs to be taken away from products (e.g. building barrier islands or

marshes), and instead should be put on the natural processes that went into creating these landforms. Although, taking such actions is risky, an understanding that large scale change will mean taking calculated risks that may hurt short-term economic gains, but can provide long-term stability necessary to maintain Louisiana for future generations.

APPENDIX A: FIGURES

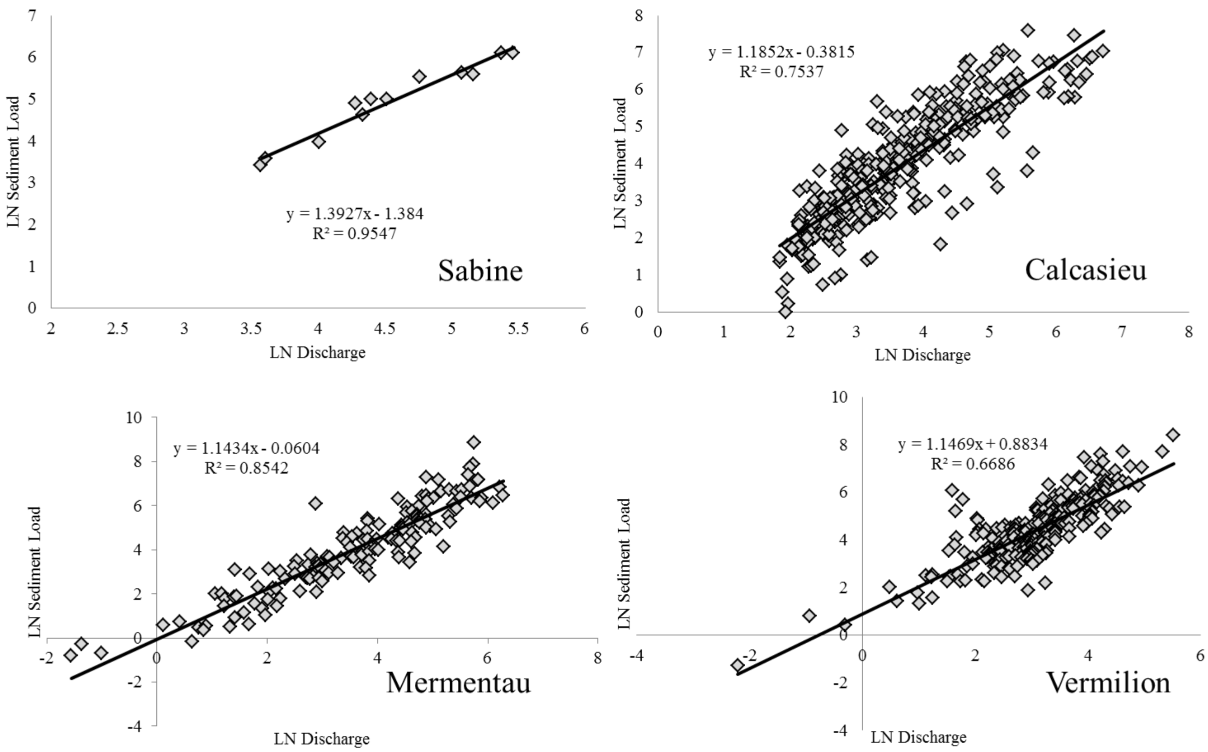

Figure A1. Linear regression of natural log of sediment load (LN sediment load) and natural log of discharge for estimating sediment load of the four Chenier Plain rivers.

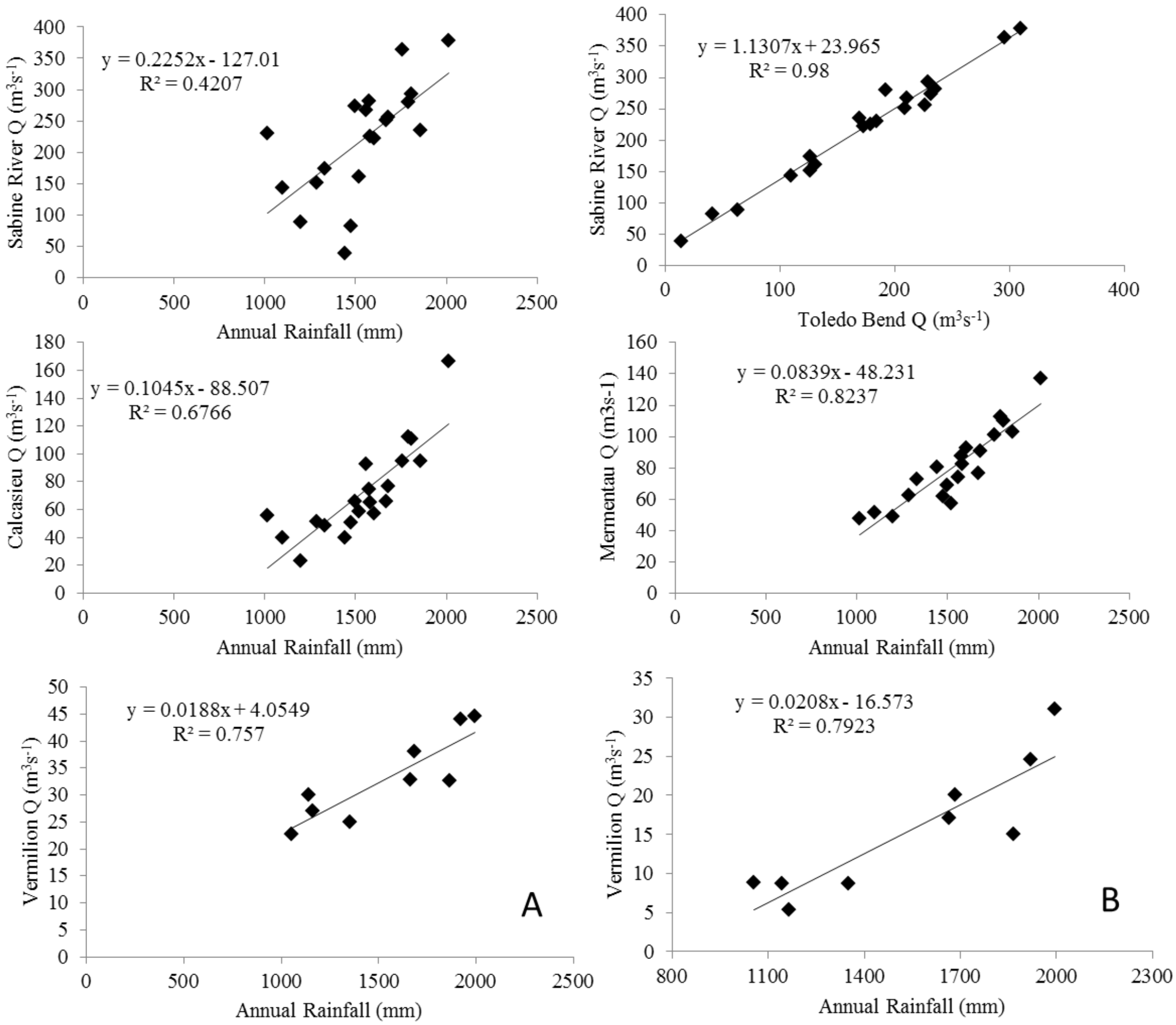

Figure A2. Linear regression of annual rainfall and discharge for the Chenier Plain rivers. A- Vermilion River without accounting for Tech-Vermilion pumping station water additions, B- Vermilion River accounting for additions.

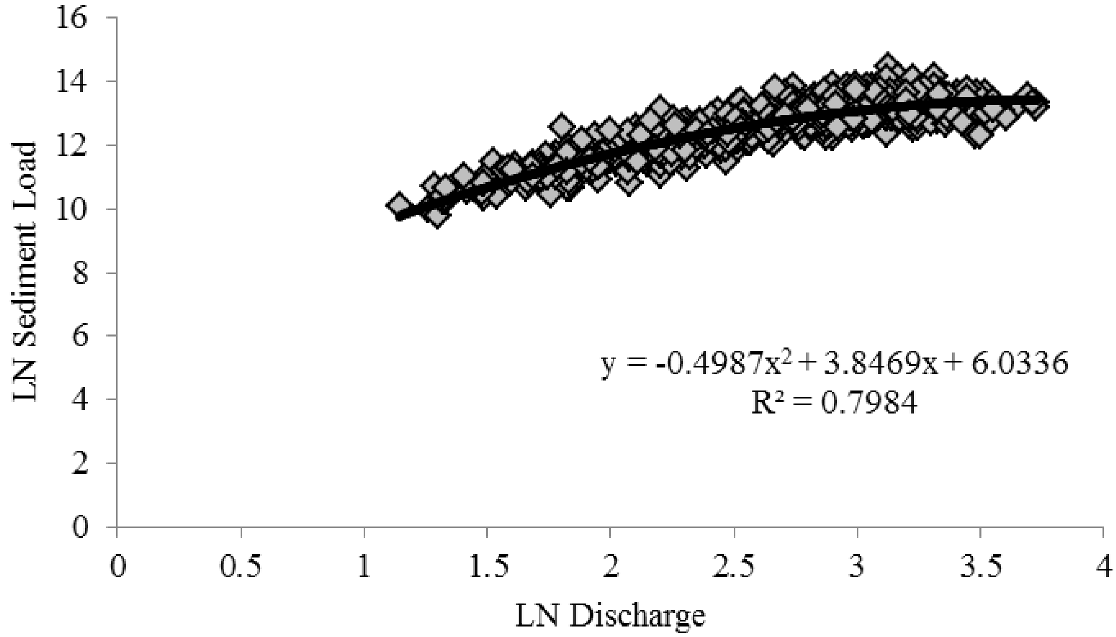

Figure A3. 2nd order polynomial regression using the natural log of observed total suspended sediment load (LN sediment load) and natural log of discharge for Mississippi River total suspended sediment load estimation.

APPENDIX B: TABLES

Table A1. Sediment rating curves used for estimation of total suspended sediment load (tonnes day^{-1}) and subsequently summed to estimate annual total suspended sediment yield (tonnes yr^{-1}) for Atchafalaya River Morgan City (ARMC) and Wax Lake Outlet (WLO).

	ARMC			WLO		
Year	**Sed. Rating Curves**	**r^2**	**% Diff**	**Sed. Rating Curves**	**r^2**	**% Diff**
1989	$y= -0.4894x^2+10.317x-40.489$	0.93	-0.58	$y= -0.5364x^2+9.9236x-33.94$	0.79	1.4
1990	$y= 2.3654x-8.3113$	0.92	-7.97	$y= 2.0552x-5.3306$	0.92	-13.4
1991	$y= 1.7549x-3.2172$	0.76	-0.31	$y= -0.5364x^2+9.9236x-33.94$	0.79	-2.43
1992	$y= -0.289x^2+6.4414x-22.148$	0.77	-1.39	$y= -0.5364x^2+9.9236x-33.94$	0.79	-18.04
1993	$y= -0.3546x^2+7.7885x-28.941$	0.92	1.01	$y= 1.6571x-2.2451$	0.77	-1.18
1994	$y= -0.289x^2+6.4414x-22.148$	0.77	5.22	$y= -0.5364x^2+9.9236x-33.94$	0.79	3.35
1995	$y= 0.141x^2-0.9496x+9.3784$	0.74	-2.12	$y= 1.4397x-0.5$	0.80	1.9
1996	$y= 1.3711x-0.1416$	0.73	-0.25	$y= 1.4397x-0.5$	0.80	1.76
1997	$y= 0.141x^2-0.9496x+9.3784$	0.74	-1.70	$y= 1.6571x-2.2451$	0.77	0.94
1998	$y= 1.6558x-2.1868$	0.71	0.52	$y= 1.7878x-3.1357$	0.83	0.41
1999	$y= 1.6558x-2.1868$	0.71	-9.70	$y= 1.7878x-3.1357$	0.83	-3.99
2000	$y= 1.7549x-3.2172$	0.76	8.73	$y= 1.6571x-2.2451$	0.77	-0.32
2001	$y= -0.289x^2+6.4414x-22.148$	0.77	-3.37	$y= 1.6571x-2.2451$	0.77	-10.04
2002	$y= 1.8979x-4.4989$	0.87	0.32	$y= -0.5364x^2+9.9236x-33.94$	0.79	-1.23
2003	$y= 1.8979x-4.4989$	0.87	13.92	$y= 1.9341x-4.5948$	0.86	20.06
2004	$y= -0.1826x^2+4.5914x-14.241$	0.92	3.46	$y= 1.479x-1.0929$	0.90	-0.28
2005	$y= -0.289x^2+6.4414x-22.148$	0.77	0.69	$y= 1.479x-1.0929$	0.90	-1.04
2006	$y=1.6849x-2.7144$	0.91	NO DATA	$y=-0.4022x^2+7.6626x-24.747$	0.91	NO DATA
2007	$y=1.7549x-3.2172$	0.76	-3.95	$y=1.479x-1.0929$	0.90	0.59
2008	$y=-0.289x^2+6.4414x-22.148$	0.77	2.65	$y=1.4665x-1.0222$	0.68	-9.22
2009	$y=0.0091x^2+1.5264x-2.2121$	0.73	-3.45	$y=1.4665x-1.0222$	0.68	-0.21
2010	$y=1.6758x-2.8236$	0.73	-1.62	$y=1.4665x-1.0222$	0.68	8.36

% Diff, is the percent difference between estimated and measured total suspended sediment load

Table A2. Sediment rating curves used for annual total suspended sediment yield estimates at Atchafalaya River Simmesport (ARS), Atchafalaya River Morgan City (ARMC), and Wax Lake Outlet (WLO).

	ARS			ARMC			WLO		
Year	**Equation**	r^2	**% Diff**	**Equation**	r^2	**% Diff**	**Equation**	r^2	**% Diff**
1996	$y=-0.3526x^2+2.753x+8.093$	0.81	0.84	$y=1.3711x-0.1416$	0.73	-0.25	$y=1.4397x-0.5$	0.8	1.76
1997	$y=-0.0871x^2+1.0782x+10.324$	0.19	0.41	$y=0.141x^2-0.9496x+9.3784$	0.74	-1.70	$y=1.6571x-2.2451$	0.77	0.94
1998	$y=-0.4772x^2+3.2823x+7.7373$	0.89	-0.92	$y=1.6558x-2.1868$	0.71	0.52	$y=1.7878x-3.1357$	0.83	0.41
1999	$y=1.4034x+9.3048$	0.85	-2.14	$y=1.6558x-2.1868$	0.71	-9.70	$y=1.7878x-3.1357$	0.83	-3.99
2000	$y=1.5778x+8.9573$	0.79	0.64	$y=1.7549x-3.2172$	0.76	8.73	$y=1.6571x-2.2451$	0.77	-0.32
2001	$y=1.8142x+8.6593$	0.85	0.39	$y=-0.289x^2+6.4414x-22.148$	0.77	-3.37	$y=1.6571x-2.2451$	0.77	-10.04
2002	$y=-0.0095x^2+1.39x+9.0786$	0.88	0.50	$y=1.8979x-4.4989$	0.87	0.32	$y=-0.5364x^2+9.9236x-33.94$	0.79	-1.23
2003	$y=0.1066x^2+1.2634x+8.689$	0.88	-0.48	$y=1.8979x-4.4989$	0.87	13.92	$y=1.9341x-4.5948$	0.86	20.06
2004	$y=-0.1321x^2+2.0284x+8.3679$	0.81	0.18	$y=-0.1826x^2+4.5914x-14.241$	0.92	3.46	$y=1.479x-1.0929$	0.90	-0.28
2005	$y=0.0129x^2+1.2867x+9.0071$	0.96	-0.30	$y=-0.289x^2+6.4414x-22.148$	0.77	0.69	$y=1.479x-1.0929$	0.90	-1.04
2006	$y=0.4312x^2+0.6435x+9.1459$	0.84	-0.76	$y=1.6849x-2.7144$	0.91	NO DATA	$y=-0.4022x^2+7.6626x-24.747$	0.91	NO DATA
2007	$y=0.1005x^2+1.1397x+9.3051$	0.82	-0.80	$y=1.7549x-3.2172$	0.76	-3.95	$y=1.479x-1.0929$	0.90	0.59
2008	$y=-0.3459x^2+2.4406x+8.5131$	0.86	-0.07	$y=-0.289x^2+6.4414x-22.148$	0.77	2.65	$y=1.4665x-1.0222$	0.68	-9.22
2009	$y=-0.9048x^2+5.1489x+5.2596$	0.70	-0.60	$y=0.0091x^2+1.5264x-2.2121$	0.73	-3.45	$y=1.4665x-1.0222$	0.68	-0.21
2010	$y=-0.3526x^2+2.753x+8.093$	0.81	0.37	$y=1.6758x-2.8236$	0.73	-1.62	$y=1.4665x-1.0222$	0.68	8.36

Table A3. Sediment rating curves used for total suspended sediment load estimates on the day of the image capture for sedimentation rate estimations. Separate curves were used for Atchafalaya River Simmesport (ARS), Atchafalaya River Morgan City (ARMC), and Wax Lake Outlet (WLO).

	ARS			ARMC			WLO		
Date	Equation	r2	% Diff	Equation	r2	% Diff	Equation	r2	% Diff
1/26/1985	$y=-0.4897x^2+3.3414x+7.7381$	0.93	7.90	$y=-0.9989x^2+18.417x-72.345$	0.91	3.91	$y=-0.5364x^2+9.9236x-33.94$	0.79	2.97
1/13/1986	$y=-0.3526x^2+2.753x+8.093$	0.81	21.92	$y=1.7549x-3.2172$	0.76	51.57	$y=1.6571x-2.2451$	0.77	0.08
3/2/1986	$y=1.5778x+8.9573$	0.79	22.52	$y=1.7549x-3.2172$	0.76	41.91	$y=1.6571x-2.2451$	0.77	10.66
1/14/1992	$y=2.0639x+8.2807$	0.83	27.02	$y=-0.289x2+6.4414x-22.148$	0.77	0.05	$y=-0.3972x^2+7.6791x-24.853$	0.85	1.74
1/16/1993	OBS	OBS	OBS	$y=-0.289x^2+6.4414x-22.148$	0.77	14.05	$y=1.6397x-1.9996$	0.84	NO DATA
3/5/1993	$y=-0.3526x^2+2.753x+8.093$	0.81	20.58	$y=1.9623x-5.0756$	0.92	6.27	$y=-0.3972x^2+7.6791x-24.853$	0.85	2.89
1/9/1996	$y=1.5778x+8.9573$	0.79	34.37	$y=1.7549x-3.2172$	0.76	63.45	$y=1.6571x-2.2451$	0.77	39.63
1/25/1996	$y=1.5778x+8.9573$	0.79	24.59	$y=1.7549x-3.2172$	0.76	53.56	$y=1.6571x-2.2451$	0.77	45.31
12/16/1998[0]	$y=-0.4772x^2+3.2823x+7.7373$	0.89	31.64	$y=1.7549x-3.2172$	0.76	1.29	$y=-0.3446x^2+7.0047x-22.743$	0.84	1.42
1/20/2000[1]	OBS	OBS	OBS	$y=1.6558x-2.1868$	0.71	12.13	$y=1.6571x-2.2451$	0.77	4.34
2/5/2000[3]	OBS	OBS	OBS	$y=1.6558x-2.1868$	0.71	12.13	$y=1.6571x-2.2451$	0.77	4.34
12/5/2000	$y=-0.3526x^2+2.753x+8.093$	0.81	27.31	$y=-0.289x^2+6.4414x-22.148$	0.77	0.62	$y=-0.5364x^2+9.9236x-33.94$	0.79	10.35
12/29/2000[0]	$y=0.7915x^2+0.6691x-10.36$	0.75	31.54	$y=-0.289x^2+6.4414x-22.148$	0.77	0.62	$y=-0.5364x^2+9.9236x-33.94$	0.79	10.35
1/22/2001	$y=-0.3526x^2+2.753x+8.093$	0.81	20.22	$y=-0.289x^2+6.4414x-22.148$	0.77	8.40	$y=-0.5364x^2+9.9236x-33.94$	0.79	1.02
2/18/2002[3]	$y=-0.3526x^2+2.753x+8.093$	0.81	6.26	$y=1.8979x-4.4989$	0.87	41.86	$y=1.9341x-4.5948$	0.86	38.69
3/22/2002[1]	$y=1.5778x+8.9573$	0.79	49.08	$y=1.8979x-4.4989$	0.87	35.88	$y=1.9341x-4.5948$	0.86	38.69
1/4/2003[1]	$y=0.1066x^2+1.2634x+8.689$	0.88	6.45	$y=1.8979x-4.4989$	0.87	19.94	$y=1.9341x-4.5948$	0.86	52.91
2/27/2008[1]	$y=-0.3526x^2+2.753x+8.093$	0.81	26.24	$y=1.7549x-3.2172$	0.76	15.79	$y=1.6571x-2.2451$	0.77	2.75
3/1/2009	$y=1.5778x+8.9573$	0.79	29.30	$y=1.7549x-3.2172$	0.76	23.50	$y=-0.5364x^2+9.9236x-33.94$	0.79	21.11
2/16/2010[1]	$y=1.5778x+8.9573$	0.79	2.59	$y=1.7549x-3.2172$	0.76	8.48	$y=-0.5364x^2+9.9236x-33.94$	0.79	22.96

APPENDIX C: PERMISSION TO REPRINT CHAPTER 2

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Riverine sediment inflow to Louisiana Chenier Plain in the Northern Gulf of Mexico

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A B S T R A C T

The Louisiana Chenier Plain is a geomorphologic extension of the Mississippi Deltaic Plain, highly influenced by sediments originating from the Mississippi River. With the Mississippi River unable to avulse closer to the Plain local riverine sediment resources are integral to maintaining the physical and ecological integrity of the estuaries and marshlands. To gain insight into the sediment resources, this study assessed two decades (1990–2009) of discharge and total suspended solids (TSS) of four rivers, Sabine River, Calcasieu River, Mermentau River, and Vermilion River that flow into the Chenier Plain. The study quantified long-term sediment delivery, analyzed seasonal and inter-annual trends of sediment transport, and investigated the effect of hydrometeorological conditions on sediment yields. Total sediment delivery from the rivers over the 20-year period was 6.86×10^6 tonnes, with the Sabine River contributing 62% of the sediment load. The Sabine River also showed a significant decreasing trend ($p = 0.03$) in annual sediment yield. Long-term trends of sediment loads in all the rivers were influenced by their discharge, not their TSS concentrations. Annual mean sediment load was 342,950 tonnes with higher sediment loading during the winter and spring months and lower during the summer and fall months. Annual sediment inflow has the capacity to create 2.3×10^7 m^2 of land to the depth of 1 cm, but most of this sediment is unable to reach the coastline. The greatest asset that these rivers provide for the Chenier Plain is sediment and freshwater for restoration of marsh lost to salinization or inundation.

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1. Introduction

Riverine sediments are integral resources to coastal environments influencing geological and hydrological processes (Masselink and Hughes, 2003). Much of southern Louisiana has been formed by Mississippi River sediments through the natural process of river avulsion and subsequent delta switching. The Chenier Plain, a physiographic province in southwestern Louisiana, has similarly been influenced by the movement of the Mississippi River sediment plume (Penland and Suter, 1989). In general, when compared with the barrier islands along Louisiana's coast or the Mississippi Deltaic Plain, the Chenier Plain is less well known. Nonetheless the area has gone through many anthropogenic alterations that have exacerbated natural land loss.

The Chenier Plain comprises an area of approximately 5000 km^2 and a coastline of about 200 km. The land cover is dominated by location sensitive salt, brackish, intermediate, and fresh marshlands (Gammill, 2002). The lowland marsh is interspaced by chenier ridges formed during transgressive phases when the Mississippi River sediment plume is unable to reach the plain (for details regarding Chenier Plain formation see Russell and Howe, 1935; Hoyt, 1969, and McBride et al., 2007). Bisecting the plain are four north to south flowing rivers, Sabine River, Calcasieu River, Mermentau River, and Vermilion River. The Sabine River has a drainage area of 25,267 km^2 with a total length of 893 km bordering Texas and Louisiana draining into Sabine Lake before the Gulf of Mexico (Phillips, 2003). The Calcasieu River drainage basin is 9780 km^2 and the river is 322 km long and discharges into Calcasieu Lake before the Gulf of Mexico (Nichol et al., 1992). The Mermentau River basin is 16,997 km^2 with a length of 115 km discharging into Grand Lake before reaching the Gulf (USACE). The Vermilion River is 116 km long with a basin area of 4470 km^2 draining into Vermilion Bay (US EPA Region 6, 2001; USACE, 2004). The Mermentau River and Vermilion River basins are dominated by agriculture and the Calcasieu River and Sabine River basins are dominated by forest (Table 1).

During the past half century all of the rivers have been hydrologically altered substantially. The Sabine River has been dammed in several locations and its lower estuary has been dredged for

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VITA

Timothy Rosen was born in Catonsville, Maryland, in 1987, the son of Sandy Rosen, and Dennis Rosen. Growing up along the shores of the majestic Back River directed his career path towards the environmental sector. He graduated from Mount Saint Mary's University in May, 2009, with a Bachelor of Science degree in biology, minoring in environmental studies. He moved to Baton Rouge, Louisiana, in September, 2009 to pursue his Master of Science degree at Louisiana State University in Renewable Natural Resources concentrating on watershed hydrology. After graduation, Timothy will move to the eastern shore of Maryland to work as a staff scientist for the non-profit Midshore Riverkeeper Conservancy.